B.Sc - Road & Railway Design I. *Lecture 2.*

VEHICLE'S MOTION ON THE ROAD - RESISTANCES - SIGHT DISTANCES & GEOMETRIC ELEMENTS

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BASIC TERMS & DESCRIPTIONS

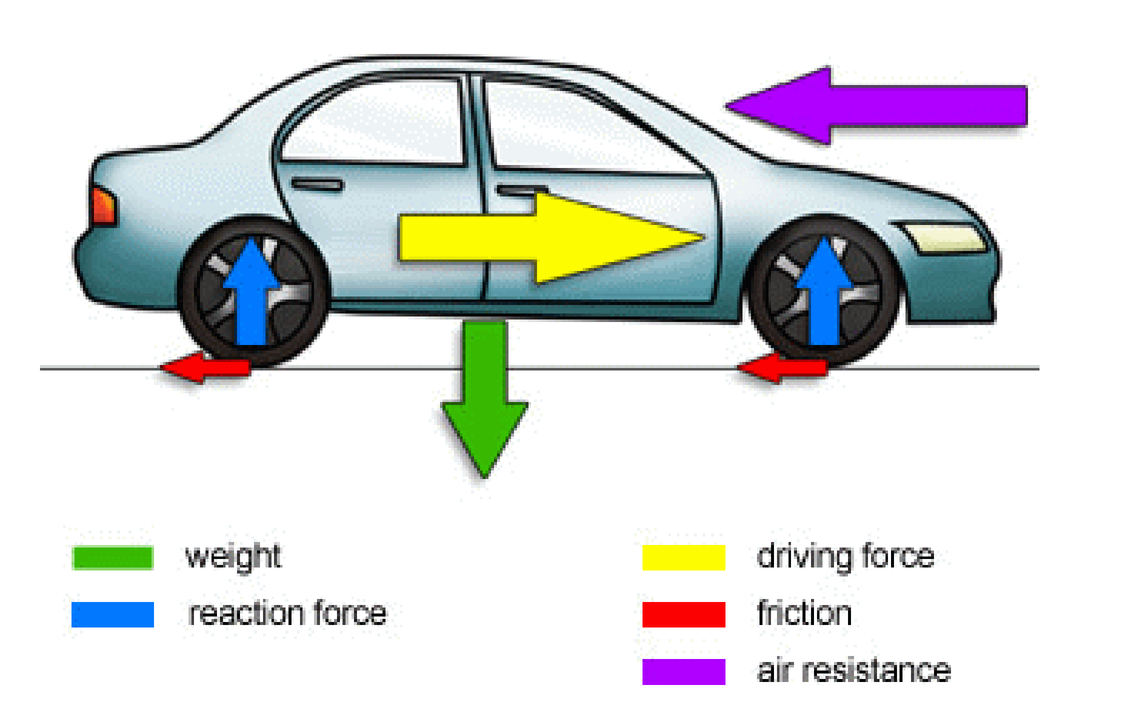
- A *Force* is a *Push* or a *Pull* that one body exerts on another
- *Mass* is a property of a physical body, it is the measure of an object's resistance to acceleration (a change in its state of motion) when a *Force* is applied
- The *Weight* of an object is defined as the *Force of gra*vity on the object and may be calculated as the *Mass* multiplied by the acceleration of gravity:

$$W = mg$$

Weight of object = mass of object x acceleration of gravity

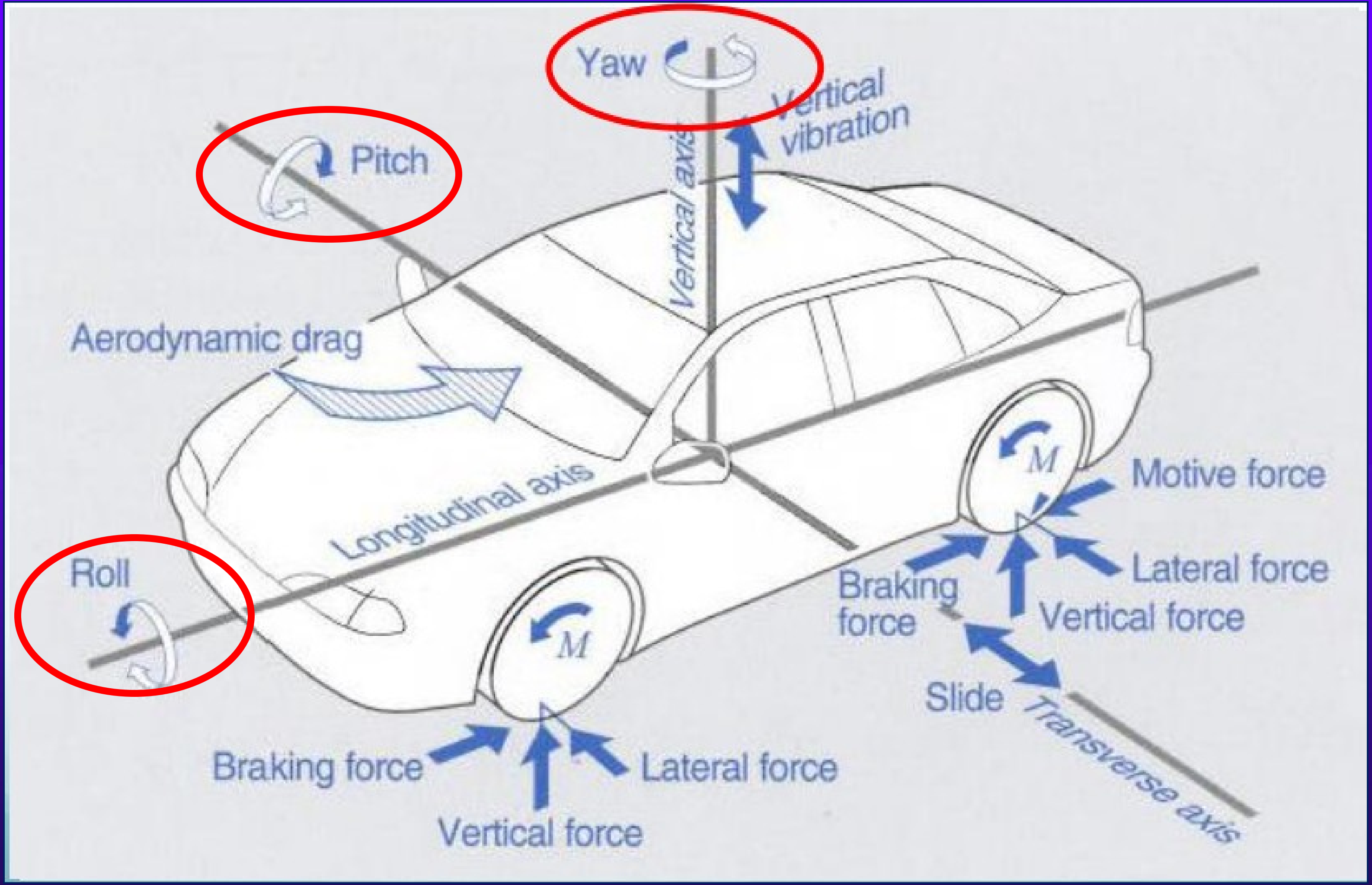
At the Earth's surface
$g = 9.8\ m/s^2$

FORCES ACTING ON A CAR



- *Gravity* pulls down on the car
- The *reaction force* from the road pushes up on the wheels
- The *driving force* from the engine pushes the car along
- There is *friction* between the road and the tyres
- *Resistances* (air, gradient) act against driving force

MOMENTS AFFECTING A VEHICLE



SPEED

- *Speed* (*v*) is determined as the distance travelled divided by the time taken
- If *s* is the length of the path travelled during time (*t*), the speed equals the time derivative of distance (*s*):

$$v = \frac{ds}{dt}$$

Conversion between common units of speed

	m/s	km/h	mph
1 m/s =	1	3.6	2.236 936
1 km/h =	0.277 778	1	0.621 371
1 mph =	0.447 04	1.609 344	1

SPEED-UP & SLOW-DOWN

- When a vehicle travels at a *steady speed,* the *driving force* (F_D) from the engine is balanced by the sum of *resistive forces* (F_R)
- F_R = friction between the road and the tyres + air resistance acting on the body of the car + component of weight, parallel with the road surface when moving *up hill* or *down hill*)
- In case the *resultant force* is NOT zero, the vehicle will accelerate/speed up ($F_D > F_R$) or decelerate/slow down ($F_D < F_R$)

FRICTION

- *Friction* is defined as the resistance to motion between two surfaces
- Basic types of friction:

