Superelevation

- The superelevation (or banking) is applied on highway curves to facilitate the turning of vehicles round a curve.
- The term superelevation indicates that the outside edge of the highway follows a path at higher elevation when compared to the path of the inner edge.
- Some portion of the centrifugal force developed during turning is counterbalanced by the superelevated highway surface and smaller curve radii can be used efficiently without decreasing safety while turning.

Superelevation

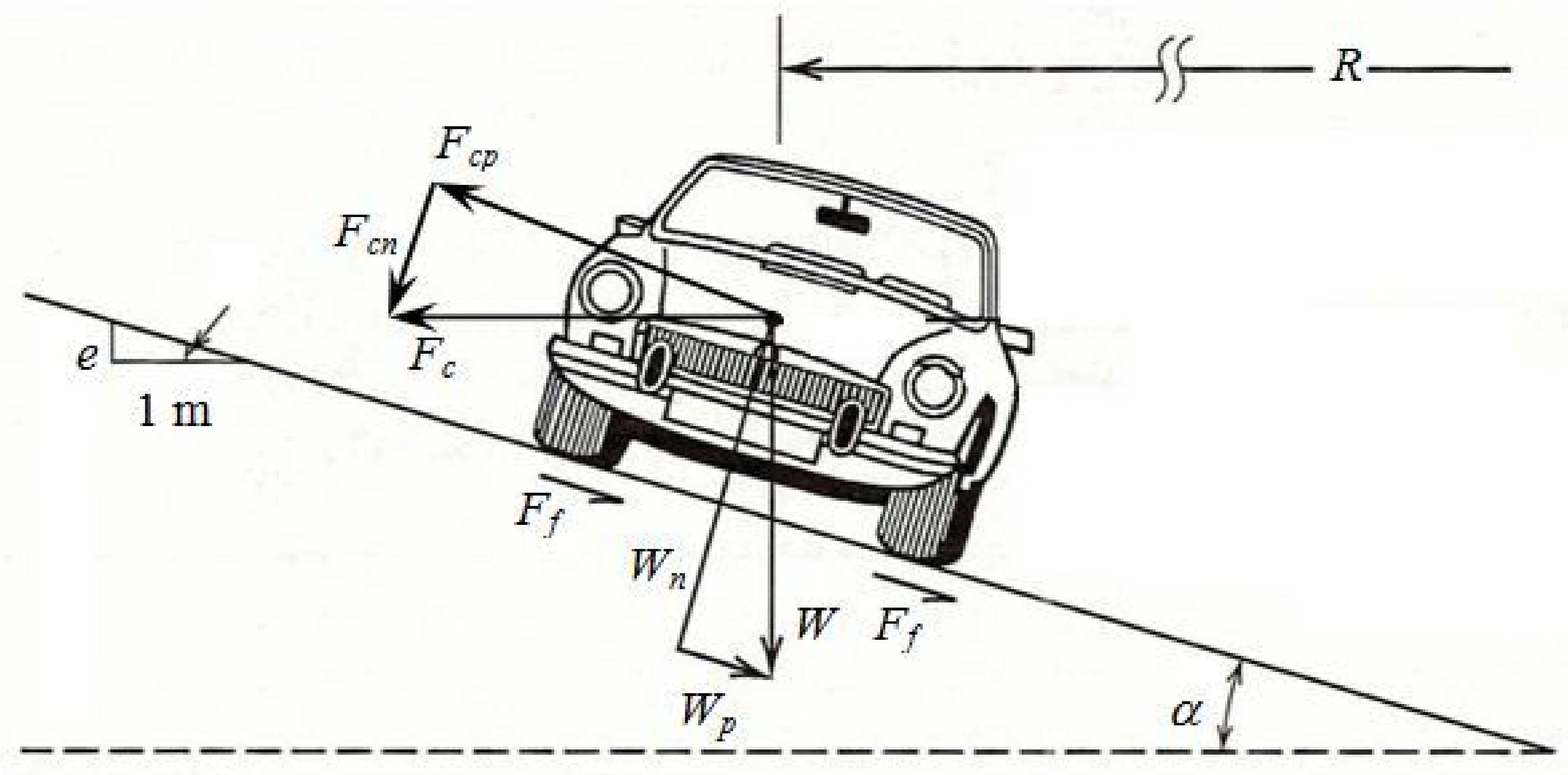


Figure 3.18 Force diagram for superelevation.

Superelevation

In Figure 3.18,

R = radius of the curved path of the vehicle (m)

α = angle of incline in degrees

e = superelevation rate (vertical rise per unit horizontal distance in transverse direction)

W = weight of the vehicle in (N)

W_n = vehicle weight normal to the roadway surface (N)

W_p = vehicle weight parallel to the roadway surface (N)

F_f = side frictional force (N)

F_c = centrifugal force (N)

F_{cn} = centrifugal force acting normal to roadway surface (N).

F_{cp} = centrifugal force acting parallel to roadway surface (N).

Superelevation

- Consider the force diagram in Figure 3.18. If the vehicle is travelling around a curve with radius R at a constant speed V, there will be a centripetal acceleration toward the center of the curve of V^2/R which is opposed by the centrifugal force of mV^2/R. The other forces acting on the vehicle are its weight and the forces developed between the wheels and the roadway surface.

- The equilibrium of the forces parallel to the surface in lateral direction is

$$W_p + F_f = F_{cp} \tag{3.17}$$

Superelevation

Or

$$W\sin\alpha + f_s\left(W\cos\alpha + \frac{WV^2}{gR}\sin\alpha\right) = \frac{W}{g}.\frac{V^2}{R}\cos\alpha \qquad (3.18)$$

Where,

f_s = coefficient of side friction
V = vehicle speed (m/s)
g = gravitational acceleration (m/s^2)

Dividing both sides by (W cos α) gives

$$\tan\alpha + f_s = \frac{V^2}{gR}\left(1 - f_s\tan\alpha\right) \qquad (3.19)$$

Superelevation

- As defined before, the term ($\tan\ \alpha$) indicates the superelevation (banking) of the curve. The term ($f_s \tan\ \alpha$) is very small and conservatively set to zero for practical applications. Then Eq.3.19 takes the following form

$$e + f_s = \frac{V^2}{gR} \qquad \text{or} \qquad R = \frac{V^2}{g(e + f_s)} \tag{3.20}$$

By expressing speed (V) in km/h and with g = 9.81 m/s^2, the relation can be rewritten as

$$e + f_s = \frac{V^2}{127R} \qquad \text{or} \qquad R = \frac{V^2}{127(e + f_s)} \tag{3.21}$$

Design Considerations

- In the actual design of a horizontal curve, the engineer must select appropriate values of e and f_s.

- The superelevation, e, is critical because high rates of superelevation can cause vehicle steering problems on the horizontal curves.

- In cold climates, ice on the roadway can reduce f_s such that vehicles traveling at less than the design speed on an excessively superelevated curve could slide inward off the curve due to gravitational forces.

- With the wide range of vehicle speeds, there usually is an unbalanced force whether the curve is superelevated or not. This force results in tire side thrust, which is counterbalanced by friction between the tires and the pavement surface.

Side Friction Factor

- This frictional counterforce is developed by distortion of the contact area of the tire. The coefficient of friction f_s is the friction force divided by the component of the weight perpendicular to the pavement surface.

- The coefficient f_s has been called lateral ratio, cornering ratio, unbalanced centrifugal ratio, friction factor, and side friction factor.

- The upper limit of the side friction factor is the point at which the tire would begin to skid; this is known as the point of impending skid.

- Because highway curves are designed to avoid skidding conditions with a margin of safety, the f_s values used in design should be substantially less than the coefficient of friction at impending skid.

Side Friction Factor

- The side friction factor at impending skid depends on a number of other factors, among which the most important are
  - the speed of the vehicle,
  - the type and condition of the roadway surface,
  - the type and condition of the vehicle tires.
- The range of the maximum side friction factors developed between new tires and wet concrete pavements is about

  From **0.5** at 30 km/h up to **0.35** at 100 km/h

- For normal wet concrete pavements and smooth tires the maximum side friction factor at impeding skid is about 0.35 at 70 km/h.

Side Friction Factor

- In all cases, the studies show a decrease in friction values as speeds increase.
- Horizontal curves should not be designed directly on the basis of the maximum available side friction factor. Rather, the maximum side friction factor used in design should be that portion of the maximum available side friction that can be used with comfort and safety.
- A key consideration in selecting maximum side friction factors for use in design is the level of centripetal or lateral acceleration that is sufficient to cause drivers to experience a feeling of discomfort and to react instinctively to avoid higher speed.

Side Friction Factor

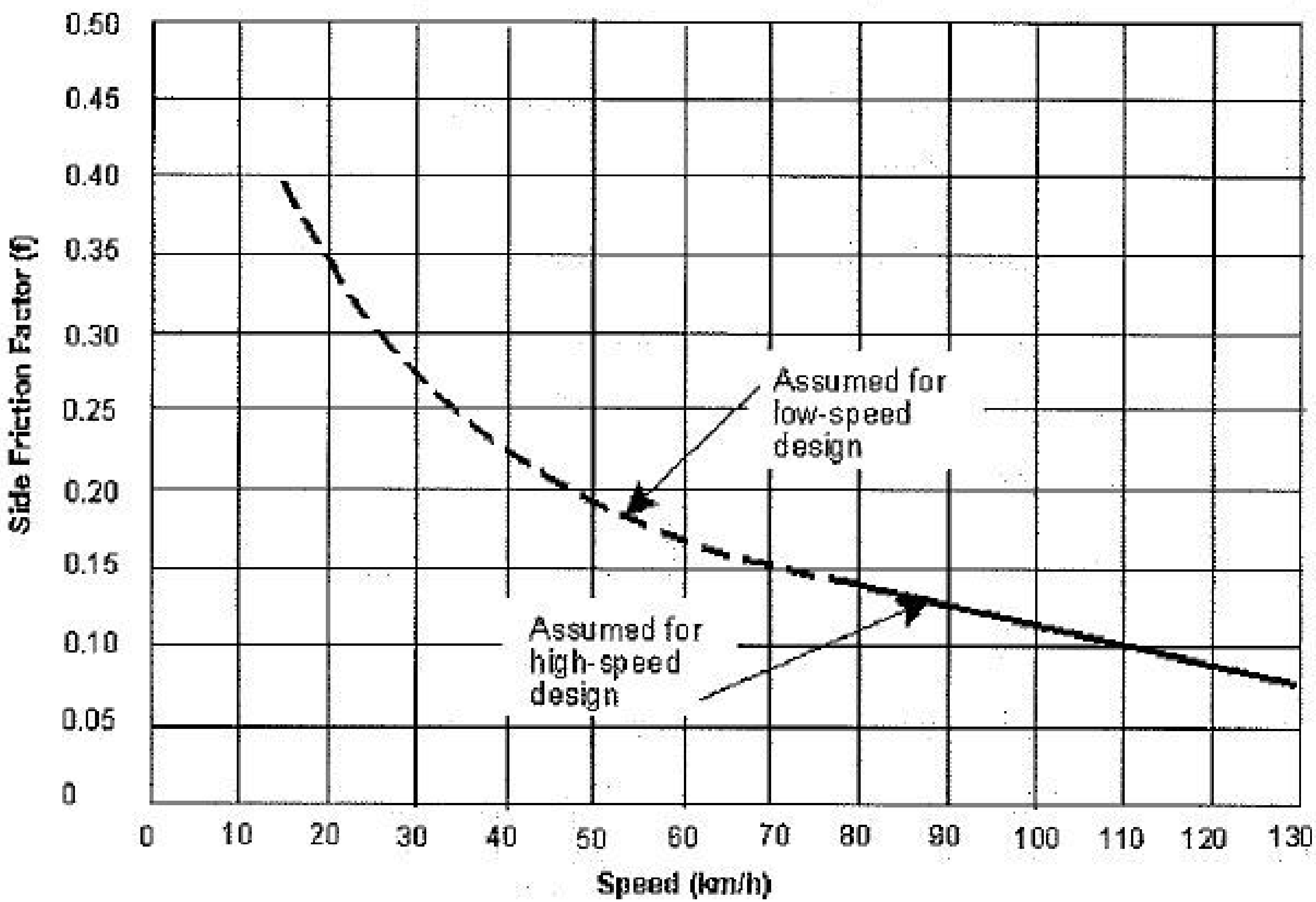


Figure 3.19 Side friction factors for design (AASHTO 2004)

Superelevation Rates

- **Maximum Superelevation rates** that are applicable over the range of curvature for each design speed have been determined for use in highway design. The maximum superelevation may be different for different highway conditions.

