Transportation Engineering

Course Code –CE-422

Contact Hours -3+3

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Roadway Alignment

- An ideal and most desirable roadway is one that follows the existing natural alignment of the country. This is the most economical type of highway to construct.
- But certain aspects of the design that has to be maintained may prevent the designer from following this undulating surface without making considerable adjustments in both the vertical and horizontal directions.

Roadway Alignment

- The designer must produce an alignment in which conditions are consistent and uniform to help reduce problems related to driver expectancy.
- Sudden changes in alignment should be connected with long sweeping curves, and short sharp curves should not be interspersed with long curves of small curvature.

Roadway Alignment

- The ideal highway location is one with consistent alignment, where both vertical grade and horizontal curvature receive consideration and are configured to satisfy limiting design criteria.
- The optimal final alignment will be that in which the best balance between grade and curvature is achieved.

Terrain

- Terrain has considerable influence on the final choice of alignment. Generally, the topography of the surrounding area is fitted into one of three classifications:
  - Level
  - Rolling
  - Mountainous

Level Terrain

- In level country, the alignment is in general limited by considerations other than grade, that is, cost of right-of-way, land use, waterways requiring expensive bridging, existing cross roads, railroads, canals, power lines and sub-grade conditions or the availability of suitable borrow material.

Rolling Terrain

- In rolling country, grade and curvature must be carefully considered and to a certain extent balanced.
- Depths of cut and heights of fill, drainage structures, and number of bridges will depend on whether the route follows the ridges, the valleys or cross drainage alignment.

Mountainous Terrain

- In mountainous country, grades provide the greatest problem, and, in general, the horizontal alignment or curvature is controlled by maximum grade criteria.

Horizontal Alignment

- Horizontal alignment consists of a series of straight sections of highway joined by suitable curves. It is necessary to establish the proper relation between design speed and curvature as well as relationship with super-elevation and side friction.
- Horizontal curves are designated by their radius or by the degree of the curve.
- The degree of a curve is the central angle sub tended by an arc of 100 ft measured along the center of the road.