  A. *Static* –the holding force between two surfaces at rest (*adhesion*)

  B. *Sliding* –the resistance to motion between two surfaces which are moving across each other

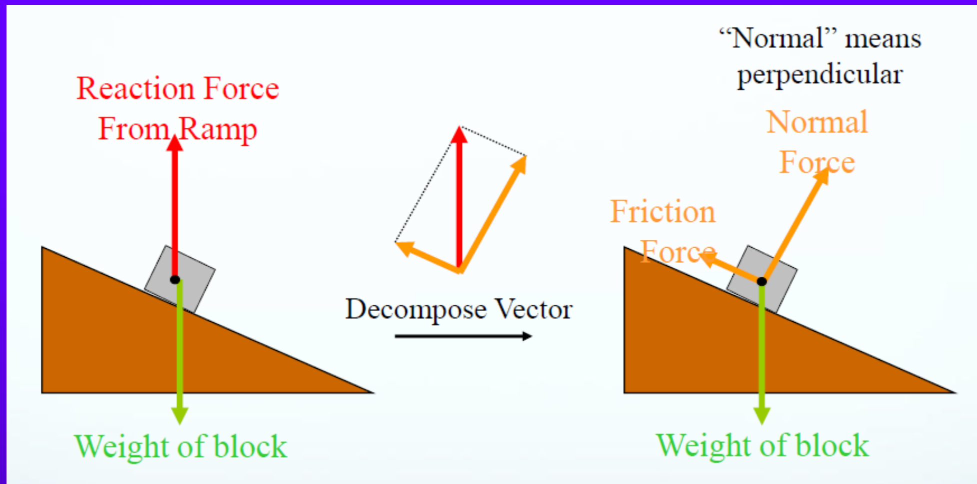
  C. *Rolling* –the resistance to motion of a rolling object like a ball, cylinder or wheel

  D. *Internal* –the resistance to motion within elastic objects (tires get warm from internal friction as they flex)

RESISTANCE

- Resistance is defined as the force impeding vehicle motion
- Types of resistance affecting a moving vehicle:
  1. Rolling resistance
  2. Up hill resistance
  3. Aerodynamic resistance (*drag*)
- Rolling resistance (F_R) is composed of
  1. Resistance from tire deformation (90%)
  2. Tire penetration and surface compression (4%)
  3. Tire slippage and air circulation around wheel(6%)

ROLLING RESISTANCE (F_{Ro})



Friction Force = Normal Force × (coefficient of friction)

$$F_{friction} = \mu \cdot F_{normal}$$

Composed primarily of :

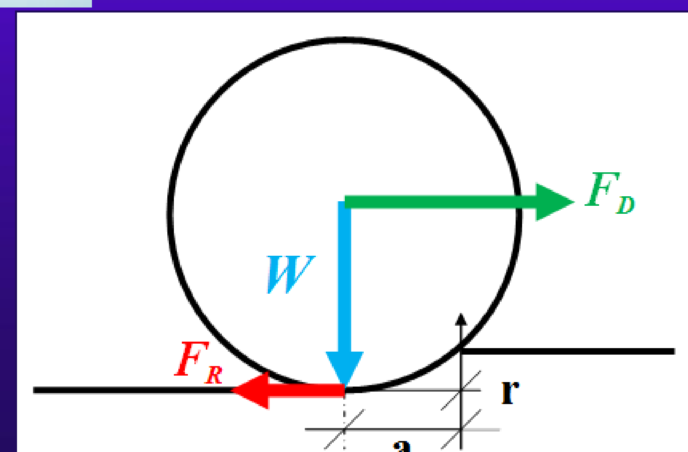
1. **Resistance from tire deformation (90%)**
2. **Tire penetration and surface compression (4%)**
3. **Tire slippage and air circulation around wheel (6%)**

$$F_R = \mu * W \ [N]$$

μ – rolling friction coefficient

Average value of tire friction coefficient

Road surface	*Peak value*	*Sliding value*
Asphalt and concrete (dry)	0.80 – 0.90	0.75
Asphalt (wet)	0.50 – 0.70	0.45 – 0.60
Concrete (wet)	0.80	0.70
Gravel	0.60	0.55
Earth road (dry)	0.68	0.65
Earth road (wet)	0.55	0.40 – 0.50
Snow (hard-packed)	0.20	0.15
Ice	0.10	0.07

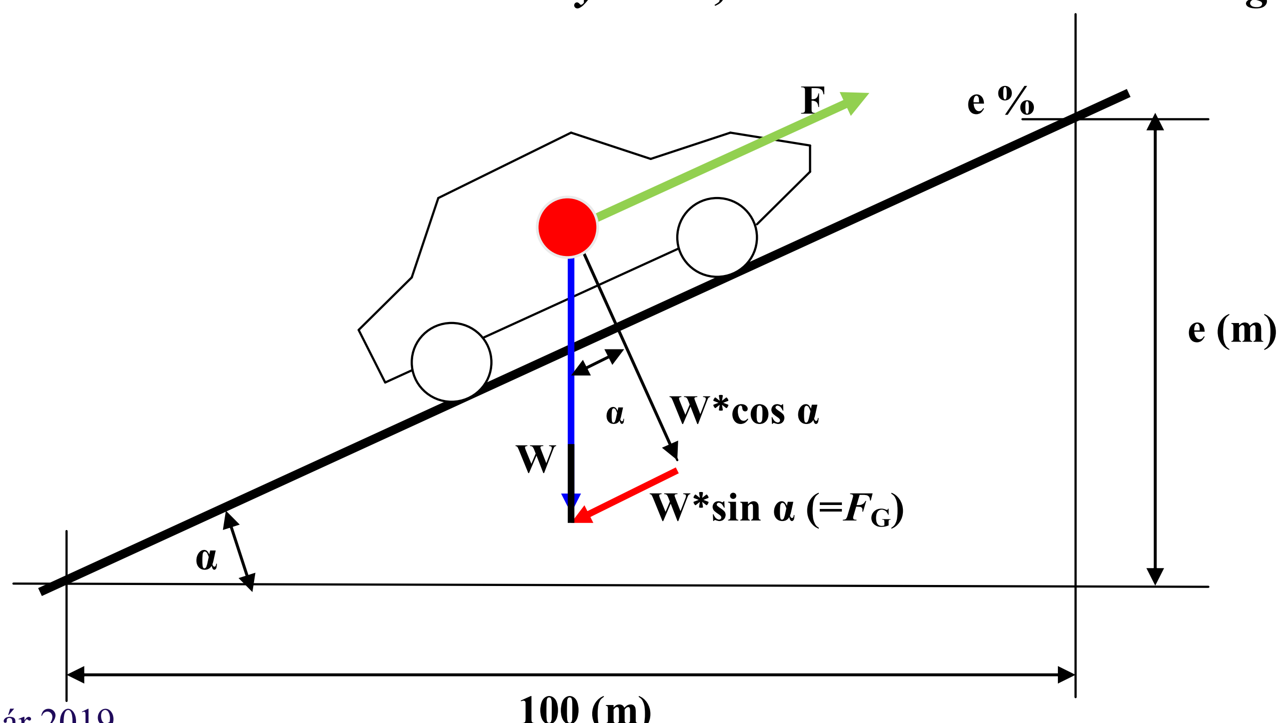


UPHILL RESISTANCE (F_G)

- ***Moving uphill***
  1. Increase the vehicle motion resistance against the direction of motion
  2. Increase the load on rear axle and decrease the load on the front one
  3. Decrease the stopping distance when using the brakes

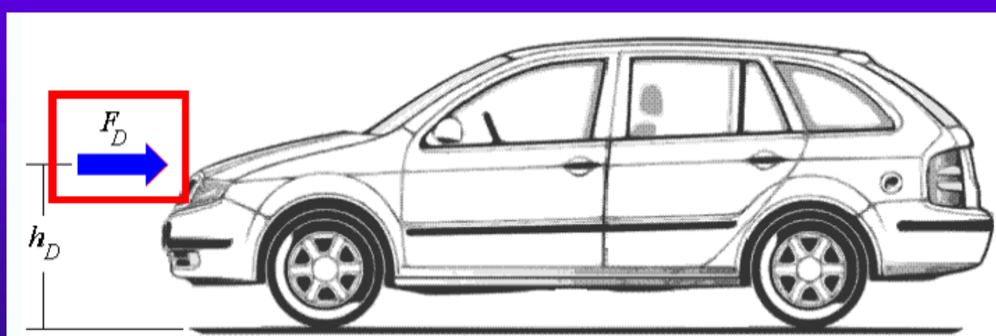
$$F_G = W^{*}\sin\alpha = W^{*}\, e/100 = W^{*}\mathrm{tg}\,\alpha$$

when α is relatively small, it is assumed that sin α = tg α



AERODYNAMIC RESISTANCE (DRAG FORCE): F_D

- Aerodynamic resistance (F_D) is composed of:
  1. Turbulent air flow around vehicle body (85%)
  2. Friction of air over vehicle body (12%)
  3. Vehicle component resistance, from radiators and air vents (3%)