- At the other extreme, no superelevation is needed for highways with extremely long-radius curves.

- For curvature between these extremes and for a given design speed, the superelevation should be chosen in such manner that there is a logical relation between the side friction factor and the applied superelevation rate.

Maximum Superelevation Rates for Streets and Highways

- The maximum rates of superelevation used on highways are controlled by four factors:
  - climate conditions (i.e., frequency and amount of snow and ice);
  - terrain conditions (i.e., flat, rolling, or mountainous);
  - type of area (i.e., rural or urban);
  - frequency of very slow-moving vehicles whose operation might be affected by high superelevation rates.

- Consideration of these factors jointly leads to the conclusion that no single maximum superelevation rate is universally applicable. However, using only one maximum superelevation rate within a region of similar climate and land use is desirable as such a practice promotes design consistency.

Maximum Superelevation Rates for Streets and Highways

- The highest superelevation rate for highways in common use is **10 percent**, although **12 percent** is used in some cases.

- Superelevation rates above **8 percent** are only used in areas without snow and ice.

- Although higher superelevation rates offer an advantage to those drivers traveling at high speeds, current practice considers that rates in excess of 12 percent are beyond practical limits.
- Where snow and ice are factors, tests and experience show that a superelevation rate of about **8 percent** is a logical maximum to minimize vehicles sliding across a highway when stopping or attempting to start slowly from a stopped position.

Maximum Superelevation Rates for Streets and Highways

- Where traffic congestion or extensive marginal development acts to restrict top speeds, it is common practice to utilize a low maximum rate of superelevation, usually **4 to 6 percent**.

- Similarly, either a low maximum rate of superelevation or no superelevation is employed within important intersection areas or where there is a tendency to drive slowly because of turning and crossing movements, warning devices, and signals. In these areas it is difficult to warp crossing pavements for drainage without providing negative superelevation for some turning movements.

Maximum Superelevation Rates for Streets and Highways

- In summary, it is recommended that

  (1) Several rates, rather than a single rate, of maximum superelevation should be recognized in establishing design controls for highway curves,

  (2) A rate of 12 percent should not be exceeded,

  (3) A rate of 4 or 6 percent is applicable for urban design in areas with little or no constraints,

  (4) Superelevation may be omitted on low-speed urban streets where severe constraints are present.

Superelevation - Minimum Radius

- The minimum radius is a limiting value of curvature for a given design speed and is determined from the maximum rate of superelevation and the maximum side friction factor selected for design (limiting value of f_s).

- Use of sharper curvature for that design speed would require superelevation beyond the limit considered practical.

- The minimum radius of curvature, *R,* can be calculated directly from the simplified curve formula introduced above (Eq. 3.21).

Superelevation - Minimum Radius

Example 3.6 : A roadway is being designed for a speed of 110 km/hr . At one horizontal curve it is known that the superelevation is 6.0% (e = 0.06) and the coefficient side friction is 0.11. Determine the minimum radius of curve that will provide for safe vehicle operation.

Solution:

From Eq. 3.21

$$R = \frac{110^2}{127(0.06+0.11)} = 560.44 \text{ m}$$

This value is the minimum radius because smaller radii will generate centripetal force higher than those counterbalanced by the superelevation and the side friction force.

Superelevation - Minimum Radius

- AASHTO provides general guidelines for the selection of e and f_s, for horizontal curve design. The values are tabulated for preselected superelevation rates, 4, 6, 8, 10 and 12% as given in Table 3.2.

Table 3.2 Minimum Radius Using Limiting values of e and f_s

Design Speed (Km/h)	Maximum e e_{max} (%)	Limiting values of f_s	Calculated Radius R (m)	Rounded Radius R (m)
20	4.0	0.18	14.3	15
30	4.0	0.17	33.7	35
40	4.0	0.17	60.0	60
50	4.0	0.16	98.4	100
60	4.0	0.15	149.1	150
70	4.0	0.14	214.2	215
80	4.0	0.14	279.8	280
90	4.0	0.13	375.0	375
100	4.0	0.12	491.9	490

Superelevation - Minimum Radius

Table 3.2 Minimum Radius Using Limiting values of *e* and f_s (Continued)

Design Speed (Km/h)	Maximum e e_{max} (%)	Limiting values of f_s	Calculated Radius R (m)	Rounded Radius R (m)
20	6.0	0.18	13.1	15
30	6.0	0.17	30.8	30
40	6.0	0.17	54.7	55
50	6.0	0.16	89.4	90
60	6.0	0.15	134.9	135
70	6.0	0.14	192.8	195
80	6.0	0.14	251.8	250
90	6.0	0.13	335.5	335
100	6.0	0.12	437.2	435
110	6.0	0.11	560.2	560
120	6.0	0.09	755.5	755
130	6.0	0.08	950.0	950

Superelevation - Minimum Radius

Table 3.2 Minimum Radius Using Limiting values of *e* and f_s (Continued)

Design Speed (Km/h)	Maximum *e* e_{max} (%)	Limiting values of f_s	Calculated Radius *R* (m)	Rounded Radius *R* (m)
20	8.0	0.18	12.1	10
30	8.0	0.17	28.3	30
40	8.0	0.17	50.4	50
50	8.0	0.16	82.0	80
60	8.0	0.15	123.2	125
70	8.0	0.14	175.3	175
80	8.0	0.14	228.9	230
90	8.0	0.13	303.6	305
100	8.0	0.12	393.5	395
110	8.0	0.11	501.2	500
120	8.0	0.09	666.6	665
130	8.0	0.08	831.3	830

Superelevation - Minimum Radius

Table 3.2 Minimum Radius Using Limiting values of *e* and f_s (Continued)

Design Speed (Km/h)	Maximum *e* e_{max} (%)	Limiting values of f_s	Calculated Radius *R* (m)	Rounded Radius *R* (m)
20	10.0	0.18	11.2	10
30	10.0	0.17	26.2	25
40	10.0	0.17	46.6	45
50	10.0	0.16	75.7	75
60	10.0	0.15	113.5	115
70	10.0	0.14	160.7	160
80	10.0	0.14	209.9	210
90	10.0	0.13	277.2	275
100	10.0	0.12	357.7	360
110	10.0	0.11	453.5	455
120	10.0	0.09	596.5	595
130	10.0	0.08	738.9	740

Superelevation - Minimum Radius

Table 3.2 Minimum Radius Using Limiting values of *e* and f_s (Continued)

Design Speed (Km/h)	Maximum e e_{max} (%)	Limiting values of f_s	Calculated Radius R (m)	Rounded Radius R (m)
20	12.0	0.18	10.5	10
30	12.0	0.17	24.4	25
40	12.0	0.17	43.4	45
50	12.0	0.16	70.3	70
60	12.0	0.15	104.9	105
70	12.0	0.14	148.3	150
80	12.0	0.14	193.7	195
90	12.0	0.13	255.0	255
100	12.0	0.12	327.9	330
110	12.0	0.11	414.0	415
120	12.0	0.09	539.7	540
130	12.0	0.08	665.0	665

Superelevation Rates (Turkish Practice)

- In Turkish practice instead of selecting different f_s and e values for different combination of design speed (V) and curve radius (R), the simplified curve formulae given by Eq.3.21 is further simplified by totally neglecting friction term f_s, and applying a reduction factor of 0.75 to the design speed.

The equation becomes

$$e = \frac{0.00443 V^2}{R} \quad \text{or} \quad R = \frac{0.00443 V^2}{e} \qquad (3.22)$$

Where, speed (V) is in km/h and R (radius) is in meters:

Superelevation Rates (Turkish Practice)

Example 3.7: A roadway is being designed for a speed of 110 km/hr . At one horizontal curve it is known that the superelevation is 6.0% (e = 0.06). According to Turkish practice determine the minimum radius of curve that will provide for safe vehicle operation.

Solution:

From Eq. 3.22

$$R = \frac{0.00443 * 110^2}{0.06} = 893.38 \text{ m}$$

When this result is compared with the result of Example 3.5, it is seen that the relation 3.22 is highly conservative.

Application of Superelevation

- As discussed before, for purpose lateral drainage requirements on straights crowned surfaces used.

- Consistent with the type of highway and amount of rainfall, snow, and ice, the usually accepted minimum values for cross slope range from **1.5 percent** to approximately **2.5 percent**.

- For superelevation application it is required to change the crowned cross section on normal alignment on straight to the superelevated cross section on the curve as shown in Fig. 3.15

Application of Superelevation

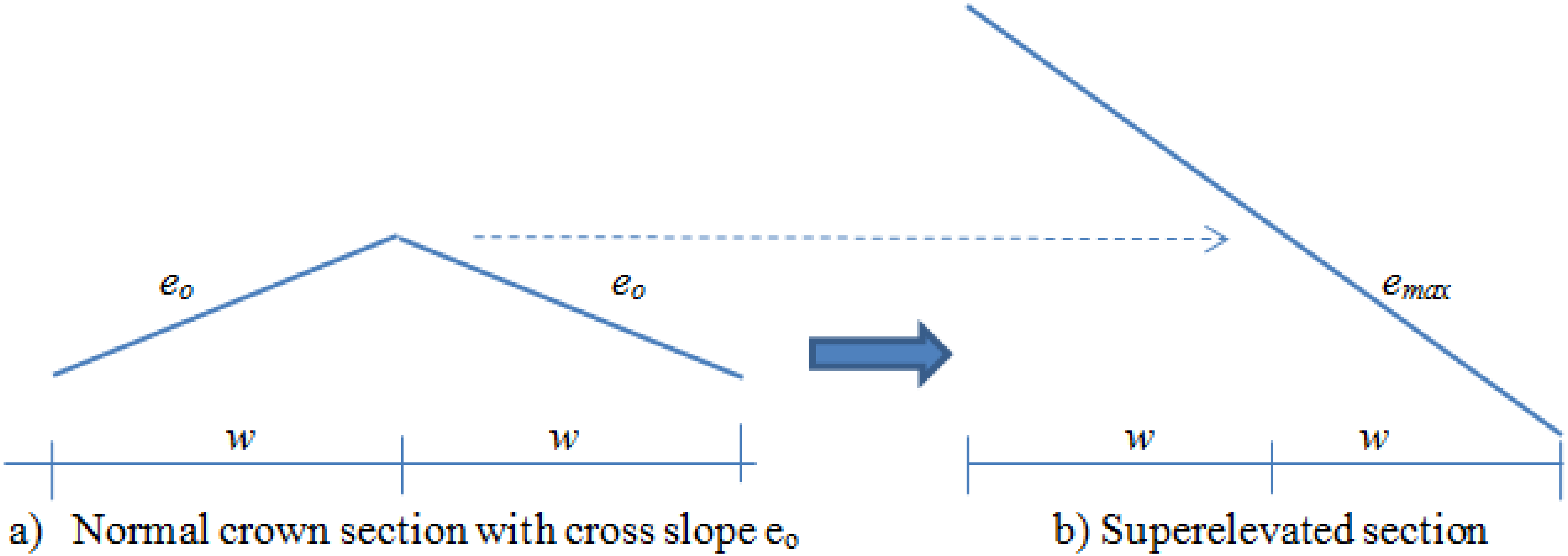


Figure 3.20 Normal and superelevated roadway surfaces for a two lane highway.

Application of Superelevation

- The application must be done gradually along an appropriate length which is called the superelevation transition length.

