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E-Content Subject: - Concrete Technology
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1. **Highway development and planning**

a) Historical development of road construction

Roman roads	They were built straight regardless of gradient, by removing softer soil (trench) till hard stratum. The total thickness was as high as 0.75 to 1.2 m. ➢ Layer of large foundation stones were laid in lime mortar at the bottom. (10-20cm) ➢ Second layer of lime concrete with large broken stones mixed in lime mortar. ➢ Another layer of lime concrete was laid over this with smaller broken stones. ➢ A wearing course of dressed large stone blocks set in lime concrete provided at the top. Enormous cost of construction cannot be justified.
Tresaguet construction	The main feature of this construction was that thickness of construction need to be only in the order of 30 cm. Due consideration was given to moisture condition and draining of surface water. ➢ Subgrade was prepared and a layer of large foundation stones were laid on edge by hand. (kerb stones) ➢ Broken stones were packed to a thickness of 8cm in between and compacted. ➢ Top wearing course was made of smaller stones and compacted with cross slope. ➢ Shoulders were also provided cross slope to drain the surface water.
Telford construction	Heavy foundation stones were used above soil subgrade. Definite cross slope for top surface was provided by varying the thickness of foundation stones.
Macadam Construction	John Macadam put forward an entirely new method of road construction compared to all previous methods. ➢ Importance of subgrade drainage and compaction were recognized and so the subgrade was compacted and was prepared with a cross slope (1:36) ➢ He was first person to suggest ***heavy foundation stone was not necessary***. Compacted layer of smaller size broken stones placed at the bottom. ➢ Thickness was less but better load distribution was achieved.

- Difference between Telford method and Macadam

Macadam method	**Telford method**
➢ The subgrade was given a cross slope of 1:36 to facilitate subgrade drainage. ➢ The bottom layer of pavement or the sub-base course consisted of broken stones of less than 5 cm size to uniform thickness equal to 10 cm only ➢ Base and surface courses consisted of broken stones of smaller sizes to compacted thickness of 10 and 5 cm respectively and the top surface was given a cross slope of 1:36 ➢ The total thickness of pavement construction was kept uniform from edge to center to a minimum value of 25 cm.	➢ The subgrade was kept horizontal and hence subgrade drainage was not proper. ➢ Heavy foundation stones of varying sizes about 17 cm towards edges and 22 cm towards the center were hand packed and prepared to serve as sub-base course. ➢ Two layers of broken stones were compacted over the foundation stones before laying the wearing course, 4cm thick with cross slope of 1:45 ➢ The total thickness of construction varied about 35 cm at the edge to about 41 cm at the centre.

b) Highway development in India

- **Jayakar committee** and recommendations
  - ♦ Indian Road development committee was appointed by the government with M.R. Jayakar as chairman, in 1927. It submitted its report in 1928 and important recommendations were:
    - Road development should be considered as national interest.
    - An extra tax should be levied on petrol, to develop a road development fund called ***Central Road fund***.

- A semi-official technical body should be formed to pool technical know-how from various parts of the country and to act as an advisory body on various aspects of roads. (Indian Road congress was formed)
- A research organisation should be instituted to carry R&D work and to be available for consultation. (Central road research institute)

c) Necessity of highway planning

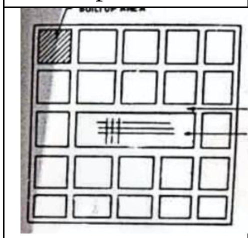
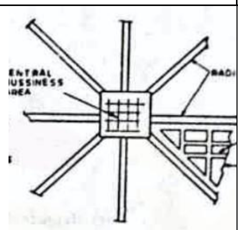
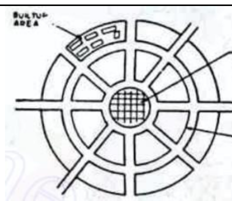
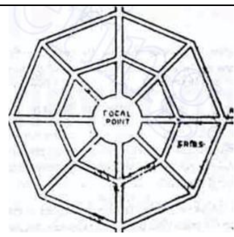
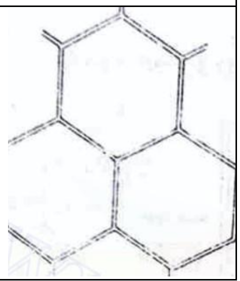
- To plan a road network for efficient and safe traffic operation, at minimum cost.
- To arrive at the road system and the lengths of different categories of roads which could provide maximum utility and could be constructed within the available resources.
- To fix up date wise priorities for development of each road link based on utility as the main criterion for phasing the road development.
- To plan for future requirements and improvements of roads.
- To work out financing system.

d) Classification of road

➢ All weather road ➢ Fair weather road	➢ Paved ➢ Unpaved	➢ Surface roads ➢ Unsurfaced roads	➢ National highways (NH) ➢ State Highways (SH) ➢ Major District Roads (MDR) ➢ Other district roads (ODR) ➢ Village roads (VR)

- Modified classification of road system by third road development plan
  - ♦ Primary system (Express ways, NH)
  - ♦ Secondary system (SH, MDR)
  - ♦ Tertiary system (ODR, VR)

e) Road pattern

Rectangular Block pattern	Radial Star and block	Radial Star and circular	Radial Star and grid	Hexagonal
				

f) Planning surveys

- Highway planning phase includes
  - ♦ Assessment of road length required for an area.
  - ♦ Preparation of master plan showing the phasing of plan in annual or 5-year plans.
- For assessing road length requirement, field surveys are to be carried out to collect data required. The field surveys thus required for collecting the factual data is called ***Fact finding surveys.*** The data collected must confirm to Adequacy, Accuracy, Availability, Accessibility.
- The Planning Surveys consists of following studies

Economic studies	The various details collected are useful in estimating the economics involved in the highway development. Helps in finding the services given by each road system to the population and products of the area. ➢ Population distribution, trend of population growth, listing of agricultural and industrial development, income per capita, banking, post office etc.
Financial studies	The financial studies are essential to study the various financial aspects like sources of income and the manner in which funds for the project may be mobilized. the detail to be collected include:

	➢ Source of income, revenue from taxation, Living standards, future trends- details like vehicle registration, court fees and local taxes etc.
Traffic or road use studies	All the details of the existing traffic, their volume and pattern of flow should be known before any improvement could be planned. ➢ Traffic volume, traffic flow pattern, O&D studies, mass transportation facilities, accidents - their costs, trends, growth of vehicular traffic, passenger trips and good movements.
Engineering studies	All the details of the topography, soil and other problems such as drainage, construction and maintenance should be investigated. ➢ Road location and alignment studies, classification, types of roads, maintenance problems – soil and topography studies, road life studies

g) Interpretation of planning surveys

- The data collected is interpreted for following important purpose
  - ♦ To arrive at the road network, out of several alternate possibilities, which has maximum utility.
  - ♦ To fix up priority of the construction projects, so as to phase the road development plan.
  - ♦ To assess the actual road use by studying the traffic flow patterns.
  - ♦ Based on traffic type, intensity, performance and cross drainage structures, new structures may be designed.
  - ♦ Comparison of the areas may be obtained on the basis on economic activities and area of immediate need identified.
  - ♦ Data can be analysed for further trends in development, can be useful in future planning.

h) Saturation system

- In this system the optimum road length is calculated for area, based on the concept of obtaining maximum utility system per unit length of road. Hence this system is called saturation system or maximum utility system. The factors taken for obtaining utility per unit length are:
  - ♦ Population served by the road network
  - ♦ Productivity served by the network
    - o Agriculture products
    - o Industrial products
- STEPS
  - ♦ For population range utility units are defined ex: 500 to 100, utility unit = 0.5.
  - ♦ Number of towns and villages with population range served is found and then converted into utility units served by each road.
  - ♦ The productivity served is assigned appropriate values of utility units per unit weight. This value is also added for the road system.
  - ♦ The proposal which gives maximum utility per unit length is chosen as the final layout with optimum road length, based on maximum utility on the saturation system.

2. Highway alignment and surveys

a) Highway alignment

- The position or the layout of the central line of the highway on the ground is called the alignment. The horizontal alignment includes the straight path, the horizontal deviations and curves. The changes in gradient and vertical curves are covered under vertical alignment.
- Requirements
  - ♦ The basic requirements of an ideal alignment between two terminal stations are that it should be:
  - ♦ Short, easy, safe and economical.
- Factors controlling alignment
  - ♦ Obligatory point (bridge site, intermediate town, mountain pass)

- Traffic, geometric design (gradient, radius, sight distance), economics, other considerations (drainage consideration).
- Special consideration

b) Engineering survey for highway location

- Before highway alignment is finalized in highway project, the engineering surveys are to be carried out. The surveys may be completed in four stages. First three stages consider all possible alternate alignments keeping in view various requirements of alignment. The stages of engineering surveys are
    - Map study
    - Reconnaissance: examine general character of the area for deciding the most feasible routes for detailed studies.
    - **Preliminary survey**: it has objectives to survey the various alternate alignments proposed after reconnaissance and to collect all the necessary physical information and details of topography, drainage and soil. To compare different proposals in view of alignment. Estimate quality of earth work materials and other construction aspects. And to finalize the best alignment. The procedure of **conventional methods** is:
        - Primary traverse
        - Topographical features
        - Levelling work
        - Drainage studies and hydrologic data
        - Soil survey
        - Material survey: survey for naturally occurring materials like stone aggregates and identification of suitable quarries. Location of cement, lime brick etc. is ascertained.
        - Traffic survey
        - Determination of final center line

        Modern **rapid approach** is by taking the required aerial photographs and by photogrammetric methods and photo-interpretation techniques for obtaining topographic details.
    - Final location and detailed survey

        The alignment finalized at the design office after the preliminary survey is to be first located on the field by establishing the centre line. Detailed survey is carried out for preparation of plans and construction details.
        - Location: layout on ground is done.
        - Detailed survey

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3. Geometric design

a) Introduction

- Geometric design deals with the dimension and layout of visible features of the highway such as alignment, sight distances and intersections.
- The geometric design of highways depends on several design factors. The important of these factors which control the geometric elements are:
    - Design speed, topography, traffic factor (vehicular, human), design hourly volume and capacity, environmental and other factors (aesthetics, landscaping, air pollution, noise)

b) Cross Section element

- Pavement surface characteristics
    - Friction
        - ***Longitudinal coefficient*** of friction is used for calculation of SSD, this friction supports movement of vehicle and depends on the area of contact. Its value ranges from **0.35 to 0.40** as recommended by IRC, depending upon speed.
            - On dry pavement old tyre generates more coefficient of friction than new tyre.

- On wet pavement, water acts as a lubricating agent and new tyre has μ_{lo}
- As the speed increases μ_{lo} decreases.

- ***Lateral Coefficient*** comes in picture only when there is a lateral force on vehicle. When moving on horizontal curve. Its value recommended by IRC is taken as **0.15**
- When translation is more than rotation then it is ***skid***
- Rotation is more than translation, ***slip***

♦ Unevenness index

- It is the cumulative measure of vertical undulations of the pavement surface recorded per unit horizontal length of the road. (mm/Km)
- **Bump Integrator** is used to measure it, as per IRC

Unevenness indicator mm/Km	Type of road
< 1500	Good
$1500 - 2500$	Satisfactory
$2500 - 3200$	Bad
> 3200	Uncomfortable

- A similar factor is used in other countries called IRI (international roughness index)

$$BI = 630(IRI)^{3.35}$$

- Camber or cross slope

♦ Cross slope or chamber is the slope provided to the road surface in the transverse direction to drain off the rain water from the road surface. Usually chamber is provided on the straight roads by raising the center of the carriageway w.r.t the edges, forming crown or highest point on the center line.

♦ At horizontal curves with super-elevation, the surface drainage is effected by raising the outer edge of pavement w.r.t. the inner edge.

♦ **Shape of cross slope**

- The chamber is given a parabolic elliptic or straight-line shape in the cross-section. Parabolic or elliptic shape is given so that the profile is flat at the middle and steeper towards edges, which is preferred by fast moving vehicles as they have to frequently cross the crown line during overtaking operation on a two-lane highway.

♦ The required camber of a pavement depends on, type of pavement surface and amount of rainfall. (IRC)

Type of road	Heavy	Light
Cement concrete and high type bituminous surface	1:50	1:60
Thin bituminous surface	1:40	1:50
Water bound macadam and gravel pavement	1:33	1:40
Earth	1:25	1:33

- Width of pavement

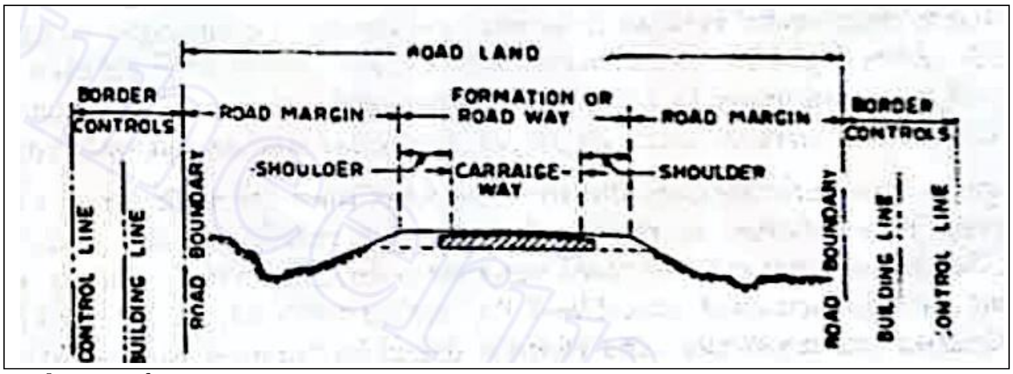
♦ The pavement or carriageway width depends on the width of traffic lane and number of lanes. The lane width is determined on the basis of the width of vehicle and the minimum side clearance which may be provided for the safety.

