B.Sc - Road & Railway Design I. *Lecture 3.*

ELEMENTS & COORDINATION OF HORIZONTAL & VERTICAL ALIGNMENT

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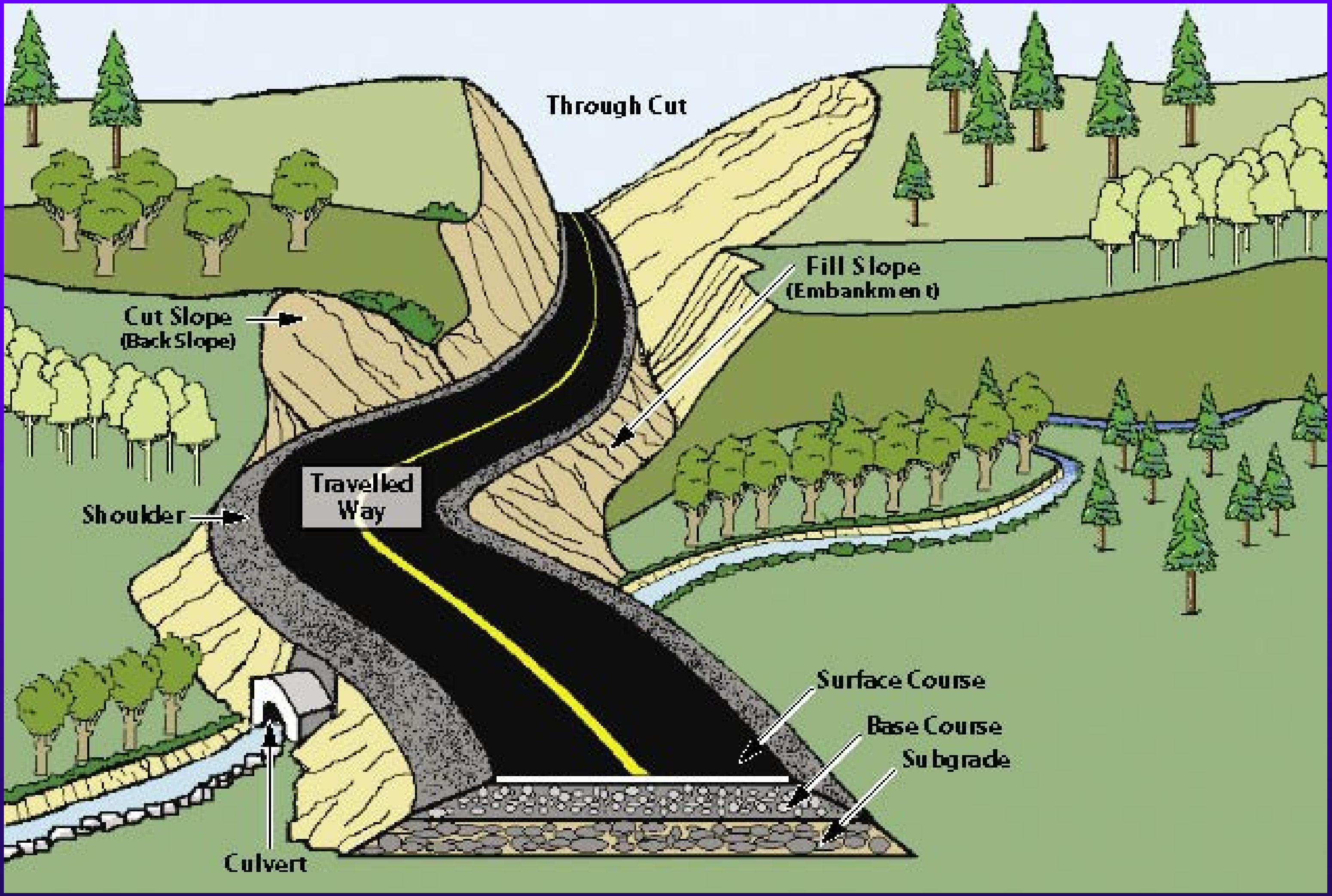
GEOMETRIC DESIGN OF ROADS

- **Geometric design of roads is the branch of *road engineering* concerned with the positioning of the elements of the road according to standards & constraints**
- **Geometric design is the process whereby the layout of the road in the terrain is designed to meet the needs of the road users**
- **It includes the design of geometric *cross section*, *horizontal alignment*, *vertical alignment*, *intersections*, and various *elements of road safety* (signs, markings, guiderails, etc.)**
- ***Objectives* in geometric design are to optimize efficiency, comfort and safety of road users, while minimizing costs and environmental damage caused by construction and traffic**

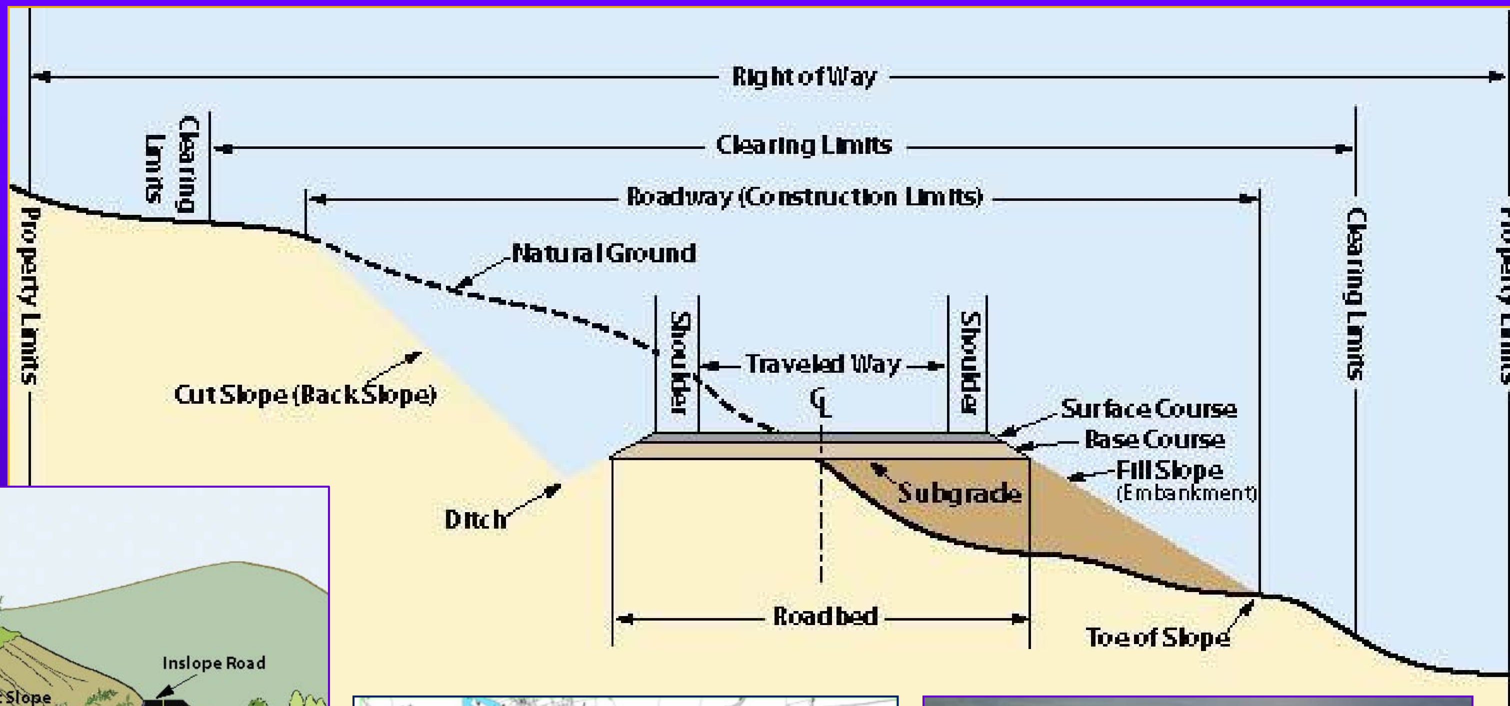
PARTS OF GEOMETRIC DESIGN

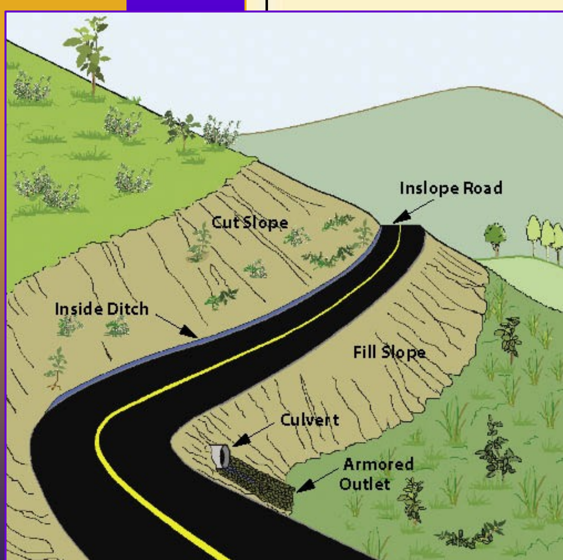
- The *alignment* is the route of the road, defined as a series of horizontal *tangents* and *curves*
- The *profile* is the vertical aspect of the road, including *crest* and *sag curves*, and the *straight grade lines* connecting them
- The *cross section* shows the position and number of vehicle lanes along with their *cross slope* or banking
- Cross sections also show *drainage* features, *pavement structure* and other items outside the category of geometric design

ROAD COMPONENTS



MAIN TERMS DEFINING A ROAD





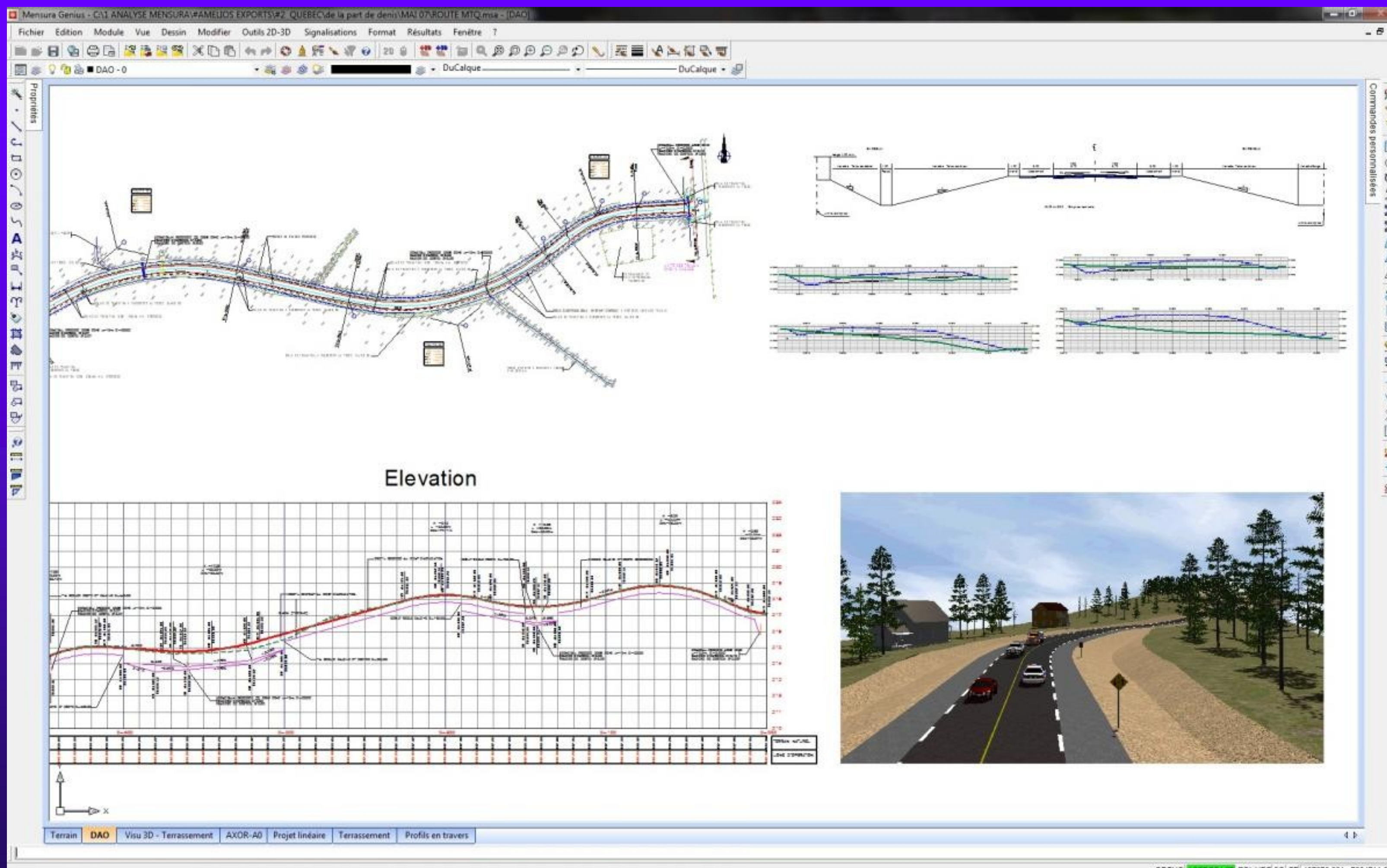
DESIGN STANDARDS & GUIDELINES

- Roads are designed in conjunction with design guidelines and standards adopted by national and sub-national authorities
- Design guidelines take into account composition and speed of expected traffic, road grade (slope), view obstructions and stopping distances
- With proper application of guidelines, along with good engineering judgement, a civil engineer can design a roadway that is comfortable, safe and harmonises with the environment (landscape)
- Computer programs are providing substantial support to design a road complying with technical and socio-economic requirements