- Superelevation transition length has two distinct parts called as “Superelevation runoff” and “tangent runout”.
  - **Superelevation runoff (L_s):** The general term denoting the length of highway needed to accomplish the change in cross slope from a section with adverse crown removed to a fully superelevated section, or vice versa.
  - **Tangent runout (T_r):** The general term denoting the length of highway needed to accomplish the change in cross slope from a normal crown section to a section with adverse crown removed, or vice versa.

Application of Superelevation

- Rotation types:

The application of superelevation may be done by three different rotation types.

1- Rotation around centerline
2- Rotation around inner edge
3- Rotation around outer edge

The rotation around centerline is the basic rotation type. Figure 3.21 shows the diagram for rotation around centerline.

Application of Superelevation

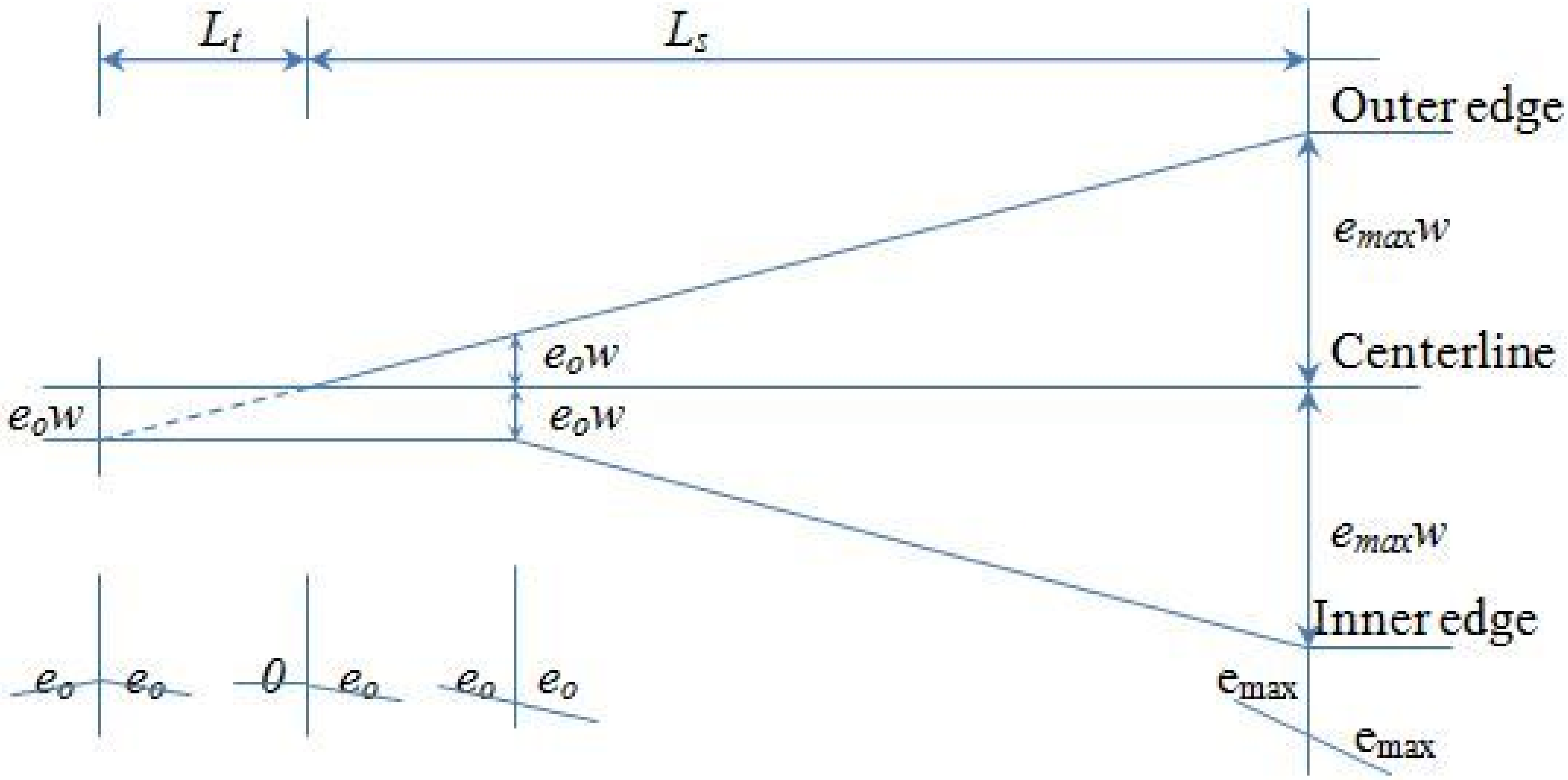


Figure 3.21 Superelevation diagram (Rotation around centerline)

Application of Superelevation

- Application of superelevation by rotation around inner edge and rotation around outer edge can be applied for two lane highways due to some topographic and adjacent land use requirements.

- Sample diagrams for rotations are shown around inner edge and rotation around outer edge in Figures 3.22 and 3.23 for a two lane highway.

- However rotation around inner edge and outer edge are generally needed at highway connections (highway ramps) to facilitate separating and connecting roadway edges and for multilane divided highways in order to have undistorted curbs and/or medians. Figure 3.5 demonstrates such applications for divided highways

Application of Superelevation

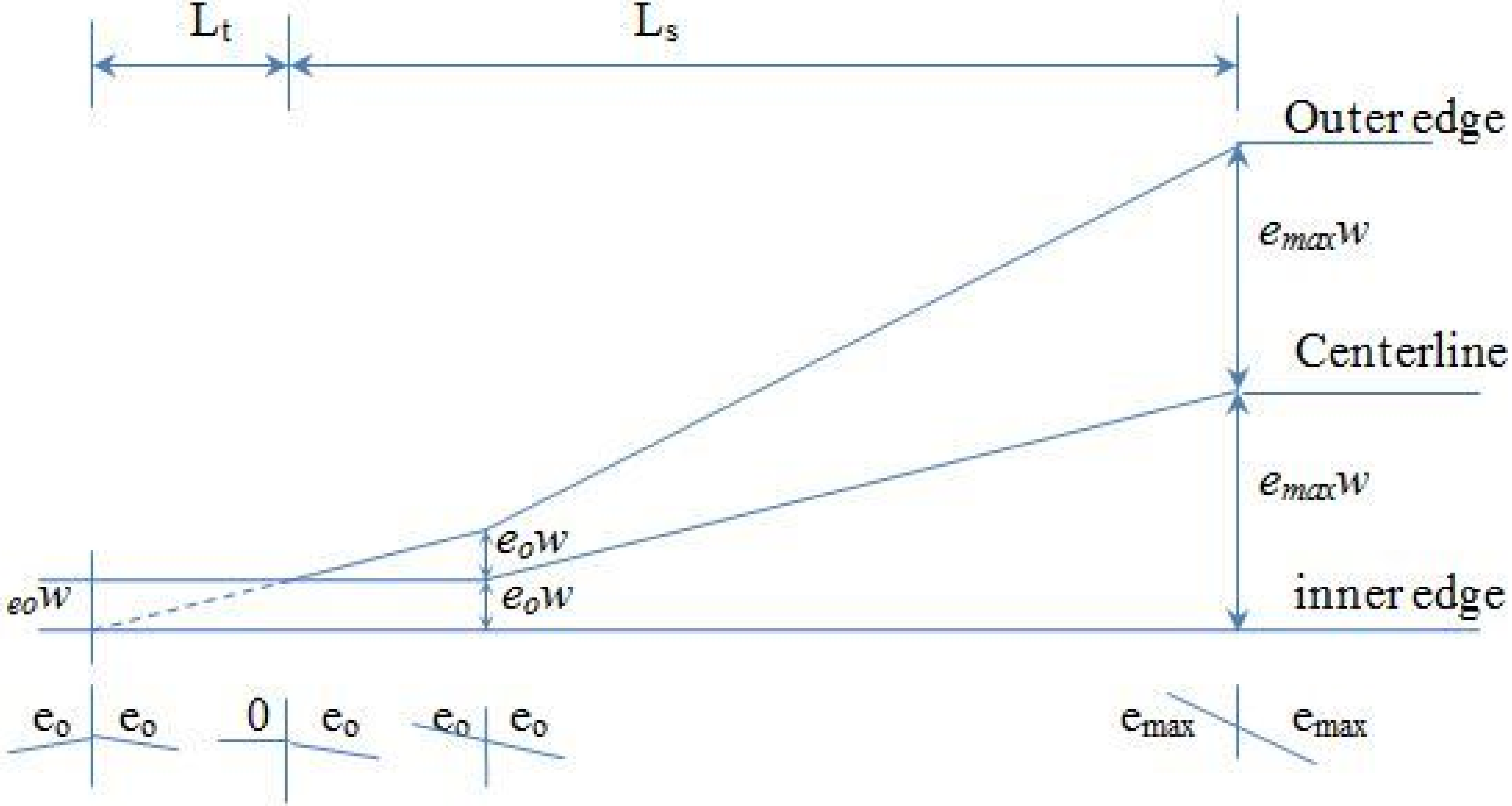


Figure 3.22. Superelevation diagram (Rotation around inner edge)