♦ The maximum width of vehicle as per IRC specification is 2.44 m.

Class of road	Width of carriageway
Single lane	3.75 m
Two lanes, without raised kerbs	7.0
Two lanes, with raised kerbs	7.5
Intermediate carriageway (except on important roads)	5.5
Multilane pavement	3.5 m per lane

- Kerbs

- ♦ Kerb indicates boundary between the pavement and shoulder; or sometimes islands or foot path or kerb paring space. It is desirable to provide kerbs on urban roads. They are mainly divided into three groups.
  - o Low or mountable type kerbs: 10cm above pavement edge with a slope or batter to help vehicles climb the kerb easily.
  - o Semi barrier type kerb: where pedestrian traffic is high. 15cm.
  - o Barrier type kerb: provided in built-up areas adjacent to foot paths with considerable pedestrian traffic. The height of kerb stone is 20cm.
- Divider
  - ♦ It separates two-way traffic. It also reduces glaring effect due to the headlight of vehicle coming from opposite direction as per IRC minimum width of divided for a highway is **5m**. when space is restricted then minimum width of divided should be 3m.
- Road margins
  - ♦ ***Shoulders*** are provided along the road edge to serve as an emergency lane for vehicle compelled to be taken out of the pavement or roadway. Minimum width as per IRC is **2.5m**. surface of shoulder should be *rougher than the traffic lanes* and colour should preferably be different. The chamber of shoulder should be 0.5% steeper than of road and minimum chamber of shoulder is 3%.



  - ♦ Width of roadway or formation
    - o It is the sum of width of pavements or carriageway including separators if any and the shoulders. Formation or roadway width is the top width of the highway embankment or bottom width of cutting.
  - ♦ **Right of way**
    - o It is the area of land acquired for the road along its alignment. The width of this acquired land is known as *land width* and it depends on the importance of the road and possible further development.
    - o It is desirable to control the building construction activities on either side of the road boundary, beyond the land width acquired for the road, in order to reserve sufficient space for further improvement of roads. Therefore, it is necessary to disallow the building activities up to ***building line*** with sufficient setback from the road boundary.
    - o In addition, it is desirable to exercise control of the nature of building up to further set back distance up to the control lines

c) Sight distance

- Stopping Sight Distance (SSD)
  - ♦ It is the minimum sight distance available on highway at any spot, should be sufficient length to stop a vehicle travelling at design speed, safely without collision. (***non-passing sight distance***)
  - ♦ Total reaction time
    - o Perception time: it is the time required for a driver to realise that brakes must be applied.
    - o Brake reaction time: it depends on several factors including the skill of the driver.

- ○ ***PIEV theory***: according to this theory the total reaction of the driver is split into four parts.
  - ▪ *Perception*:
  - ▪ *Intellection*: time in understanding situation.
  - ▪ *Emotion*: time elapsed during emotional sensation.
  - ▪ *Volition*: time taken for final action

♦ **Lag distance**

- ○ $= 0.278Vt_r$
- ○ Reaction time as per IRC is given as:

Distance	t_r
SSD	2.5 s
OSD	2.0 s
Min. space headway	0.7 s

♦ **Braking distance**

- ○ $= \frac{V^<}{5=>(\mu \pm n)}$
- ○ + sign when going uphill
- ○ -ve sign when going downhill

$$\text{SSD, m} = 0.7\text{V} + \frac{\text{V}^5}{254(\mu \pm \text{n})}$$

- ○ On roads with restricted width with two-way movement, minimum SSD is Twice the SSD.

- Overtaking Sight Distance
  - ♦ The minimum distance open to the vision of the driver of a vehicle intending to overtake slow vehicle ahead with safety against the traffic of opposite direction. (***safe passing sight distance***)
  - ♦ For one-way road,

$$\text{OSD} = \text{d}_3 + \text{d}_5 + \text{d}_\text{M}$$

- ○ for two-way divided road d_3 is not required

$$= v_b t_r + (v_b T + 2s) + v_c T$$
$$= 0.278\, V_b t_r + (0.278\, V_b T + 2s) + 0.278 V_c T$$

  - ▪ in Kmph, t_r = 2s reaction time,
- ○ Time taken for overtaking (T) and relative distance $2s$,
- ○ were $s = 0.2V_b + 6 = 0.7v_b + 6$

$$2s = \frac{1}{2} aT^5$$

$$T = \sqrt{\frac{4s}{a}}$$

$$T = \sqrt{\frac{4 \times 3.6s}{A(\text{kmph/s})}}$$

- ○ In case speed of overtaken vehicle is not give $V_b = (V - 16)$ kmph is assumed
- ○ $V_a = V_c$ is taken as design speed
- ○ The acceleration a of the overtaking vehicle is to be specified.

♦ For OSD and ISD, height of obstruction and height of observer both are taken as 1.2m, effect of grade is not taken.

- Overtaking zone
  - ♦ It is desirable to construct highways in such a way that the length of road visible ahead at every point is sufficient for safe overtaking. This is seldom practicable and there may be stretches where the safe overtaking distance cannot be provided.
  - ♦ But the overtaking opportunity for vehicles should be given at frequent intervals. These zones which are meant for overtaking are called ***overtaking zones***.
  - ♦ The sign posts should be installed at sufficient distance in advance to indicate the start of the overtaking zones. Which is equal to OSD. The end of the overtaking zones is also indicated by appropriate sign posts.

- ♦ The minimum length of overtaking zone is **three times** OSD, it is desirable that the length is kept **five times** the OSD.
- Intermediate Sight distance
  - ♦ At stretches of the road where required overtaking sight distance cannot be provided, as far as possible Intermediate sight distance, ISD equal to **twice of SSD**, may be provided.

d) Horizontal Alignment

- Terrain classification
  - ♦ Done on the basis of cross slope

Terrain classification	Cross slope of the country, %
Plain	0-10
Rolling	10-25
Mountainous	25-60
Steep	Greater than 60

- **Super elevation**
  - ♦ In order to counter the effect of centrifugal force and to reduce the tendency of the vehicle to overturn or skid, the outer edge of the pavement is raised w.r.t. the inner edge, thus providing a transverse slope throughout the length of the horizontal curve. This transverse inclination to the pavement surface is known as ***superelevation*** *or* ***cant*** *or* ***banking.***

$$\mu + e = \frac{(0.278\,V)^5}{9.8\,R} = \frac{V^5}{127R}$$

$\mu = 0.15$ lateral coefficient of friction

  - ♦ At **equilibrium super elevation** the friction force generated is zero, and pressure in inner and outer tire is equal, but this will result in a very high value of superelevation.
  - ♦ From practical view point it is necessary to limit the **maximum** allowable **superelevation** to avoid very high values of *e*. This is particularly necessary when the road has to cater for mixed traffic, consisting of fast and slow traffic. IRC has limited maximum *e* to **7%.**
    - ○ On urban roads with frequent intersection 4%, hilly road 10%.

Terrain	e_{max}
Plain and rolling, snow bound	7%
Mountainous & steep	10%
Urban area	4%

  - ♦ Minimum superelevation based on drainage consideration is equal to camber.
- Super elevation DESIGN
  - ♦ In case of mixed traffic condition, speed of travelling vehicles are different, hence the required super elevation is also different. In this case IRC suggest to design the super elevation with 75% of design speed. Considering coefficient of lateral friction as zero.

$$e = \frac{(0.75V)^5}{127R} = \frac{V^5}{225R}$$

  - ♦ STEPS
    - ○ $e = \frac{V^{<}}{55{=}R}$ is calculated neglecting the friction.
    - ○ If $e < 7\%$ provide the calculated superelevation.
    - ○ $e > 7\%$ provide 7% and check
      - ▪ If $\mu = \frac{V^{<}}{35\mathrm{b}R} - 0.07$ is less than 0.15 then 7% is safe, OK

○ Else

      - ▪ Find allowable design speed using
      - ▪ $\mu(0.15) + e(0.07) = 0.22 = \frac{a^{<}}{35\bar{\mathrm{b}}R}$
      - ▪ $V_a = \sqrt{27.94\,R}$ kmph
- Attainment of super elevation

- ♦ Introducing superelevation on a horizontal curve in the field is an important feature in construction.
- ♦ Elimination of crown of cambered section is done by two ways
  - The outer half of the cross slope is rotated about the crown at a desired rate. The elevation of centerline is not altered. No point has negative superelevation. Drawback is that surface drainage will not be proper
  - Diagonal crown method: the crown is progressively shifted outwards, thus increasing the width of the inner half of cross section progressively. This method is not usually adopted as a portion of the outer half has increasing values of negative superelevation on outer half.
- ♦ Two methods of rotating the pavement cross section to attain full superelevation are
  - By rotating the pavement cross section about the centre line, depressing the inner edge and raising the outer edge each by half the total amount of superelevation.
    - Balancing of earth work is achieved but cause drainage problem.
  - By rotating the pavement cross section about the inner edge of the pavement section raising both the centre as well as the outer edge of the pavement by the full amount of superelevation.

- Ruling minimum radius
  - ♦ It is the minimum radius of the curve for a given ruling design speed, considering maximum super elevation and lateral friction.

$$R_{ghijkl} = \frac{V^5}{127(e_{max} + 0.15)}$$

- Absolute minimum design speed
  - ♦ When the minimum design speed V_{min} is adopted instead of ruling design speed, then it is called absolute minimum radius.

$$R_{njk} = \frac{V^5_{min}}{127(e_{max} + 0.15)}$$

- Radius beyond which no super elevation is needed
  - ♦ It is radius of curve corresponding to which super elevation is adopted as equal to camber of road. It is designed on the basis of 75% of design speed considering coefficient of friction as zero.

$$R = \frac{V^5}{225 \times camber}$$

- **Extra Widening**
  - ♦ Mechanical Widening

$$w_m = \frac{nl^5}{2R}$$

  - l is 6 to 6.1m, n is no of lanes
  - ♦ Psychological Widening

$$w_{ps} = \frac{V}{9.5\sqrt{R}}$$

  - ♦ Recommendation of IRC

For single lane	$R > 300$	$50 \le R \le 300$	$R \le 50$
$w_{ps} = 0$ $w_m = \frac{18}{R}$	Extra widening not required	Extra widening is provided in both sides of curve	Extra widening is provided in inner side of curve

- Horizontal Transition curve
  - ♦ Object of providing transition curves
    - Gradual introduction of centrifugal force, avoiding sudden jerk on the vehicle
    - Gradual steering for comfort and security.

- Gradual introduction of super elevation and extra widening.
- To improve aesthetic appearance of the road

- Different types of transition curves
  - The ***ideal shape*** of a transition curve should be such that the rate of introduction of centrifugal force or the rate of change of centrifugal acceleration should be consistent. The length L_s a $\frac{3}{R}$
  - Spiral (*clothoid*)
    - Spiral transition curve fulfils the requirement of ideal transition curve. Radius is inversely proportional to length and rate of change of acceleration is uniform throughout the length. (**IRC *also recommends this***.)
    - The geometric property of spiral is such that the calculations and setting out the curve in the field is ***simple and easy***.
  - For Lemniscate and Cubic parabola rate of change of radius is not constant, at deflection angle higher than 4°.
- Length of transition curve
  - The length of transition curve is designed to fulfil three conditions.
  - The highest of the three values mentioned is length of transition curve.

Rate of change of centrifugal acceleration	The maximum allowable value of rate of change of super elevation, without producing any discomfort $C, m/s^M = \frac{80}{75 + V}$ $[0.5 < C < 0.8]$ $L_t = \frac{(0.278V)^M}{CR}$	
Rate of introduction of super elevation	Rotation about center $L_s = \frac{eN}{2}(w + w_e)$ Rotation about inner edge $L_s = eN(w + w_e)$ where 1:N is the allowed slope	Open country 1:150 Built up area 1:100 Hill roads 1:60
Empirical formula by IRC	for *plain and rolling terrain* $L_s = \frac{2.7V^5}{R}$	for *mountainous and steep terrain* $L_s = \frac{V^5}{R}$

- **Setting Out** of transition curve
  - When transition curves are to be provided on both ends of a circular curve, the curve will shift by an amount *s*

$$s = \frac{L_t^5}{24R}$$

  - Chainage of junction points are

Point of tangency (A1)	Second point A2	Third point	End point (A4)
Chainage of point of intersection – length of tangent	A1+ ½ transition curve	A4 – ½ transition curve	A1+ length of combined curve

  - Total length of combined curve

$$L_c \approx \frac{\pi R \Delta}{180} + L_s$$

  - Length of tangent

$$(R + s)\tan\frac{\Delta}{2} + \frac{L_s}{2}$$

- In this calculation the assumption is that half of the transition curve is in the straight portion and half in the combined circular part.