DRAWINGS TO BE PREPARED

- The plan consists of construction drawings and specifications for each section of road
- Most common views of plans to be prepared by the road designer are:
  - *plan view*: a drawing depicting a section of the road from a bird's eye view (vertical projection)
  - *profile view*: a drawing depicting the vertical plane along the longitudinal centerline of the road, expressed in elevation or gradient
  - *cross-section view*: a drawing depicting a section of the road viewed vertically, as if cut across the width of the road
  - *landscape-view*: a drawing depicting the layout of the roadway from a driver’s perspective

COMPUTER AIDED DESIGN (CAD)



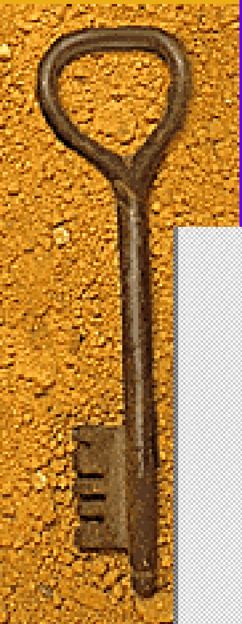
PLAN VIEW

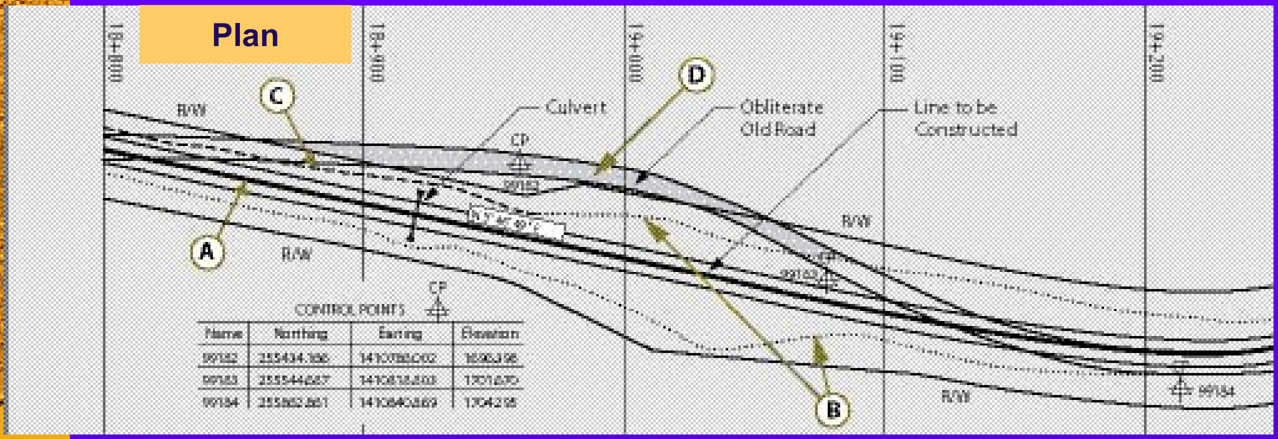
- On a plan the proposed road is designated with solid lines: centreline & borderlines
- The centreline is divided into 100 meter *sections*, with 20 meter subdivisions called *stations*, representing a discrete, surveyed, and identifiable point within the road corridor
- Each station is identified with a unique num-ber that indicates its distance on a horizontal plane from the *initial* or *datum point* (e. g. station 19+040 indicates this point is located at 19.040 m from the start of the road project, i. e. from station 0+000)

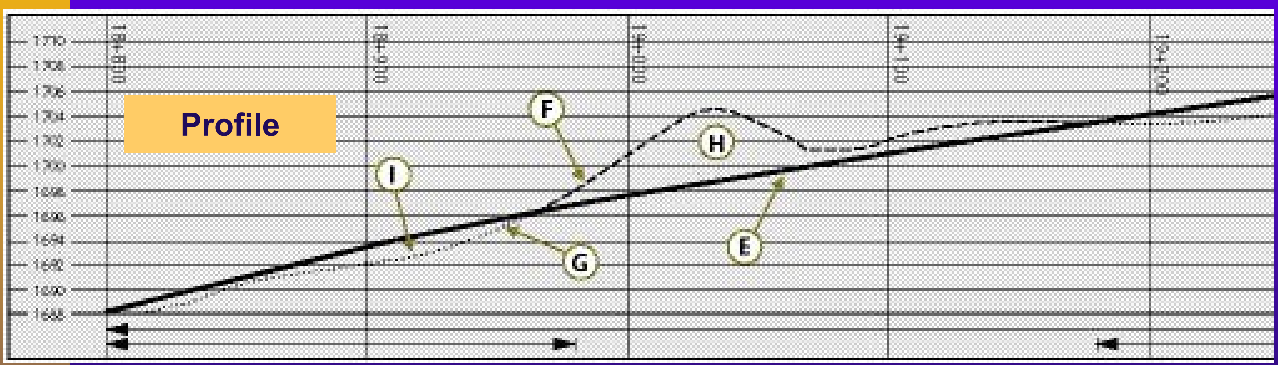
IDENTIFIERS

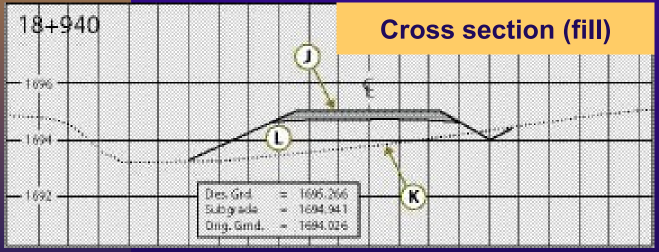
- Sections and stations as identifiers are also used to indicate the placement of road-related infrastructure, such as culverts, the beginning and end of guardrail construction, or the placement of a sign, etc.
- The plans also show the horizontal and vertical layout and numerical co-ordinates of the centerline on the surface of the pavement, the lines of the road crown, the top of the cut slopes and the toe of the fill slopes, as well as the layout and borderlines of the surface dewatering system

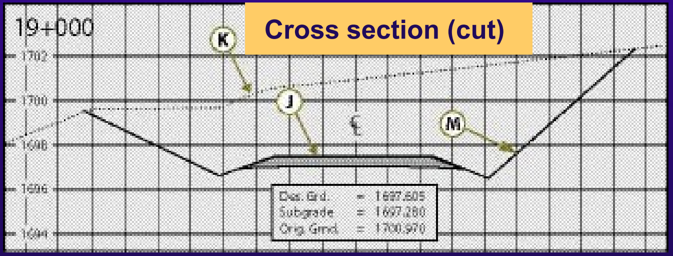
ROAD DESIGN - DRAWINGS





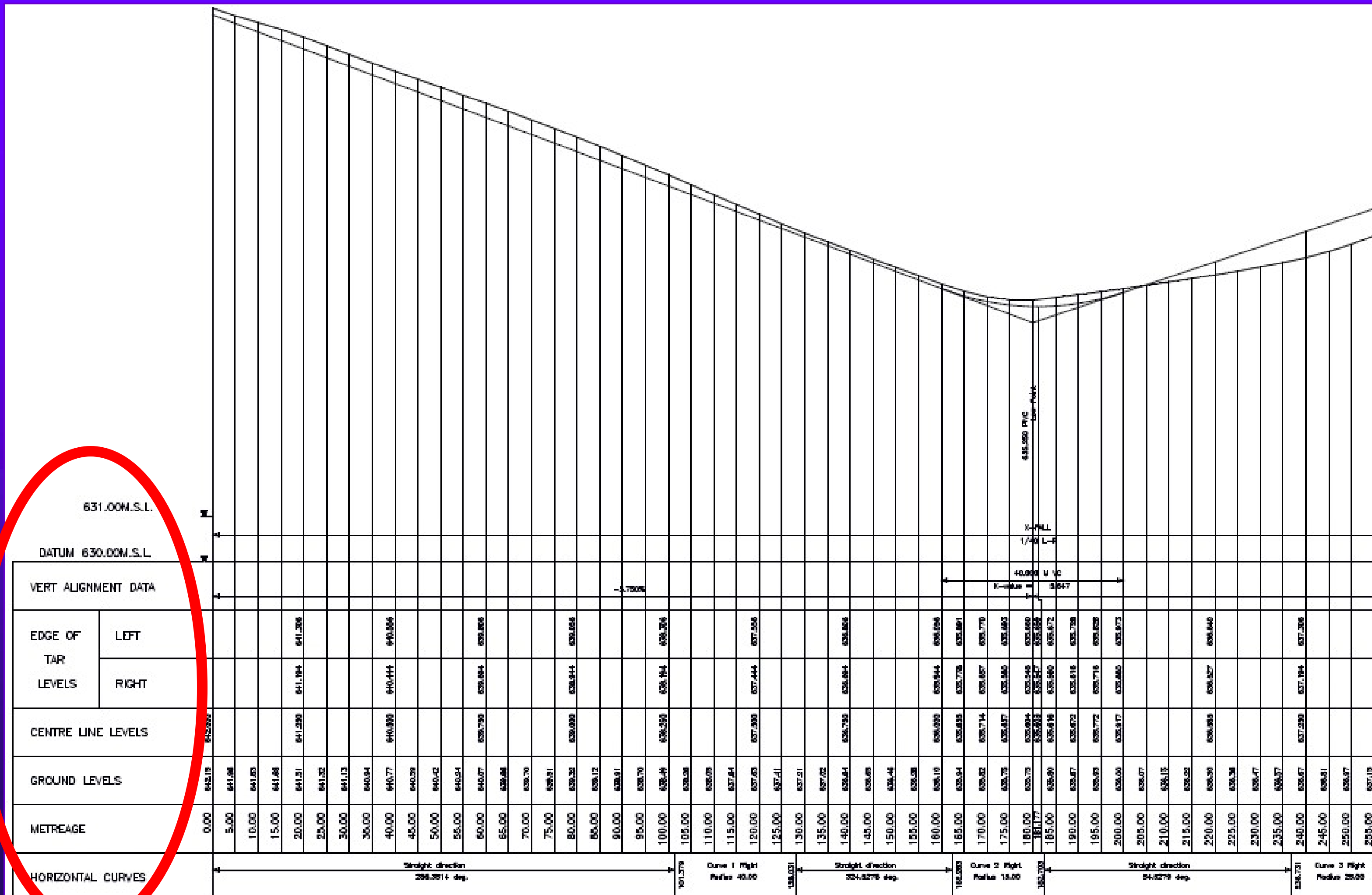






- A - centerline and crown borderlines
- B - top edge of the cut slope
- C – toe of the fill slope
- D - location of the original road (to be obliterated)
- E - centerline of the road
- F - ground level above the centerline
- G - ground level below centerline
- H - cut top line above center line
- I – fill bottom line below centerline
- J - surface of new road
- K – natural ground line
- M – artificial ground line (slope in cut)

ROAD PROFILE DRAWING



GENERAL CONTROLS OF HORIZONTAL ALIGNMENT 1

- Much of the criteria for horizontal alignment seeks to establish minimum design values which are based on specific limiting factors like side-friction, super-elevation, longitudinal gradients, camber and values for sight distances
- The designer should adhere to several general controls for horizontal alignment based on aesthetic and safety considerations as follows:
  1. Horizontal alignment should be as directional as possible; where feasible, minimum radii should be avoided; flatter curvature with shorter tangents is generally preferable to sharp curves connected by long tangents
  2. Curves with small deflection angles should be long enough to avoid the appearance of a kink; for a central angle of 5° or less, the curve should be at least 150 m long; on main roads the designer should try to provide a curve length of at least 6 times the design speed in km/h; on other roads, try to provide a curve length 3 times the design speed

GENERAL CONTROLS OF HORIZONTAL ALIGNMENT 2

3. Very small deflection angles may not require a horizontal curve; i.e., the roadway may be designed with an angular break; as a general guide, the designer may consider using an angle point when the deflection angle is less than 1°
4. Broken back curvature should be avoided
5. Sharp horizontal curves should not be introduced near crest or sag vertical curves; the combination of horizontal and vertical curves can greatly reduce sight distance and increase the likelihood of accidents
6. Horizontal curves and superelevation transitions should be avoided on bridges (these may cause design, construction and operational problems when snow and ice are present). Where a curve is necessary on a bridge, a simple curve is preferred
7. The crossover line will often be a control for setting the rates of superelevation and radius and profile where two roadways converge
8. The radius of a ramp curve ending parallel to a motorway should be within 300 meters of the radius of the motorway

HORIZONTAL ALIGNMENT 1

- **The horizontal alignment of a road is usually a series of straights (tangents) and circular curves (e. g. simple, compound, reverse, broken back curves) that may or may not be connected by transition curves**
- **The initial process in developing a road's alignment is through a series of straight lines or *tangents* that form a *traverse***
- **A *traverse* should follow the alignment of a „*neutral line*" as closely as possible**
- **The process of measuring and assigning *stations* to a traverse is an essential component of horizontal alignment**