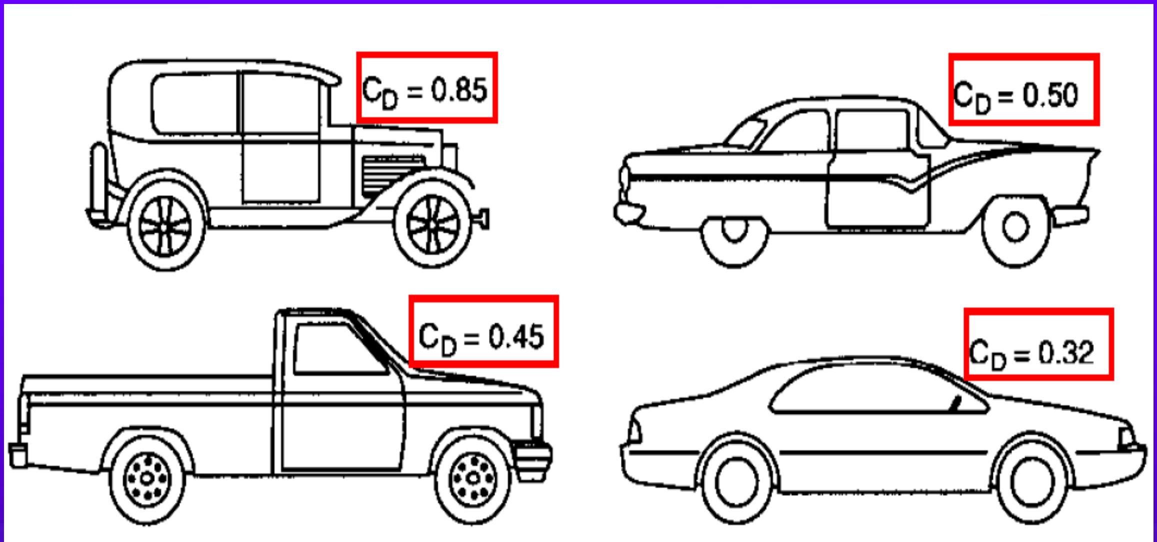


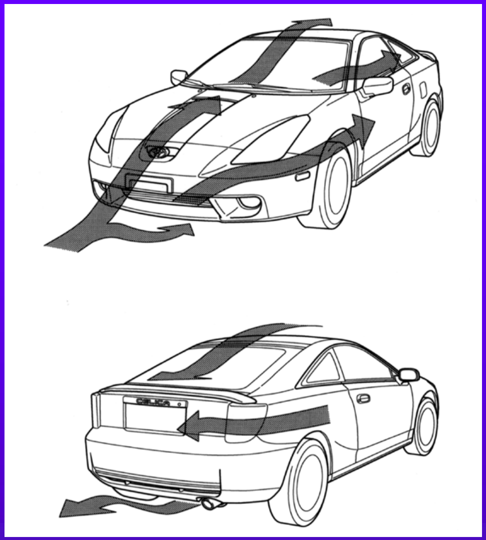
The drag force is acting at height h_D above the ground:

$$F_D = 0.5 \rho C_D A v^2$$

where
- ρ - atmospheric air density (1.2 kg/m³)
- C_D - drag factor
- A - area of vehicle frontal projection (m²)
- v - speed of vehicle (m/s)

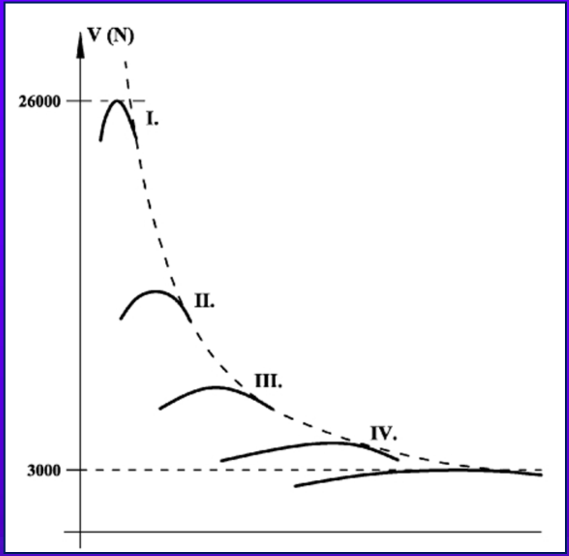
AIR FLOW & DRAG FACTORS

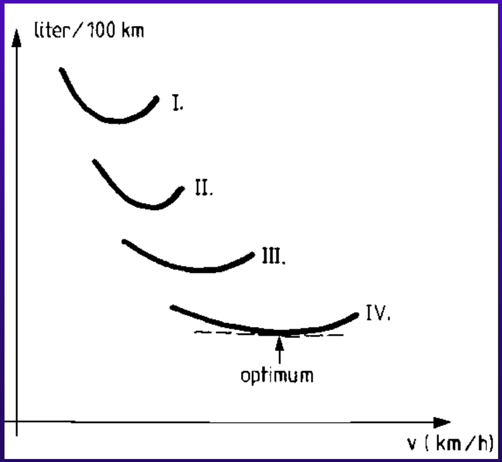




DRIVING FORCE & FUEL EFFICIENCY

- *Driving force* is changing in function of the status of the *gear-box* (transmission ratio)
- Many applications require the availability of multiple *transmission ratios*
- This is to ease the starting and stopping of a vehicle, though another important need is that of maintaining good *fuel efficiency*

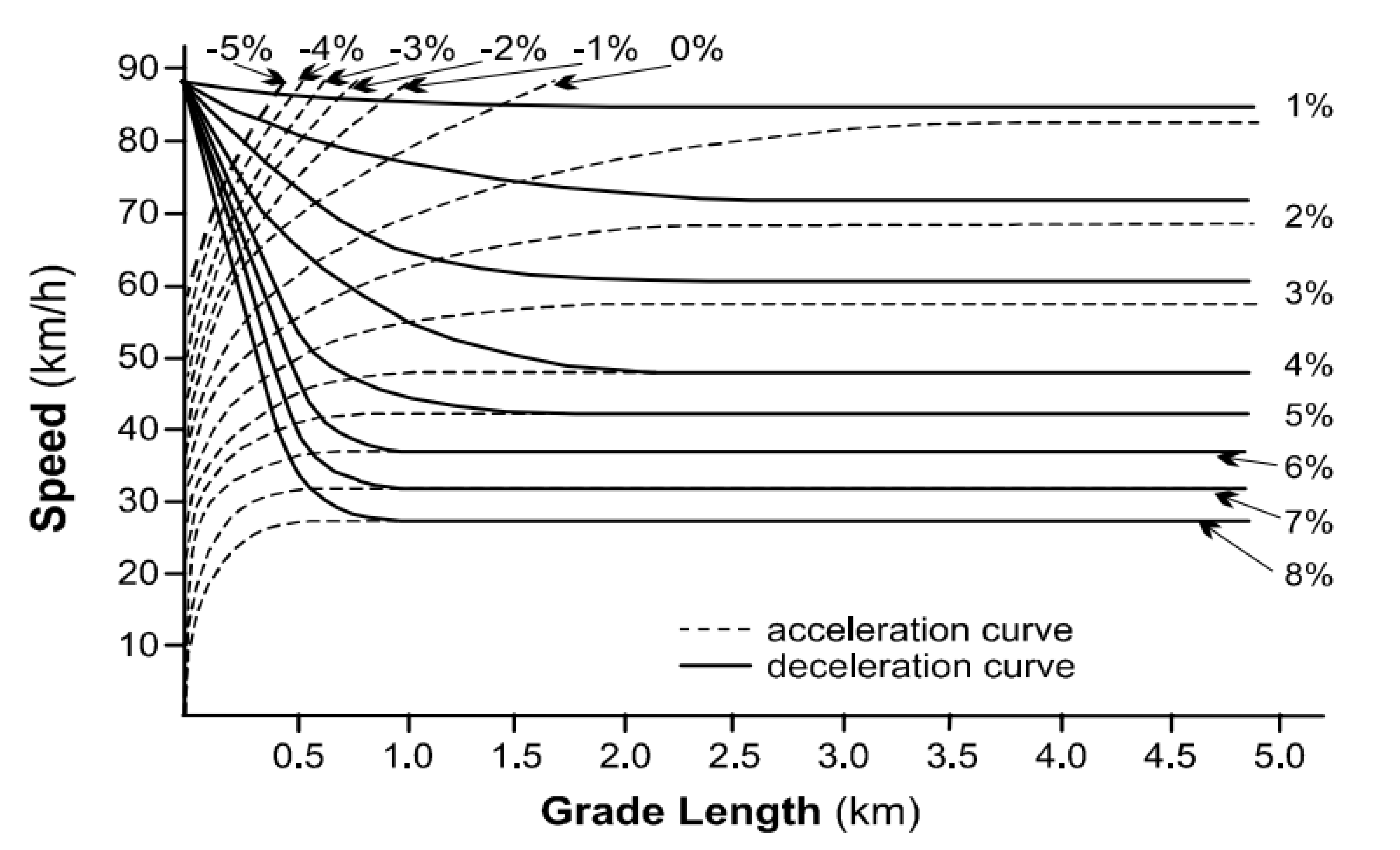




TRUCK PERFORMANCE CURVES

- *Speed-up* and *slow-down diagrams* or *truck performance curves* are reflecting the impact of a given up hill gradient onto the speed of the so-called „representative” vehicle
- These curves are used to determine the distance travelled from the starting point of the up hill section until the point where the speed of the vehicle reaches the minimum allowed speed limit, i. e:
  - whether *climbing lanes* are needed or not;
  - the *minimum length* of acceleration lanes on *motorways*

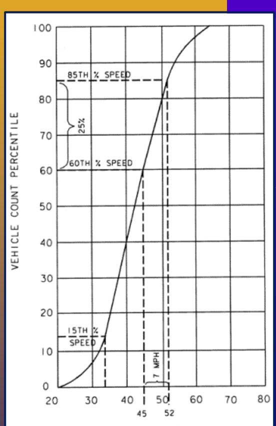
HCM 2000 TRUCK PERFORMANCE CURVES



BASIC NOTIONS OF VEHICLE & TRAFFIC FLOW SPEED

- The *speed* of a vehicle (v) is defined as the *distance* it travels per *unit of time*
- *Time mean speed* or *average speed* ($\underline{v}_t$) of a traffic flow composed from *N* vehicles is the arithmetic *mean* of speeds of vehicles passing a given point:

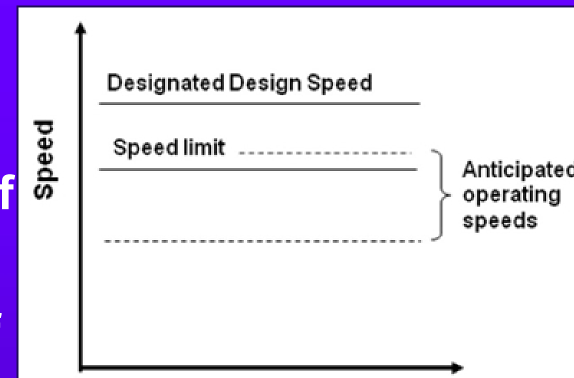
$$\underline{v}_t = \frac{1}{N}\sum_{n=1}^{N} v_n$$



- *Operating speed* is the speed at which drivers are observed operating their vehicles; most frequently the *85th percentile* of the *cumulative distribution* of observed speeds is used as being the operating speed

DESIGN SPEED & SPEED LIMITS

- **Design speed definitions:**



  - **The *maximum safe speed* that can be maintained over a specified section of highway when conditions are so favourable that the design features of the highway govern and prevail**
  - **The *assumed design speed* should be a logical one with respect to the topography, the adjacent land use and the functional classification of the road under scrutiny**
  - **A purposefully selected speed used to determine the various geometric design features of a new road during road design**

- ***Speed limits* are maximum speeds allowed, as prescribed by the relevant *Road/Highway Code***
- ***Design speed* is generally exceeds (for safety reasons) the speed limit**

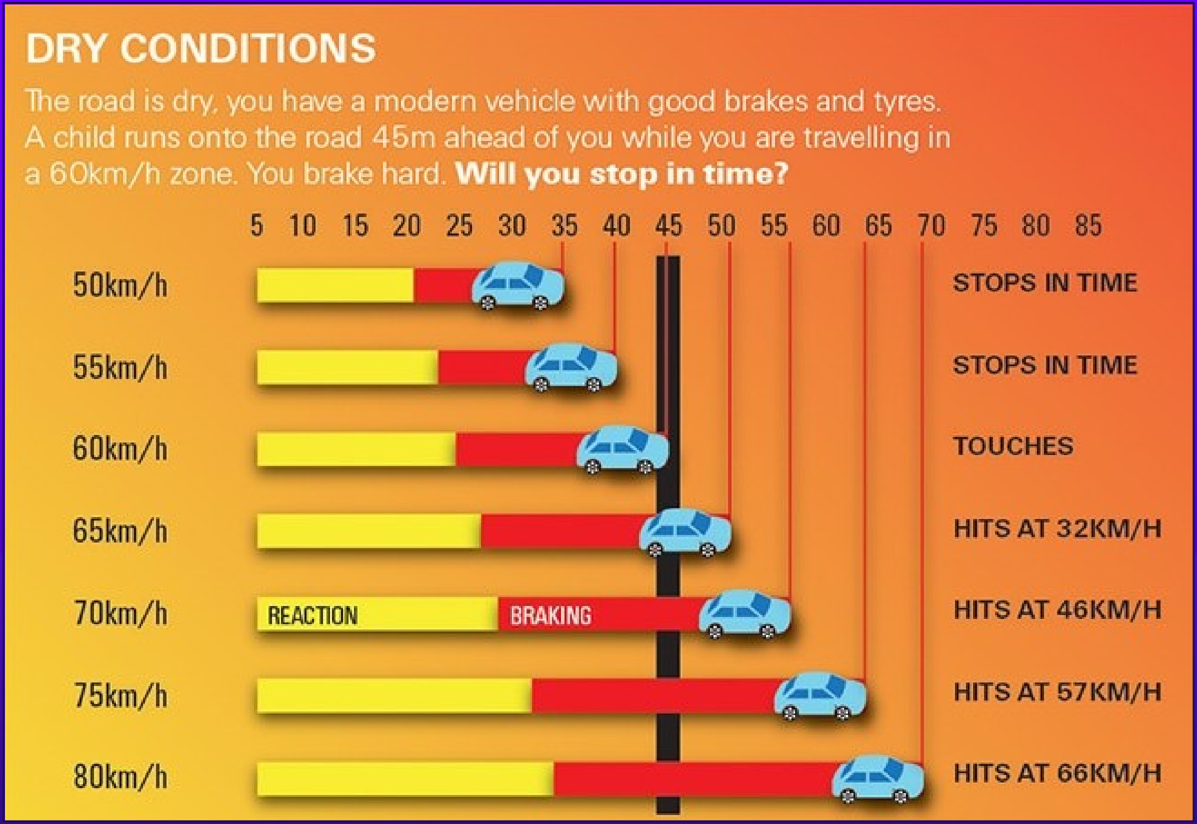
SELF EXPLAINING ROADS

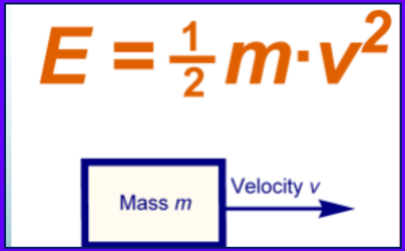
- A new concept: a road on which the driver is encouraged to naturally adopt behaviour consistent with design and function
- The aim is that different classes of roads should be distinctive, and within each class features such as *width of carriageway*, *road markings, signing*, and use of *street lighting* would be *consistent* throughout the route
- Drivers would perceive the type of road and *instinctively* know how to behave, assuming the environment effectively provides a *label* for each particular type of road

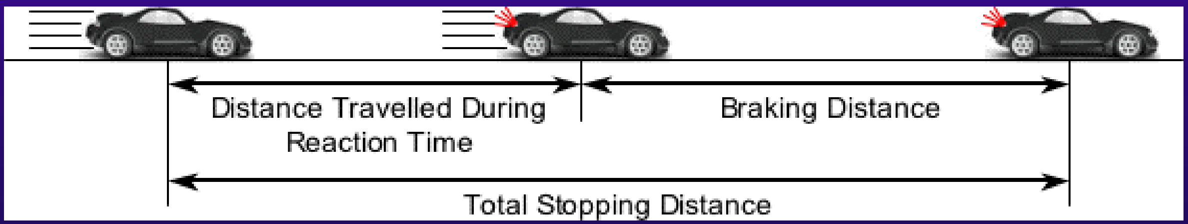
SIGHT DISTANCES

- *Sight distance* is the length of road ahead visible to the driver; it should be long enough for the dri-ver to see a situation and successfully *react to it*
- *Stopping sight distance* is the distance necessary for a vehicle running at or near the *design speed* to stop before reaching a stationary object in its path
- Stopping sight distance is the sum of distance travelled during *perception* + *reaction time* and distance travelled during *braking time*
- Stopping sight distance ***should be assured all along the road*** – this is the responsibility of the civil engineer preparing the road design

STOPPING SIGHT DISTANCE 1







- ***Kinetic energy*** is a term that describes the energy a vehicle has due to its mass and speed
- ***Braking distance*** is needed to transform the kinetic energy of a vehicle into ***heat-energy*** at its brakes and tyres

STOPPING SIGHT DISTANCE 2

Distance traveled during reaction time: $D' = s/3.6 * t_R = 0.28 * s * t_R$ [m]

where t_R is the reaction time, i. e. t_R=1.5-2.0 [sec]

Braking distance: $Ms^2/2 = W/2g * s^2/3.6^2 = 0.0039 * Ws^2 =$

$= (Wf_1 \pm W * e/100)U''$

$D'' = 0.0039 * s^2/(f_1 \pm e/100)$ [m]

where $Ms^2/2$ kinetic energy of the moving vehicle

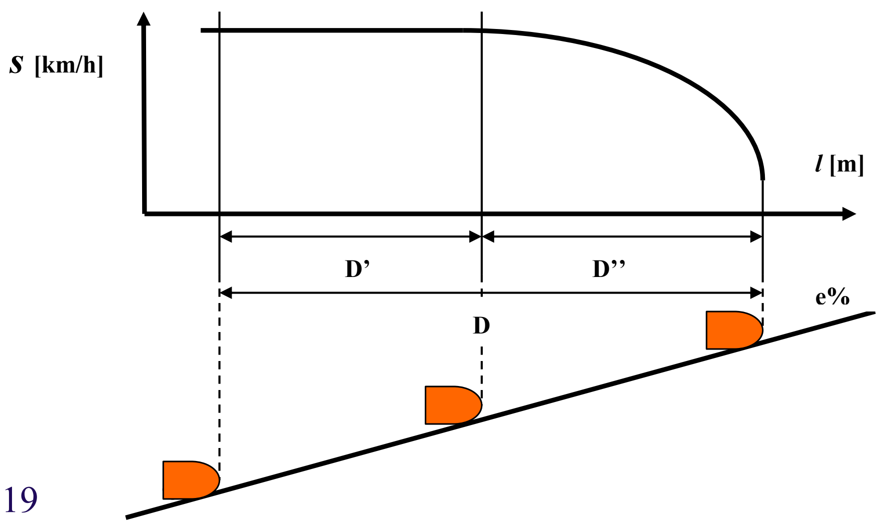
f_1 coefficient of longitudinal road surface friction (0.35-0.40)