- **Setback distance**
  - In the design of horizontal alignment, the sight distance along the inner side of the curves should be considered.
  - The *clearance distance or set back distance* is required from the centre line of a horizontal curve to an obstruction on the inner side of curve.
    - $d = \frac{3}{>}(w + w_e)$

	Case I Single lane	Case II Wide roads (more lanes)
$L_c > S.D.$	Length of curve is greater than sight distance, the angle subtended by the arc length S at the centre is α $\frac{\alpha}{2} = \frac{180^o S}{2\pi R}$ Distance from obstruction to center $m = R - R\cos\frac{\alpha}{2}$	d is distance between centre line of road and centre line of the inside lane in meter. $\frac{\alpha^{\text{å}}}{2} = \frac{180S}{2\pi(R-d)}$ $m^{\text{å}} = R - (R-d)\cos\frac{\alpha'}{2}$
$L_c < S.D.$	$\frac{\alpha}{2} = \frac{180^o L_c}{2\pi R}$ $m = R - R\cos\frac{\alpha}{2} + \frac{(S-L_c)}{2}\sin\frac{\alpha}{2}$	$\frac{\alpha^{\text{a}}}{2} = \frac{180L_c}{2\pi(R-d)}$ $m^{\text{å}} = R - (R-d)\cos\frac{\alpha^{\text{å}}}{2} + \frac{(S-L_c)}{2}\sin\frac{\alpha'}{2}$

- Curve resistance
  - Automobiles are steered by turning the front wheels, but rear wheels do not turn. When a vehicle driven by rear wheels moves on a horizontal curve, the direction of rotation of rear and front are different, so there is some loss in the tractive force.
  - This loss of tractive force due to turning on a horizontal curve is termed as *curve resistance*:

$$T(1 - \cos\alpha)$$

e) Vertical Alignment

- Gradient
  - It is the rate of rise or fall along the length of the road w.r.t. the horizontal. It is expressed as ratio of 1 in *x*. it is also expresses as a percentage, *n* i.e., *n* in 100.
  - Gradients are divided into following categories

Ruling gradient	It is maximum gradient within which the designer attempts to design the vertical profile of a road. (design gradient) The IRC has recommended ruling gradient of 1:30 on plain and rolling terrain, 1:20 on mountainous terrain, 1:16.7 on steep terrain.
Limiting gradient	Where topography of a place compels adopting steeper gradient than ruling gradient. Limiting gradients are used in view of enormous increase in cost in constructing roads with gentler gradients. However, the length of continuous grade line steeper than ruling value should be limited.
Exceptional gradient	In some extra ordinary situations, it may be unavoidable to provide still steeper gradients at least for short stretches and in such cases the steeper gradient up to exceptional gradients may be provided. (100m at a stretch)
Minimum gradient	A certain longitudinal slope is essential, to drain the water along the side drains. Hence it is desirable to have certain minimum gradient on roads.

- Grade compensation

- When sharp horizontal curve is to be introduced on a road which has already the maximum permissible gradient, then the gradient should be decreased to compensate for the loss of tractive effort due to the curve.

$$\left(\frac{30+R}{R}\right)\% \; k \; \left(\frac{75}{R}\right)\%$$

- According to IRC the grade compensation is no necessary for gradients **flatter than 4%** therefore, when applying grade compensation correction, the gradients need not be eased beyond 4%.

- **Summit curve**
  - These are vertical curves with ***convexity upwards***. Vertical point of intersection always lies above the curve.
    - They are ***only designed for sight distance criteria***, as a **parabola** shape, due to best riding quality and simplicity of calculations. *Ideal shape* of summit curve is ***circular*** as it can get a constant sight distance throughout the curve.
  - Equation of summit curve
    - Parabolic summit curves are generally adopted, the equation

$y' = \left(-\frac{N}{2L_s}\right)x^5 + n_3 x$	$y = \left(\frac{N}{2L_s}\right)x^5$
y' is taken from horizontal	y is taken from tangent, *Apex equation*

      - Where $N = \lvert n_3 + n_5 \rvert$
      - Length of summit curve L_s measured horizontally
    - Position of crest

$$x = \frac{n_3}{N} L_s$$

    - Position of VPI from VPC is

$$x = \frac{L_s}{2}$$

  - Length of Summit Curve

	General case	SSD ($H = 1.2, h = 0.15$)	OSD ($H = 1.2, h = 1.2$)
$L_s > S$	$L_s = \frac{NS^5}{2(\sqrt{H}+\sqrt{h})^5}$	$L_s = \frac{NS^5}{4.4}$	$L_s = \frac{NS^5}{9.6}$
$L_s < S$	$L_s = 2S - \frac{2(\sqrt{H}+\sqrt{h})^5}{N}$	$L_s = 2S - \frac{4.4}{N}$	$L_s = 2S - \frac{9.6}{N}$

- **Valley curve**
  - These curves have concavity upwards. VPI lie below the curve, it is designed taking headlight sight distance into account. These are made ***fully transitional with cubic parabolic*** shape. Centrifugal forces act downwards so comfort condition is taken into account.
    - HSD: headlight sight distance is the total distance visible through the headlight of vehicle
  - Position of lowest point of valley Curve

$$x = L_v\left(\frac{n_3^{3}}{2N}\right)^5$$

  - Length of **Valley curve**

	General case	SSD ($\alpha = 1^{\circ}, h = 0.75$)
$L_v > HSD$	$L_v = \frac{NS^5}{2h + 2S\tan\alpha}$	$L_v = \frac{NS^5}{1.5 + 0.035S}$

$L_v < HSD$	$L_v = 2S - \frac{2h + 2S\tan\alpha}{N}$	$L_v = 2S - \frac{1.5 + 0.035S}{N}$
Comfort condition	$L_v = 2\sqrt{\frac{Nv^{3}}{C}}$ $C \approx 0.6$	$L_v = 0.38\sqrt{NV^{3}}$

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4. TRAFFIC ENGINEERING

a) Traffic characteristics

- Road user characteristics
  - ♦ Factors affecting road user characteristics
    - o Physical: vision, hearing, strength and general reaction to traffic situation.
    - o Psychological: the emotional factors such as attentiveness, fear, superstition, impatience, general attitude towards traffic and regulations and maturity also comes under this.
    - o Mental: knowledge, skill, intelligence, experience and literacy can affect the road user characteristics.
    - o Environmental: it includes traffic stream characteristics, facilities to the traffic, atmospheric conditions and the locality.
  - ♦ Vision
    - o 6/6 Normal vision: ability to see 8.5mm letter from 6m distance
    - o 6/9 A normal person can see from 9 m but poorer vision person recognizes from 6 m
  - ♦ Design hourly traffic volume is taken as the 30^{th} highest hourly traffic volume, ie that will be exceeded only 29 times in a year.
- Vehicular characteristics
  - ♦ Dimension of vehicle
  - ♦ Weight: maximum weight affects design of pavement thickness and gradients.
  - ♦ Power
  - ♦ Speed
- Braking characteristics
  - ♦ Retardation, Skid distance, Skid resistance, Braking efficiency

b) Traffic study and analysis

- Traffic *studies or surveys* are carried out to analyse the traffic characteristics. These studies help in deciding the geometric design features and traffic control for safe and efficient traffic movements. The traffic surveys for collecting traffic data are also called traffic census. Various traffic studies generally carried out are:

➢ Traffic volume study ➢ Speed study ◊ Spot speed study ◊ Speed and delay study ➢ Origin and destination study	➢ Traffic flow characteristics ➢ Traffic capacity study ➢ Parking study ➢ Accident studies or the traffic flop

c) Traffic volume study

- Traffic volume is the number of vehicles crossing a section of road per unit time at any selected period. Traffic volume counts may be done mechanically or manually.
  - ♦ *Mechanical counters*: they may be either fixed type or portable type. The mechanical counter can automatically record the total number of vehicles crossing a section of road in a desired period. It is not possible to get the traffic volumes of various classes of traffic in the stream and the details of turning movement.
  - ♦ Manual counts: this method employs a field team to record traffic volume on the prescribed record sheets.

- Presentation of traffic volume data
  - ♦ The data collected during the traffic volume studies are sorted out and are presented in any of the following forms depending upon the requirement
    - o Annual average daily traffic (AADT or ADT): in order to convert the different vehicle classes to one class such as passenger car, conversion factors known as *Passenger car units* are used.
    - o *Trend chart* shows volume trends over period of years, used for future planning.
    - o *Variation chart* shows hourly or seasonal variations
    - o Traffic flow maps along the routes are drawn
    - o Volume flow diagram at intersections, showing the details of crossing or turning traffic.
    - o ***Thirtieth highest hourly volume*** or design hourly volume is found from the plot between hourly volume and the number of hours in a year that the traffic volume is exceeded. It is exceeded 29 times in a year.

d) Speed study

- Terms
  - ♦ *Travel time*: it is the reciprocal of speed and is a simple measure of how all well a road network is operating.
  - ♦ *Spot speed*: it is the instantaneous speed of a vehicle at a specific section or location.
  - ♦ ***Time mean speed***: it represents the speed distribution of vehicles ***at a point*** on the roadway, it is the average of instantaneous speeds of observed vehicles at the spot.

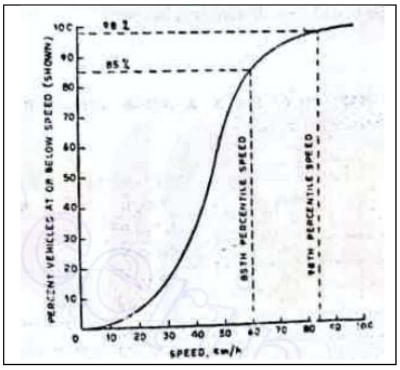
$$V_t = \frac{\sum V_i}{n}$$

  - ♦ ***Space mean speed***: it represents average speed in a road length at any time. It is obtained from the observed travel time of vehicles over a relatively long stretch of the road.

$$V_s = \frac{3.6 \times n \times d}{\sum t_i}$$

d = length of the road	n =number of vehicles observed
t_i = observed time for ith vehicle to travel distance d (meters)	

  - ♦ *Running speed*: it is the average speed maintained by a vehicle over a particular stretch, while the vehicle is in motion; this is obtained by dividing the distance covered by the time during which the vehicle is actually in motion.
  - ♦ *Travel speed*: it is the effective speed with which a vehicle traverses a particular route between two terminals; this is obtained by dividing the total distance travelled by total time taken including all delays and stoppages enroute.
- Spot speed study
  - ♦ One of the simplest methods of finding spot speed is by using ***enoscope*** which is just a mirror box supported on a tripod stand.
    - o Other equipment used for spot speed measurements are graphic recorder, electronic meter, photo electric meter, radar, speed meter and by photographic methods.
  - ♦ **Cumulative speed distribution chart**



    - o After collecting spot speed data, in a stretch, a graph is plotted with the average values of each speed group on the X-axis and the cumulative percent of vehicles travelled at or below the different the different speeds on the Y-axis. From this graph the 85th percentile speed is found out. It is this speed 15% of vehicles exceed.
      - ▪ ***85th percentile speed*** is taken for speed regulations as ***safe speed limit***.

- However, for the purpose of highway geometric design, ***the 98th percentile*** speed is taken as the ***design speed*** of existing road facility.
- 15th percentile speed represents the lower speed limit if it is desired to prohibit slow moving vehicles to decrease delay and congestion.

- Speed and delay study
  - ♦ The speed and delay studies give the running speed, overall speeds, fluctuations in the speeds and the delay between two stations of a road spaced far apart. They also give the information such as amount, location, duration, frequency and cause of the delay in the traffic stream.
  - ♦ Various methods of carrying out speed and delay study are:

➢ Floating car or riding check method ➢ License plate or vehicle number method ➢ Interview technique	➢ Elevated observer ➢ Photographic technique

  - ♦ **Floating Car method**
    - o In the floating car method, a test vehicle is driven over a given course of travel at approximately the average speed of the stream, thus trying to float with the traffic stream. A number of test runs are made along the study stretch and a group of observers record various details.

➢ Observer 1 Seated with two stop watches, record time at various control points and duration of individual delays.	➢ Observer 2 Time location and cause of delays are recorded in a tabular form.
➢ Observer 3 Number of vehicles overtaking the test vehicle and that overtaken by test vehicle is noted	➢ Observer 4 Number of vehicles travelling in opposite direction in each trip is noted.