Application of Superelevation

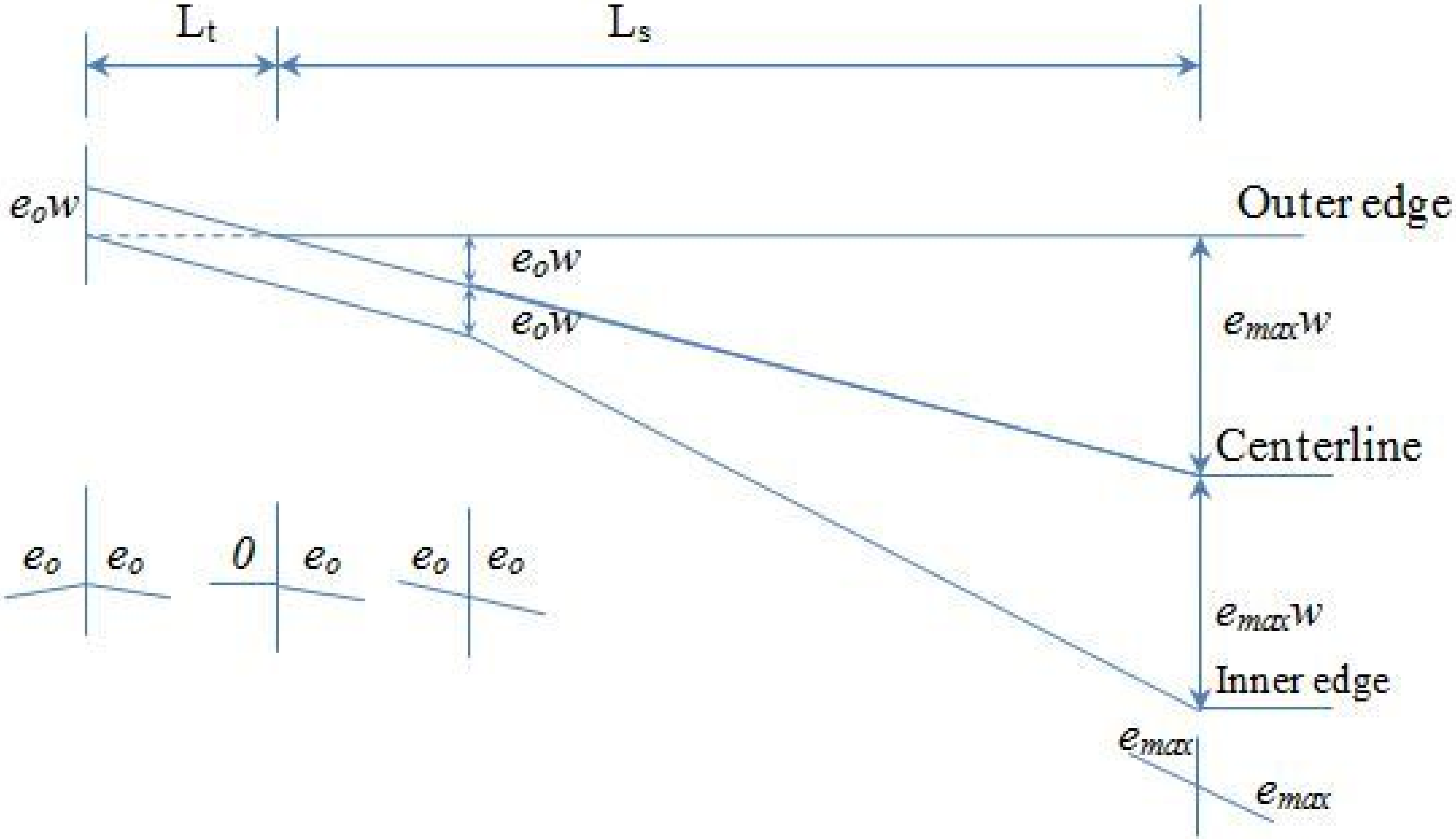
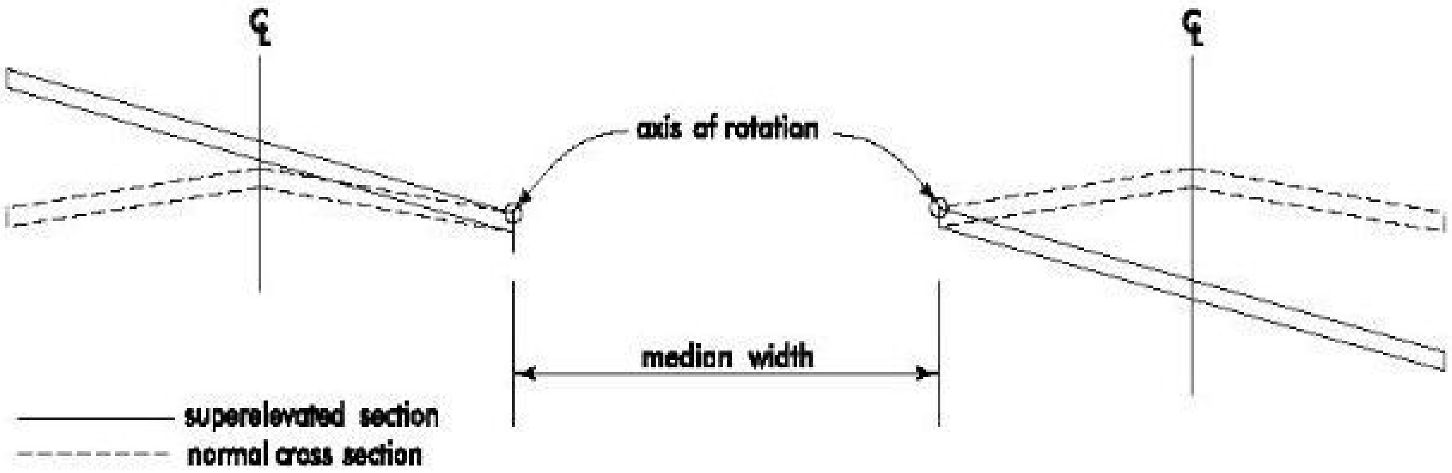
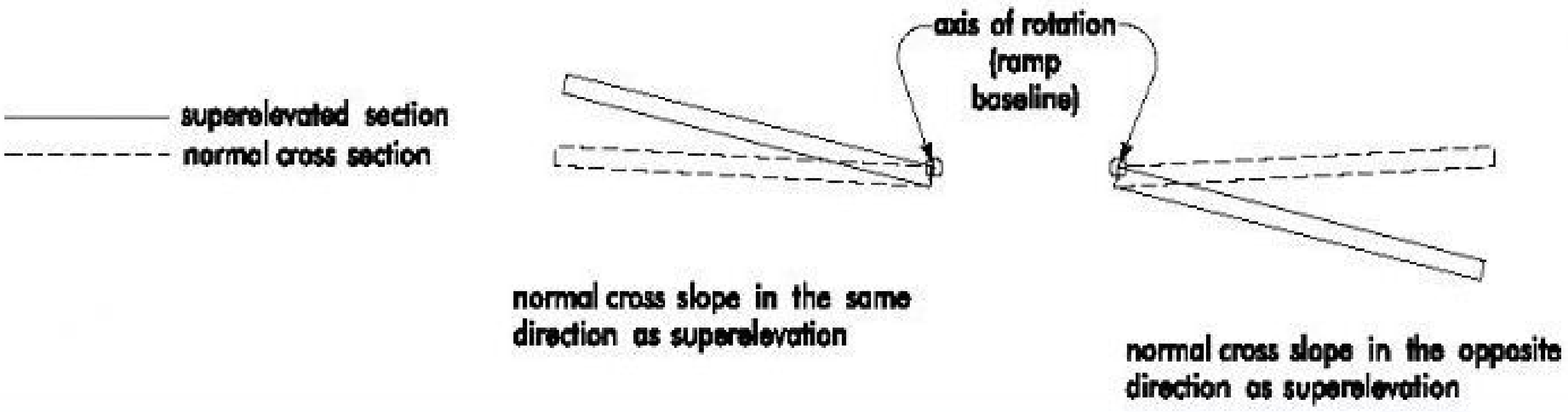


Figure 3.23. Superelevation diagram (Rotation around outer edge)

Application of Superelevation



a) Two way crowned travel way sections



b) One way crowned travel way sections

Figure 3.24 Axis of rotation, normal and superelevated sections, divided highways

Superelevation Transition Distance

- **The superelevation runoff** should be affected uniformly over a length adequate for the likely operating speeds for comfort and safety.

- The length of superelevation runoff is determined:

  1- According to vehicle dynamics. More specifically, **transition theory** for spiral application can be used. In other words, the superelevation runoff distance is taken as the spiral transition distance. If spiral is to be applied, superelevation runoff distance coincides with transition curve length.

  2- For **appearance and comfort**, the length of superelevation runoff should be enough not to exceed a relative longitudinal slope (edge compared to centerline of a two lane highway) for the governing operating speed.

Superelevation Transition Distance

- Current practice indicates that for appearance and comfort the length of superelevation runoff should not exceed a longitudinal slope (edge compared to centerline of a two lane highway) of 1/200 at operating speed of 80 km/hr. In other words, for a two lane highway and an operating speed around 80/km/h, the difference the longitudinal gradient between the edge of the pavement profile and its centerline profile should not exceed 0.5 %.

- For operating speeds other than 80 km/h, the relative longitudinal slopes that satisfy the comfort and appearance criteria will be greater or less than 1/200.

Superelevation Transition Distance

- Spiral length based on transition theory is given by the following equation:

$$L_s = \frac{V^3}{RC} \tag{3.23}$$

Where,

L_s = minimum length of spiral (m)
V = vehicle speed (m/s)
R = radius (m)
C = rate of lateral acceleration ($m/s^2/s$)

Value of C of 0.30 m/s^3 is used in railroad practice, whereas when this criteria is to be used for highway design, values of C ranges from 0.30 m/s^3 to 0.90 m/s^3.

Superelevation Transition Distance

- The second criteria, namely the comfort criteria stated above for two lane highways can be expressed as

$$L_s = \frac{e_{\max} D}{S_r} \tag{3.24}$$

Where

S_r = relative gradient (relative slope of edge compared to rotation axis or slope ratio)

D = the distance measured from centerline (rotation axis) to the edge (m)

Superelevation Transition Distance

- For two lane highways D will be equal to lane width w. The relation can be rewritten for two lane highways by replacing D with w and taking S_r = 1/200 for moderate design speeds (about 80 km/h).

$$L_s = \frac{e_{\max} w}{0.005} \tag{3.25}$$

- AASHTO recommends varying maximum relative gradient (S_r) with design speed in order to provide longer runoff lengths at higher speeds and shorter lengths at lower speeds. Table 3.5 gives suggested relative gradient values.

Superelevation Transition Distance

Table 3.5 Suggested maximum relative gradients for various design speeds

(AASHTO 2004)

Metric		
Design speed (km/h)	Maximum relative gradient (%)	Equivalent maximum relative slope
20	0.80	1:125
30	0.75	1:133
40	0.70	1:143
50	0.65	1:154
60	0.60	1:167
70	0.55	1:182
80	0.50	1:200
90	0.47	1:213
100	0.44	1:227
110	0.41	1:244
120	0.38	1:263
130	0.35	1:286

Superelevation Transition Distance

- The use of Eq. 3.25 is suitable when a two lane highway is rotated around centerline. Only in this case, the maximum relative gradient, S_r, (the relative slope of edge with respect to rotation axis, in this case centerline), selected for design would be provided. For multilane sections, the equation should be revised to account the number of lanes as follows

$$L_s = \frac{e_{\max}(wn)}{S_r} b_w \tag{3.26}$$

Where,

n = number of lanes rotated

b_w = adjustment factor

Superelevation Transition Distance

- The adjustment factors (b_w) are given in Table 3.6 and the number of rotated lanes are shown in Fig. 3.25 for undivided multilane highways.

Table 3.6: Adjustment factors for number of lanes rotated (AASHO 2004)

Metric		
Number of Lanes Rotated, n_1	Adjustment Factor,* b_w	Length Increase Relative to One-Lane Rotated, $(=n_1 b_w)$
1	1.00	1.0
1.5	0.83	1.25
2	0.75	1.5
2.5	0.70	1.75
3	0.67	2.0
3.5	0.64	2.25

* Note: $b_w = [1 + 0.5(n_1 - 1)]/n_1$

Superelevation Transition Distance

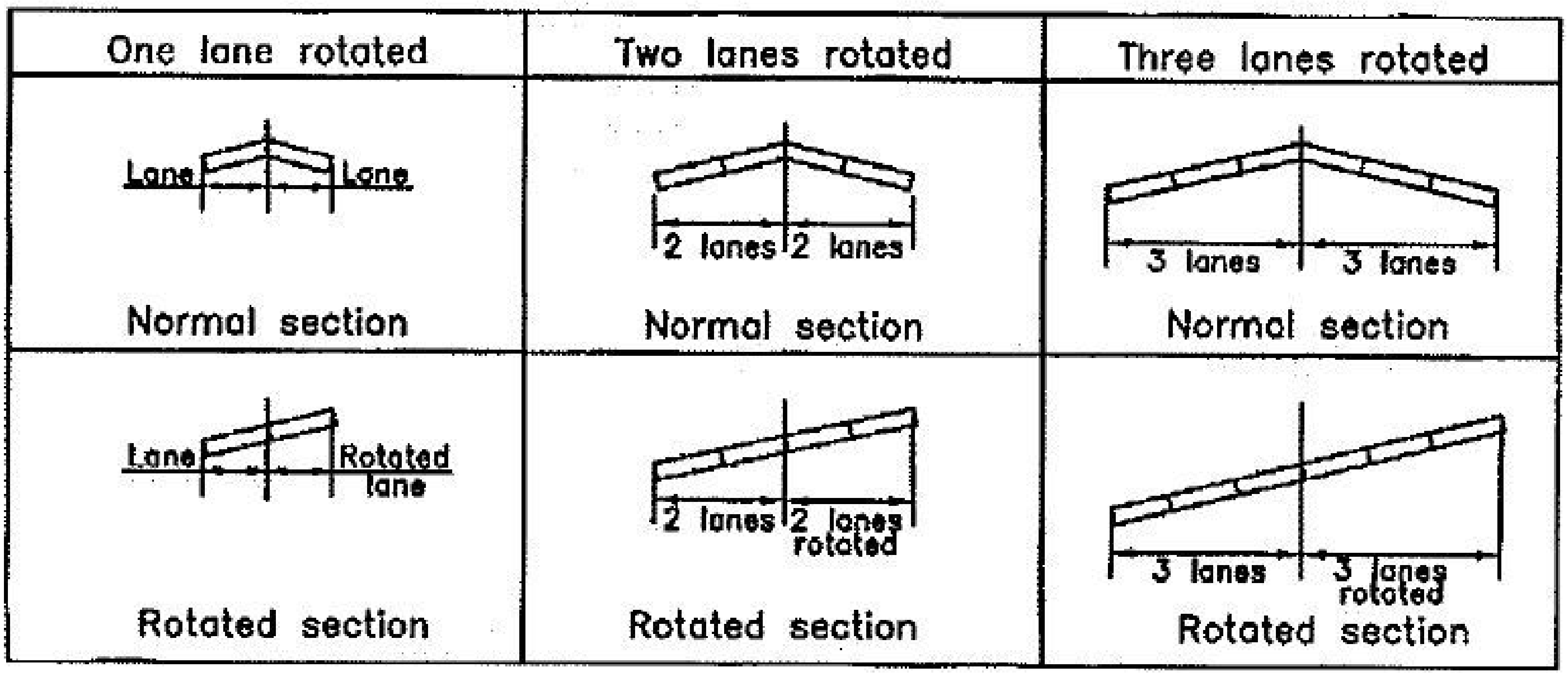


Figure 3.25 Number of lanes rotated for multilane undivided highways (AASHO 2004)

Superelevation Transition Distance

- **Minimum length of tangent runout (*L_t*):** The length of tangent runout is determined by the amount of adverse cross slope to be removed and the rate at which it is removed.