NEUTRAL LINE

- The *neutral line* is a useful tool to find out the best layout (traverse + alignment) of a road
- It is an *imaginary* line with *constant grade* g_n running on the surface of the natural ground
- Its upward or downward grade should remain below maximum grade value:

$$g_{n\max} \leq 0{,}85\, g_{\max}$$

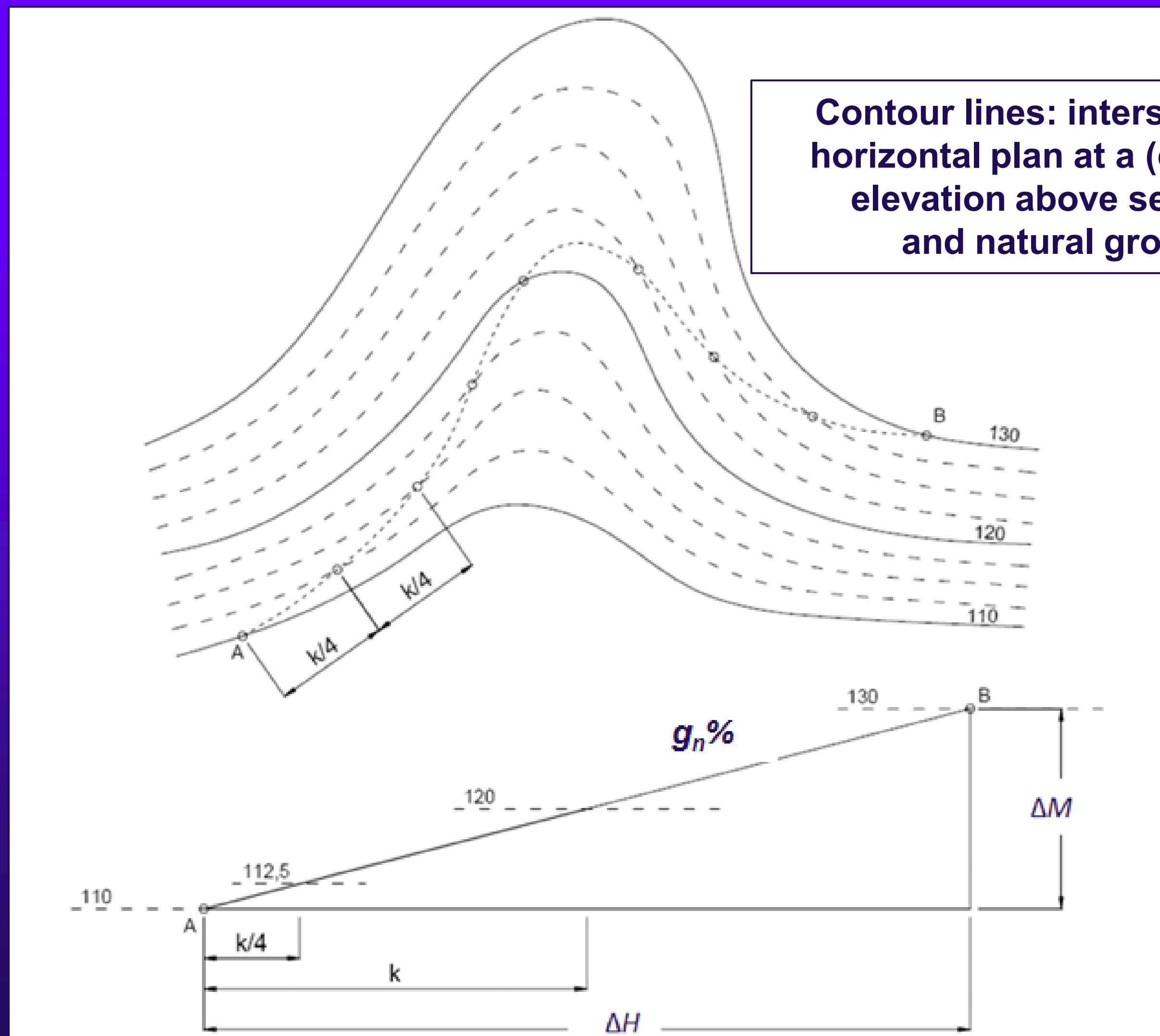
- Grade of neutral line: $g_{n=}100\ \Delta M/\Delta H$, where

  ΔH difference of elevations above sea level

  ΔD estimated distance on a horizontal plane

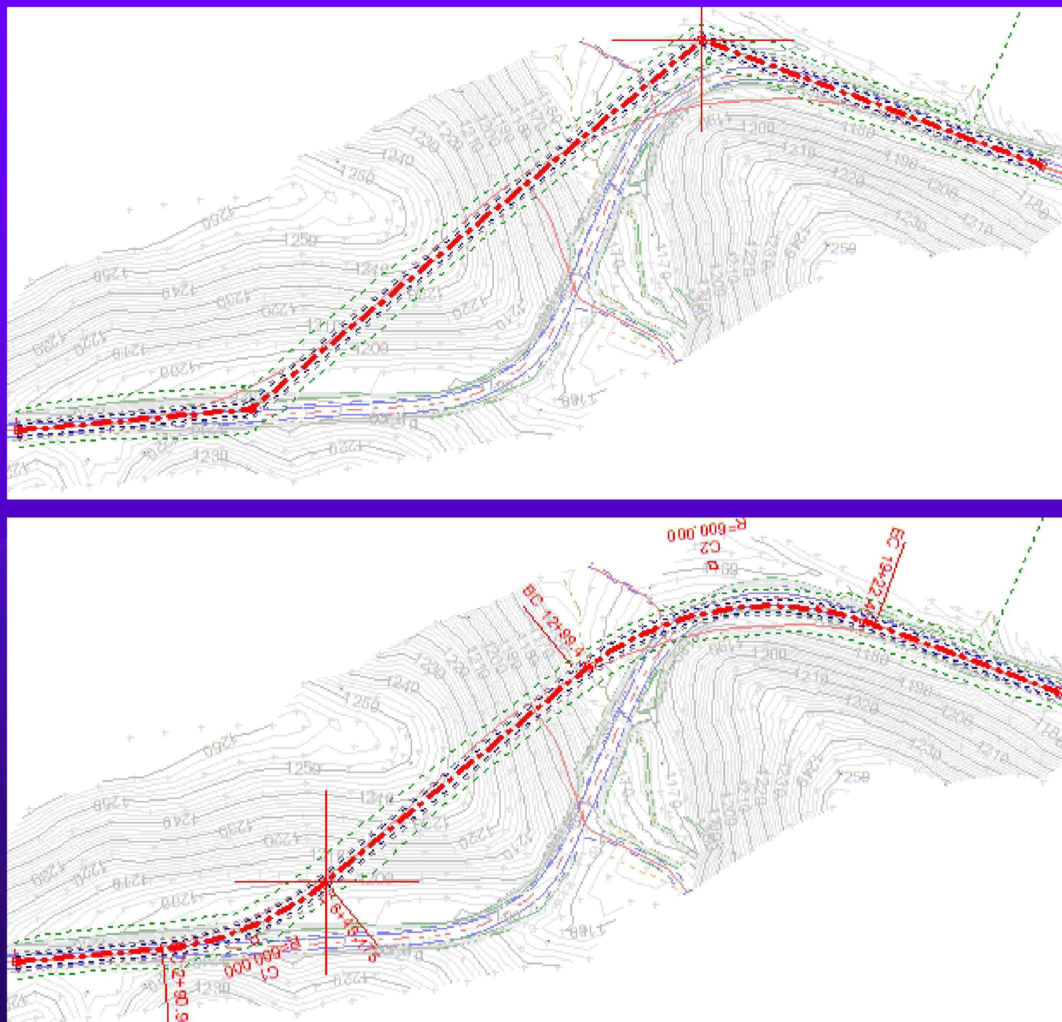
  between its starting (A) and end (B) point

NEUTRAL LINE ON A CONTOUR-MAP



Contour lines: intersection of horizontal plan at a (constant) elevation above sea level and natural ground

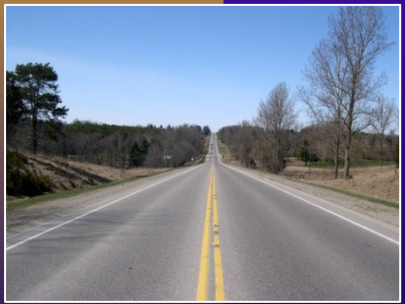
CURVES CONNECTING TANGENTS

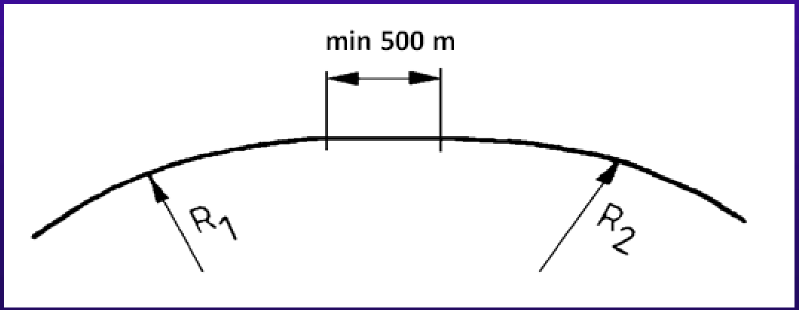


Horizontal alignment before and after curves applied

HORIZONTAL ALIGNMENT: TANGENT SECTIONS

- ***Tangents*** **(straight line) sections:**
  - ***Passing/overtaking*** **is allowed and could be safely completed mostly here**
  - ***Junctions*** **and** ***intersections*** **are to be located there**
  - **From aesthetic point of view they are** ***rigid*** **elements**
  - **Aiming to avoid fatigue of drivers, the length of a tangent could not exceed 20v_D (v_D =design speed)**
  - **For comfort of drivers the minimum length of a tangent between two horizontal curves should** ***not be less*** **than 500 m**





HORIZONTAL ALIGNMENT: CURVES

- Horizontal curves provide a *smooth transition* from one tangent to the next
- From a safety perspective they are a particular focus because of the prevalence of collisions at curves relative to tangent sections
- Proper design of horizontal curves, including elements within a single curve and *consistency of curvature* along a road can reduce the likelihood of accidents
- The *radius* is a term used to describe the sharp-ness of a curve; the simple curve is an *arc of circle* with a constant radius

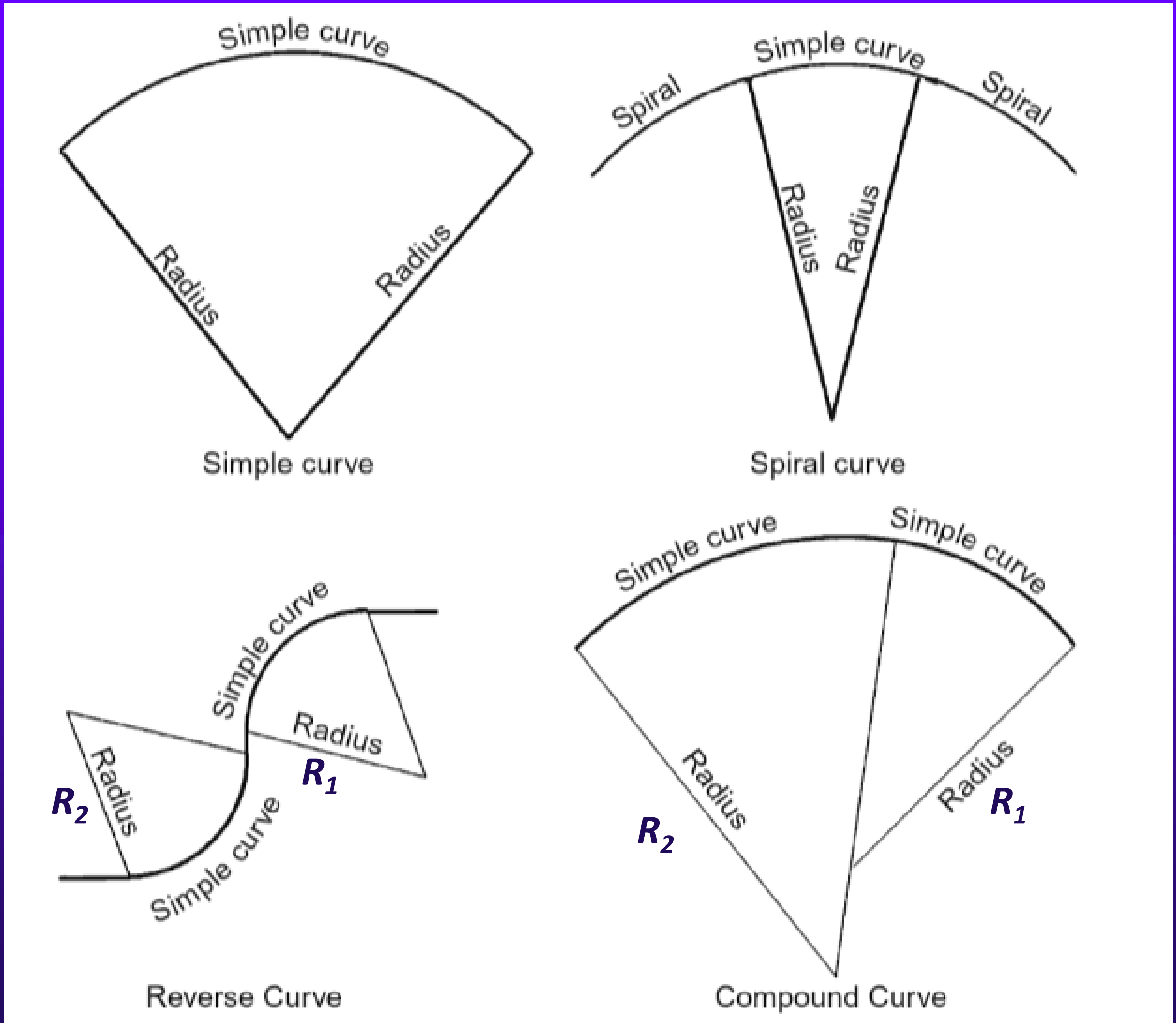
HORIZONTAL ALIGNMENT 2

Design speed v_D (km/h)	Minimum radius of a curve $R_{min} = v_D^2 / 127 (f_2 + 0.01e)$ (m)	Maximum length of tangent L_{max} (m)
120	750	2400
100	500	2000
80	300	1600
70	200	1400
60	150	1200
50	100	1000
40	60	800
30	30	600

Values of minimum radii of horizontal curves and maximum lengths of tangents in function of design speed

(Road Design Manual)