    - o The ***average journey tim***e $\bar{t}$ (minute) for all the vehicles in a traffic stream in the direction of flow q is given by:

$$\bar{t} = t_\dagger - \frac{n_y}{q}$$

    - o q = flow of vehicles (volume per min), in one direction of the stream

$$q = \frac{n_a + n_y}{t_\dagger + t_a}$$

      - n_a = average number of vehicles counted in the direction of the stream when the test vehicle travels in the opposite direction.
      - n_y = average number of vehicles overtaking the test vehicle minus the number of vehicles overtaken when the test is in the direction of q
      - $t_\dagger$ = average journey time, in minute when the test vehicle is travelling with the stream q
      - t_a = average journey time, in minute when the test vehicle is travelling against the stream q

e) Origin and destination (O&D) study

- O&D studies are carried out mainly to
  - ♦ Plan the road network and other facilities for vehicular traffic
  - ♦ Plan the schedule of different modes of transportation for the trip demand of commuters.
- Method
  - ➢ Road side interview method
  - ➢ License plate method
  - ➢ Tag on car method
  - ➢ Return post card
  - ➢ Home interview
  - ➢ Work spot interview method
- Presentation of O&D data
  - ♦ O&D tables are prepared showing number of trips between different zones

- ♦ O&D study provides the basic data for determining the desired directions of flow or the ***desire lines***. Width of desire line is drawn proportional to the number of trips in both directions.
- ♦ With pie charts the relative magnitude of generated traffic and geometrical relationships of the zones involved may be represented.
- ♦ Contour lines plotted similar to topographic contours, the shape of the contours would indicate the general traffic need of the area.

f) Traffic flow characteristics

- The basic traffic maneuvers are diverging, merging and crossing.
- The points studied in traffic flow are transverse and longitudinal distribution of vehicles in on the various routes
  - ♦ The time interval between the passage of successive vehicles moving in the same lane and measured from head to head as they pass a point on the road is known as *time headway*.
  - ♦ The distance between successive vehicles moving in the same line measured from head at any instance is the *space headway* or the spacing of the vehicles in the stream.

g) Capacity studies

- Terms
  - ♦ **Traffic volume** is the number of vehicles moving in a specified direction on a given lane or roadway that pass a given point or cross section during specified unit of time. (vehicles per day)
  - ♦ **Traffic density** is the number of vehicles occupying a unit length of lane of roadway at a given instant, usually expresses as vehicles per kilometer.
  - ♦ Traffic capacity
    - o It is the ***ability of a roadway to accommodate traffic volume***. It is expresses as the maximum number of vehicles in a lane or a road that can pass a given point in unit time. Capacity indicates a capability or maximum rate of flow with a certain level of service characteristics that can be carried by the roadway.
    - o *Basic capacity*: it is a theoretical capacity under ideal condition, two road having same physical features will have the same basic capacity.
    - o *Possible capacity*: it is the maximum number of vehicles that can pass a given point on a lane or roadway during an hour under prevailing roadway and traffic conditions.
    - o ***Practical capacity***: is the maximum number of vehicles that can pass a given point on a lane or roadway during one hour, without traffic density being so great as to cause unreasonable delay, hazard or restriction to the driver's freedom to maneuver. It is also called design capacity.
- Determination of theoretical capacity
  - ♦ An estimate of theoretical maximum or basic capacity of a single lane may be made from the relation

$$C = \frac{1000V}{S}$$

    - o Thus, the capacity depends upon the speed *V* and spacing *S*.
    - o Space headway $S = (0.2V + L)$ m
  - ♦ It has been observed that with increase in speed of the traffic stream, the time headway decreases and after reaching a minimum value at an optimum speed, starts increasing. The maximum theoretical capacity of a traffic lane may therefore be obtained if the minimum headway H_t is known.

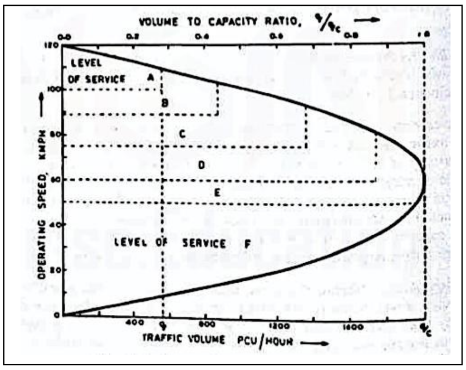
$$C = \frac{3600}{H_t}$$

- Factors affecting practical capacity

➢ Lane width	➢ Alignment
➢ Lateral clearance	➢ Presence of intersections at grade

➢ Width of shoulders ➢ Commercial vehicles	➢ Other factors driver characteristics, stream speed

- Design capacity and **level of service**
  - ♦ The capacity flow or the maximum possible flow on a roadway or a traffic lane is attained at particular ***optimum speed***, the flow decreases at higher as well as lower speed values.
  - ♦ Highway capacity manual considers two factors for level of service
    - o Ratio of service volume to capacity q/q_c
    - o Operating or travel speed
  - ♦ HCM has suggested ***six levels*** of services A, B, C, D, E and F
    - o A is considered to exist when the volume to capacity is so low that most of the individual vehicles have opportunities to travel at their own desired speeds.
    - o With increase in volume or the volume to capacity ratio, the operating speeds of faster vehicles and their opportunities to overtake decreases and the level of service fall to decreasing values of B C D and E.
    - o Further increases in vehicle causes further decrease in stream speed as well as in maximum flow, resulting in undue congestion and lowest level of service F when forced flow condition exist.



- Passenger Car unit
  - ♦ This is used to convert the different vehicle class to one class such as passenger car, conversion factors known as PCU are used.
    - o $PCU = \frac{speed\ ratio}{Length\ ratio}$
    - o Tentative equivalency factors suggested by the IRC

Vehicle class	Equivalency factor
Passenger car, tempo	1.0
Bus, truck	1.6
Motor cycle	0.5
Cycle rickshaw	1.5
Horse drawn vehicles	4.0
Small bullock cart	6.0
Large bullock cart	8.0

h) Traffic analysis

- The fundamental relationship between traffic volume, density and speed may be given by

$$q = kv$$

  - o time headway $= 1/q$
  - o space headway $= \frac{1}{k}$ also $s = 0.2V\left(\frac{km}{hr}\right) + 6$

Green Shield Method	**Greenberg's model**
$$v = v_f\left(1 - \frac{k}{k_j}\right)$$ Form maximum capacity $$q = kv_f\left(1 - \frac{k}{k_j}\right)$$ $$\frac{dq}{dk} = 0$$ we get	$$v = v_o \ln\left(\frac{k_j}{k}\right)$$ Form maximum capacity $$q = kv_o \ln\left(\frac{k_j}{k}\right)$$ $$\frac{dq}{dk} = 0$$ we get

$k = \frac{k_{\pm}}{2}$ $q_{max} = \frac{1}{4} v_{ø} k_{\pm}$	$k = \frac{k_{\pm}}{e}$ $q_{max} = \frac{1}{e} v_{¥} k_{\pm}$

- Queue and delay study Poisons distribution
  - Probability of occurrence of event x time in a given time period

$$p(x) = \frac{\lambda^x e^{-}}{x!}$$

  - λ = mean of the distribution
  - $\sigma^5 = \lambda$

i) Accident Studies

- Objectives
  - To study the cause of accidents and to suggest corrective treatment at potential location.
  - To evaluate existing design, support proposed design and carry out before and after studies to demonstrate improvement.
  - To compute financial loss and give economic justification for improvements.
- Analysis of individual traffic accidents
  - In perfectly plastic collision

$$m_a v_a + m_b v_b = (m_a + m_b) v^{å}$$

  - Skid distance

$$S = \frac{V_3^5 - V_5^5}{254\mu}$$

  - Using basic conservation of momentum equation to find skid distance and other parameters required.

j) Parking studies

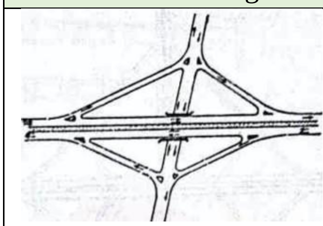
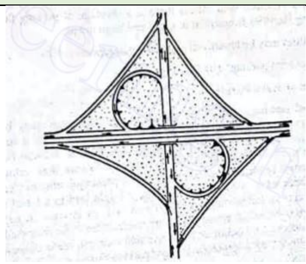
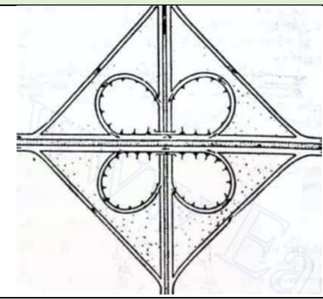
- Various aspects to be investigated during parking studies are:
  - Parking demand
  - Parking characteristics: present parking practices and general problems in parking.
  - Parking space inventory: survey of area where parking space can be provided.
- On street parking
  - When the parking facilities is provided along the kerb of road.
  - Angle parking is allowed (45º is considered best)

	Parallel	30º	45º	60º	90º
Number of vehicles N	$\frac{L}{6.6}$	$\frac{L - 0.85}{5.1}$	$\frac{L - 2}{3.6}$	$\frac{L - 2}{2.9}$	$\frac{L}{2.5}$

- Off street parking
  - When parking facility is provided away from curve it is called off-street parking. There is no congestion and delay caused due to this.

k) Traffic control devices

- Grade separated intersection

Diamond interchange	Partial clover leaf	Full clover leaf
		

- At Graded intersection

- Conflict points
    - Crossing conflict points are major conflict points.
    - Merging and diverging conflict points are minor conflict points.
        - In two-way two-lane road total **24** conflict points (*16 major, 8 minor*)

- **Rotary design**
    - A traffic rotary is an enlarged road intersection where all converging vehicles are forced to move round a large central island in one direction before weaving out. It eliminates the necessity of stopping even for crossing streams of vehicles and reduces the area of conflict.
    - Shape of central island
        - It depends on the number and layout of the intersecting roads.
        - Circular rotary, elliptical rotary is provided, Tangential and turbine rotary is not provided, as there is problem of over speeding.
    - DESIGN guidelines
        - Maximum traffic 3000 PCU/hr and minimum 500 PCU/hr

Parameters (IRC)	Urban	Rural
Design Speed	30kmph	40kmph
Radius of entry curve	15m	30m
Radius of central island	20m	40m
Width of entry (e_1)	8.5	7.25
Width of exit	11.25	10

        - Radius at entry, exit and central island:

Entry	Exit	Center
$R = \frac{V^3}{127\mu}$	$(1.5 \text{ to } 2)R_{entry}$	$\frac{4}{3}R_{entry}$

        - Width at entry depends upon the traffic entering the intersection and width of approaching road. Minimum width of carriageway at entrance and exit should be 5m. the entry width can be increased to 6.5, 7.0 and 8.0 when the carriageway width of approach road is 7.0, 10.5 and 14.0 m respectively.
        - Width and length of weaving section
            - Weaving length should be at least four times the width of weaving section.

$$L \nless 4w$$

            - The minimum width of roadway between edge of central island and adjoining kerb is the effective width of the rotary roadway or the weaving section and this determines the capacity of the rotary.
            - Width of non-weaving section (e_2) should be equal to the widest single entry to the rotary. The width of weaving section W should be one traffic lane wider than mean width of the entry and non-weaving section.

$$W = \left(\frac{e_3 + e_5}{2} + 3.5\right)$$

    - Practical capacity of a rotary
        - Practical capacity of a rotary is the minimum capacity among various weaving section, which is obtained corresponding to maximum weaving ratio.

$$Q_p = \frac{280W\left(1 + \frac{e}{W}\right)\left(1 - \frac{p_{max}}{3}\right)}{\left(1 + \frac{W}{L}\right)}$$

        - Proportion of weaving traffic (0.4 - 1) or weaving ratio.

$$p = \frac{b + c}{a + b + c + d}$$

    - Advantages of Rotary

        - There is necessity of any vehicles, to stop and proceed, thus the journey is more consistent and comfortable.
        - The variable cost of operation of automobile is less at traffic rotary.
        - There is no necessity of traffic police or signal to control the traffic. The maintenance cost is almost nil.
        - The possible number of accidents and the severity of accidents are quite low because of low relative speed.
    - Limitation
        - Rotary requires comparatively large area of land, costly in built up area.
        - When pedestrian traffic is large, rotary by itself cannot control the traffic.
        - When the angle of intersection is too acute or when there are more than seven intersecting roads, rotaries are unsuitable.

- **Traffic signal**
    - At intersection where there are a large number of crossing and right-turn traffic, there is possibility of several accidents. The engineer has to design the signal with the sequence and duration of individual phases to serve all approaching traffic at a desired level of service. The level of service is measured by the vehicle delay, queue length or the number of vehicles backed up and the probability of a vehicle entering the intersection.
    - Types of signals and signal system
        - Signal types
            - Traffic control signal
                - Fixed-time signal
                - Manually operated signal
                - Traffic actuated (automatic) signal
            - Pedestrian signal
            - Special traffic signal
        - **Signal system**

Simultaneous system	All the signals along a given road always show the same indication at the same time, as the division of cycle is also the same at all intersection, this system does not work satisfactorily.
Alternate system	Alternate of groups of signals show opposite indications in a route at the same time. More satisfactory than simultaneous system.
Simple progressive system	➢ A time schedule is made to permit, as nearly as possible, a continuous operation of groups of vehicles along the main road at a reasonable speed. ➢ The signal phases are scheduled to work at the predetermined time schedule. The phases and intervals at each signal installation may be different, but each signal unit works as fixed time signal, with equal signal cycle length.
Flexible progressive	In this system, it is possible to automatically vary the length of cycle, cycle division and time schedule at each signalized intersection with the help of a computer. This is most efficient system of all the four types.

    - Terms
        - The period of time required for one complete sequence of signal indications is called cycle.
        - A part of the signal cycle allocated to a traffic movement or a combination of traffic movement is called phase.