  To affect a smooth edge of pavement profile, the rate of removal should equal the relative gradient used to define the superelevation runoff length. Based on this rationale, the following equation should be used to compute the minimum tangent runout length:

$$L_t = \frac{e_o}{e_{\max}} L_s \tag{3.27}$$

Superelevation Transition Distance

- **Location (tangent-to-curve design):** The location of the superelevation runoff length with respect to the Point of Curvature (PC) must be determined.

  - Normal practice is to divide the runoff length between the tangent and curved sections and to avoid placing the entire runoff length on either the tangent or the curve.

  - Two extreme applications are either locating the runoff length entirely on the approach tangent or locating the runoff entirely on the circular curve. Both of these extreme applications are not desirable.

  - Experience indicates that locating a portion of the runoff on the tangent, in advance of the PC is preferable, since this tends to minimize the peak lateral acceleration and the resulting side friction demand.

Superelevation Transition Distance

- Theoretical considerations indicate that values for the proportion of runoff length on the tangent in the range of 0.7 to 0.9 offer the best operating conditions. The specific value to be selected in this range should be dependent on design speed and rotated width for minimizing the lateral shift of the vehicle. Suggested values are given in Table 3.7 (AASHTO 2004).

Table 3.7 Runoff locations that minimize vehicle's Lateral motion (AASHTO 2004)

Metric				
Design speed (km/h)	Portion of runoff located prior to the curve — No. of lanes rotated			
	1.0	1.5	2.0–2.5	3.0–3.5
20–70	0.80	0.85	0.90	0.90
80–130	0.70	0.75	0.80	0.85

Superelevation Transition Distance

- Experience obtained from existing practice indicates that deviation from the values in Table 3.7 by 10 percent should not lead to measurable operational problems.
- In this regard, use of a single value for the proportion of runoff length on the tangent in the range of 0.6 to 0.9 (60 to 90 percent) for all speeds and rotated widths is considered acceptable.

Superelevation Transition Distance

- **Location (spiral transition - circular curve design)**

  - In alignment design with spirals, the superelevation runoff is affected over the whole of the transition curve. The length of the superelevation runoff should be equal to the spiral length for the tangent-to-spiral (*TS*) transition at the beginning and the spiral-to-curve (*SC*) transition at the end of the circular curve. (Refer to Fig. 3.15).

  - The change in cross slope begins by removing the adverse cross slope from the lane or lanes on the outside of the curve over a length of tangent just ahead of *TS* (the tangent runout). Between the *TS* and *SC*, the spiral curve and the superelevation runoff are coincident and the traveled way is rotated to reach the full superelevation at the SC. This arrangement is reversed on leaving the curve. In this design, the whole of the middle circular curve has full superelevation.

Superelevation Application (Turkish Practice)

- **tangent-to-curve design (Turkish practice)**

  - As mentioned before, Turkish General Directorate of Highways adopts the use of Eq. 3.22 to calculate the rate of superelevation or minimum curve radius.

  - For the superelevation runoff length, Eq. 3.26 and related applications suggested by AASHTO (Table 3.5 and 3.6) are adopted.

  - Alternatively, the superelevation runoff distance is calculated by Eq. 3.23 (Short's Equation) based on vehicle dynamics. *C* value of 0.60 m/s^3 is adopted. Using speed (*V*) in units of km/hr

$$L_s = \frac{0.0354V^3}{R} \tag{3.28}$$

Superelevation Application (Turkish Practice)

- Eq. 3.28 is used to control the superelevation runoff distance, L_s, determined by comfort criteria (Eq. 3.26, Table 3.5 and Table 3.6).

- Turkish General Directorate of Highways adopts locating 2/3 of superelevation runoff distance on tangent and 1/3 on the circular curve. Figure 3.25 and 3.26 demonstrates this application for rotation around centerline

- **Spiral transition- circular curve design (Turkish practice)**

  AASHTO criteria are adopted and when spiral transition is used to connect tangent to circular curve, the superelevation runoff distance and spiral distance coincides.

Superelevation Application (Turkish Practice)

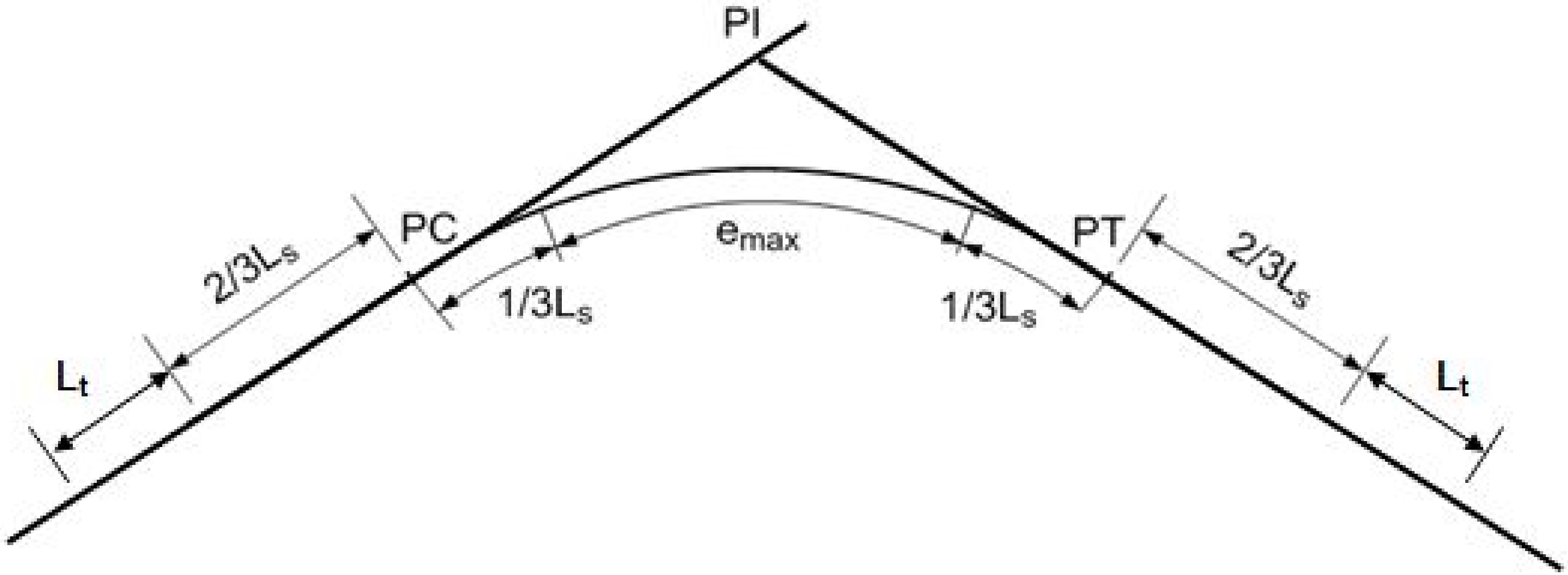


Figure 3.25 Locating L_s distance (Turkish practice)

Superelevation Application (Turkish Practice)

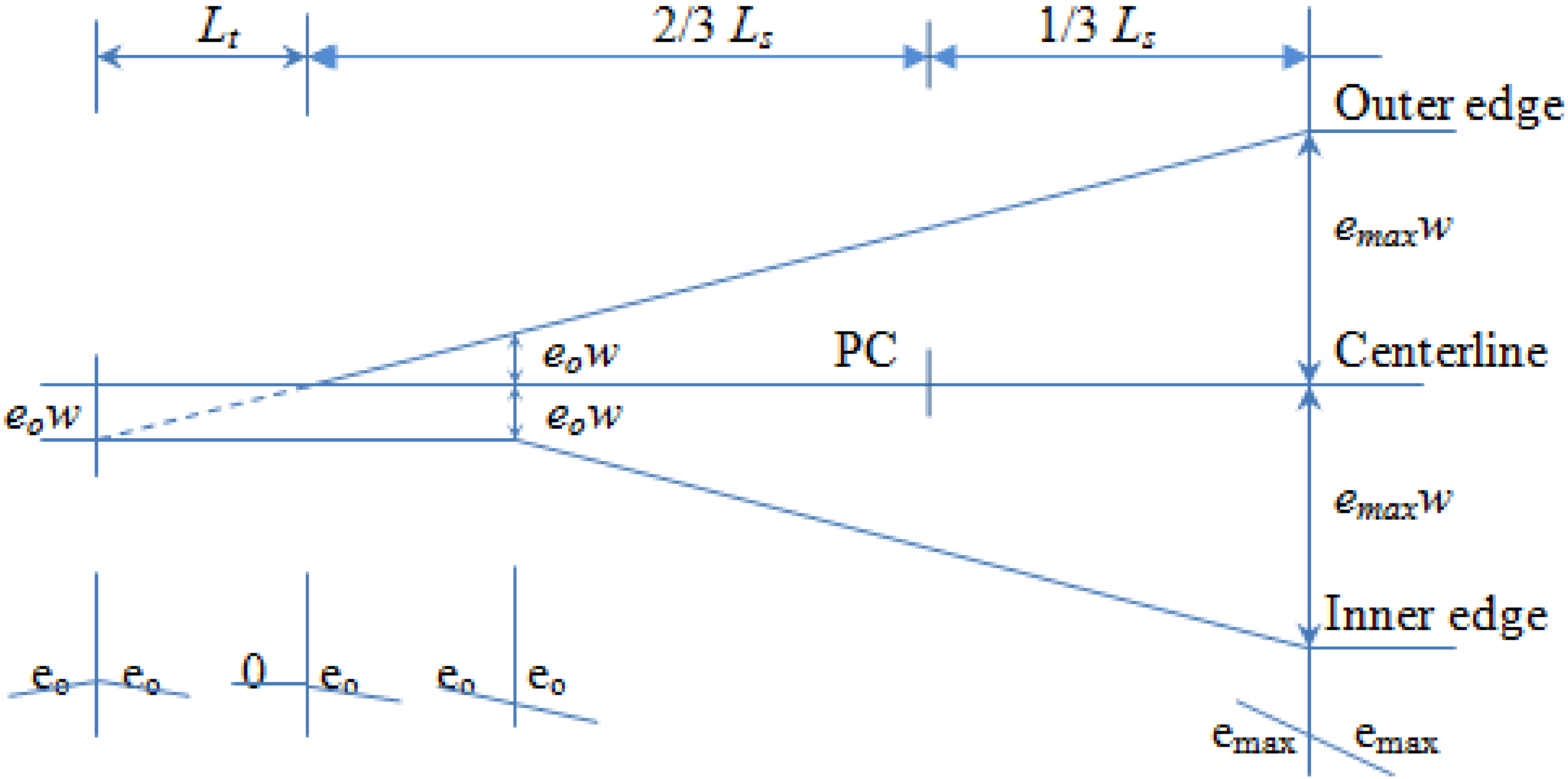


Figure 3.26 Superelevation diagram (Rotation around centerline), Turkish practice

Superelevation (Example Problem)

Example 3.8:

The plan and the cross-section of a two lane highway segment are shown below. The road rises at a uniform grade of 2.5% from A to B. The design speed (V) is 90 km/hr. The radius (R) of the circular curve is 500 m.