e gradient of the road (m/100m)

$$D = D' + D'' = 0.28 * s * t_R + 0.0039 * s^2/(f_1 \pm e/100)$$

Example: in case s = 100 km/h; f_1 = 0.4; t = 1.5 sec; the gradient e = +3%

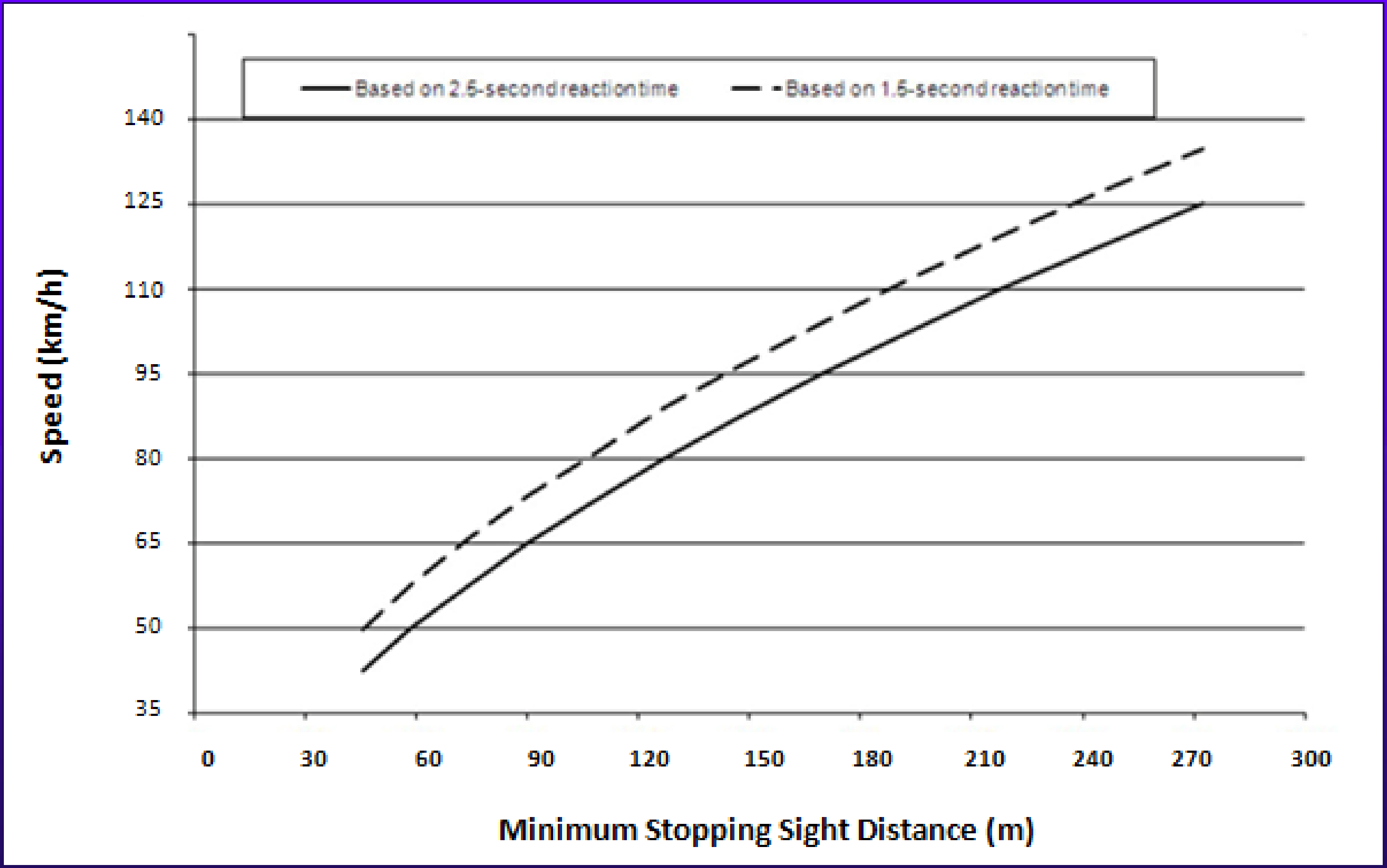
$$D = 0.28 * 100 * 1.5 + 0.0039 * 100^2 / (0.4 + 3/100) = 42 + 90.7 = 132.7 \text{ [m]}$$



Indicative values of f_1

- dry pavement, careful braking: 0,6-0,8
- wet pavement, harsh braking: 0,3-0,35
- wet pavement, careful braking: 0,25-0,33
- icy pavement: 0,1-0,15

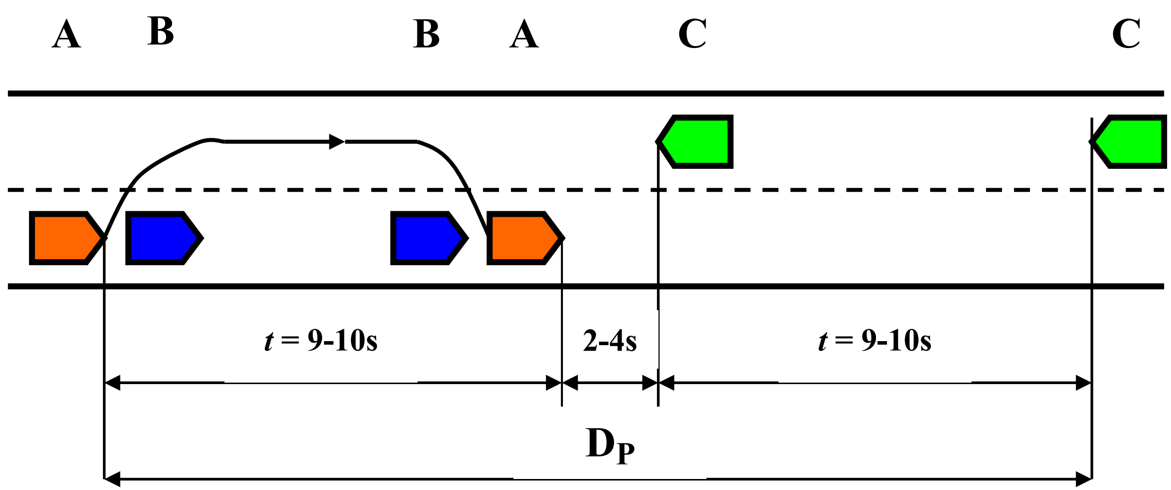
STOPPING SIGHT DISTANCE 3



PASSING/OVERTAKING SIGHT DISTANCE 1

- ***Passing/overtaking sight distance*** **is the minimum sight distance required on a road (generally a two-lane, two-directional one), that will allow a driver to pass another vehicle *without colliding* with a vehicle approaching in the opposing lane**
- **Main components:**
  1. **Distance travelled during perception-reaction time and acceleration into the opposing lane**
  2. **Distance required to pass in the opposing lane**
  3. **Distance necessary to clear the slower vehicle**
- **Passing/overtaking sight distance is *conside-rably greater* than stopping sight distance and can only be economically provided where the alignment permits (flat terrain, straight road)**

PASSING SIGHT DISTANCE 2



The driver of the passing (red, A) vehicle should clearly view the distance to be traveled during 2*11=22 sec, assuming the speed of the (green, C) vehicle approaching from the opposite direction is nearly the same as that of the passing vehicle

Rule of thumb: $D_P = 2 \,.\, 11 \,.\, v/3{,}6 = 6v$ [m]