        - Amber time
            - It is provided after the green time just for the clearance of the moving traffic. It can be calculated as

- ◊ $A_{req} = \frac{\text{øø¿ ¡ ¬jdf• ™« ™f•»g g™…d ¡}}{v}$
  - If provided amber time is less than the required amber time then dilemma zone is created.
- Lost time
  - It is part of cycle time not utilized effectively by any phase
    - ◊ *Startup lost time*: it is total lost time at the start of the green time.
    - ◊ *Clearance lost time*: it is the green time which is not utilized. It can be taken as amber time if not known
- Effective green time
  - It is actual time available for traffic to cross the intersection

$$G_i = G + A - (t_{sl} + t_{cl})$$

- Some important formula
  - Dividing total effective green time according to traffic volume

$$G_{i3} = \frac{q_3}{q_3 + q_5} \times (G_{i3} + G_{i5}) = \frac{q_3}{q_3 + q_5}(R - L_3 - L_5)$$

  - Capacity

$$= \left(\frac{G_i}{T} \times \frac{3600}{h_i}\right)$$

  - Cycle time on the basis of startup lost time

$$Cycle\ time\ T = \left(\frac{nt_{sl}}{1 - \frac{\Sigma v_i}{s_i}}\right)$$

♦ Design of signal timing (**Webster's method**)

- In this method optimum signal cycle C_o corresponding to least total delay to the vehicles at the signalized intersection has been worked out. This is a *rational approach*. The field work consists of finding (i) saturation flow on each approach (ii) normal flow *q* on each approach during the design hour.
- Optimum cycle time

$$C_o = \frac{1.5L + 5}{1 - Y}$$

  - $L = 2n + R$ is total lost time per cycle
    - ◊ n is number of phase and R is all Red time
  - $Y = y_3 + y_5$ for two phase and $y_3 + y_5 + y_M + y_>$ for 4 phases
  - Critical flow ratio $y_i = \frac{q_i}{S_i}$
- Green time

$$G_3 = \frac{y_3}{Y}(C_o - L)$$

$$G_5 = \frac{y_5}{Y}(C_o - L)$$

- **Traffic sign**

♦ Prohibitory/ Regulatory signs

- These signs are mandatory signs, meant to inform the road users of certain laws regulations and prohibitions; the violation of these signs is a legal offence.
- Stop sign is red in colour with white border, others are white in colour with red borders.

- Warning signs
    - These signs are used to warn the road users of certain hazardous conditions that exist on or adjacent to the roadway. They are in the shape of equilateral triangle with its apex pointing upwards. With red boundary and white background.
- Informatory signs
    - These signs are used to guide road users along routes, provide information to make travel easier, safe and pleasant.

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5. Pavement Design

a) Types of pavement

- *Flexible pavement*: these have negligible flexural strength. It reflects the deformation of the lower layers on-to the surface. A typical flexible pavement consists of four components.

Surface course	It is to give a smooth riding surface that is dense. Resists pressure of tyres and take up wear and tear due to the traffic. Offers water tight layer against the surface infiltration.
Base course Sub-base course	These layers are made of broken stones, bound or unbound aggregates. Sub-base course primarily has the similar function as of the base course and is provided with inferior materials than of base course. ➢ Improve load supporting capacity by distributing the load through a finite thickness.
Soil subgrade	It is a layer of natural soil prepared to receive the layers of pavement materials placed over it.

- *Rigid pavement*: these possesses flexural rigidity. The stresses are not transferred from grain to grain as in flexible pavement layers. They have slab action and is capable of transmitting the wheel load stress through a wider area below. It can bridge the minor variations of the lower layer.

Cement concrete slab	Same as above
Base course	➢ Prevent pumping ➢ Protecting subgrade against frost action
Soil subgrade	Same as above

- *Semirigid pavement*: sub base and base course of a flexible pavement is replaced by pozzolanic concrete then strength of pavement increases.
- *Composite pavement*: bituminous course is provided at the top of cement concrete pavement.

	Flexible pavement	**Rigid pavement**
Layers	Surface course (BC, DBC) Base course (WMM, WBM) Sub-base course (GSB) Subgrade (soil)	Surface course (PCC, RCC) Base course (dry lean concrete) Subgrade (soil)
Load	Grain to grain contact	layer
Flexural rigidity	Negligible	Significant
joints	No joints required	Expansion contraction joints are provided

Failure	Failure at subgrade appear at top	Failure not reflected on top surface
Cost	Low initial cost, high maintenance	High initial cost, low maintenance

b) Design Parameters

- Maximum wheel load
  - ♦ The wheel load configurations are important to know the way in which the loads of a given vehicle are applied on the pavement surface. For highways the maximum legal axel load as per IRC is
    - o Maximum standard Axel load = 8170 kg = 8.2 tones = 80kN
    - o Single wheel load 4085 kg
    - o Dual wheel assembly load = 10.2 tones
  - ♦ Total load influences the thickness requirement of pavements. Tyre pressure influences the quality of surface (wearing) course.
  - ♦ Vertical stress at any depth under a uniformly distributed circular load, *Boussineq's theory*

$$\sigma_z = p\,\text{Ÿ}1 - \frac{z^{M}}{(a^5 + z^5)^{\frac{M}{5}}}\text{¤}$$

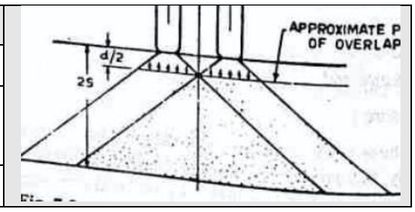
$$\sigma_z = p(1 - \cos^{M}\alpha)$$

- Contact pressure
  - ♦ Tyre pressure of high magnitudes demand high quality of materials.

$$p = \frac{P}{\pi a^5} = \frac{\text{Load on wheel}}{\text{contact area}}$$

    - o z is depth, a is radius of contact area.
  - ♦ Rigidity factor
    - o $RF = \frac{\text{›™kƒ…›ƒ fig»flflhg»}}{\text{ƒ‡g» fig»flflhg»}}$
    - o Value of rigidity factor is 1 for an average tyre pressure of 7kg/cm^2. RF > 1 for lower tyre pressure and RF < 1 for higher tyre pressure.
    - o For design contact pressure is taken as tyre pressure = 7kg/cm^2
- Equivalent Single Wheel Load (ESWL) for a dual wheel assembly
  - ♦ It is defined as the load on single tyre which will cause an equivalent magnitude of parameter such as stress, strain and deflection at the given location is same as that resulting from multiple wheel load at same location

Depth	Equivalent load
$d/2$	$ESWL = P$
$\frac{d}{2} < z < 2S$	$\frac{\log 2P - \log P}{\log 2S - \log d/2} = \frac{\log p_z - \log p}{\log z - \log d/2}$
$2S$	$ESWL = 2P$



    - o d is clear spacing between tyres and S = d+2a is c-c spacing between types
- Repetition of loads
  - ♦ Deformation of pavement or subgrade due to a single application of wheel load may be small, but due to repeated application of the load there would be increased magnitude of plastic and elastic deformations and the accumulated unrecovered or permanent deformations may even result in pavement failure.
  - ♦ Traffic composition in India is mixed type and it is essential for design purpose to convert the various wheel loads to one single standard wheel load.
  - ♦ If a pavement structure fails with N_1 number of repetitions of P_1 load and similarly with N_2 number of repetitions of P_2 load, then
  - ♦ McLeod theorem

- P a $\frac{3}{N}$
- $P_3 N_3 = P_5 N_5$

c) Flexible Pavement

- For design purpose, it is required that various pavement materials are assigned strength parameters suitable to the design method employed for the purpose. Various materials used in subbase course and base course are evaluated by different tests.
- **Group Index Method**

$$GI = 0.2a + 0.01bd + 0.005ac$$

$a = (p - 35) < 40$	$b = (p - 15) < 40$	$c = (LL - 40) < 20$	$d = (I_p - 10) < 20$

  - ♦ $p\ is\ \%\ finner$
  - ♦ GI value ranges from Zero to 20, as GI value increases soil become poorer for pavement.
  - ♦ Thickness of pavement depends on GI value only, whereas thickness of surface course and base course depends on GI value as well as traffic volume.
  - ♦ This method does not consider the quality of pavement material used.
- **CBR method**
  - ♦ CBR test
    - The strength of the subgrade is an important factor in the determination of the thickness required for a flexible pavement. It is expressed in terms of its 'California Bearing Ratio', usually abbreviated as 'C.B.R.'.
    - The results obtained by these tests are used in conjunction with empirical curves, based on experience, for the design of flexible pavements.
    - The test is arbitrary and the results give an empirical number, expressed usually in per cent, which may not be directly related to fundamental properties governing the shear strength of soils, such as cohesion and angle of internal friction.
    - The California bearing ratio (CBR) is defined as the ratio of the force per unit area required to penetrate a soil mass with a standard circular plunger of 50 mm diameter at the rate of 1.25 mm/min to that required for the corresponding penetration of a standard material.
    - The standard material is crushed stone and the load which has been obtained from a test on it is the standard load, this material being considered to have a CBR of 100%.
    - Soil sample is taken and load is applied through the mechanical arrangement of loading system.
    - Load settlement graph is plotted and value corresponding to *2.5mm* and *5mm* penetration is noted, by comparing it with standard values, CBR value is calculated.
  - ♦ CBR Value

$$= max \begin{cases} \frac{P_{5.=mm}}{1370\ kg} \times 100 \\ \frac{P_{=mm}}{2055\ kg} \times 100 \end{cases}$$

    - Generally, CBR 2.5 is more than CBR 5.0, but if CBR 5 is found more then, the experiment is repeated and if confirmed that CBR 5 is more, maximum value is taken.
  - ♦ Thickness of pavement above test layer

$$t(cm) = \sqrt{P}\sqrt{\frac{1.75}{CBR} - \frac{1}{\pi p}}$$

$$t = \sqrt{\frac{1.75P}{CBR} - \frac{A}{\pi}}$$

    - P = wheel load in kg, p = tyre pressure kg/cm^2

- $\frac{P}{\pi p} = \frac{P}{\pi P/A} = \frac{A}{\pi} = a^5$

- This method is **not valid** for CBR more than **12%,** and quality of material used in not taken into consideration.
- IRC recommendation: in new constructions the CBR test samples may be soaked in water for four days period before testing. However, in areas with arid climate or when the annual rainfall is less than 50cm and the water table is too deep to affect the subgrade adversely and when thick and impermeable bituminous surfacing is provided, it is not necessary to soak the soil specimen before carrying out CBR test. Whenever possible the most adverse moisture condition of the subgrade should be determined from the field study.

- **Triaxial Load Method**
  - This design method is based on Boussinesq's displacement equation for homogeneous elastic single layer:

$$\Delta = \frac{3pa^5}{2E(a^5 + z^5)^{\frac{3}{5}}}$$

$$\Rightarrow \Delta = \frac{3}{2\pi}\frac{P}{E\sqrt{a^5 + z^5}}$$

$$\Rightarrow \sqrt{a^5 + z^5} = \frac{3P}{2\pi E}$$

$$\Rightarrow a^5 + z^5 = \left(\frac{3P}{2\pi E\Delta}\right)^5$$

$$z = \sqrt{\left(\frac{3P}{2\pi E\Delta}\right)^5 - a^5}$$

- Assuming the pavement is incompressible $z = t$

$$t(cm) = \sqrt{\left(\frac{3P}{2\pi E_s\Delta}\right)^5 - a^5}$$

- $\Delta = 0.25$cm is ***design deflection***,
- Efl is modulus of elasticity of subgrade from triaxial test result, kg/cm^2
- P wheel load in kg

  - The triaxial compression test is used to determine the value of elastic moduli for various materials. A lateral pressure of 1.4 kg/cm^2 is applied in the test to find E value of the material. Empirical modification for traffic and degree of saturation is used as multiplying factor, to the total pavement thickness value.

$$t(cm) = \sqrt{\left(\frac{3PXY}{2\pi E_s\Delta}\right)^5 - a^5}$$

- X traffic coefficient,
- Y rain fall coefficient

  - If pavement and subgrade are considered as two-layer system, *a stiffness factor* has to be introduced to take into account the different values of modulus of elasticity of the two layers. The pavement thickness is then modified using the stiffness factor equal to $\left(\frac{E_s}{E_p}\right)^{3/M}$, E_s modulus of elasticity of subgrade, E_p modulus of elasticity of pavement.
    - Modified thickness of pavement above subgrade

$$t(cm) = \sqrt{\left(\frac{3PXY}{2\pi E_s\Delta}\right)^5 - a^5} \cdot \left(\frac{E_s}{E_p}\right)^{3/M}$$

  - The relation between pavement thickness t_3 and t_5 is

$$\frac{t_3}{t_5} = è \frac{E_5}{E_3} ê^{3/M}$$

- **Burmister's (layered system) Method**
  - This method is based on modulus of elasticity of different layers of pavement. Mainly plate bearing test is employed for this purpose.
  - $E_{sc} > E_{BC} > E_{SBC} > E_{SG}$
  - Assumptions:
    - Material is homogeneous, isotropic and elastic
    - Surface layer is infinite in horizontal direction but finite in vertical direction.
    - Layers are in continuous contact. The top layer is free of shearing and normal stress outside the loaded area.
  - Displacement Equations
    - Plate bearing test/ **rigid plate**

$$\Delta = 1.18 \frac{pa}{E_s} F_5$$

    - Wheel load test/ flexible plate

$$\Delta = 1.5 \frac{pa}{E_s} F_5$$

      - F_2 – deflection factor (= 1, if test is conducted over soil subgrade)
      - F_2 is dependent on E_s/E_p and h/a

p- surface pressure, *a*- *contact radius*, *Es*- elastic modulus of subgrade

- IRC Method (IRC 37: 1985)
  - Cumulative number of standard axle load repetition:
    - Code recommends design in terms of cumulative number of standard axle load repetitions for flexible pavement *instead of design in terms of commercial vehicles* as done earlier.
    - The mixed commercial vehicle with different axles loads is to be converted in terms of **cumulative standard axle** load N_s

$$N_s = \frac{365\mathrm{A}[(1+\mathrm{r})^{\mathrm{k}} - 1]}{\mathrm{r}} \mathrm{F} \times \mathrm{D}$$