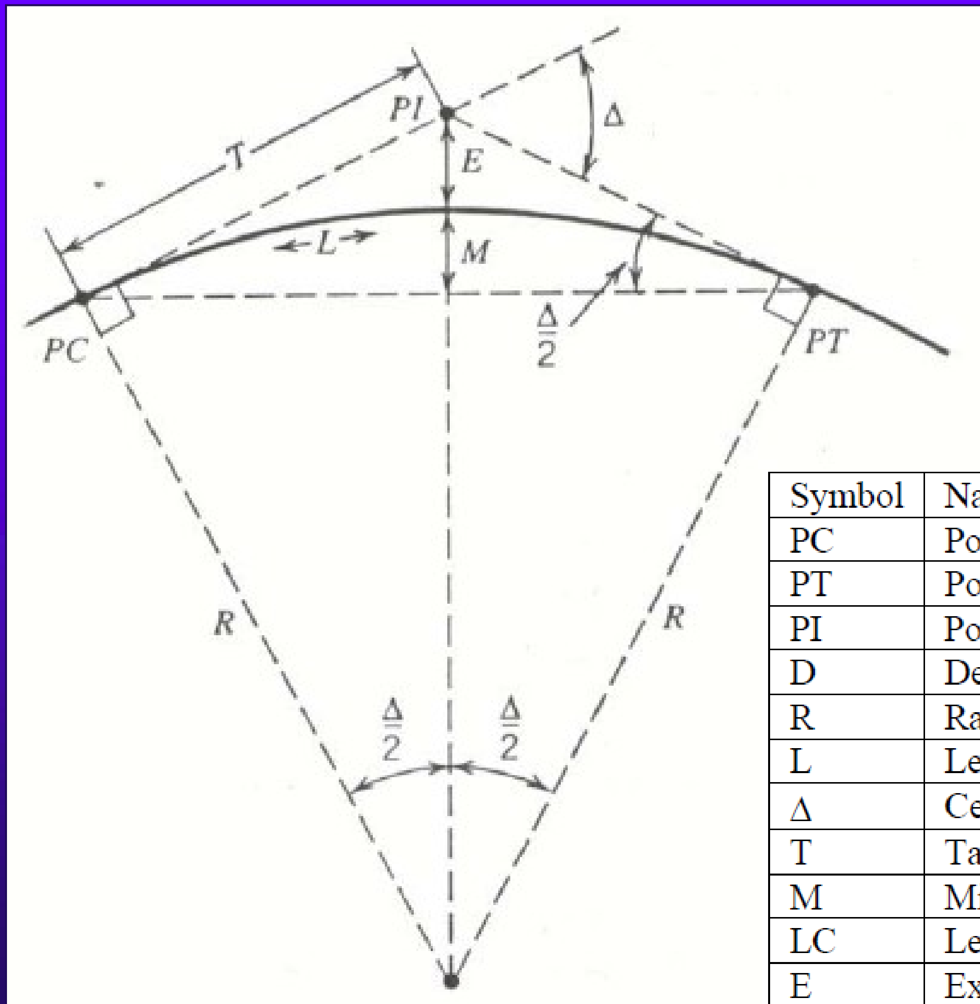
TYPES OF HORIZONTAL CURVES



Radii of circular curves following each other on the alignment could not be too different:

$R_1 / R_2 \leq 1/3$

ELEMENTS OF A SIMPLE (CIRCULAR) CURVE



$$T = R\tan\left(\frac{\Delta}{2}\right)$$

$$L = \frac{R\Delta\pi}{180}$$

$$M = R\left(1 - \cos\left(\frac{\Delta}{2}\right)\right)$$

$$E = R\left(\frac{1}{\cos\left(\frac{\Delta}{2}\right)} - 1\right)$$

Symbol	Name
PC	Point of curvature, start of horizontal curve
PT	Point of tangency, end of horizontal curve
PI	Point of tangent intersection
D	Degree of curvature
R	Radius of curve (measured to centerline)
L	Length of curve (measured along centerline)
Δ	Central (subtended) angle of curve, PC to PT
T	Tangent length
M	Middle ordinate
LC	Length of long chord, from PC to PT
E	External distance

COMPOUND CURVE 1

- A *compound curve* consists of two or more adjacent simple circular arcs curving in the same direction with centers of curvature on the same side of the common tangent
- Frequently the terrain or unavoidable obstacles will require the use of compound curves
- The radius of the smaller curve should be

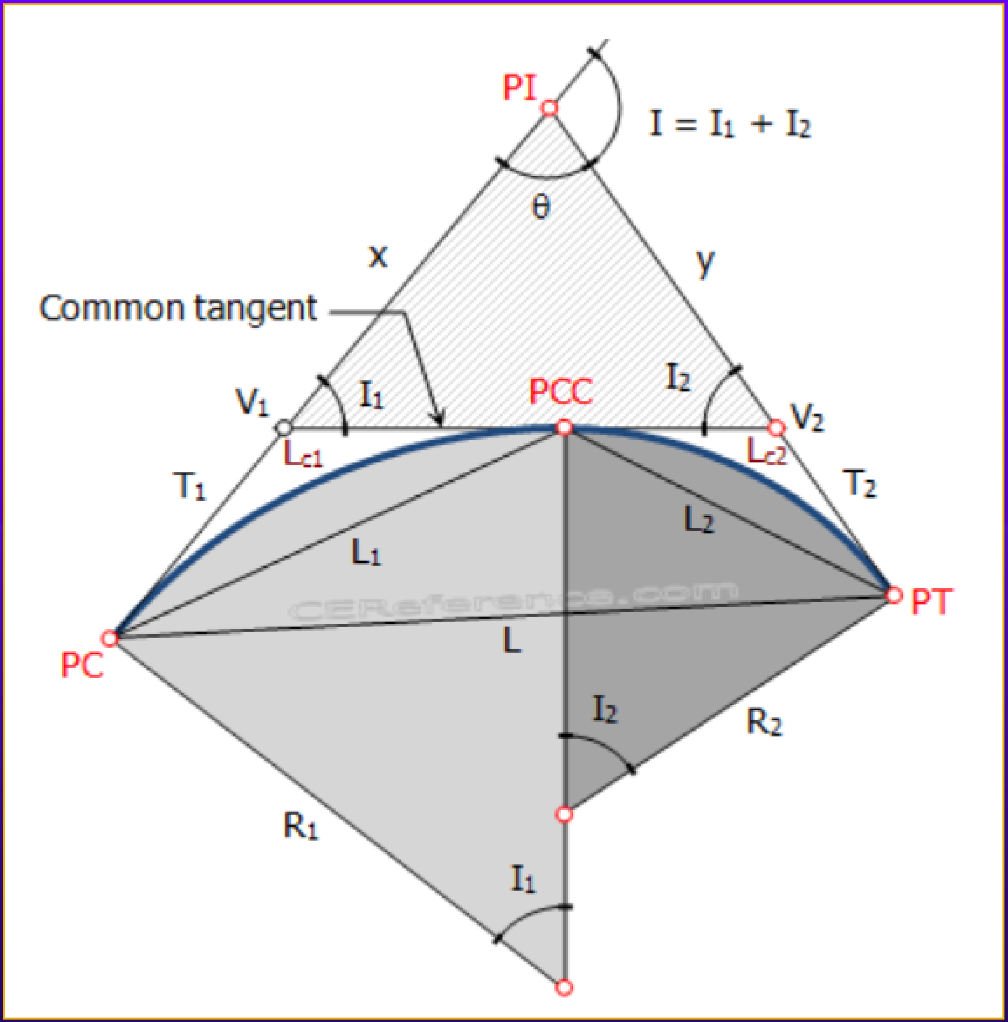
$$R_2 \geq 2500\text{m}$$

- The ratio between the two radii should be

$$R_1/R_2 \leq 2 \text{ (exceptionally 1.5)}$$

- A short tangent may connect the two component curves, creating a *broken back curve*

COMPOUND CURVE 2

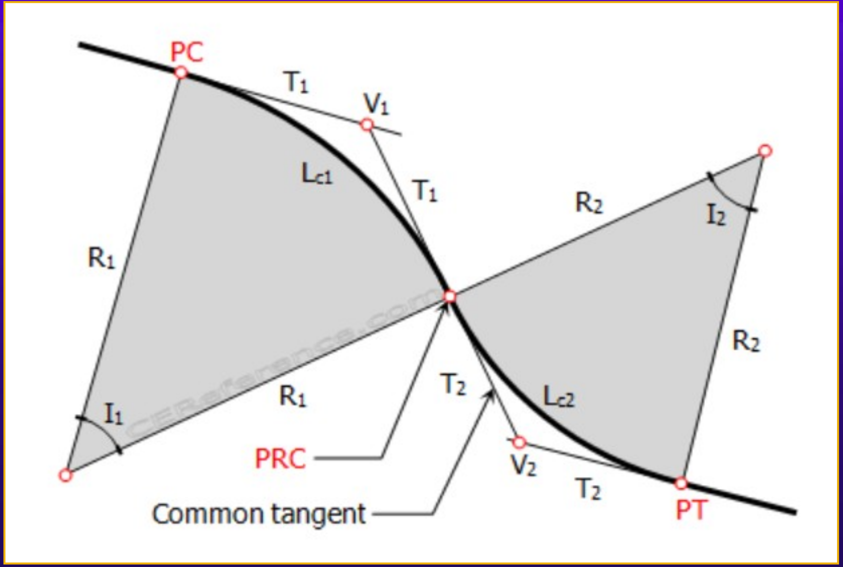


ELEMENTS:

PC = point of curvature
PT = point of tangency
PI = point of intersection
PCC = point of compound curve
T_1 = length of tangent of the first curve
T_2 = length of tangent of the second curve
V_1 = vertex of the first curve
V_2 = vertex of the second curve
I_1 = central angle of the first curve
I_2 = central angle of the second curve
I = angle of intersection = $I_1 + I_2$
L_{c1} = length of first curve
L_{c2} = length of second curve
L_1 = length of first chord
L_2 = length of second chord
L = length of long chord from PC to PT
$T_1 + T_2$ = length of common tangent measured from V_1 to V_2
θ = 180° - I
x and y can be found from triangle V_1-V_2-PI.
L can be found from triangle PC-PCC-PT

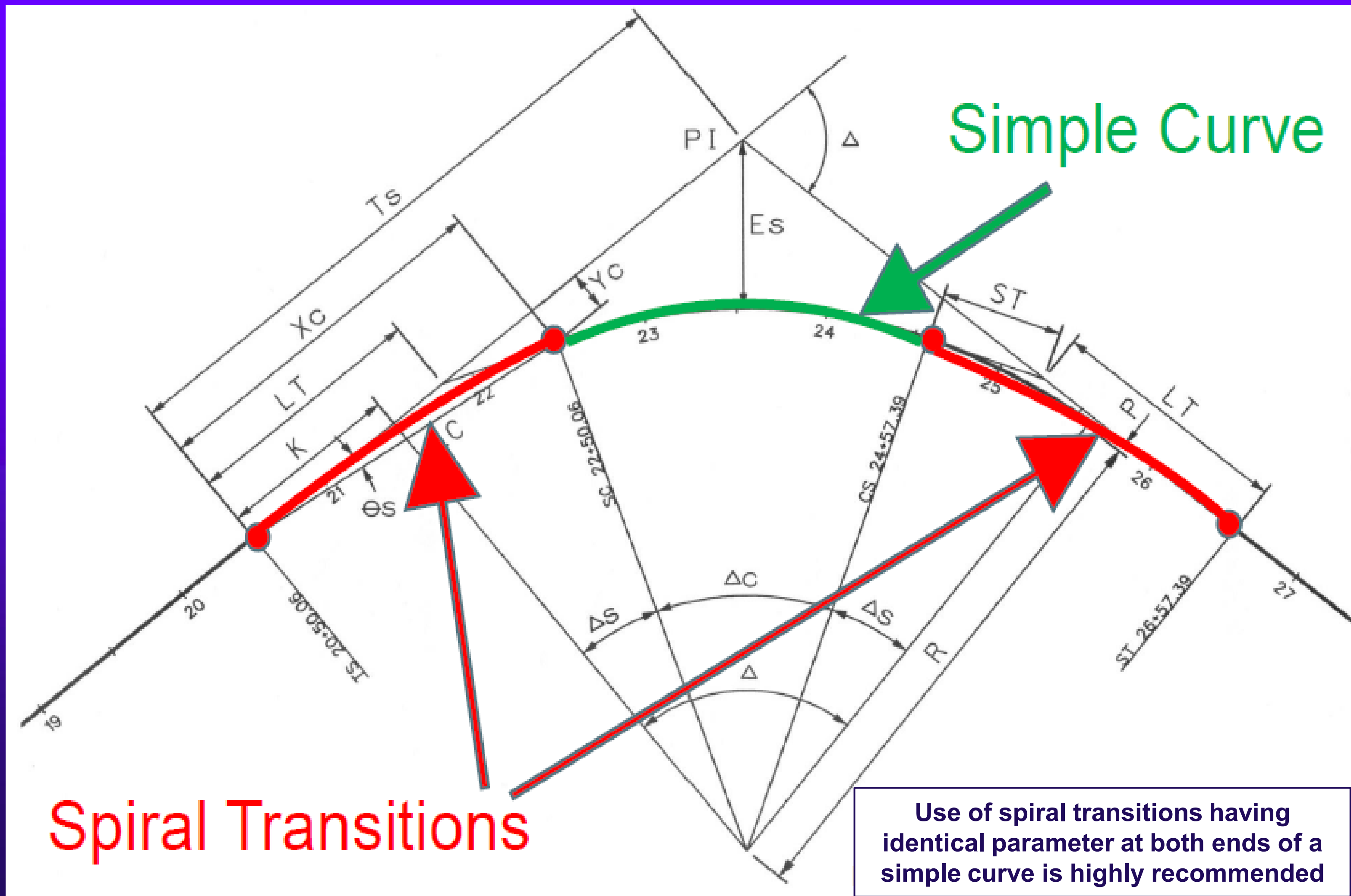
REVERSE CURVE

- Reverse curves consist of two circular arcs turn in the opposite direction, which have their centers of curvature on the opposite side of the common tangent
- Reverse curves would bring discomfort to motorist, while the instant change in direction at the *PRC* brought safety problems, so their use should be avoided when possible