Prepare superelevation table showing superelevations of each travel lane and the elevations of CL, OE, IE at 10 m even stations starting from the beginning of L_t distance up to the ending point of L_s distance. And draw superelevation diagram showing all necessary details.

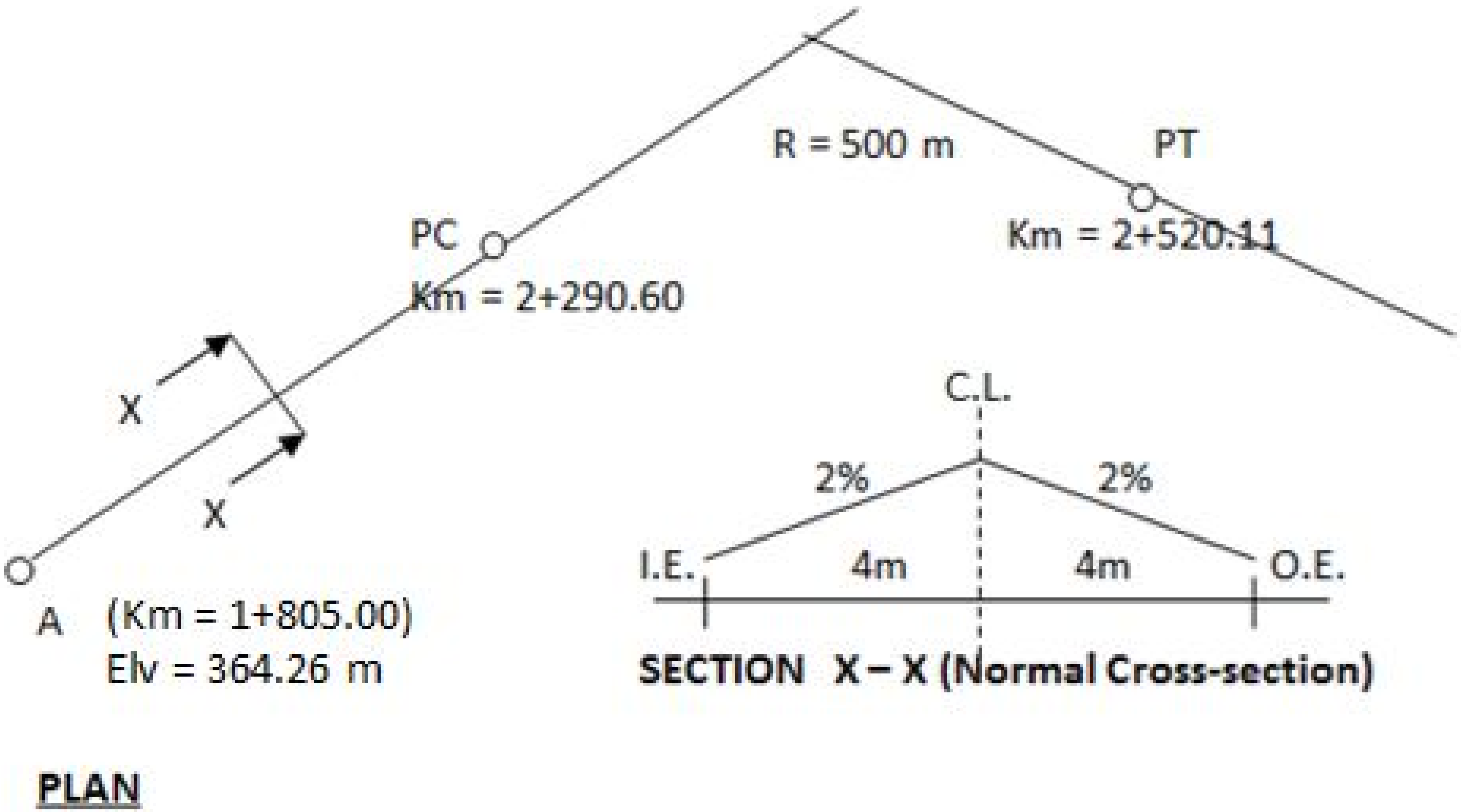
Notes: 1) Apply Superelevation by rotating around CL

2) Add critical stations (End TR/Start LS, PC) to superelevation tables,

3) (max e = 0.08, take S_r = 1/200)

4) Do not round the calculated figures

Superelevation (Example Problem)



Superelevation (Example Problem)

Solution:

Rotation around C.L.

$e = 0.00443*90*90/500 \quad = 0.072 < 0.08$ OK

$L_s = 0.0354*90*90*90/500 \quad = 51.61$ m (according to Turkish practice)

$L_s = 0.072*4.0/0.005 \quad = 57.60$ m

Take $e_{max} = 0.072$ and $L_s = 57.60$ m

$L_t = 0.02/0.072 * 57.60 \quad = 16.00$ m

St. (End L_t/Start L_s)	= (2+290.60) - 2/3L_s	= (2+290.60) – 2/3*57.60	= **2 + 252.20**
St. (Start L_t)	= (2+252.20) – Lt	= (2+252.20) – 16.00	= **2 + 236.20**
St. (End Ls)	= (2+290.60) + 1/3L_s	= (2+290.60) + 1/3*57.60	= **2 + 309.80**
Rate of Superelevation (e_{rate}) = e_{max}/Ls		= 0.072/57.60 = 0.00125	= **0.125 %/m**

C.L. Elev. (Start L_t) = (St. Start Lt - St. A)*G + Elev (A) =(2236.20-1805.00)*0.025+364.26 = **375.04 m**
I.E. Elev. (Start L_t) = O.E. Elev. (Start L_t) = C.L. Elev. (Start L_t) - $e_o\, w$ = 375.04 – 0.02*4.00 = **374.96 m**

Superelevation (Example Problem)

S.E. TABLE BY ROTATION AROUND CENTERLINE (Step 1):

			Superelevation (%)		Elv. Diff. w.r.t. CL (m)		Elevation (m)		
POINT	Km	Distance (m)	Outer lane	İnner lane	Outer edge	İnner edge	Outer edge	Center-line	İnner edge
START L_t	2 + 236,20	0	-2.00	-2.00	-0.08	-0.08	374.96	**375.04**	374.96
	2 + 240,00	3.80		-2.00		-0.08			
	2 + 250,00	13.80		-2.00		-0.08			
End L_t / Start L_s	2 + 252,20	16.00	0.00	-2.00		-0.08			
	2 + 260,00	23.80		-2.00		-0.08			
	2 + 268.20	32.00	2.00	-2.00		-0.08			
	2 + 270,00	33.80							
	2 + 280,00	43.80							
	2 + 290,00	53.80							
PC	2 + 290,60	54.40							
	2 + 300,00	63.80							
END LS	2 + 309,80	73.60	7,20	-7.20					

Superelevation (Example Problem)

S.E. TABLE BY ROTATION AROUND CENTERLINE (Step 2):

			Superelevation (%)		Elv. Diff. w.r.t. CL (m)		Elevation (m)		
POINT	Km	Distance (m)	Outer lane	İnner lane	Outer edge	İnner edge	Outer edge	Center-line	İnner edge
START L_t	2 + 236,20	0	-2.00	-2.00	-0.08	-0.08	374.96	**375.04**	374.96
	2 + 240,00	3.80		-2.00		-0.08		**375.14**	
	2 + 250,00	13.80		-2.00		-0.08		**375.39**	
End L_t / Start L_s	2 + 252,20	16.00	0.00	-2.00		-0.08		**375.44**	
	2 + 260,00	23.80		-2.00		-0.08		**375.64**	
	2 + 268.20	32.00	2.00	-2.00		-0.08		**375.84**	
	2 + 270,00	33.80						**375.89**	
	2 + 280,00	43.80						**376.14**	
	2 + 290,00	53.80						**376.39**	
PC	2 + 290,60	54.40						**376.40**	
	2 + 300,00	63.80						**376.64**	
END LS	2 + 309,80	73.60	7,20	-7.20				**376.88**	

Superelevation (Example Problem)

S.E. TABLE BY ROTATION AROUND CENTERLINE:

			Superelevation (%)		Elv. Diff. w.r.t. CL (m)		Elevation (m)		
POINT	Km	Distance (m)	Outer lane	İnner lane	Outer edge	İnner edge	Outer edge	Center-line	İnner edge
START L_t	2 + 236,20	0	-2.00	-2.00	-0.08	-0.08	374.96	**375.04**	374.96
	2 + 240,00	3.80	-1.53	-2.00	-0.06	-0.08	375.07	**375.14**	375.06
	2 + 250,00	13.80		-2.00		-0.08		**375.39**	
End L_t / Start L_s	2 + 252,20	16.00	0.00	-2.00		-0.08		**375.44**	
	2 + 260,00	23.80		-2.00		-0.08		**375.64**	
	2 + 268.20	32.00	2.00	-2.00		-0.08		**375.84**	
	2 + 270,00	33.80						**375.89**	
	2 + 280,00	43.80						**376.14**	
	2 + 290,00	53.80						**376.39**	
PC	2 + 290,60	54.40						**376.40**	
	2 + 300,00	63.80						**376.64**	
END LS	2 + 309,80	73.60	7,20	-7.20				**376.88**	

Superelevation (Example Problem)

S.E. TABLE BY ROTATION AROUND CENTERLINE:

			Superelevation (%)		Elv. Diff. w.r.t. CL (m)		Elevation (m)		
POINT	Km	Distance (m)	Outer lane	İnner lane	Outer edge	İnner edge	Outer edge	Center-line	İnner edge
START L_t	2 + 236,20	0	-2.00	-2.00	-0.08	-0.08	374.96	**375.04**	374.96
	2 + 240,00	3.80	-1.53	-2.00	-0.06	-0.08	375.07	**375.14**	375.06
	2 + 250,00	13.80	-0.28	-2.00	-0.01	-0.08	375.37	**375.39**	375.31
End L_t / Start L_s	2 + 252,20	16.00	0.00	-2.00		-0.08		**375.44**	
	2 + 260,00	23.80		-2.00		-0.08		**375.64**	
	2 + 268.20	32.00	2.00	-2.00		-0.08		**375.84**	
	2 + 270,00	33.80						**375.89**	
	2 + 280,00	43.80						**376.14**	
	2 + 290,00	53.80						**376.39**	
PC	2 + 290,60	54.40						**376.40**	
	2 + 300,00	63.80						**376.64**	
END LS	2 + 309,80	73.60	7,20	-7.20				**376.88**	

Superelevation (Example Problem)

S.E. TABLE BY ROTATION AROUND CENTERLINE:

			Superelevation (%)		Elv. Diff. w.r.t. CL (m)		Elevation (m)		
POINT	Km	Distance (m)	Outer lane	İnner lane	Outer edge	İnner edge	Outer edge	Center-line	İnner edge
START L_t	2 + 236,20	0	-2.00	-2.00	-0.08	-0.08	374.96	**375.04**	374.96
	2 + 240,00	3.80	-1.53	-2.00	-0.06	-0.08	375.07	**375.14**	375.06
	2 + 250,00	13.80	-0.28	-2.00	-0.01	-0.08	375.37	**375.39**	375.31
End L_t / Start L_s	2 + 252,20	16.00	0.00	-2.00	0.00	-0.08	375.44	**375.44**	375.36
	2 + 260,00	23.80		-2.00		-0.08		**375.64**	
	2 + 268.20	32.00	2.00	-2.00		-0.08		**375.84**	
	2 + 270,00	33.80						**375.89**	
	2 + 280,00	43.80						**376.14**	
	2 + 290,00	53.80						**376.39**	
PC	2 + 290,60	54.40						**376.40**	
	2 + 300,00	63.80						**376.64**	
END LS	2 + 309,80	73.60	7,20	-7.20				**376.88**	