      - A is commercial vehicle per day when construction is completed

$$A = N(1+r)^m$$

      - n is design life of pavement, taken 10 to 15 years.
      - F is vehicle damage factor
  - Cumulative standard Axel for design purpose ***for more than one type of vehicle*** we can directly use this formula

$$\mathrm{CSA}_3 = \frac{365\mathrm{N}_3\mathrm{DF}_3\{(1+\mathrm{r}_3)^{\mathbf{ni}\,\mathrm{k}} - 1\}}{\mathrm{r}_3}$$

$$CSA = {}^{\circ}\, CSA_3 + CSA_5 + \cdots$$

      - N- repetitions,
      - D- distribution factor,
      - F- load factor/damage factor,
      - *m* is the period of delay between the date of traffic studies and the date of completing construction and opening to traffic.
      - *n* is design life
      - *r* is average rate of growth,

Single carriage way, two-way traffic	N should be sum of two-way traffic
Dual carriageway, divided traffic	N should be one side traffic

- **Distribution factor**

# carriage way	#Lanes	Distribution factor *D*	
1	1	1	Total number of vehicles in both direction
1	2	0.75	Total number of vehicles in both direction
1	4	0.40	Total number of vehicles in both direction
2	2	0.75	Total number of vehicles in **each** direction
2	3	0.60	Total number of vehicles in **each** direction
2	4	0.45	Total number of vehicles in **each** direction

- F (vehicle **damage factor**)
    - It is the factor which converts number of commercial vehicles of different axle load to the number of standard axle load repetitions.
    - Equivalent axel load factor

$$EALF = \left[\frac{L_o}{L_s}\right]^4$$

    - According to fourth power law, the number of passes N_f of a wheel load P needed to cause failure is approximately inversely related to fourth power.
        - $N_f \propto \frac{1}{P^4}$

d) Rigid Pavement

- Modulus of Subgrade Reaction
    - Westergaard considered the rigid pavement slab as a thin elastic plate resting on soil subgrade, which is assumed as a dense liquid. Here it is assumed that the upward reaction is proportional to the deflection $p = K\Delta$, where the constant K is defined as modulus of subgrade reaction.
        - The displacement Δ is taken as $\Delta = 0.125$ cm, and the rigid plate of diameter 75cm is used.

$$K = \frac{p}{\Delta} = \frac{p}{0.125}\ (\text{kg/cm}^3)$$

    - For different plate size (***75cm standard plate***)

$$K \times A = K_1 \times A_1$$

    - It can be considered as spring constant per unit area.
- **Radius of relative stiffness**
    - A certain degree of resistance to the slab deflection is offered by the subgrade. This is dependent upon the stiffness or pressure deformation characteristics of subgrade material.
    - The tendency of the slab to deflect is dependent upon its properties of flexural strength.
    - The resultant deflection of the slab which is also the deformation of subgrade is a direct measure of the magnitude of subgrade pressure.
    - The pressure deformation characteristics of rigid pavement is a function of relative stiffness of slab to that of subgrade.
    - Westergaard defined this term as ***radius of relative stiffness*** *l*, cm

$$l = \left[\frac{Eh^3}{12K(1-\mu^2)}\right]^{1/4}$$

        - E is modulus of elasticity of cement concrete kg/cm^2
        - μ is poisson's ratio of concrete = 0.15
        - h is slab thickness, cm
        - K is subgrade reaction, kg/cm^3
    - It is radius of area of soil effective in resisting deflection of slab
- ***Equivalent radius of resisting section***
    - It is radius of slab effective in resisting bending moment in the case of interior loading.

$$b = \sqrt{(1.6a^5 + h^5)} - 0.675h \qquad \frac{a}{h} < 1.724$$

$$b = a \qquad \frac{a}{h} \geq 1.724$$

- Position of crack due to corner loading
  - ♦ Distance from apex of slab corner to section of maximum stress along the corner bisector, cm

$$x = 2.58\sqrt{al}$$

- Stresses

Load stresses (kg/cm^2)	$\sigma_i = \frac{0.316P}{h^5}\left[4\log_{10}\left(\frac{l}{b}\right) + 1.069\right]$ $\sigma_e = \frac{0.572P}{h^5}\left[4\log_{10}\left(\frac{l}{b}\right) + 0.359\right]$ $\sigma_c = \frac{3P}{h^5}\left[1 - \left(\frac{a\sqrt{2}}{l}\right)^{0.6}\right]$	P wheel load, kg h thickness of slab, cm l radius of relative stiffness, cm b radius of resisting section, cm a radius of contact area cm.
Warping stresses (temperature)	$\sigma_{ti} = \frac{E\alpha T}{2}\left[\frac{C_x + \mu C_y}{1-\mu^5}\right]$ $\sigma_{te} = \max\begin{cases}\frac{C_x E\alpha T}{2}\\ \frac{C_y E\alpha T}{2}\end{cases}$ $\sigma_{tc} = \frac{E\alpha T}{3(1-\mu)}\sqrt{\frac{a}{l}}$	μ – Poisson's ratio α- thermal coefficient per °C T- temperature difference, °C C_x- coefficient based on L_x/l in desired direction C_y- coefficient based on L_y/l in right angle to above direction
Friction stresses (temperature)	$\sigma_f hB \times 100 = B\frac{L_c}{2} \times \frac{h}{100}\gamma_c \mu$ $\sigma_f = \frac{L\gamma_c\mu}{2}$	h- thickness in cm L- length of slab m, γ_c- unit weight of concrete 2400kg/cm[2] μ- friction coefficient

- Critical combination of stresses
  - ♦ + means compressive, – means tension

		Load stress	Warping stress: Day ☀	Warping stress: Night 🌓	Frictional stress: Summer ☀	Frictional stress: Winter ❄	Worst condition
Interior	Top	+ →←	+ →←	- ←→	+ →←	- ←→	At bottom during day time in winter
	Bottom	- ←→	- ←→	+ →←	+ →←	- ←→	
Edge	Top	+ →←	+ →←	- ←→	+ →←	- ←→	At bottom during day time in winter
	Bottom	- ←→	- ←→	+ →←	+ →←	- ←→	
Corner	Top	- ←→	+ →←	- ←→	0	0	At top during night
	Bottom	+ →←	- ←→	+ →←	0	0	

- ♦ During summer
  - o Critical combination = (Load stress + warping stress – frictional stress), daytime, bottom
  - o The load stress at edge region is higher than interior.
- ♦ During winter
  - o Critical combination = (Load stress + warping stress +friction stress), at edge region, during day time, bottom fiber
  - o Since differential temperature is lower magnitude during winter than in summer, combination (i) may be worst for most of the region in India.

- At corner
  - The critical combination occurs at the top fiber of the slab
  - Critical combination = (Load stress + warping stress) during night time

- **Design of joints**
  - Spacing of Expansion joints
    - The width or the gap in expansion joint depends upon the length of slab. Greater the distance between the expansion joints, the greater is the width required of the gap for expansion. The use of wider expansion joint space is avoided as it would be difficult to keep them properly filled in when the gap widens during winter season.
    - The dowels would develop high bending and bearing stress with wider openings. It is recommended ***not to have a gap more than 2.5 cm*** **=** Δ in any case.
    - IRC has recommended that the maximum spacing between expansion joints should not exceed 140m for rough interface layer.

$$L_e = \frac{\Delta}{2\alpha T}$$

    - *50% allowance is made for filler material.*
  - Contraction Joints without bars
    - The slab contracts due to fall in slab temperature below the construction temperature, also during the initial curing period, shrinkage occurs in cement concrete.
    - This movement is resisted by friction between bottom fiber of the slab and subgrade.

$$L_c = \left[\frac{2\sigma_{\emptyset}}{\gamma_c \mu}\right]$$

      - Since the contraction develops mainly during initial period of curing, a very low value of $\sigma_{\emptyset}$ is considered in design. The permissible stress is kept as low as about 0.8 kg/cm^2
    - As per IRC spacing between contraction joint cannot be greater than 4.5m for PCC
  - Design of dowel bars
    - Dowel bars of expansion joints are mild steel round bars of short length. Half length of this bar is bonded in one cement concrete slab and the remaining portion is embedded in adjacent slab, but is kept free for the movement during expansion and contraction.
    - They transfer the wheel load from one slab to another slab, and to reduce the differential deflection between slab at joints.
    - The IRC recommends that dowel bar system may be designed on the basis of *Bradbury's analysis* for load transfer capacity of a single dowel bar in shear, bending and bearing in concrete.

Shear	Bending	Bearing
$P = 0.785 d^5 f_s$	$P = \frac{2 d^M f_{\emptyset}}{L_d + 8.8\delta}$	$P = \frac{f_b L_d^5 d}{12.5(L_d + 1.5\delta)}$
P load transfer capacity of a single dowel bar, kg d diameter of dowel bar, cm L_d total length of embedment of dowel bar, cm δ joint width cm f_s permissible shear stress in dowel bar, kg/cm^2 f_s permissible flexural stress in dowel bar, kg/cm^2 f_s permissible bearing stress in dowel bar, kg/cm^2		
➢ In order to obtain balanced design for equal capacity in bending and bearing, length of embedment is obtained $L_d = 5d \left[\frac{f_{\emptyset}(L_d + 1.5\delta)}{f_b(L_d + 8.8\delta)}\right]^{3/5}$ ➢ The minimum dowel length is taken as $L_d + \delta$		

- ➢ Lowest of the three values of P is taken as the load capacity of a dowel bar.
- ➢ The load capacity of dowel system is assumed as 40% of design wheel load.
- ➢ Load capacity factor required

$$LC_{required} = \frac{0.4 \times design\ wheel\ load}{P_{min}}$$

- ➢ Distance on either side of load position upto which the group of dowel bars are effective in load transfer is $= 1.8l$
- ➢ Assuming spacing s load capacity is calculated as

$$= 1 + \frac{1.8l - s}{1.8l} + \frac{1.8l - 2s}{1.8l} + \frac{1.8l - 3s}{1.8l} + \cdots > LC_{required}$$

- ♦ Design of *tie bars*
  - They are designed just to resist the frictional force so that they can hold the slabs in the position
  - Area of steel required

$$A_{st} = \frac{\mu \gamma_c bh}{\sigma_{st}}$$

    - Assume dia of tie bar = ϕ
    - Number of tie bars per meter of slab

$$n = \frac{A_{St}}{\frac{\pi}{4}\phi^5}$$

    - Spacing

$$s = \frac{1000}{n}$$

    - As per IRC ϕ k 20cm, $s\ k\ 75cm$
  - Length of tie bar

$$L_t = \frac{\phi \sigma_{st}}{2r_{bd}}$$

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6. Highway material and construction

a) Tests for aggregates

Crushing test (strength)	Size of aggregate 10 to 12 mm, is packed in 3 layers, with rate of loading 4T/min, for 10 min, and passed through 2.36 mm sieve.	$ACV = \frac{W_5}{W_3} \times 100$ W_5weight of aggregate passing W_3total weight of aggregates ACVk 30% for surface course ACVk 45% for base course
Impact test (toughness)	Aggregate specimen of size 10-12mm is filled in the cylinder in 3 layers with 25 blows each, is subjected to a falling hammer from height of fall 38cm, weight 13.5-14.5 kg with 15 number of blows, and passed through 2.36 mm sieve. Energy (7980 kgcm)	$AIV = \frac{W_5}{W_3} \times 100$ AIVk 30% for surface course AIVk 35% for base course
Abrasion test (wear and tear)	It is done in Los Angeles machine, rate of rotation 33rpm, 500 revolutions are given, and passed through 1.7mm sieve. $\text{coeff of hardness} = 20 - \frac{1}{3}\text{loss of wt in gm}$	$AV = \frac{W_5}{W_3} \times 100$ AVk 30% for surface course AVk 50% for base course
Soundness test (durability)	Aggregates of specified size are subjected to cycles of alternate wetting (16-18hrs) in saturated solution of sodium Sulphate or	Loss of weight k 12% $Na_5SO_>$

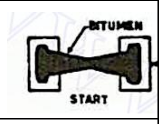
	Magnesium sulphate at a certain temperature and then drying in air (4hr). After 5 cycles loss of weight is determined.	k 18% $MgSO_{>}$
Shape test	➢ <u>Flakiness index</u> Size of aggregate > 6.3mm, it is the percentage by weight of aggregate particles having their least dimension less than 0.6 times the mean dimension. ➢ <u>Elongation index</u> Size of aggregate > 6.3mm, it is the percentage by weight of aggregate particles having their biggest dimension more than 1.8 times the mean dimension. ➢ <u>Angularity number</u> It shows the degree of packing, w.r.t. rounded aggregates which have 67% solids and 33% voids. It measures voids excess of 33%. For rounded agg. $AN = 0$ For angular agg $AN \neq 0$	$FI = \frac{W_5}{W_3} \times 100$ $FI\ k$ 25% for bituminous concrete $FI\ k$ 15% for WBM $EI = \frac{W_5}{W_3} \times 100$ $EI\ k$ 15% as per IRC $AN = 67 - \frac{100W}{CG_a}$ C weight of water Wweight of aggregates G_a specific gravity Acceptable range $0 - 11$
Water absorption test	Water absorption should not be more than 0.6% of weight of aggregates.	
Specific gravity test	It measures the quality of strength of material Specific gravity of solids lies between 2.6 to 2.9	