ELEMENTS:
PC = point of curvature
PT = point of tangency
PRC = point of reversed curvature
T_1 = length of tangent of the first curve
T_2 = length of tangent of the second curve
V_1 = vertex of the first curve
V_2 = vertex of the second curve
I_1 = central angle of the first curve
I_2 = central angle of the second curve
L_{c1} = length of first curve
L_{c2} = length of second curve
L_1 = length of first chord
L_2 = length of second chord
$T_1 + T_2$ = length of common tangent measured from V_1 to V_2

SPIRAL TRANSITION CURVES 1



Use of spiral transitions having identical parameter at both ends of a simple curve is highly recommended

SPIRAL TRANSITION CURVES 2

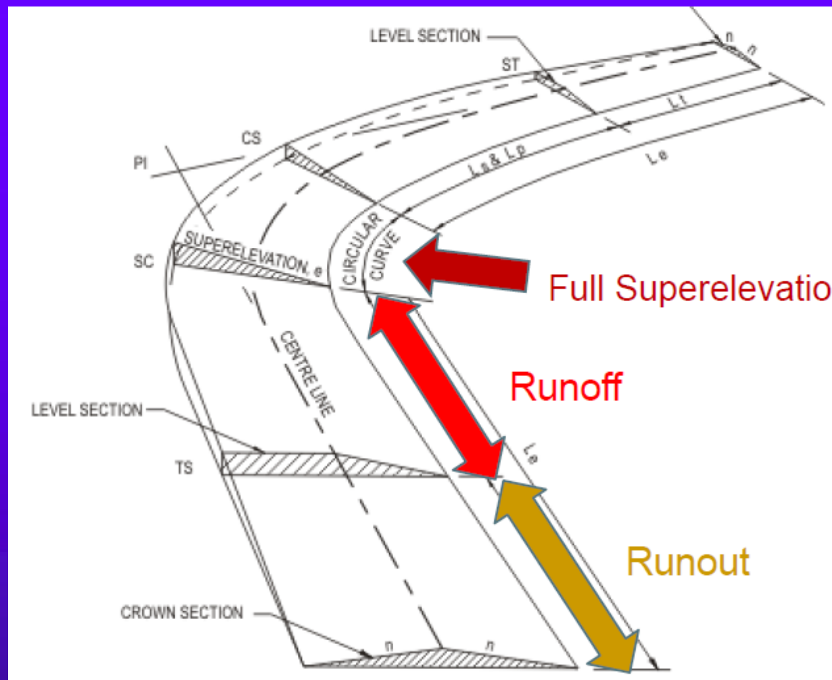
- Spiral transitions provide a gradual change in curvature from tangent to circular curve thus improves appearance and driver comfort
- Provides location for superelevation runoff
- Length shouldn't be less than $L_{min} \geq v_D^3 / 23.3R$
- Rule of thumb to select parameter: p = 0.3R [m]
- Minimum parameter depends upon design speed

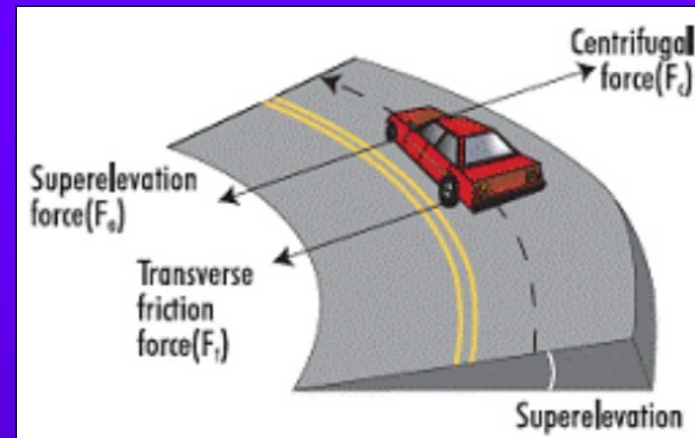
v_D [km/h]	p_{min} [m]
100	175
80	130
70	85
60	64

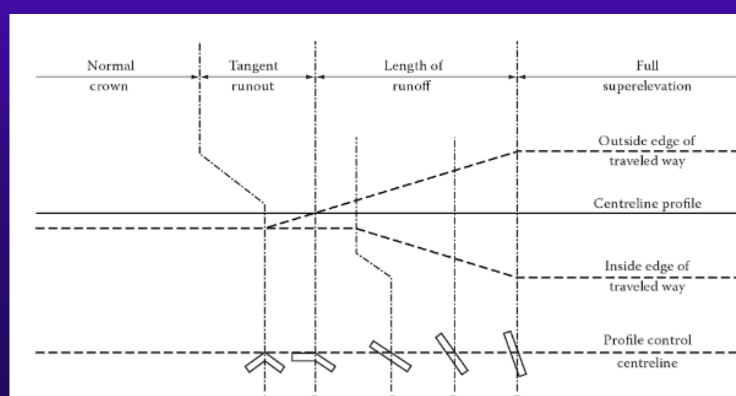
- Spiral transitions may be omitted when

v_D [km/h]	and	R [m] ≥
100		3000
80		1500
60		1000

SUPERELEVATION IN A TRANSITION CURVE 1

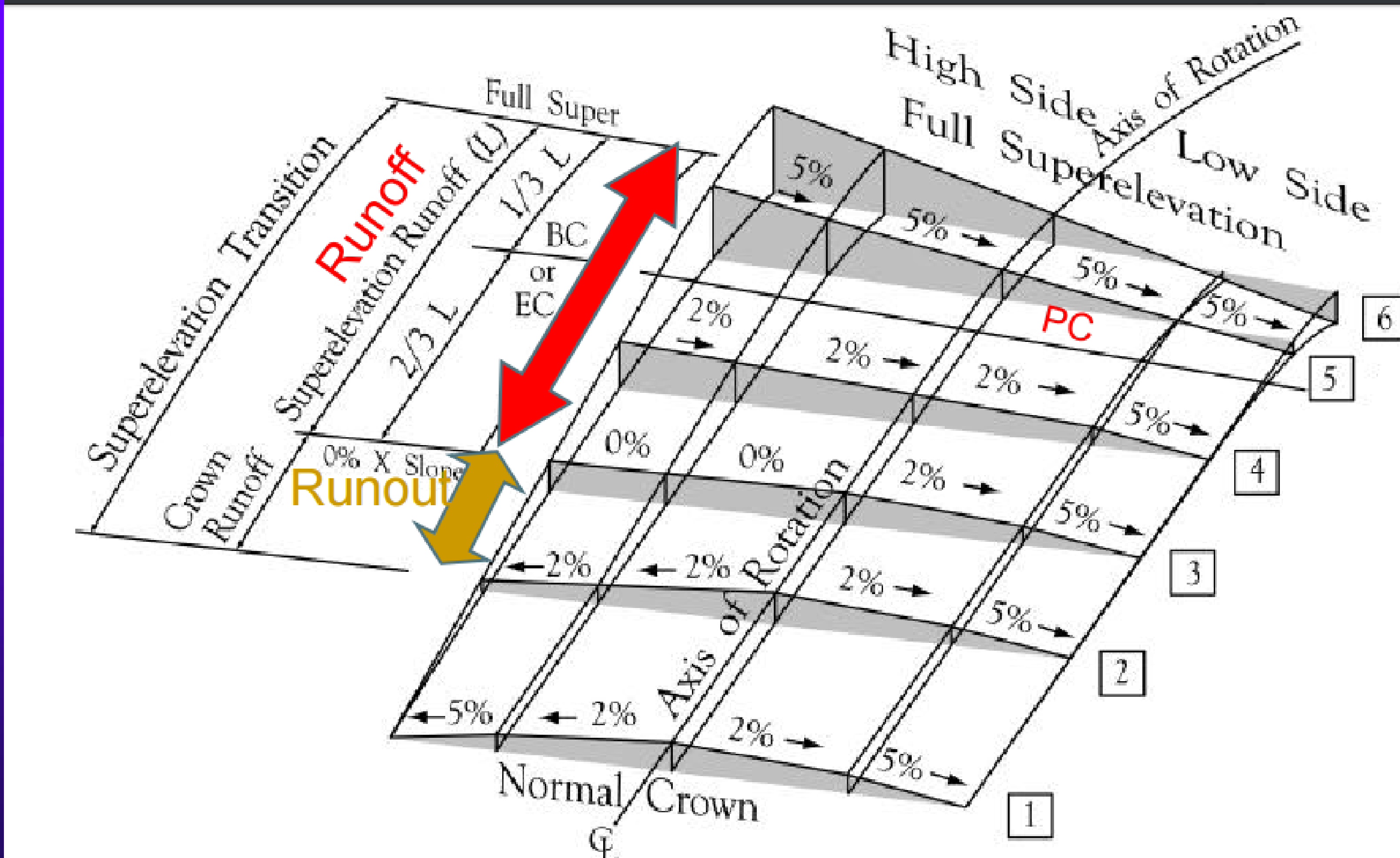






- ***Runoff*****: length of roadway needed to accomplish a change in outside lane cross slope from zero to full □**
- ***Runout*****: length of roadway needed to accomplish a change in outside lane cross slope from normal rate to zero**

SUPERELEVATION IN A TRANSITION CURVE 2



VERTICAL ALIGNMENT 1

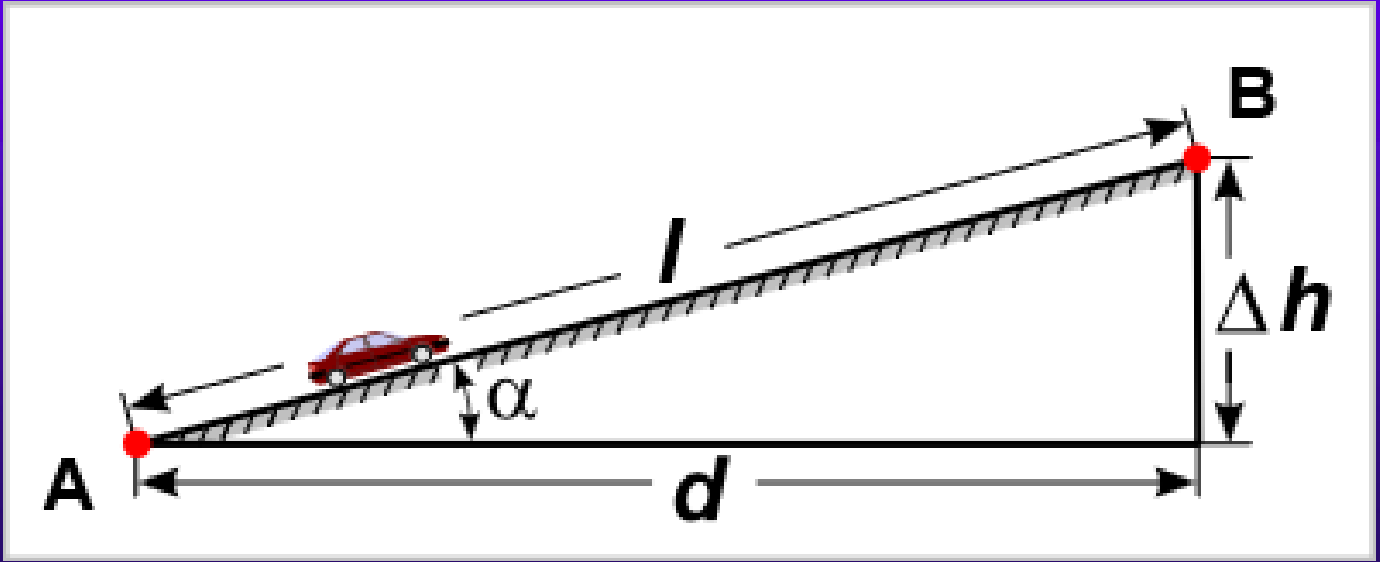
- Basic components:
  - *grades* (uphill and downhill slopes)
  - *vertical curves* (summit/crest curves and valley/sag curves)
- The profile is composed from *crest* and *sag curves* and the *straight grade lines* connecting them
  - *Crest vertical curves* when viewed from the side, are *convex* upwards, including those at hill crests and locations where an uphill grade becomes less steep, or a downhill grade becomes steeper
  - *Sag vertical curves* when viewed from the side, are *concave* upwards, including those at valley bottoms, and locations where an uphill grade becomes steeper, or a downhill grade becomes less steep