SUPER-ELEVATION

k0666068 www.fotosearch.com

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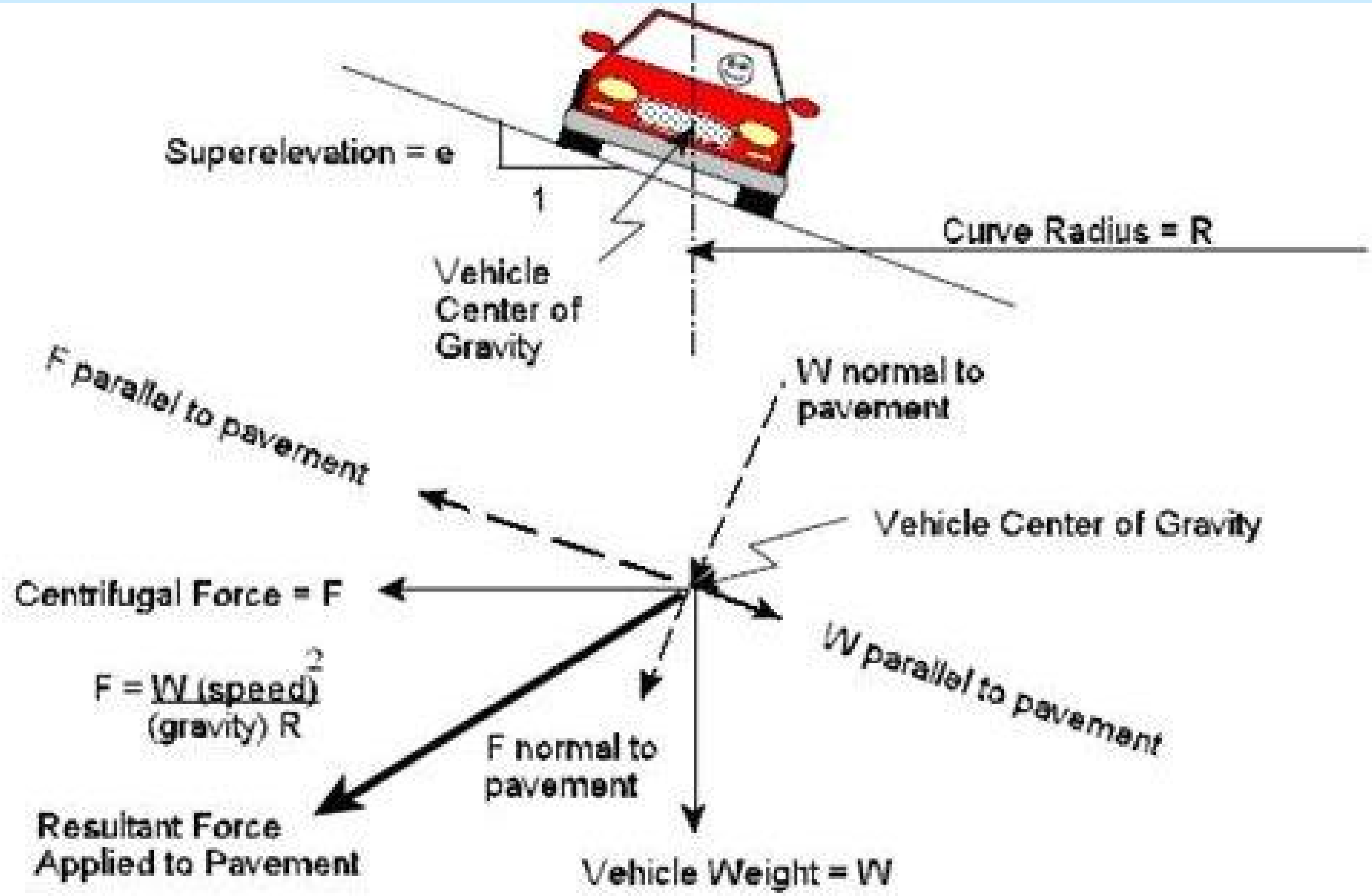
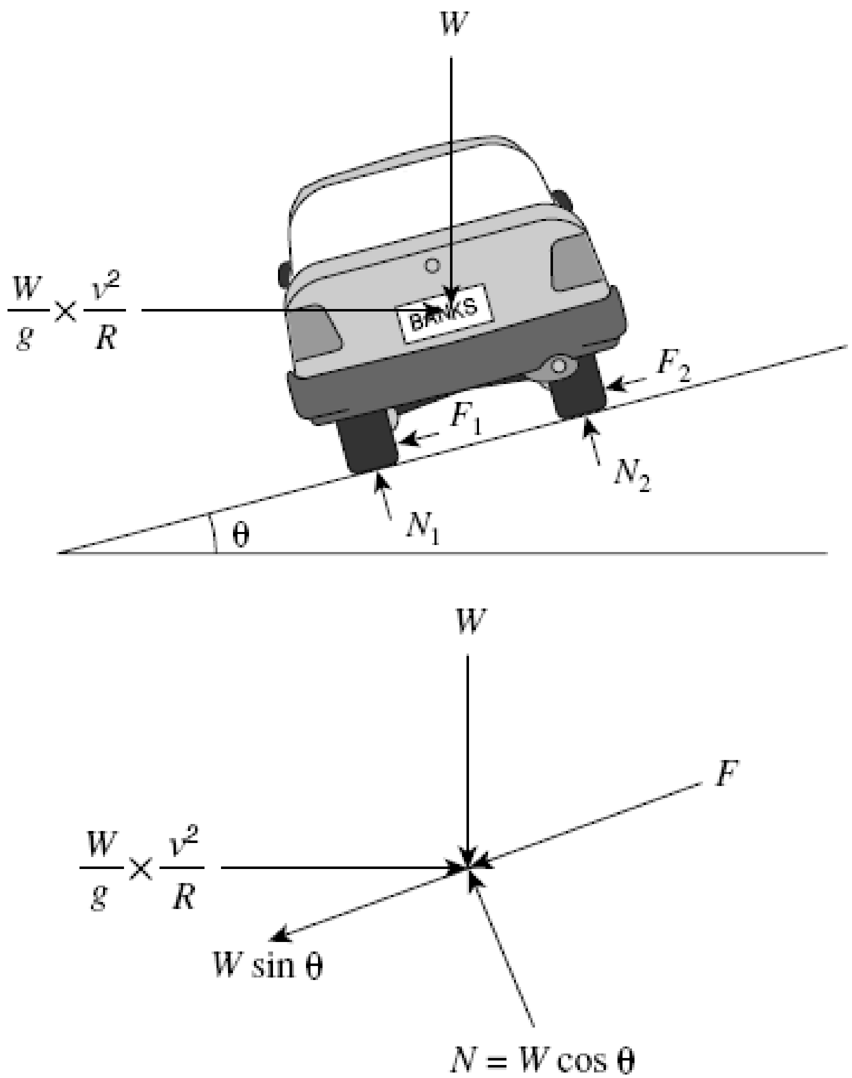
Superelevation