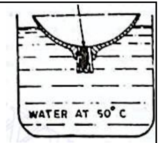
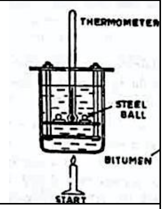
b) Types of binders

Bitumen	It is manufactured by ***fractional distillation*** of crude oil. It is soluble in CS_5 and $CCl_>$ and is more resistant to water. Free carbon content is less and has less temperature susceptibility. ➢ Grading is done according to viscosity VG 40 used in high stress areas, toll plaza, truck terminal VG 30 used for paving application VG 20 used for paving application in cold climate VG 10 used for spraying application
Tar	It is manufactured by ***destructive distillation*** of coal and wood, it is soluble in ***toluene***, it is less resistant to water, has more free carbon content and more temperature susceptible. ➢ Grading is done as RT (road tar) RT 1: it is used for surface dressing in very cold weather condition RT 2: used for surface dressing in normal climatic condition RT 3: used for surface dressing and renewal coat RT 4: pre-mix tar macadam RT 5: used for grouting
Asphalt	Asphalt is produced in a plant that heats, dries and mixes aggregate, bitumen and sand into a composite mix
Cutback	These are a grade of bitumen that comes under *penetration grade bitumen*. This type of bitumen has a ***temporarily reduced viscosity*** by the introduction of a volatile oil. Once after the application, the volatile material is evaporated and bitumen gain its original viscosity. In areas of road construction, it is necessary for the material to be fluid in nature at the time of laying i.e. during surface dressing. It is also essential for the material to regain back to its original hardness and property after setting. This is ensured by cutback bitumen. The fluidity can be obtained for any bitumen

	by raising the temperature, But when it is necessary to have fluidity at ***lower temperatures*** during surface dressing, cutback bitumen is employed. ➢ They are available in three types: RC– rapid curing (RC-0, having minimum viscosity, 1,2,3,4,5 higher) MC– medium curing SC– slow curing
Bituminous emulsion	This type of bitumen forms a two-phase system with two immiscible liquids. One of them is dispersed as fine globules within the other liquid. When discrete globules of bitumen are ***dispersed in a continuous form of water***, bitumen emulsion is formed. ➢ An emulsifier having a long hydrocarbon chain with either a cationic or anionic ending is used for dispersing the bitumen globules. This emulsifier provides an electrochemical environment. The ionic part of the chain has an affinity towards water and the bitumen is attracted by hydrocarbon part. ➢ The emulsions can be cationic (positive charge) or anionic (negatively charged). The globules of the same charge hence repel each other, making the whole system stable. To facilitate adhesion with the aggregates (that are negatively charged), cationic emulsions are more preferred. ➢ Three types of bituminous emulsion are prepared Rapid setting (RS): suitable for surface dressing and penetration macadam. Medium setting (MS): used for premixing with coarse aggregates Slow setting (SS): it is suitable for fine aggregate mixes.
Penetration grade bitumen	The penetration grade bitumen is refinery bitumen that is manufactured at different viscosities. The penetration test is carried out to characterize the bitumen, based on the hardness. Thus, it has the name penetration bitumen. The penetration bitumen grades range from 15 to 450 for road bitumen. But the most commonly used range is 25 to 200. This is acquired by controlling the distillation process.
Blown bitumen	By maintaining a controlled temperature, the air is introduced under pressure into soft bitumen. Compounds of higher molecular weight are formed by the reaction of this introduced oxygen and bitumen components. Thus, the Asphaltenes and the Maltenes content increases resulting in a harder mix. This harder mix has a *lower ductility* and *temperature susceptibility*. The oxidized bitumen is used in industrial applications such as roofing and coating for pipes. By this method of processing, the bitumen that has a lower penetration can be manufactured, which can be employed for paving roads.

c) Tests on Bitumen

Penetration test	It is a measure of softness and hardness of bitumen by measuring the depth in 1/10th of mm to which a standard needle carrying a weight of 100g penetrates in 5sec at temperature 25ºC. grade of bitumen is decided on the basis of penetration test. ▪ Grade 80/100 means penetration value lies between 8 to 10 mm. ▪ A-30 means manufactured from Assam petroleum ▪ S-30 means manufactured from other parts.
Ductility test	It is the ***distance in cm*** to which a standard briquette of size 10mm✕10mm can be stretched before the thread breaks at a standard temperature of 27ºC. ▪ Minimum ductility for grade 45 and above is 75cm. 
Viscosity test	It measures resistance to flow. It is the time taken in seconds by 50ml of bitumen to flow from a beaker through a standard orifice under standard test condition. It is measured by ***'saybolt furol'***. Standard temperature for this test is 25ºC and 50ºC. ▪ Viscosity of tar is measured by tar viscometer.

Float test	It is used to measure consistency of material for which penetration and viscosity test cannot be conducted. It measures the time required to inject through bitumen, in the nozzle of a floating bowl in warm water (50ºC). higher the float value stiffer the bitumen	
Softening test	Softening point is the temperature at which the substance attains a particular degree of softening under standard test condition. This test is also known as **ring and ball** test. Softening point of various bitumen grade used in paving jobs varies between 35ºC to 70ºC.	
Flash and fire point test	Bitumen materials leave out volatiles at temperatures depending upon their grade. These volatiles catch fire causing flash ***Flash point***: it is the lowest temperature at which vapours of a substance momentarily takes fire in the form of a flash under specified condition of test. ***Fire point***: it is the lowest temperature at which material gets ignited and burns. ▪ It is measured with ***Pensky-Martens*** cup tester	

d) Marshal mix design

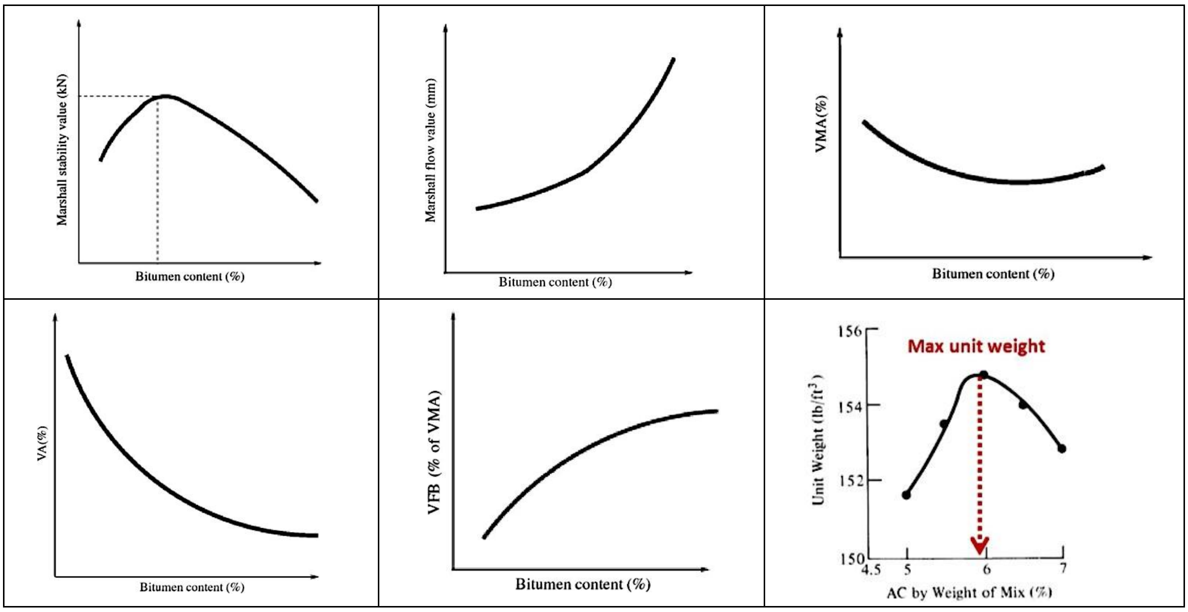
- The mix design determines the Optimum Bitumen Content for evaluation of performance of bituminous mix. The mechanism of failure in Marshall test apparatus is complex but it is essentially a type of unconfined compression test. This being so, it can only have a limited correlation with deformation in a pavement where the material is confined by tyre, the base and the surrounding soil.
- Test specifications
  - Diameter 101.6 mm, thickness 63.5 mm
  - Rate of deformation 51mm/min
  - At 60ºC
  - Marshal stability number: it is the maximum load carried in kg at the standard temperature.
  - Flow values: it is the total deformation that test specimen undergoes.
- Analysis

Theoretical specific gravity	G_t is the specific gravity *without considering air voids*, and is given by: $$G_t = \frac{W_3 + W_5 + W_M + W_b}{\left(\frac{W_3}{G_3}\right) + \left(\frac{W_5}{G_5}\right) + \left(\frac{W_M}{G_M}\right) + \left(\frac{W_b}{G_b}\right)}$$
Bulk specific gravity G_m	Or ***actual specific gravity*** of the mix is the specific gravity considering air voids and is found out by: $$G_m = \frac{W_m}{W_m - W_\dagger}$$ W_m weight of mix in air, $W_\dagger$ weight of mix in water, $(W_m - W_\dagger)$ gives the volume of the mix
Air void percentage	It is percentage of air voids by volume in the specimen. $$v_v = \frac{G_t - G_m}{G_t} \times 100$$
% volume of bitumen v_b	$$v_b = \frac{\frac{W_b}{G_b}}{\frac{W_3 + W_5 + W_M + W_b}{G_m}}$$
Voids in mineral aggregate (VMA)	It is the sum of air voids and volume of bitumen. $$VMA = v_v + v_b$$
Voids filled with bitumen	It is voids in mineral framework filled with bitumen. $$VFB = \frac{v_b}{VMA} \times 100$$

- Curves are plotted based on the results of Marshall test.
  - To determine the optimum binder content for the mix design, average value of following three bitumen content is found from the plotted graphs

- Bitumen content corresponding to maximum stability, maximum bulk specific gravity, and design limit of % air voids in total mix.

- Graphs



e) Symptoms and causes of defects

	symptoms	*causes*
➢ **Surface defects:** these are associated with the surfacing layers with and may be due to excessive or deficient quantities of bitumen in these layers.		
Fatty surface	➢ Bitumen binder moves upward and collects as a thin film of bitumen ➢ Wet in summer season ➢ Slippery in winter season	◊ Excessive binder in premix surfacing ◊ Non uniform spreading ◊ loss of cover aggregate in surface dressing.
Smooth surface	➢ Very low skid resistance value ➢ Very slippery in wet condition	◊ Excessive binder ◊ Polishing of aggregate under traffic
Streaking	➢ Appearance of alternate lean and heavy lines of bitumen either in longitudinal or transverse direction	◊ Careless operation of bituminous distribution, sometimes machine fault ◊ Too low temperature of application
Hungry surface	➢ Loss of aggregate from surface ➢ Appearance of fine cracks	◊ Less bitumen in surfacing ◊ Use of absorptive aggregates in the surfacing
➢ **Cracks:** a common defect in bituminous surfaces is the formation of cracks, the crack pattern in many cases indicate the cause of the defect.		
Hairline cracks	➢ These appear as short and fine cracks at close intervals on the surface.	◊ Insufficient bitumen content ◊ Improper compaction
Alligator cracks (crazing)	➢ These appear as Inter connected cracking forming a series of small block which resemble the skin of an alligator.	◊ Excessive deflection of surface over unstable subgrade ◊ Overloading ◊ Brittleness of binder due to ageing
Longitudinal cracks	➢ Cracks in a line between two lanes or at edges	◊ Alternative wetting and drying ◊ Weak joints between lanes
Edge cracks	➢ Cracks parallel to outer edge 0.3m-0.5m inside the edge	◊ Lack of lateral support from the shoulder ◊ Frost heave ◊ Settlement or yielding of underlying material
Shrinkage crack	➢ These are cracks appearing in transverse direction or interconnected cracks forming a series of large blocks	◊ Shrinkage of bituminous layer with age
Reflection crack	They appear in the bituminous surfacing over joints and cracks in the pavement underneath.	◊ Cracks due to pavement layer underneath