GRADES

- The *grade* of a road is a ratio of its *rise* to its *run* and is given as a decimal or percent:

$$g = \text{rise/run} = \tan\alpha = \Delta h \,/\, d \;[m/m]$$

$$g = 100*\text{rise/run} \;[\%]$$



d = run; Δh = rise; l = slope length; α = angle of inclination

VERTICAL ALIGNMENT 2

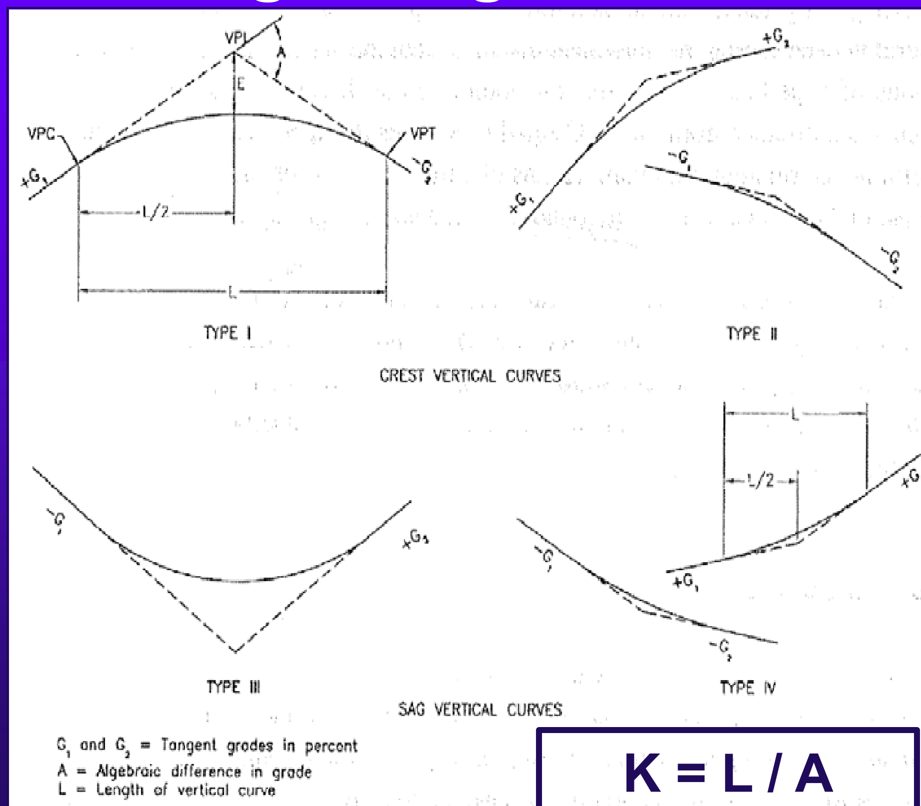
- Values of maximum permitted grades (g_{max}[%]) depend upon the design speed v_D [km/h] selected in compliance with characteristics of the terrain (*flat, hill* or *mountain*):

v_D [km/h]	g_{max} [%]
100	4,5
80	6
60	8

- g_{max} should be applied only under extreme condi-tions, otherwise lower values are preferred, but for *surface drainage* purposes $g_{min} \geq$ 0.7%
- In *horizontal curves* of mountain-like terrain values of g_{max} should be *reduced by 15%*
- On *secondary roads* g_{max} may reach 15%

VERTICAL CURVES 1

- Vertical curves shall be provided at all changes in gradient, their types are:

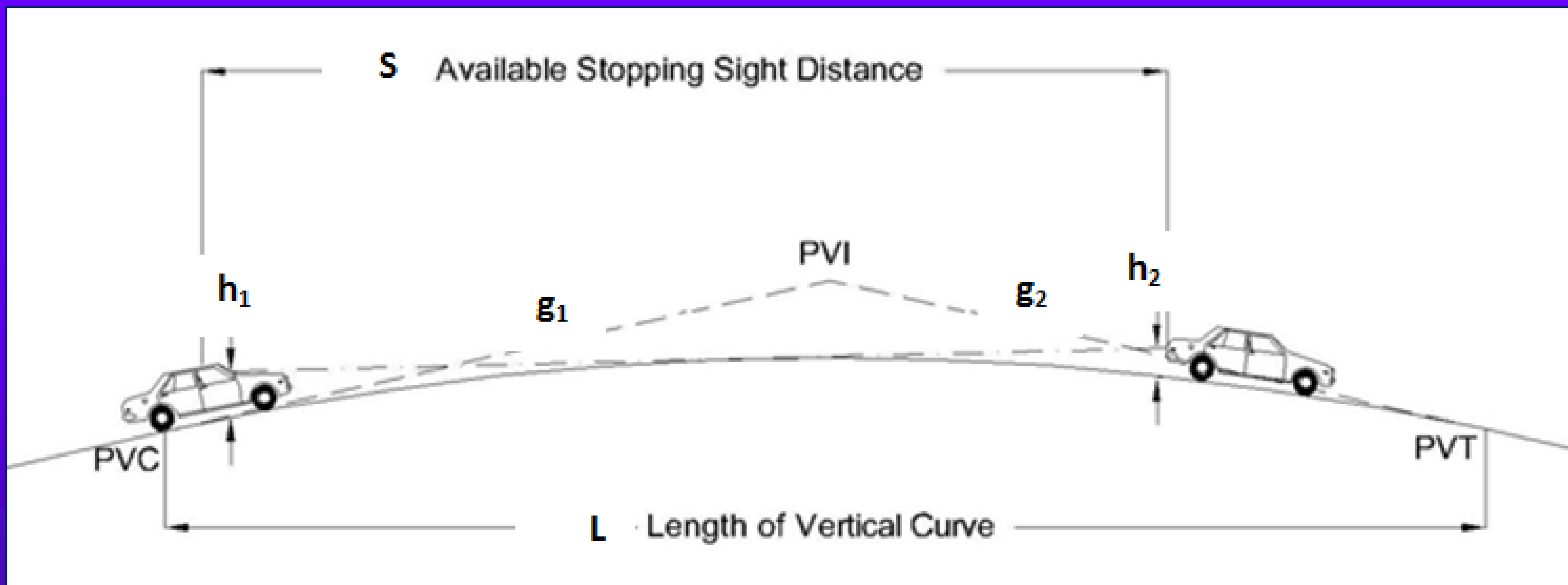


- *K* value of a vertical curve is the horizontal distance in meters needed to make 1° change in gradient; it is applied:
  - to determine the minimum lengths of vertical curves, and
  - to determine the horizontal distance from the VPC to the high point of Type I or the low point of Type III curves

VERTICAL CURVES 2

- Minimum length of a vertical curve depends upon the following considerations:
  - visibility (sight distances)
  - driver’s comfort
  - esthetics of road layout in the landscape
  - economics (cost)
- At design speeds of 50 km/h and above the crest in the road will restrict forward visibility, thus *minimum stopping sight distance* is to be considered first
- *Passing/overtaking sight dis*tance applies only to crest curves, it is to be considered only, when conditions allow

CREST CURVES 1



- For the drivers eye height (h_1=1.05 m) an object height (h_2=0.6 m) such as the taillight of a stop-ped or slowly moving car allow for determining the minimum radius (R_{min}) of the crest curve pro-viding *stopping distance* (D_s) at design speed (v_D)

CREST CURVES 2

- Length of vertical crest curve (where $|A| = g_1 - g_2$):

- To calculate the minimum crest curve length L_{min} it is assumed that the available sight distance *S* is the same as the stopping sight distance *SSD*

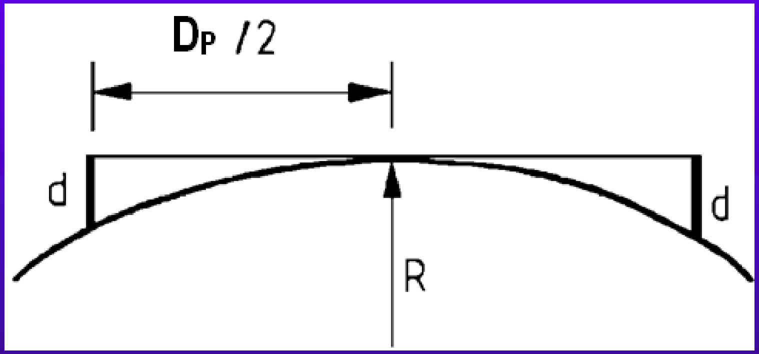
Relation between S and L	Length of the Vertical Curve L
$S \leq L$	$L = \frac{\lvert A\rvert \cdot S^2}{200 \cdot (\sqrt{h_1} + \sqrt{h_2})^2}$
$S > L$	$L = 2 \cdot S - \frac{200 \cdot (\sqrt{h_1} + \sqrt{h_2})^2}{\lvert A\rvert}$

$$L_{min} = \frac{|A| \cdot SSD^2}{200 \cdot (\sqrt{1.08} + \sqrt{0.60})^2} = \frac{|A| \cdot SSD^2}{658} \qquad SSD < L$$

$$L_{min} = 2 \cdot SSD - \frac{658}{|A|} \qquad SSD > L$$

CREST CURVES 3

- For the *passing sight distance* criterion on two-lane, two-way roads an object assumed of height $d = 1.05$ *m* (i. e. height of the drivers eye above the road surface) shoud be seen:



$$d = (D_p/2)^2 / 2R$$

$$9 * D_p^2 / 2d = R_{min}$$

where

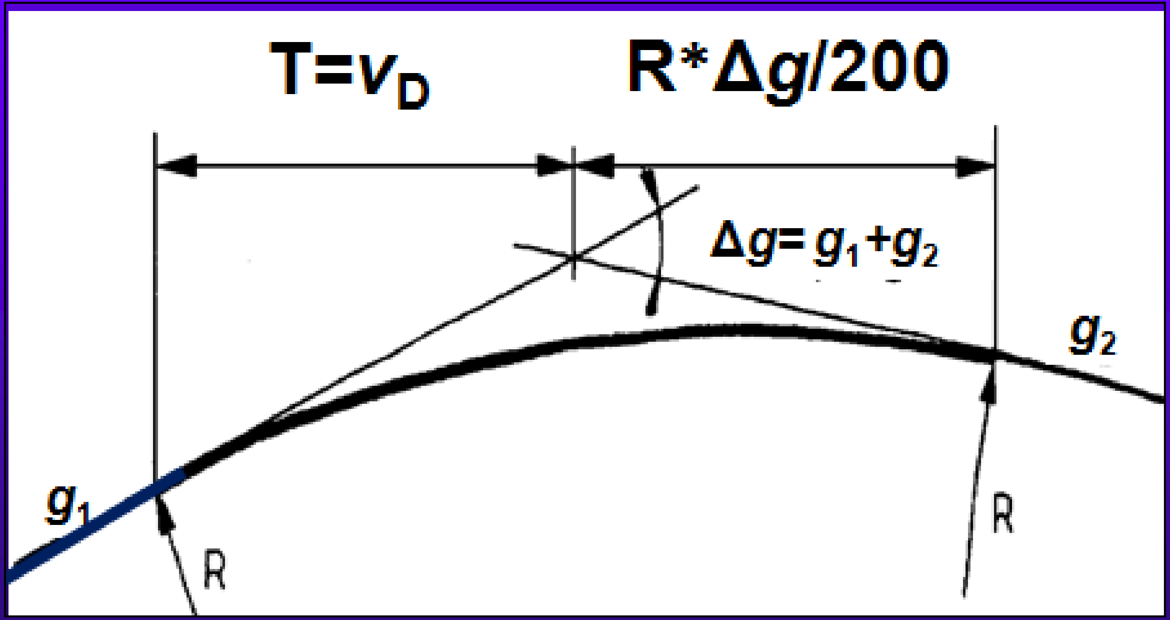
D_p – passing sight distance: $6 * v_D$ (m)

R_{min} – minimum radius to secure safe passing (m)

d – obstacle height (1.05 m)

CREST CURVES 3

- For the *drivers' comfort* the tangent length of the crest curve (T) should be equal to the design speed v_D (km/h)



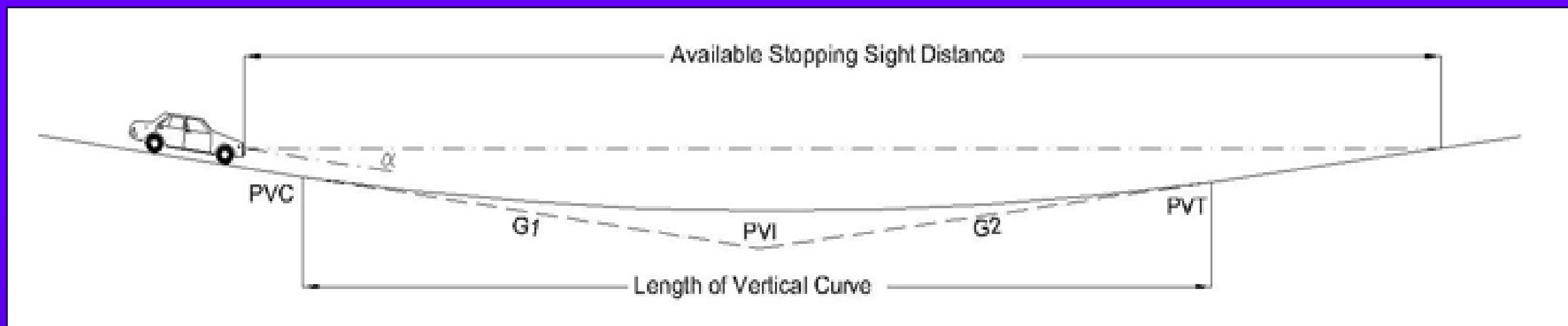
$$T = v_D = R^*\Delta g / 200$$

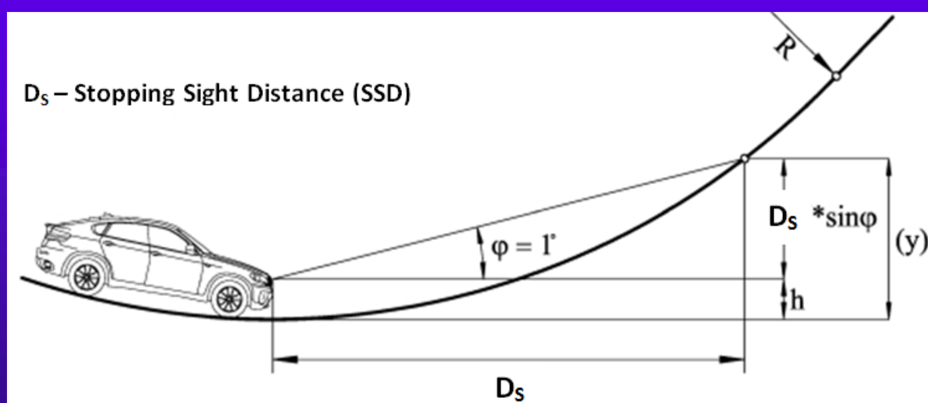
$$R = 200 v_D / \Delta g$$

SAG CURVES 1

- For design speeds of 70 km/h and below in unlit areas shallower curves are necessary to ensure that headlamps illuminate the road surface for a stopping sight distance
- Computations for an appropriate length or radius of a sag curve include the assumption of a 1^o angle above the headlight direction until the light strikes the surface of the road
- Visibility at sag curves is usually not obstructed unless overbridges, signs or other features are present, where comfort criteria apply (0.3 m/sec^2 maximum rate of vertical acceleration)