Superelevation (Example Problem)

S.E. TABLE BY ROTATION AROUND CENTERLINE:

			Superelevation (%)		Elv. Diff. w.r.t. CL (m)		Elevation (m)		
POINT	Km	Distance (m)	Outer lane	İnner lane	Outer edge	İnner edge	Outer edge	Center-line	İnner edge
START L_t	2 + 236,20	0	-2.00	-2.00	-0.08	-0.08	374.96	**375.04**	374.96
	2 + 240,00	3.80	-1.53	-2.00	-0.06	-0.08	375.07	**375.14**	375.06
	2 + 250,00	13.80	-0.28	-2.00	-0.01	-0.08	375.37	**375.39**	375.31
End L_t / Start L_s	2 + 252,20	16.00	0.00	-2.00	0.00	-0.08	375.44	**375.44**	375.36
	2 + 260,00	23.80	0.98	-2.00	0.04	-0.08	375.67	**375.64**	375.56
	2 + 268.20	32.00	2.00	-2.00		-0.08		**375.84**	
	2 + 270,00	33.80						**375.89**	
	2 + 280,00	43.80						**376.14**	
	2 + 290,00	53.80						**376.39**	
PC	2 + 290,60	54.40						**376.40**	
	2 + 300,00	63.80						**376.64**	
END LS	2 + 309,80	73.60	7,20	-7.20				**376.88**	

Superelevation (Example Problem)

S.E. TABLE BY ROTATION AROUND CENTERLINE:

			Superelevation (%)		Elv. Diff. w.r.t. CL (m)		Elevation (m)		
POINT	**Km**	**Distance (m)**	**Outer lane**	**İnner lane**	**Outer edge**	**İnner edge**	**Outer edge**	**Center-line**	**İnner edge**
START L_t	2 + 236,20	0	-2.00	-2.00	-0.08	-0.08	374.96	**375.04**	374.96
	2 + 240,00	3.80	-1.53	-2.00	-0.06	-0.08	375.07	**375.14**	375.06
	2 + 250,00	13.80	-0.28	-2.00	-0.01	-0.08	375.37	**375.39**	375.31
End L_t / Start L_s	2 + 252,20	16.00	0.00	-2.00	0.00	-0.08	375.44	**375.44**	375.36
	2 + 260,00	23.80	0.98	-2.00	0.04	-0.08	375.67	**375.64**	375.56
	2 + 268.20	32.00	2.00	-2.00	0.08	-0.08	375.92	**375.84**	375.76
	2 + 270,00	33.80						**375.89**	
	2 + 280,00	43.80						**376.14**	
	2 + 290,00	53.80						**376.39**	
PC	2 + 290,60	54.40						**376.40**	
	2 + 300,00	63.80						**376.64**	
END LS	2 + 309,80	73.60	7,20	-7.20				**376.88**	

Superelevation (Example Problem)

S.E. TABLE BY ROTATION AROUND CENTERLINE:

			Superelevation (%)		Elv. Diff. w.r.t. CL (m)		Elevation (m)		
POINT	Km	Distance (m)	Outer lane	İnner lane	Outer edge	İnner edge	Outer edge	Center-line	İnner edge
START L_t	2 + 236,20	0	-2.00	-2.00	-0.08	-0.08	374.96	**375.04**	374.96
	2 + 240,00	3.80	-1.53	-2.00	-0.06	-0.08	375.07	**375.14**	375.06
	2 + 250,00	13.80	-0.28	-2.00	-0.01	-0.08	375.37	**375.39**	375.31
End L_t / Start L_s	2 + 252,20	16.00	0.00	-2.00	0.00	-0.08	375.44	**375.44**	375.36
	2 + 260,00	23.80	0.98	-2.00	0.04	-0.08	375.67	**375.64**	375.56
	2 + 268.20	32.00	2.00	-2.00	0.08	-0.08	375.92	**375.84**	375.76
	2 + 270,00	33.80	2,23	-2.23	0.09	-0.09	375.97	**375.89**	375.80
	2 + 280,00	43.80						**376.14**	
	2 + 290,00	53.80						**376.39**	
PC	2 + 290,60	54.40						**376.40**	
	2 + 300,00	63.80						**376.64**	
END LS	2 + 309,80	73.60	7,20	-7.20				**376.88**	

Superelevation (Example Problem)

S.E. TABLE BY ROTATION AROUND CENTERLINE:

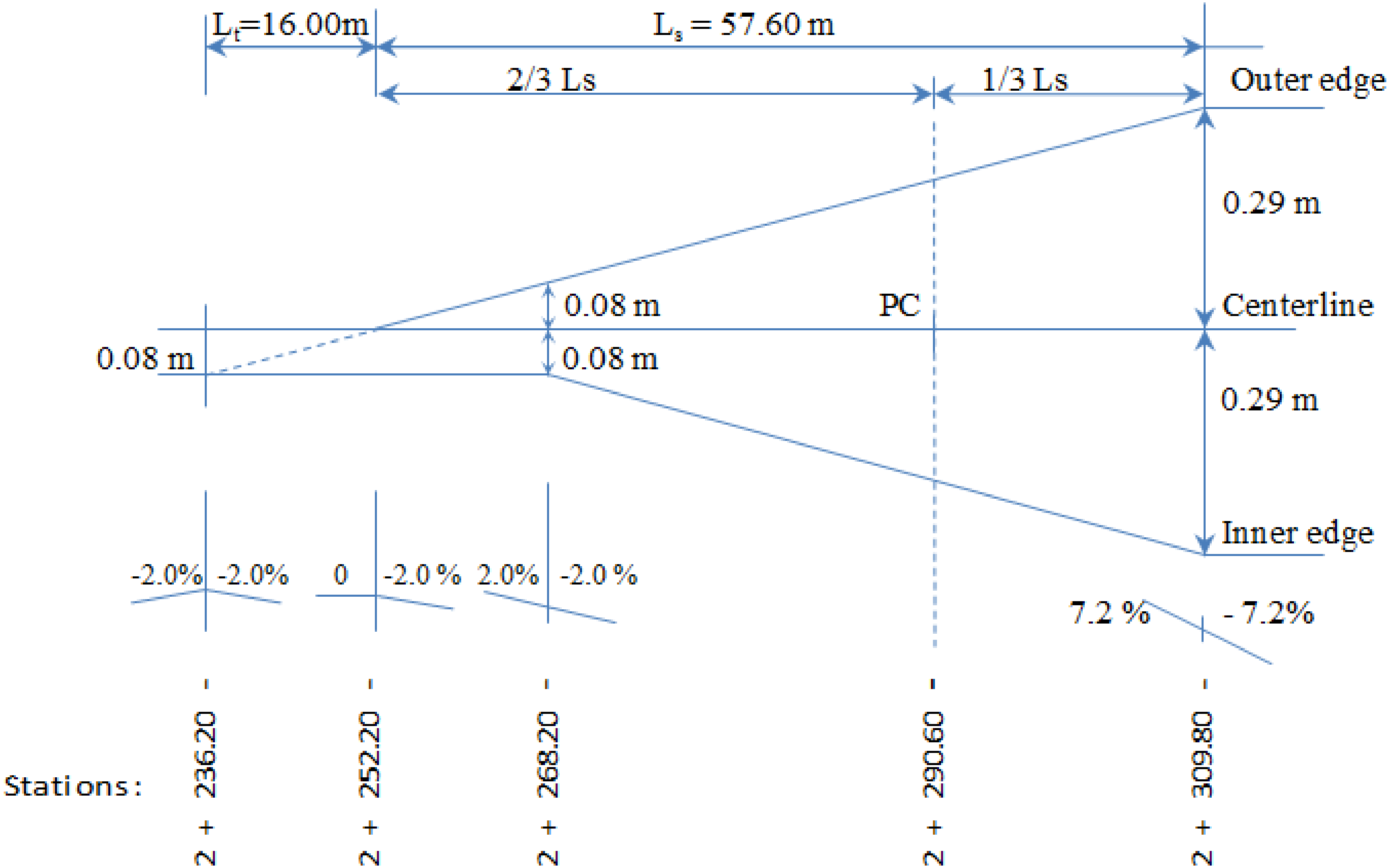
			Superelevation (%)		Elv. Diff. w.r.t. CL (m)		Elevation (m)		
POINT	Km	Distance (m)	Outer lane	İnner lane	Outer edge	İnner edge	Outer edge	Center-line	İnner edge
START L_t	2 + 236,20	0	-2.00	-2.00	-0.08	-0.08	374.96	**375.04**	374.96
	2 + 240,00	3.80	-1.53	-2.00	-0.06	-0.08	375.07	**375.14**	375.06
	2 + 250,00	13.80	-0.28	-2.00	-0.01	-0.08	375.37	**375.39**	375.31
End L_t / Start L_s	2 + 252,20	16.00	0.00	-2.00	0.00	-0.08	375.44	**375.44**	375.36
	2 + 260,00	23.80	0.98	-2.00	0.04	-0.08	375.67	**375.64**	375.56
	2 + 268.20	32.00	2.00	-2.00	0.08	-0.08	375.92	**375.84**	375.76
	2 + 270,00	33.80	2,23	-2.23	0.09	-0.09	375.97	**375.89**	375.80
	2 + 280,00	43.80	3,48	-3.48	0.14	-0.14	376.27	**376.14**	376.00
	2 + 290,00	53.80	4,73	-4.73	0.19	-0.19	376.57	**376.39**	376.20
PC	2 + 290,60	54.40	4,80	-4.80	0.19	-0.19	376.59	**376.40**	376.21
	2 + 300,00	63.80	5,98	-5.98	0.24	-0.24	376.87	**376.64**	376.40
END LS	2 + 309,80	73.60	7,20	-7.20	0.29	-0.29	377.17	**376.88**	376.59

Superelevation (Example Problem)

S.E. TABLE BY ROTATION AROUND CENTERLINE:

			Superelevation (%)		Elv. Diff. w.r.t. CL (m)		Elevation (m)		
POINT	**Km**	**Distance (m)**	**Outer lane**	**İnner lane**	**Outer edge**	**İnner edge**	**Outer edge**	**Center-line**	**İnner edge**
START L_t	2 + 236,20	0	-2.00	-2.00	-0.08	-0.08	374.96	**375.04**	374.96
	2 + 240,00	3.80	-1.53	-2.00	-0.06	-0.08	375.07	**375.14**	375.06
	2 + 250,00	13.80	-0.28	-2.00	-0.01	-0.08	375.37	**375.39**	375.31
End L_t / Start L_s	2 + 252,20	16.00	0.00	-2.00	0.00	-0.08	375.44	**375.44**	375.36
	2 + 260,00	23.80	0.98	-2.00	0.04	-0.08	375.67	**375.64**	375.56
	2 + 268.20	32.00	2.00	-2.00	0.08	-0.08	375.92	**375.84**	375.76
	2 + 270,00	33.80	2,23	-2.23	0.09	-0.09	375.97	**375.89**	375.80
	2 + 280,00	43.80	3,48	-3.48	0.14	-0.14	376.27	**376.14**	376.00
	2 + 290,00	53.80	4,73	-4.73	0.19	-0.19	376.57	**376.39**	376.20
PC	2 + 290,60	54.40	4,80	-4.80	0.19	-0.19	376.59	**376.40**	376.21
	2 + 300,00	63.80	5,98	-5.98	0.24	-0.24	376.87	**376.64**	376.40
END LS	2 + 309,80	73.60	7,20	-7.20	0.29	-0.29	377.17	**376.88**	376.59

Superelevation (Example continued)



Superelevation diagram (rotation around CENTERLINE).

Compound Curves

- Compound curve is the combination of two circular curves of different radii. It is shown in Figure 3.27.
- Such curves are normally not used in horizontal alignment of highways.
- Compound curves are not desirable on highway due to its abrupt appearance, difficulty in superelevation transition and possible deception of drivers to the sharpness of the curve.
- Compound curves may be acceptable if the difference in radius is small and if they occur in one-way roadway when radius increases in the direction of travel.
- They are generally acceptable in intersections and at highway ramps.