➢ **Deformation:** any change in the shape of the pavement from its original shape is a deformation.		
Slippage	It is relative motion between surface layer and layer underneath.	◊ Unusual thrust of a vehicle in a particular direction. ◊ Failure of bond between two layers.
Rutting	➢ Longitudinal depression or grove on the surface.	◊ Heavy channelized traffic ◊ Weak pavement ◊ Improper compaction
Corrugation	It is formation of fairly regular undulations across bituminous surface.	◊ Lack of stability in mix ◊ Oscillations set up by vehicle springs can cause valley and ridges.
Shoving	It is a form of plastic movement within the layer resulting in localized bulging of pavement surface	◊ Lack of stability in the mix ◊ Heavy traffic movement of start and stop type
Shallow depression	These are localized low areas of limited size, where water will normally collect.	◊ Settlement of lower pavement layers due to pockets of inadequately compacted sub-grade or pavement layer.
Settlement/ upheaval	➢ Large deformation ➢ Extremely uncomfortable	◊ Inadequate compaction in the fill ◊ Excessive moisture in subgrade
➢ **Disintegration:** these are defects which if not rectified immediately, results in the disintegration of the pavement into small loose fragments.		
Stripping	➢ Separation of bitumen adhering to the surface of aggregate particles, in the presence of moisture. ➢ Loss of material from the surface	◊ Continuous contact of water ◊ Inadequate mix composition ◊ Aging of bitumen leading to embrittlement of binder film.
Raveling	➢ Progressive disintegration of the surface due to failure of binder to hold the material together	◊ Inadequate compaction ◊ Construction during cold weather ◊ Poor mix design
Pot holes	These are Bowl-shaped holes in surface layer or extending into the base course caused by localized disintegration of material.	◊ Ingress of water into the pavement through the surface course. ◊ Lack of proper bond between the bituminous surfacing and underlying WBM. ◊ Insufficient bitumen content in localized area
Edge breaking/ frayed surface	➢ Edges of the bituminous surface gets broken, may peel off in large chunks at edges	◊ Worn out shoulders resulting in Insufficient side support ◊ Lower layer of pavement not being wider than upper layer

7. Pavement construction

a) Construction of subgrade

- Material used
  - Soil, moorum, gravel – mixture of these material which are free from organic matter that are likely to deteriorate.
- Requirement of soil properties
  - Liquid limit < 50
  - Plasticity index < 25
  - Non-expansive soil
  - Minimum acceptable CBR
- Construction operation
  - After vegetation and organic dirt are removed from the earth surface, it requires mild compaction.
  - Spreading of soil → additional water sprayed to obtain OMC → compaction by PTR/SFR → process repeated till desired range of compaction

- As per IRC the specified compaction requirement of highway subgrade is 97% in terms of maximum dry density.

b) Construction of sub-base course

- Material used
  - Granular sub base in one or more layer
  - GSB is made by crushed stones, gravel, coarse sand and moorum
- Requirement of material used
  - Liquid limit < 25
  - Plasticity index < 6
  - Minimum acceptable CBR is 30%
- Construction operation
  - Spreading of GSB → compaction by vibratory roller → process repeated up to 98% of maximum density
- This layer also acts as a drainage layer

c) Construction of Granular Base Course

- **Wet Mix Macadam**
  - The construction of WMM consist of laying and compacting clean, crushed and graded aggregates, premixed with water.
  - WMM is prepared in mixing plant, in which aggregates and water (OMC) with suitable proportion are mixed together.
  - Primary function is to provide load distribution and contribution to sub-surface drainage.
  - ***Construction operation***
    - Compaction test is carried out in the laboratory using the selected grade of WMM material. The optimum moisture content of the WMM mix is determined in the laboratory under heavy compaction.
    - The selected WMM mix (with OMC water content) is prepared in a mixing plant.
    - The WMM mix is transported to the site and is spread using self-propelled type paver-finisher machine to the required thickness, grade and cross slope.
    - The layer is compacted using vibratory roller of minimum static weight of 10 tonnes.
    - The WMM surface is checked for defects, if any and allowed to dry; no traffic shall be allowed before a bituminous surface course is constructed.
- **Water Bound Macadam**
  - The term 'Macadam' in present day means, the pavement base course made of crushed or broken aggregate, mechanically interlocked by rolling and voids filled with screening and binding material with the assistance of water.
  - The WBM may be used as a sub-base, base course or surface course. The thickness of each compacted layer of WBM depends on the size and gradation of the aggregate used.
  - When used as a surfacing course, WBM gets deteriorated rapidly under adverse conditions of traffic and weather; therefore, it is desirable to provide a bituminous surfacing course over the WBM layer in order to prolong its life.
  - ***Construction procedure***
    - The foundation layer is prepared to the required grade and camber and the dust and loose materials are cleaned.
    - Lateral confinement is to be provided before starting WBM construction. This may be done by constructing the shoulders in advance.
    - The coarse aggregates are spread uniformly to proper profile to even thickness.
    - After spreading, compaction is done by three wheeled power roller of capacity 8 to 10 tonnes. Rolling is started from edges; the roller being run forward and backward until the edges are compacted. The run of the roller is then gradually shifted towards the

center line of the road, uniformly overlapping each preceding rear wheel track by one half width.

- ➢ Dry screenings are applied gradually over the surface to fill the interstices in three or more applications. Dry rolling is continued as the screenings are being spread and brooming carried out.
- ➢ Surface is sprinkled with water, swept and rolled. Wet screenings are swept into the voids using hand brooms. Additional screenings are applied and rolled till the CA are well bonded and firmly set.
- ➢ Binding material is applied at a uniform and slow rate at two or more successive thin layers. After each application of binding materials, the surface is copiously sprinkled with water and wet slurry swept with brooms to fill the voids.
- ➢ After final compaction, the WBM coarse is allowed to set over-night. On the next day the hungry spots are located and are filled with screenings or binding materials.

d) Bituminous course

- Interface treatment
    - ♦ Prime coat
        - o 1st application of low viscous liquid bituminous material over an existing porous pavement surface like WBM base course.
        - o The main objective of priming is to plug capillary voids of porous surface and to bound the loose mineral particles on existing surface.
        - o Only low viscous binder is used for better penetration. Generally, tar, low viscous bitumen, MC/SC cutback are used.
        - o Primed surface is allowed to cure for at least 24hr during with no traffic is allowed.
    - ♦ Track coat
        - o Bituminous track coat is the application of bituminous material over an existing pavement surface which is *relatively impervious* like an existing bituminous surface or a cement concrete pavement.
        - o It can also be applied to pervious surface like WBM which are *already treated by prime coat*.
        - o Track coat is usually applied by spraying Bituminous material of *higher viscosity* like hot bitumen at a rate of 4.9 to 9.8 kg/10m^2 depending in the type of surface. However, in some special circumstances, a track coat of bituminous emulsion may also be applied in cold state.
- Bituminous base coarse
    - ♦ Bituminous macadam
        - o Bituminous macadam consists of crushed aggregates and bituminous binder heated and mixed in a hot mix plant at specified temperature, transported to the construction site, laid with a mechanical paver and compacted by rollers.
    - ♦ Penetration macadam
        - o Bituminous penetration macadam may be used as a base course of flexible pavements in certain short road stretches or in small road projects where hot mix plant facility is not available.
        - o The coarse aggregates of specified size are first spread and compacted well in dry state and then hot bituminous binders of specified grade is sprayed in fairly large quantity at top.
        - o The bitumen penetrates into voids from the surface of compacted aggregate and fill up a part of void and binds aggregate together.
    - ♦ Built up spray grout (MAINS)

- BUSG consists of ***two-layer*** of composite construction of compacted crushed stone aggregates with bituminous binder applied after each layer and ***key aggregates*** placed on the top surface of second layer to provide a total thickness of 75mm.
- This method is commonly used for strengthening of existing bituminous pavements.
- Preparation of existing base → track coat → spreading first layer → rolling → application of binder → spreading of second layer of coarse aggregate → rolling → second application of binder → application of key aggregates → surface finishing → opening of traffic.

- Thin bituminous surfacing
  - Bituminous pavements constructed using granular and/or open graded bituminous layers in the base course are to be protected from the entry of surface water into the pavement layer and causing them possible damages or deterioration. Therefore, a thin bituminous surface coarse is laid over the base coarse to prevent the entry of surface water into the pavement layers during rain.
  - Seal coat
    - Seal coat usually recommended as a top coat over certain bituminous pavement which are not impervious, such as open graded bituminous constructions like premixed carpet and grouted Macadam.
    - It can also be provided over worn out existing bituminous pavement.
    - The main functions are to seal the surface against action of water and to develop skid resistance texture.
  - Surface dressing
    - *Bituminous surface dressing* (BSD) is provided over a prepared base course or an existing pavement to serve as thin wearing coat.
    - Surface dressing work consists of application of suitable grade of bitumen by spraying over a prepared base, followed by spreading specified size of hard aggregates at the recommended rate and rolling.
    - The surface dressing does not add to the structural stability or strength of the pavement nor will it improve the existing ride quality.
    - IRC has provided two types of surface dressing work, (i) single coat surface (ii) double coat surface.
    - The single coat surface dressing consists *of single application of bituminous binder material followed by spreading of aggregate and rolling*.
    - The main function is to serve as *thin wearing coat* and to protect base course, to water proof the pavement surface, to provide dust free pavement in dry weather and mud free pavement in wet weather.
  - Premixed method
    - In this method the aggregates and bituminous binders are mixed thoroughly before spreading and compacting. It is possible to coat each particle of aggregate with binder but still quantity of bitumen used is less than penetration Macadam.
    - In premixed constructions, the quantity of bitumen used could be precisely controlled and they offer increased stability of the mix even with lower bitumen contents.
    - Depending on the gradation of aggregate chosen, premixed construction is classified as:
      - Open graded
      - Semi dense
      - Dense mixes
    - Ex: Bituminous macadam, bituminous premixed carpet, bituminous concrete, sheet asphalt, mastic asphalt.

e) **Overlay design** (Benkelman Beam deflection) MAINS

- Mean deflection $\bar{D} = \frac{\Sigma D}{n}$ mm

- Standard deviation $\sigma = \sqrt{\frac{\Sigma(D-\bar{D})^2}{n}}$
- Characteristic deflection $D_c = \bar{D} + \sigma$
  - ♦ Corrections after deflection $D'_c = D_c + (35^\circ - T^\circ) \times 0.01$ mm/ºC
  - ♦ Corrected deflection for subgrade moisture $D''_c = F \times D'_c$
- Overlay thickness design
  - ♦ The overlay thickness requirement h_o may be determined after deciding the allowable deflection D_a in the pavement under the design load. IRC suggest following formula for design

$$h_o(mm) = 550 \log_{10} \frac{D''_c}{D_a}$$

D_a	Design traffic A	
1	1500-4500	$A = P(1+r)^{n+10}$
1.25	450-1500	n construction period
1.5	150-450	r rate of growth

  - ♦ When superior materials are used in the overlay layer, the thickness value has to be suitably decreased taking equivalency factor of the material into consideration.
  - ♦ When bituminous concrete or bituminous macadam with bituminous surface course is provided as the overlay, an equivalency factor of 2.0 is suggested by IRC.
  - ♦ $h' = \frac{h_o}{2}$

8. Miscellaneous

a) Previous year

- Ratio between the adopted centrifugal ratios for road (1/4) and railways (1/8) is (2:1)
- IRC recommends longitudinal friction between 0.35 to 0.4 and lateral friction 0.15
- Spiral is an ideal horizontal transition curve.
- Transitional property of a lemniscate curve is disrupted when its deflection angle is 45^o
- Light reflecting devices used to guide the driver along the proper alignment are called Delineators.
- Collision diagrams are diagrams showing the approximate path of vehicles and pedestrians involved in the accidents. they are used to compare and study accident pattern and determine remedial measures.
- Emergency escape ramps are provided on the downgrade of a highway for use by a truck that has lost control and cannot slow down. A lane is provided diverting from main highway such that when a vehicle enters the escape ramp, its speed is gradually reduced and eventually it stops.
- Divisional island is used to segregate opposing flow of traffic in a multi-lane highway.
- A trip is a one-way movement, with single purpose using single or different mode of transportation.
- Modal split: it is the proportion of total trips between any two zones that can be shared between the private vehicle and public transportation system is determined in this stage, hence decides the choice of mode.
- In modal choice study, trip purpose influences the shape of diversion curves.
- Duration of green signal depends upon traffic volume only.
- International traffic intelligent survey data are related to accident profiling studies.
- Simple progressive system, is useful when there is continuous operation of group of vehicles along the main road.
- Flexible progressive signaling system, it is possible to vary length of cycle, cycle division and time schedule at each signal point.
- Reinforcements in pavements are placed at mid-depth, as their main function is to hold on the portions of cracked parts.
- Chronological sequence in road design: Tresaguet, Telford, Macadam, CBR
- In premix carpet, compaction by pneumatic roller is also specified.

- Sufficient voids in compacted mix is given as to provide a reserve space for a slight amount of additional compaction due to traffic and to avoid flushing, bleeding and loss of stability.
- Mastic asphalt is obtained by taking suitable proportions of bitumen binder, materials fillers and fine aggregates and heating them in sequence and cooked at temperature of 200-250°C for 5 hours in a special cooker. On cooking it hardens to solid state which gives a void less hard material. The bitumen binder content 15 to 19%. Aggregates of large sizes are placed manually at top to give friction.
- Plastic coated aggregate (PCA) is a preferred raw material for construction of bituminous pavements in areas of heavy rainfall. In PCA, no stripping is needed as there is improved binding and there by stability is also improved.
- <u>Benkleman beam</u> deflection method is used for design of flexible overlays on flexible pavements.
- <u>Gabion wall</u> are constructed with dry stone masonry encased in wire mesh.

b) Mains exam

- **Dilemma Zone** determination
  - ♦ Distance for stopping the vehicle

$$X_{¥} = SSD = vt_r + \frac{v^5}{2a}$$

  - ♦ Maximum distance from stop line, a vehicle can cross.

$$X_c = 0.278\, Vt_a - L - W$$

  - ♦ $X_o > X_c$ then dilemma zone is created, where vehicle can neither stop nor cross the intersection
  - ♦ if $X_c > X_{¥}$ there is option to either stop or cross