SAG CURVES 2





$$h + D_S * \sin \varphi = D_S^2/2R$$
$$R = D_S^2/2\,(h + D_S * \sin \varphi)$$

where h – vehicle headlight height above the road (0.6 m)

D_S – stopping sight distance in function of design speed (m)

φ – angle above the headlight direction

R_{min} – minimum radius of the sag curve (circular arc)

COMFORT CONSIDERATIONS

- The comfort effect of change in vertical direction is greater on sag than on crest curves because gravitational and centrifugal forces are combining rather than opposing forces
- Comfort due to change in vertical direction is affected appreciably by vehicle body suspension, tire flexibility, mass carried and other factors
- Riding is comfortable on vertical curves when the centrifugal acceleration doesn't exceed 0.3 m/sec^2
- The general expression for such a criterion is:

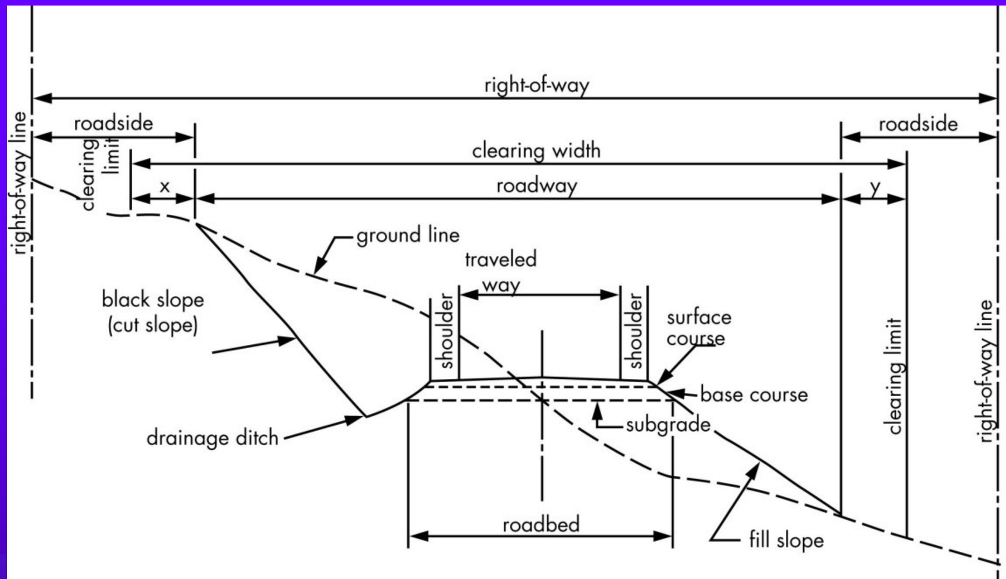
$$L = (A^* v_D^2) / 395$$

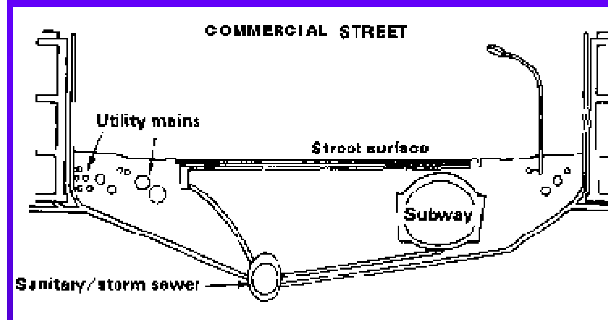
where *L* is the length of vertical curve (m)

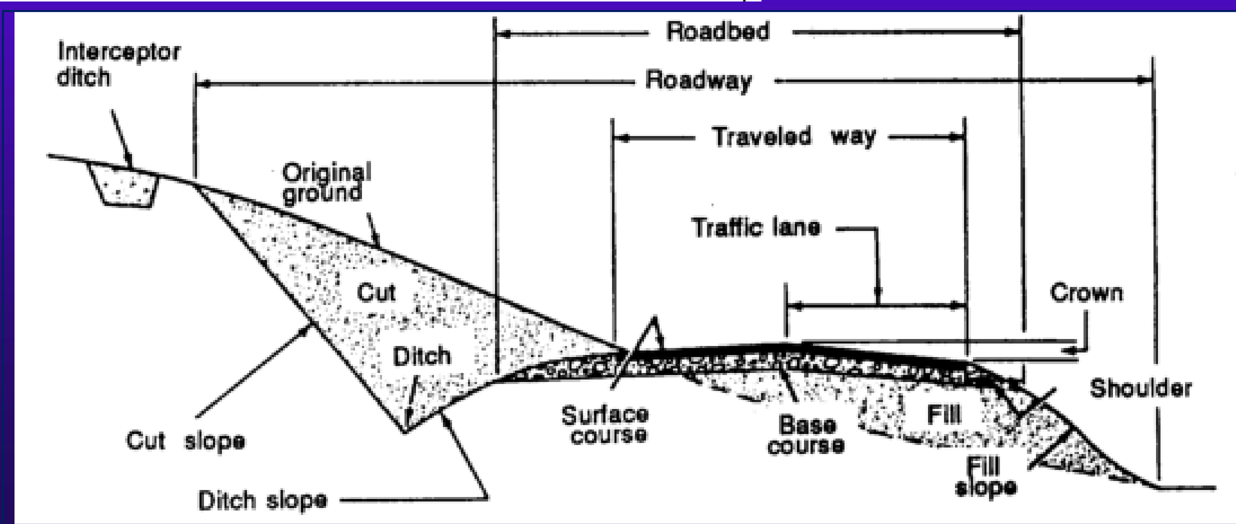
A is the algebraic difference in grades (percent)

v_D is the design speed (km/h)

CROSS SECTION & TERMS







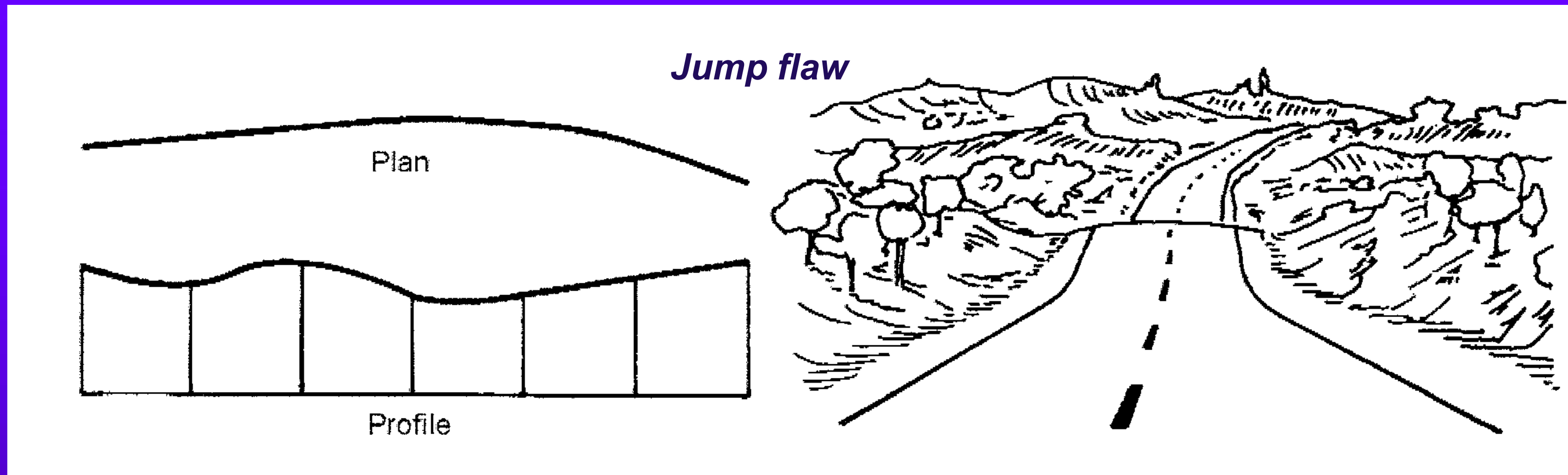
COORDINATION OF HORIZONTAL & VERTICAL ALIGNMENT 1

- **Horizontal and vertical alignments should be designed concurrently, since their designs complement each other**
- **Coordinate horizontal and vertical alignment to obtain safety, uniform speed, pleasing appearance, and efficient traffic operation**
- **Horizontal and vertical alignments are among the most important of the permanent design elements, quality in their design and in their combined design increases usefulness and safety, encourages uniform speed, and improves appearance in the landscape**

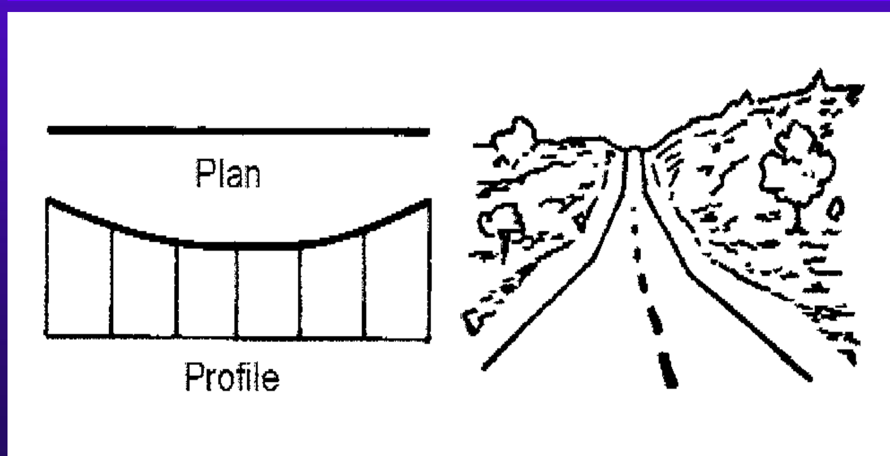
COORDINATION OF HORIZONTAL & VERTICAL ALIGNMENT 2

- **Rules to be considered in co-ordinating horizontal and vertical alignment:**
  - **Balance curvature and grades: use of steep grades to achieve long tangent and flat curves, or excessive curvature to achieve flat grades, are both poor designs**
  - **Vertical curvature superimposed on horizontal curvature results in a more pleasing facility: curvature in the horizontal plane should be accompanied by comparable length of curvature in the vertical plane**
  - **Successive changes in profile not in combination with horizontal curvature may result in a series of dips not visible to the driver**
  - **Horizontal curvature should lead vertical curvature, i.e., the horizontal curve should be longer than the vertical curve**
  - **Avoidance of a sharp horizontal curve at or near the low point of a sag vertical curve is important: trucks’ speed is often high at the bottom of grades so erratic operation may result, especially at night**
  - **In residential areas, the alignment design should minimize nuisance factors to the neighborhood**

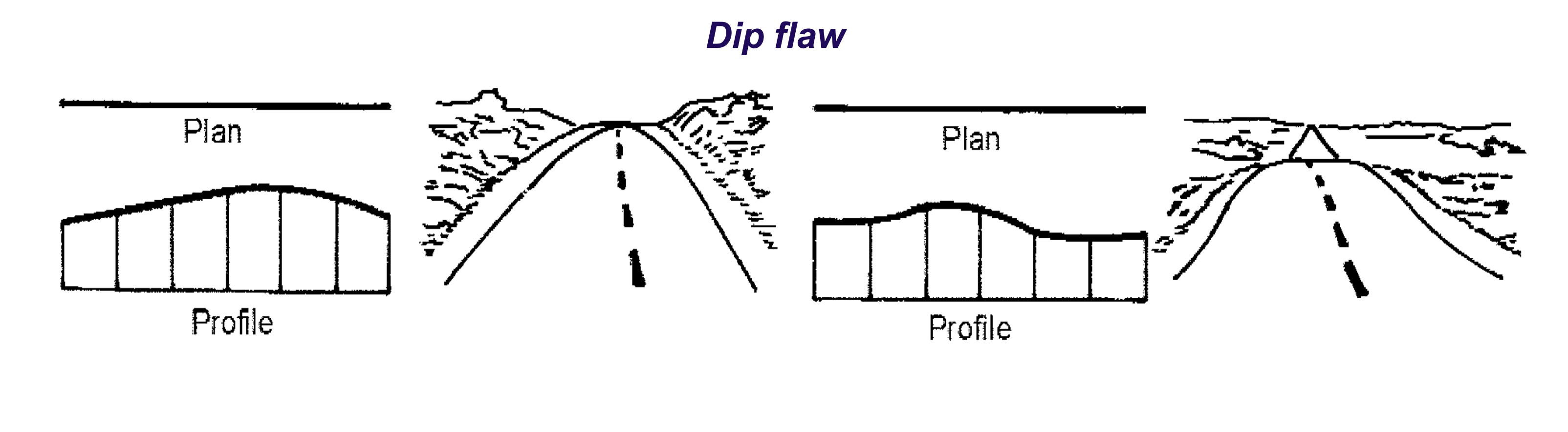
COORDINATION OF HORIZONTAL & VERTICAL ALIGNMENT 3



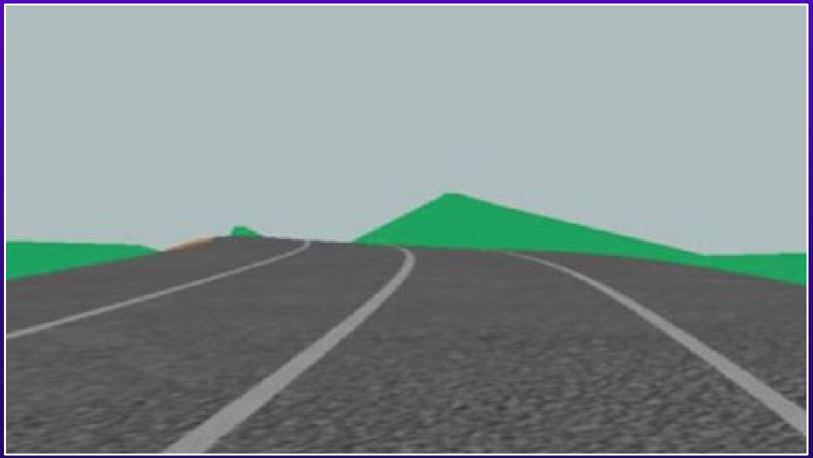
***Wrong coordination*: the road disappears, lines are broken**