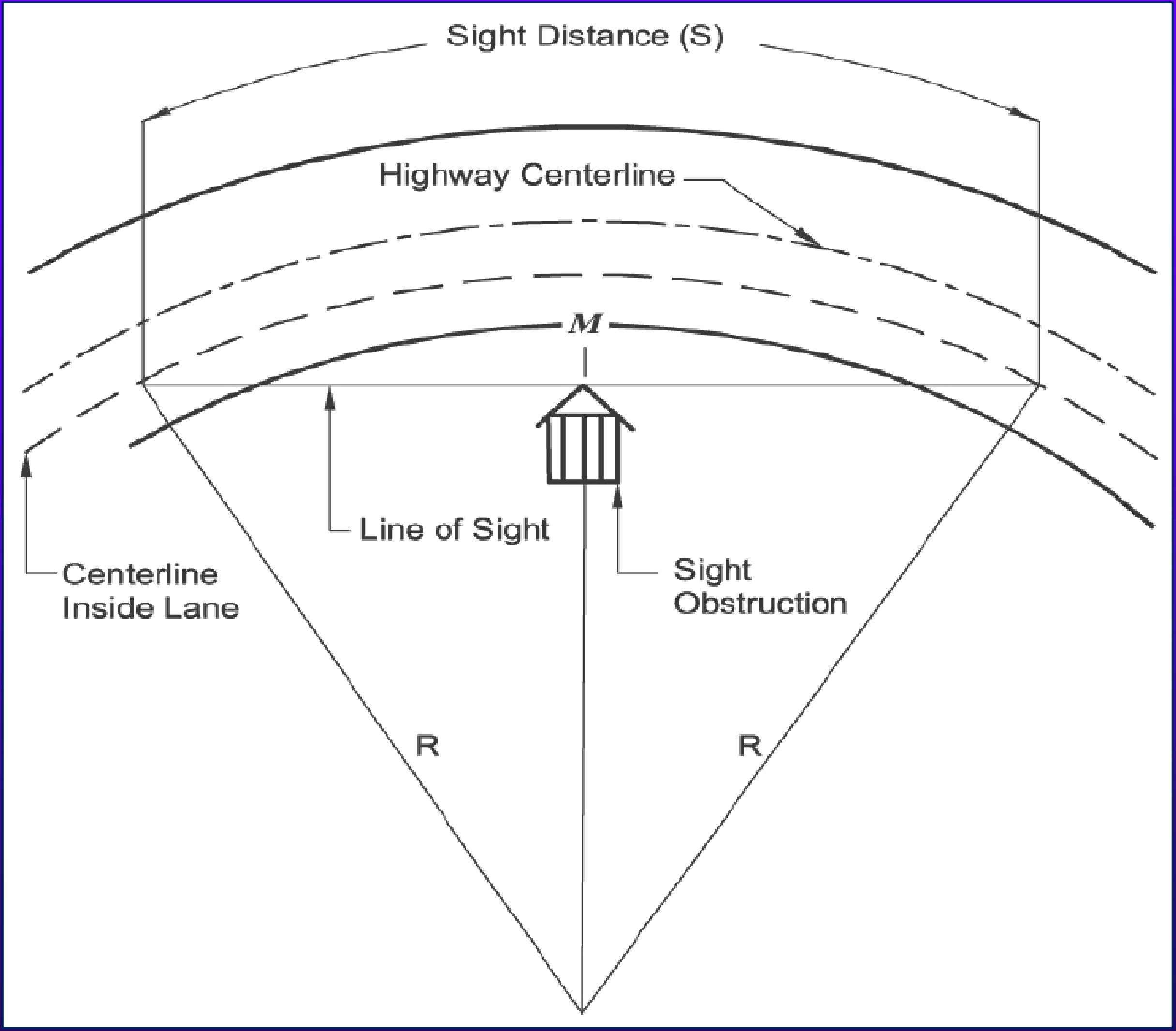
Examples:

if $v = 100$ *km/h*, than $D_P = 600m$

if $v = 80$ *km/h*, than $D_P = 480m$

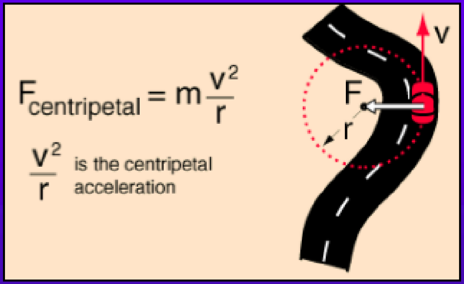
if $v = 50$ *km/h*, than $D_P = 350m$

SIGHT DISTANCE ON A HORIZONTAL CURVE

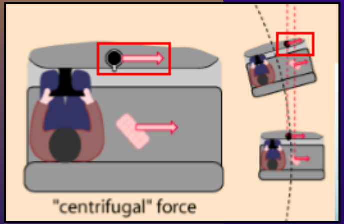


MOTION OF VEHICLE IN A HORIZONTAL CURVE

- On a straight road section the *lateral forces* on a vehicle are negligible
- On a horizontal curve the vehicle is subjected to a *centripetal force* that acts toward the centre of the curve and sustained by the *friction* between the tyres and the pavement + the vehicle's *weight*



- The *friction force* acts along the cross slope of the road surface, in a *perpendicular direction* from the normal force



- The *superelevation* counteracts of a tendency of the vehicle to slide out of the curve (caused by the *centrifugal force*)

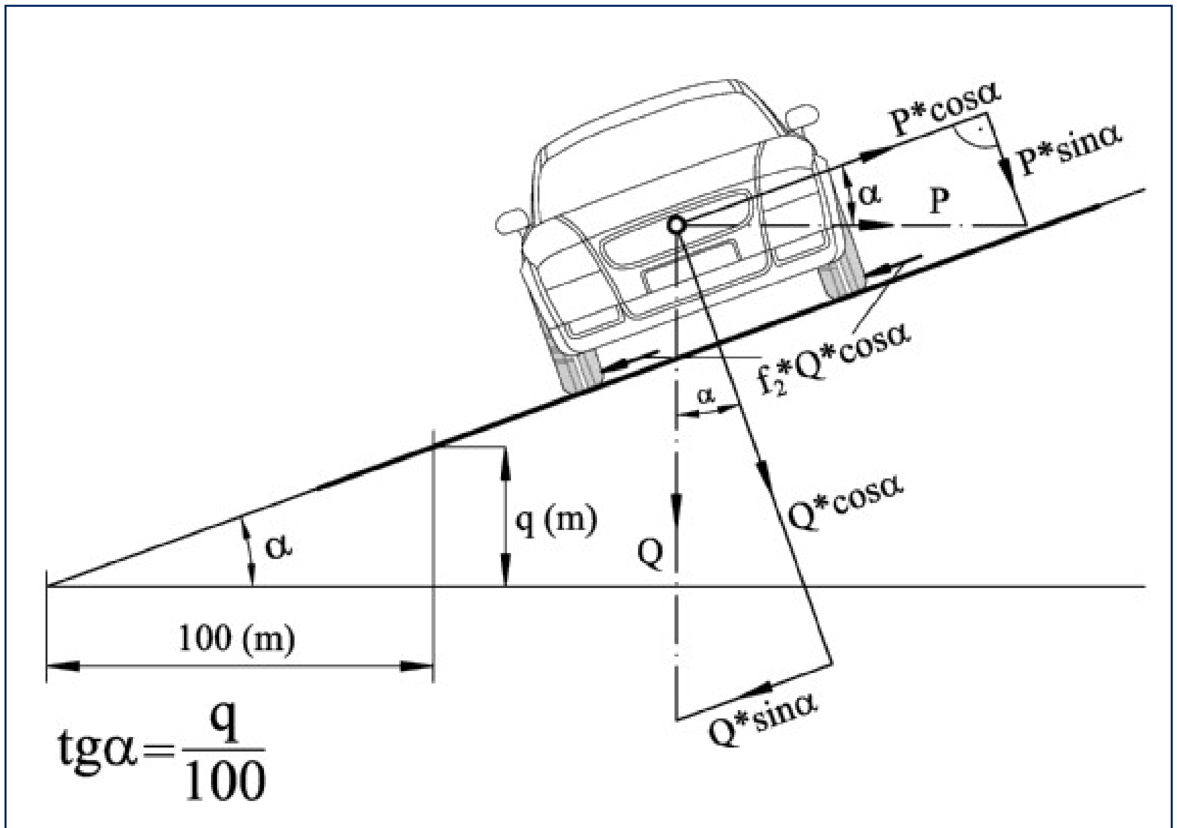
FORCES ACTING ON A VEHICLE IN A HORIZONTAL CURVE

- **All forces acting on the vehicle must be in *equilibrium* for the vehicle to resist the tendency to slide up or down the pavement while travelling through the curve**
- **The components include the *weight (W* or *Q)*, the side *frictional resistance* & the *normal force***
- **The friction force is equal to the *side-friction coefficient* (f_2) multiplied by the *normal force***
- **These equations of equilibrium of all horizontal and vertical forces are used to calculate the minimum values of the *radius* of the *horizontal curve* and the *superelevation* in the function of the *design speed***

$$F = M \cdot s^2/R = Wv^2/(g \cdot 3.6^2 \cdot R) = Wv^2/127 \cdot R$$

where

q	superelevation (*m/100m*, or *%*)
M	mass of vehicle (*kg*)
Q	weight of vehicle (*kN*)
g	acceleration of gravity (9.81 m/s^2)
s, ill. v	speed (in *m/s*, or in *km/h*)
R	radius of horizontal curve (*m*)