Compound Curves

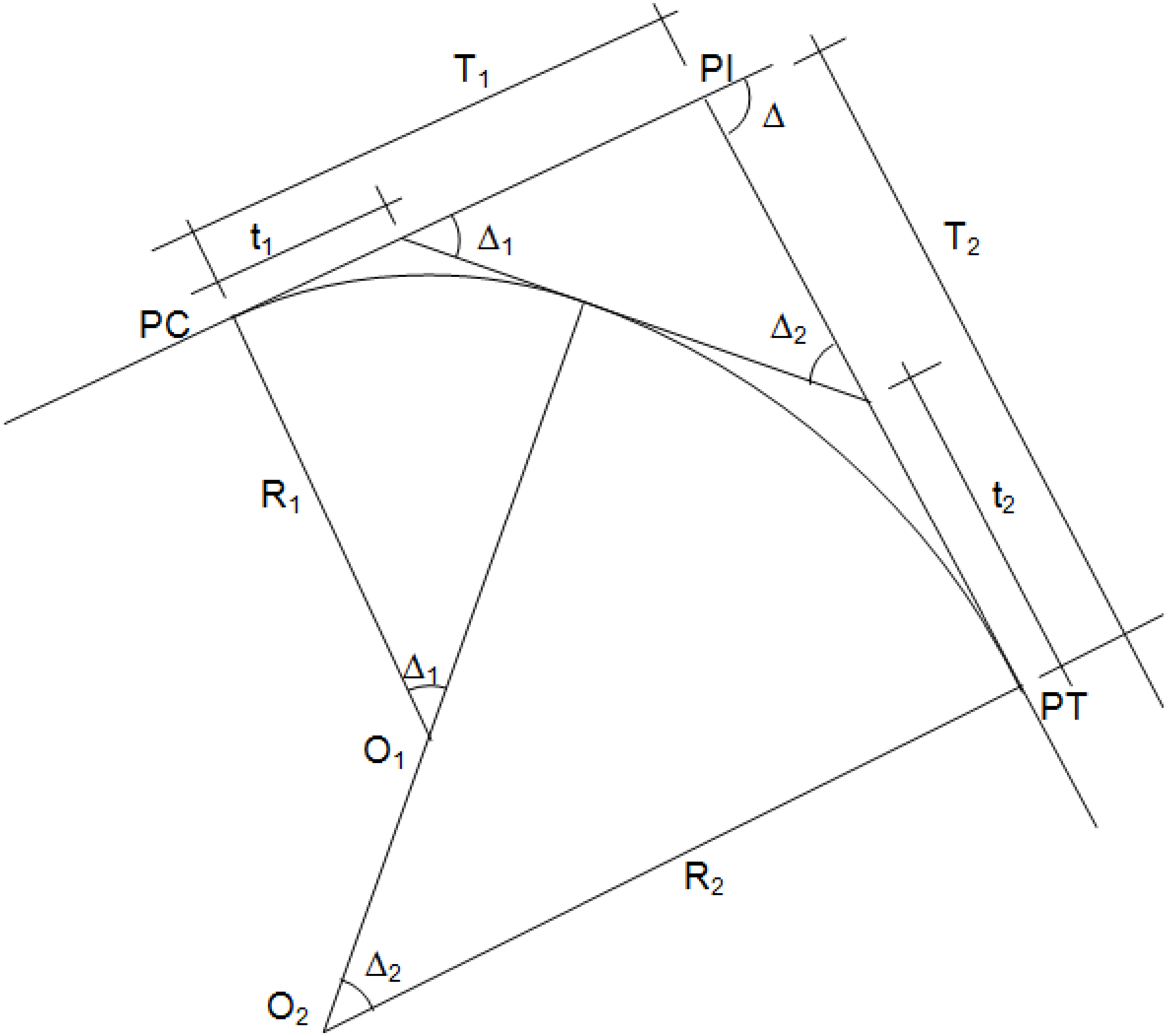


Figure 3.27 Compound curve

Equations:

$$\Delta = \Delta_1 + \Delta_2 \tag{3.29}$$

$$t_1 = R_1 \tan\frac{\Delta_1}{2} \tag{3.30}$$

$$t_2 = R_2 \tan\frac{\Delta_2}{2} \tag{3.31}$$

$$T_1 = R_1 \tan\frac{\Delta_1}{2} + \frac{(t_1 + t_2)\sin\Delta_2}{\sin\Delta} \tag{3.32}$$

$$T_2 = R_2 \tan\frac{\Delta_2}{2} + \frac{(t_1 + t_2)\sin\Delta_1}{\sin\Delta} \tag{3.33}$$

Broken-back Curve

- Two curves in the same direction separated by a short tangent

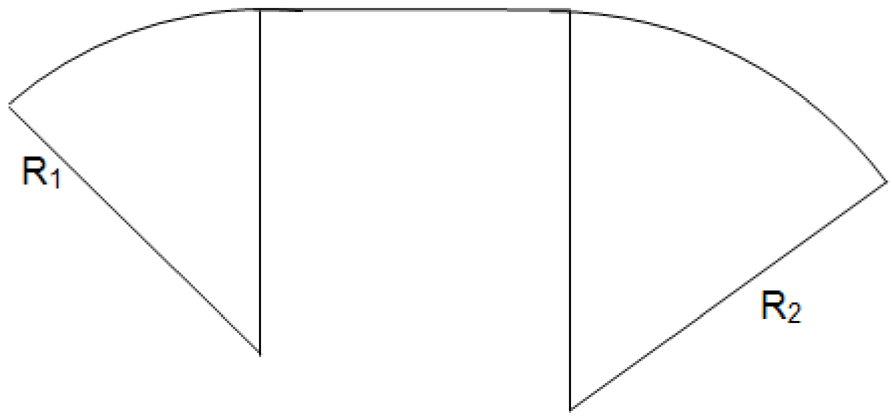


Figure 3.28 Broken-back Curve

- Such curves are not desirable and should be replaced by a single larger radius curve.

Reverse Curves

- Two simple circular curves separated by a sort common tangent and having centers on opposite sides of the common tangent. The distance between *PT* point of the first curve and the *PC* point of the second curve ($\overline{PT_1 - PC_2}$) is controlled by the placement of L_s lengths.
- Turkish practice: $\overline{PT_1 - PC_2} \geq$ 2/3 (Ls_1+Ls_2).

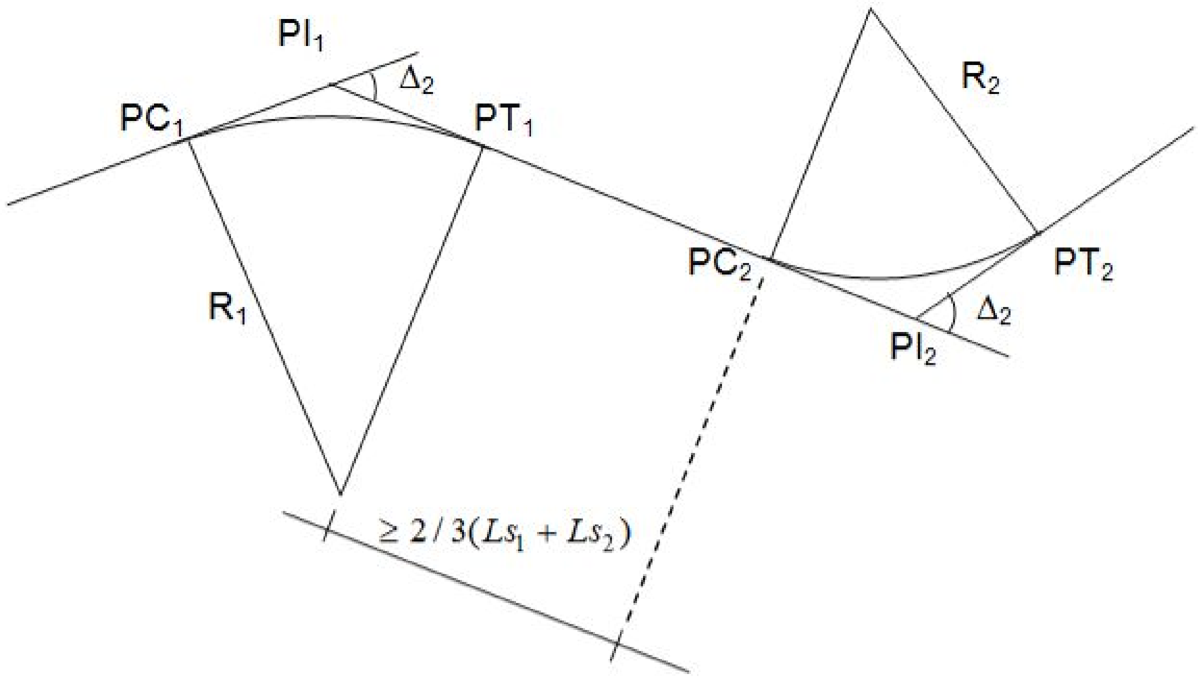


Figure 3.29: Reverse Curves (Turkish Practice)

Reverse Curves

- For the limiting case, in other words when $\overline{PT_1 - PC_2} = 2/3(Ls_1 + Ls_2)$, the superelevation application between the first curve and the second curve will be as shown in Figure 3.30
-

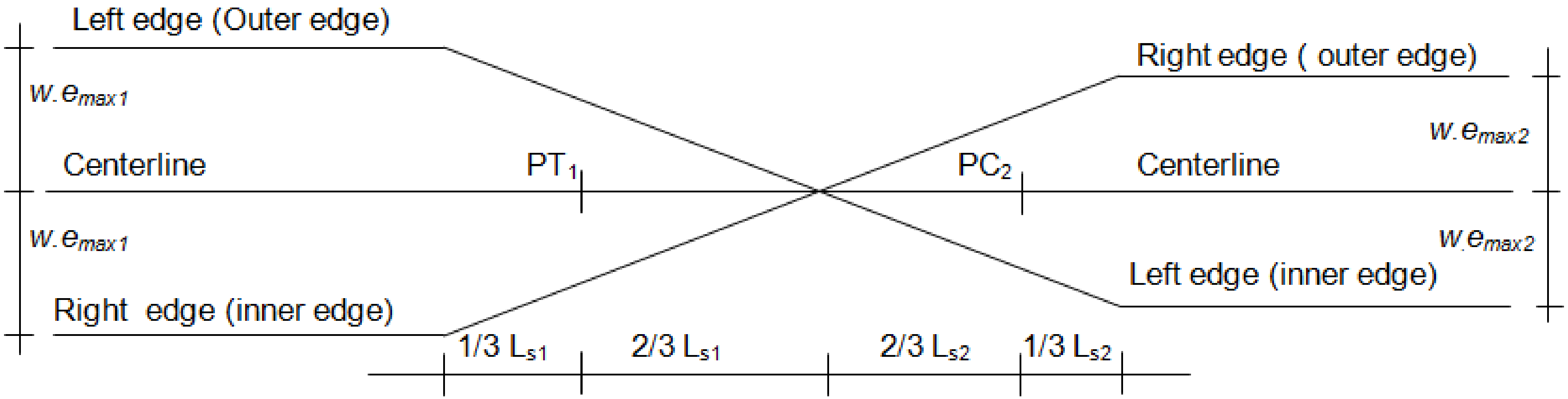


Figure 3.27: Superelevation diagram between reverse curves (Turkish Practice for limiting case, i.e. *PT_1* to *PC_2* distance is equal to 2/3(L_{s1}+L_{s2}))

Reverse Curves

- Similar full platform rotation is applied between the curves if

$$2/3(L_{s1}+L_{s2}) \le \overline{PT_1 - PC_2} < 2/3(L_{s1}+L_{s2}) + L_{t1} + L_{t2}$$

- Superelevation application of the curves will be independent when

$$\overline{PT_1 - PC_2} \ge 2/3(L_{s1}+L_{s2}) + L_{t1} + L_{t2}$$