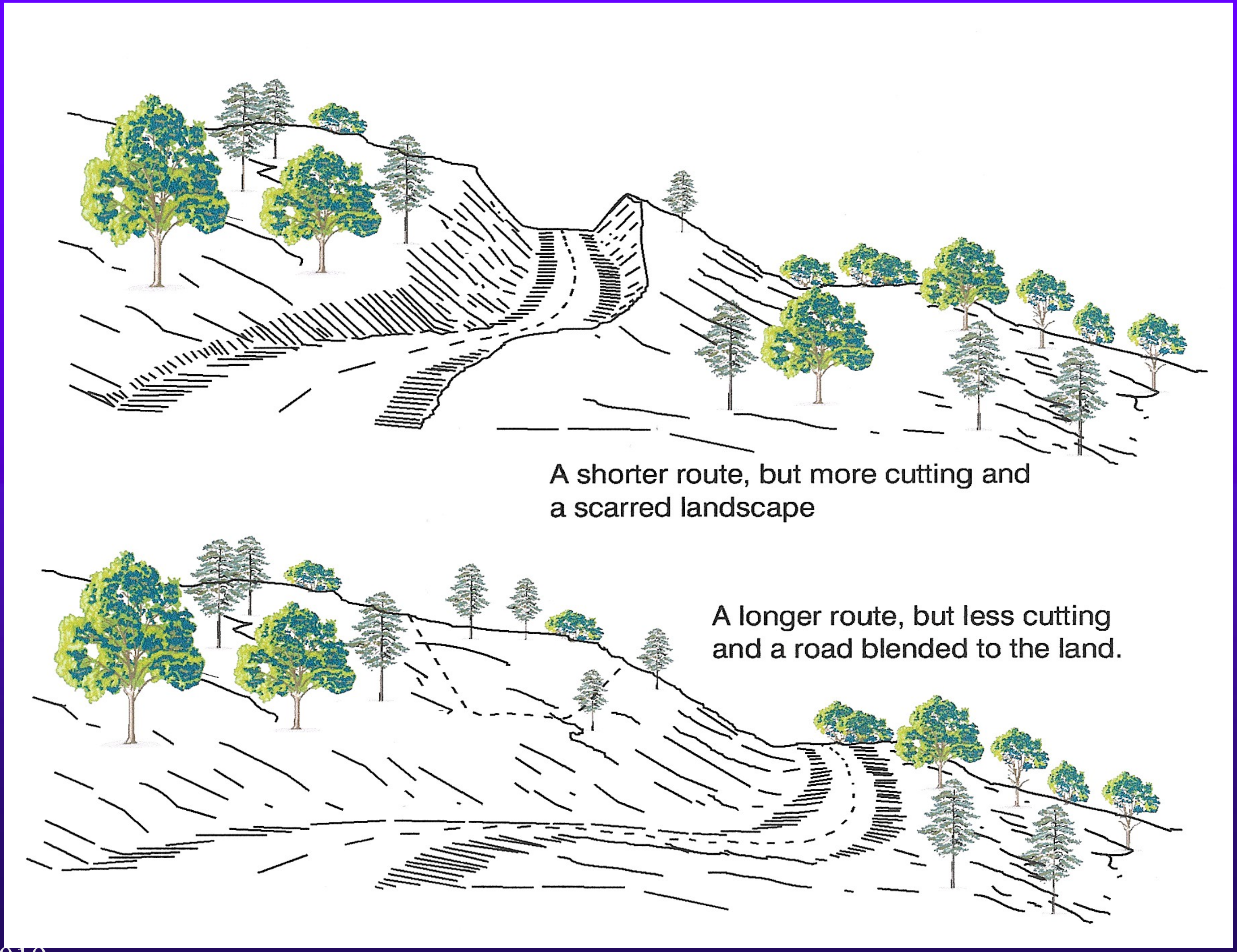
COORDINATION OF HORIZONTAL & VERTICAL ALIGNMENT 4



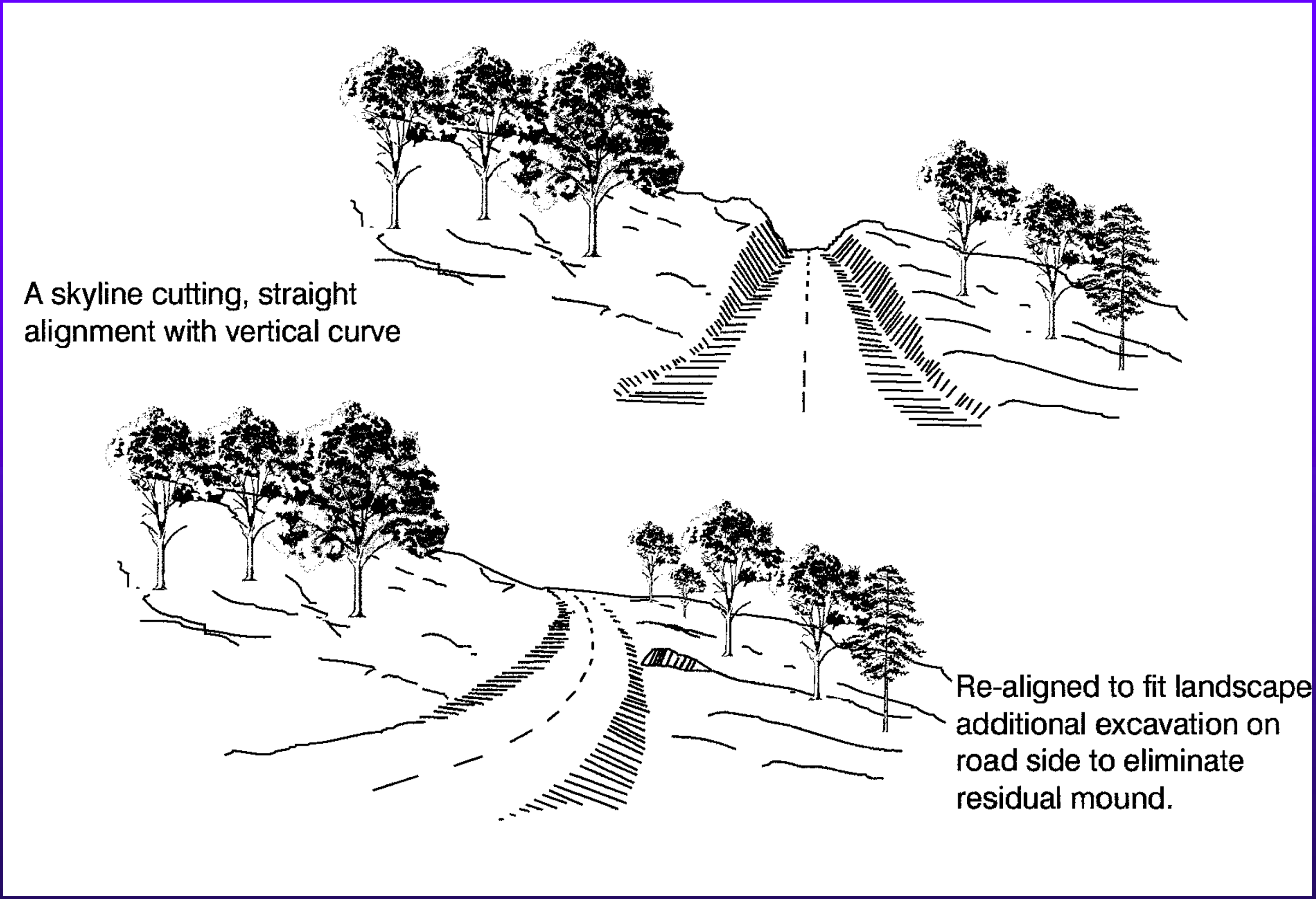
Wrong coordination: **the road disappears from driver's sight**



FIT INTO THE LANDSCAPE 1



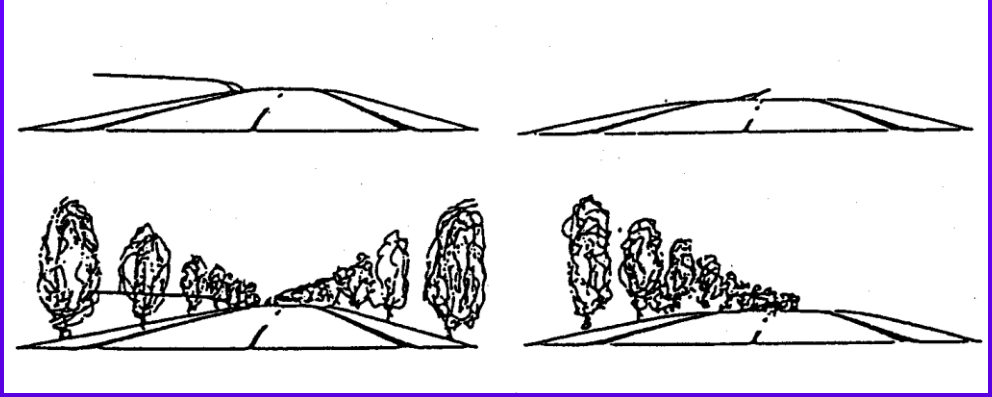
FIT INTO THE LANDSCAPE 2



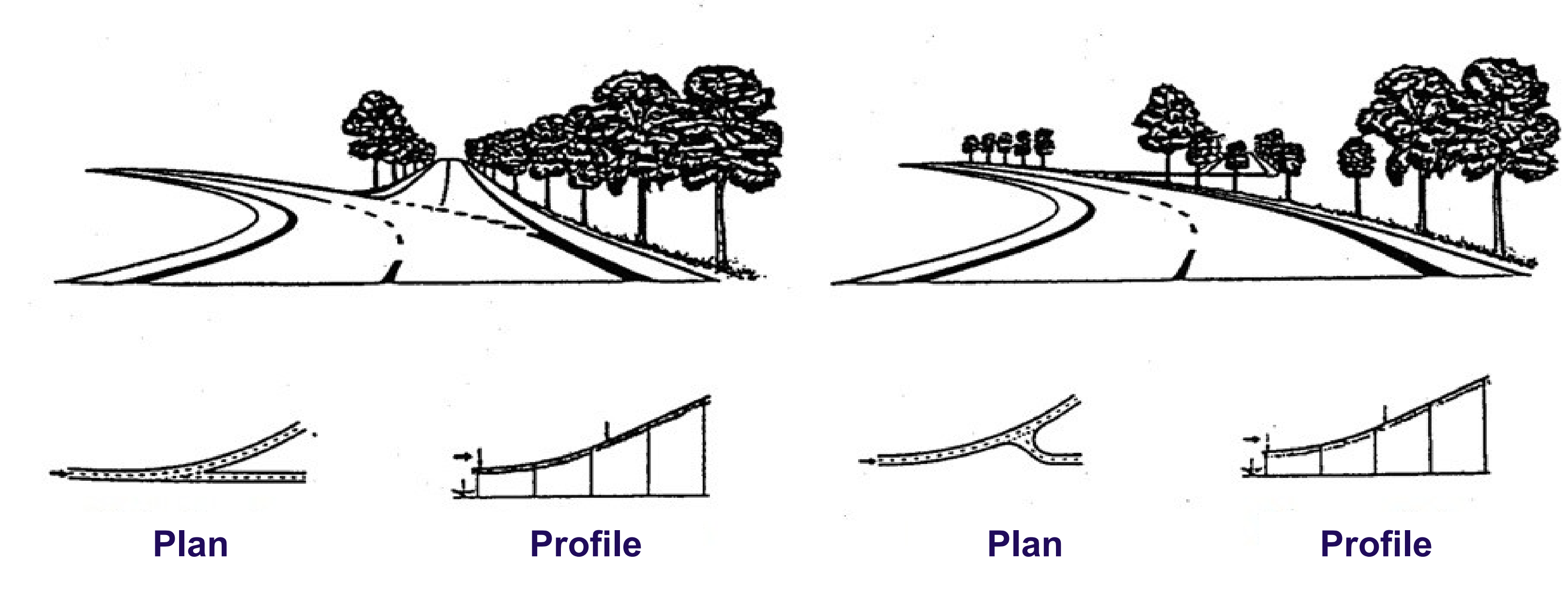
ROADSIDE PLANTATIONS 1

- Roadside trees increase the comfort of travellers by providing optical guidance, shade and attractive surroundings
- Trees may protect the road itself against moving snow or act as a windbreak for adjacent fields
- Replantation plan became an important element of road design
- Trees should not planted close to the inside of curves or near road junctions where they could obscure vision and so create a driving hazard

ROADSIDE PLANTATIONS 2



Planted on the outer side of the curve trees may provide optical guidance to driver



ROADSIDE PLANTATIONS 3