Equation of marginal equilibrium:

$$F^*\cos\alpha = f_2{}^* W^* \cos\alpha + f_2{}^* F^* \sin\alpha + W^* \sin\alpha$$

$$v^2 / 127R = f_2 + q$$

Value of marginal (maximum allowed) speed:

$$v_{max} = \sqrt{127R \,.\, (f_2 + q)} \qquad \text{(km/h)}$$

Value of marginal (minimum) radius of horizontal curve:

$$R_{min} = v^2 / 127\,(f_2 + q) \qquad \text{(m)}$$

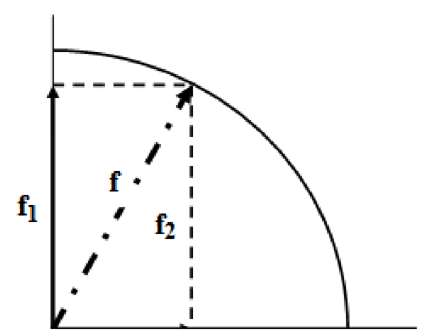
Value of the superelevation in the horizontal curve:

$$q = (v^2 / 127R) - f_2 \qquad \text{(m)}$$

superelevation

The sum of lateral (f_2) and longitudinal (f_1) friction coefficients on the 2nd power is constant, thus it is not recommended to brake when the vehicle travels in the curve (consuming longitudinal friction when braking decreases the amount of available lateral friction to be mobilised against sliding out from the curve)

$$f = \sqrt{f_1{}^2 + f_2{}^2}$$



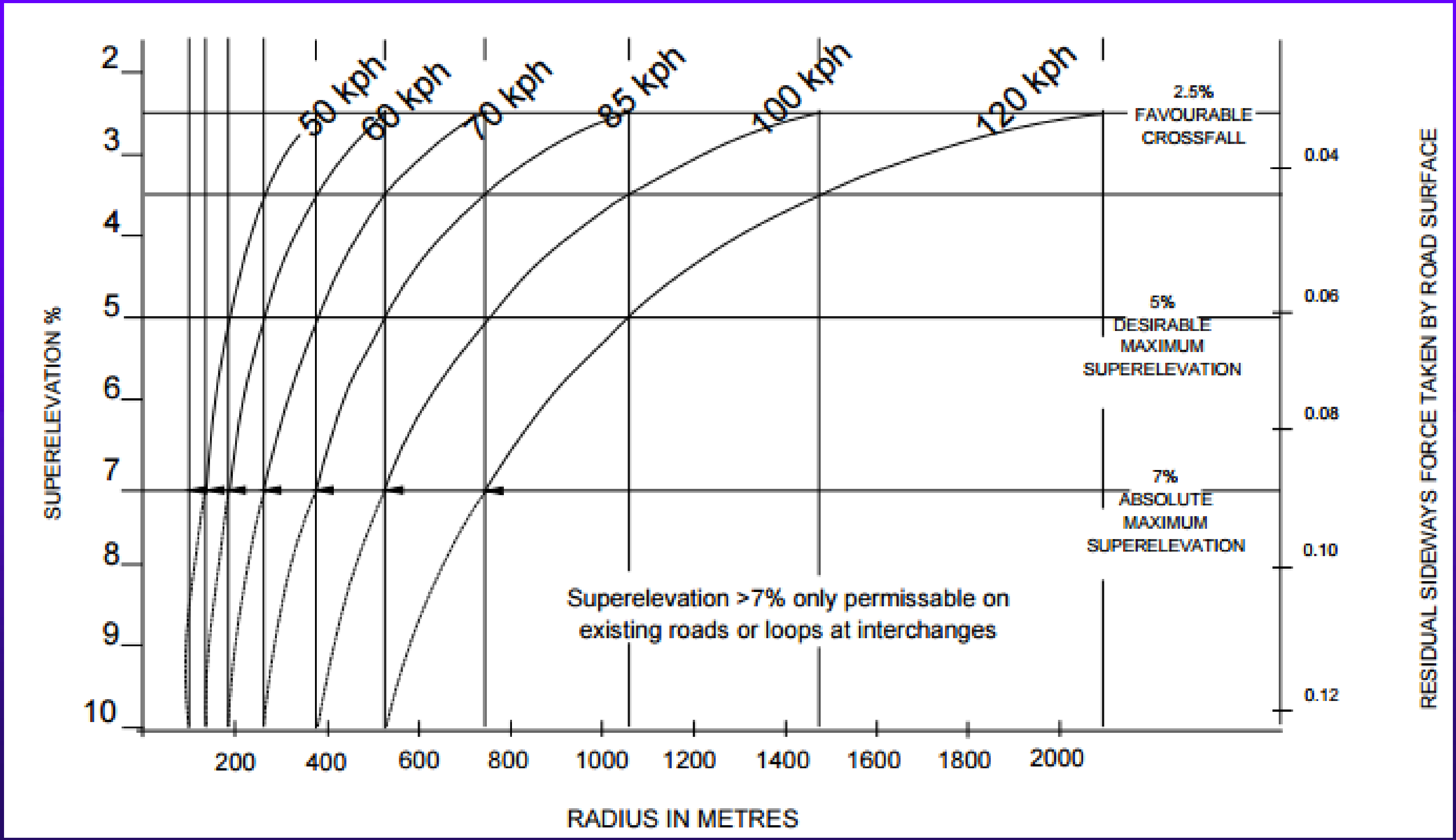
DESIGN SPEED RELATED PARAMETERS (UK, 1993)

DESIGN SPEED kph	120	100	85	70	60	50	V^2/R
STOPPING SIGHT DISTANCE m							
Desirable Minimum	295	215	160	120	90	70	
One Step below Desirable Minimum	215	160	120	90	70	50	
HORIZONTAL CURVATURE m.							
Minimum R* without elimination of Adverse Camber and Transitions	2880	2040	1440	1020	720	520	5
Minimum R* with Superelevation of 2.5%	2040	1440	1020	720	510	360	7.07
Minimum R* with Superelevation of 3.5%	1440	1020	720	510	360	255	10
Desirable Minimum R with Superelevation of 5%	1020	720	510	360	255	180	14.14
One Step below Desirable Minimum R with Superelevation of 7%	720	510	360	255	180	127	20
Two Steps below Desirable Minimum Radius with Superelevation of 7%	510	360	255	180	127	90	28.28
VERTICAL CURVATURE							
Desirable Minimum* Crest K Value	182	100	55	30	17	10	
One Step below Desirable Min Crest K Value	100	55	30	17	10	6.5	
Absolute Minimum Sag K Value	37	26	20	20	13	9	
OVERTAKING SIGHT DISTANCES							
Full Overtaking Sight Distance FOSD m.	*	580	490	410	345	290	
FOSD Overtaking Crest K Value	*	400	285	200	142	100	

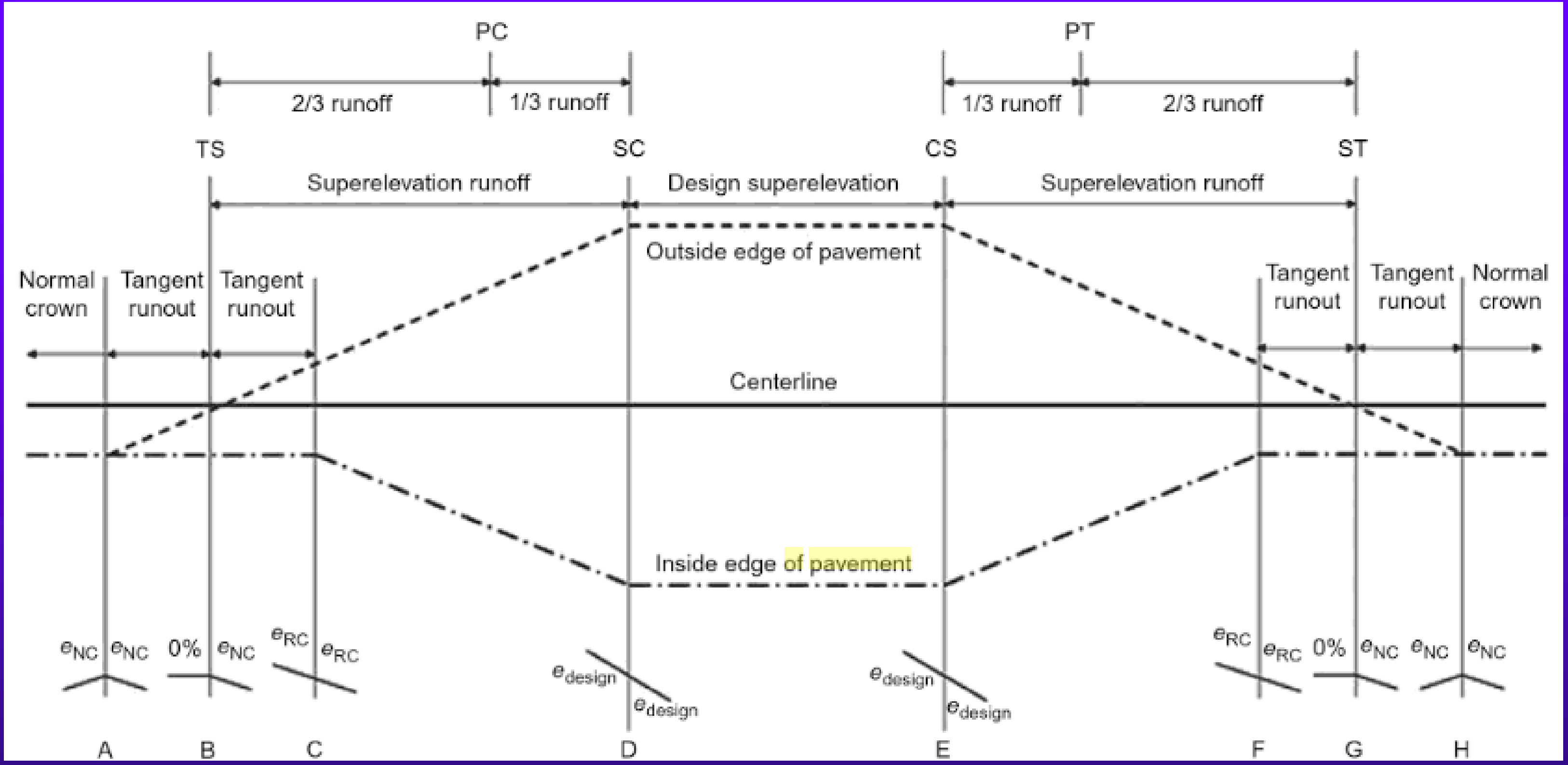
SUPERELEVATION

- Horizontal curves can be *superelevated*, with an elevated cross slope along the width of the pavement, to allow vehicles to travel through the curve at higher speeds, without sliding out
- The cross section of the pavement must be rotated around the centerline or edgeline of a road, to create the *superelevation*
- The *superelevation rate* (%) should be selected so that equilibrium of acting forces (based on the design speed & radius of the horizontal curve) is maintained for the vehicle
- The length of the spiral transition of a spiral curve is often used to accomplish the transition from normal crown to the designed superelevation

SUPERELEVATION OF HORIZONTAL CURVES (UK, 1993)



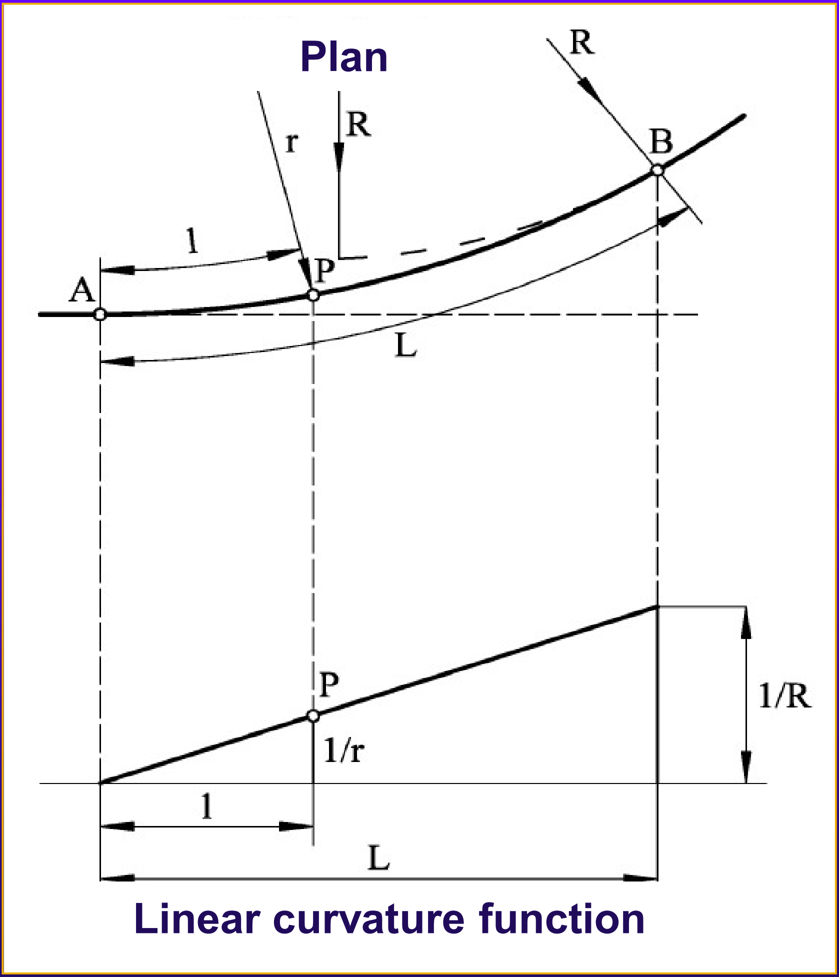
SUPERELEVATION LAYOUT



The transition distance consists of two lengths: *tangent runout* and *superelevation runoff* with a horizontal curve that turns to the right and runs from point *A* to point *H*

SPIRAL TRANSITION CURVE 1

- A *spiral curve* consists of a simple curve (*arc* of a *circle*) bounded by *spiral transitions* on each end
- *Spiral transitions* provide a transition from the *tangent segment,* which allows for the equilibrium of vehicles to be maintained throughout the curve in a designed (comfor-table and safe) manner
- Geometrically the *spiral transition curve* has a radius changing constantly between *infinite radius* (of the tangent) and *fix radius* (*R* of the horizontal curve)



SPIRAL TRANSITION CURVE 2

- The fundamental requirement of a *transition curve* is that its radius of curvature at any given point shall vary inversely as the distance from the beginning of the spiral. Such a curve is called *clothoid* or *Glover's spiral* and is known as an *ideal* transition
- Using the geometric similarity of the two triangles on the previous figure:

$$\frac{l}{L} = \frac{1/r}{1/R};$$

$r*l = R*L = p^2$ (constant)

where:

L - length of the spiral transition curve [m]
R - radius of the horizontal curve [m]
r - radius at a randomly selected point P on the spiral transition curve [m]
l - distance from the beginning of the spiral transition curve up to point P [m]
p – so called *parameter* of the spiral transition curve: $p = \sqrt{R \cdot L}$

MINIMUM LENGTH OF TRANSITION CURVE

- **The *minimum length* of transition curve can be calculated by the following 3 conditions:**
  - **Based on rate of change of acceleration: $L_{min} = v^3 / C*R$**
  - **Based on rate of change of superelevation and extra widening: $L_{min} = (W + Wq)*q*N$**
  - **Based on empirical formula:**
    - **for plain and ruling terrain: $L_{min} = 2.7\ (v^2/R)$**
    - **for mountainous and steep terrains. $L_{min} = v^2/R$**

where

v - is the design speed (m/s)

C - is the coefficient of rate of change of centrifugal acceleration (m/sec^3)

R - is the radius of the horizontal curve (m)

W - is the normal width of pavement (m)

Wq - is the extra width of pavement in

q – is the superelevation (m/100m)

N - is the allowable rate of introduction of superelevation

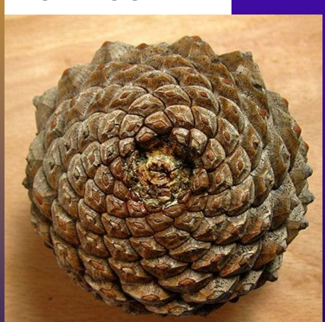
SPIRAL TRANSITION CURVE 3

- Coordinates to be used to design horizontal spiral transition curve

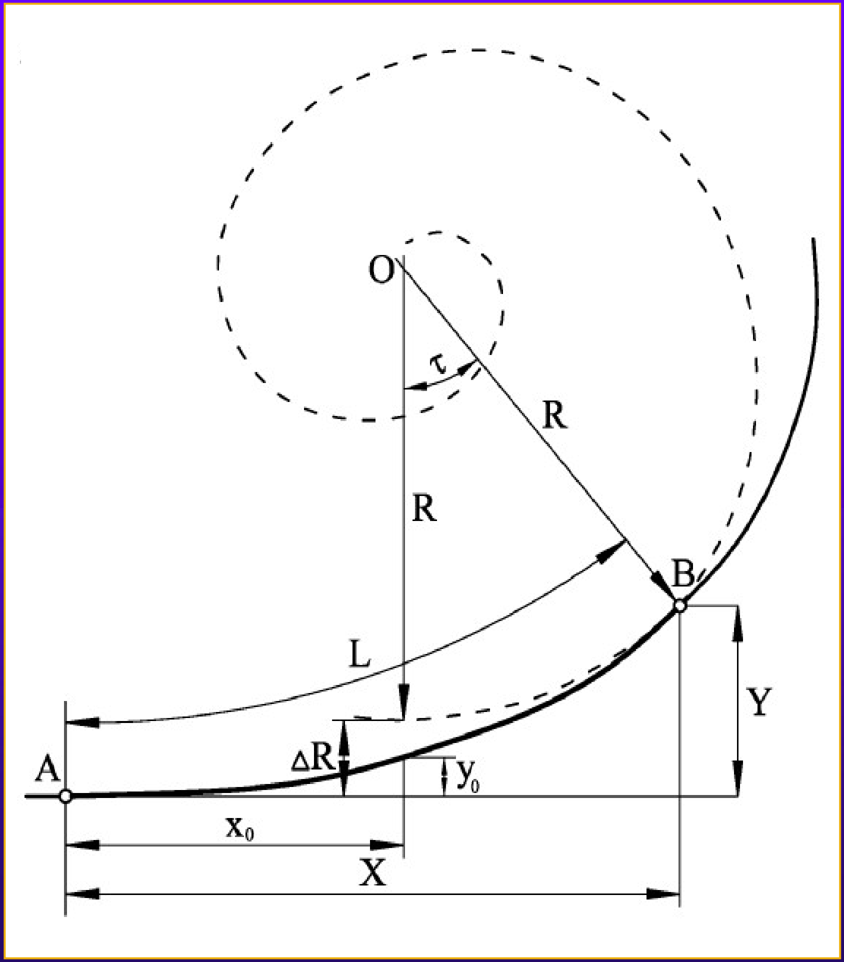
$$\Delta R = \frac{L^2}{24R}$$

$$y_o = \frac{\Delta R}{2} \qquad L = \frac{p^2}{R}$$

SNAIL'S SHELL



PINE CONE



$X = L \qquad Y = 4\,\Delta R$

$X_0 = L/2$