- A vehicle is forced radially outward by centrifugal force when it moves in a circular path.
- The vehicle weight component creates friction between the road surface and tires to counterbalance the centrifugal force.
- In addition, the superelevated section of a highway offsets the tendency of the vehicle to slide out-ward.

Superelevation



Force Diagram for Superelevation



R- Radius

v– speed

w- weight of vehicle

N_1& N_2 - normal forces

F_1& F_2 - lateral forces/ friction forces

Force Diagram for superelevation

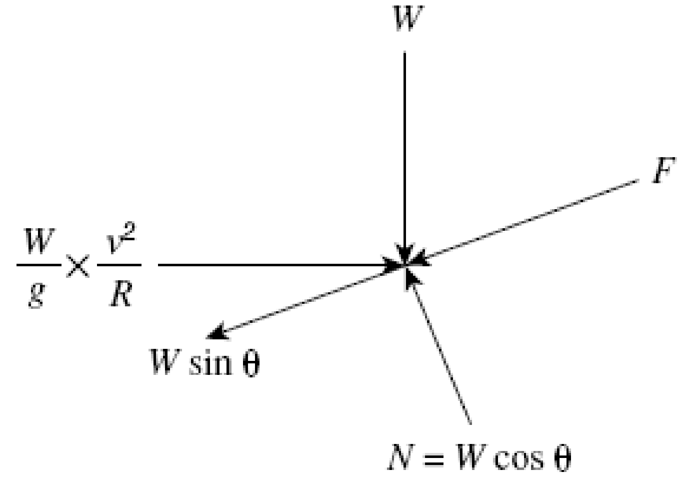
μ- coefficient of friction between tires and roadway

ϕ – angle of pavement cross slope

$e = \tan \phi$ = superelevation rate = cross slope of the road way

Derivation of Superelevation equation

For Highway F_1 and F_2 are friction forces



$$F_1 \leq \mu N_1$$

and

$$F_2 \leq \mu N_2$$

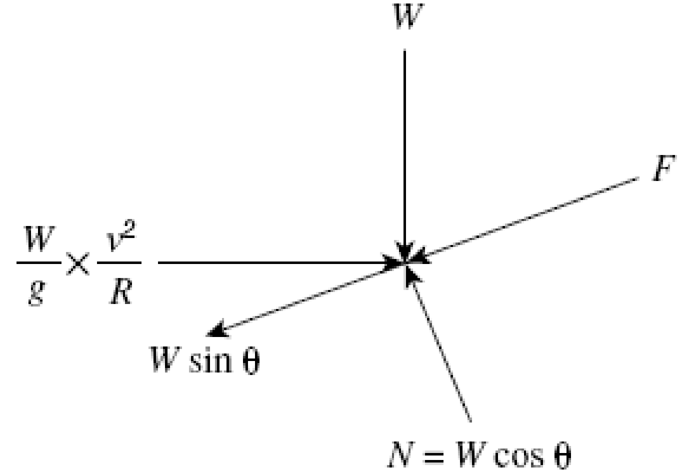
Summing forces parallel to roadway

$$\cos\theta\left(\frac{W}{g}\right)\left(\frac{v^2}{R}\right) = F + W\sin\theta$$

Derivation of Superelevation equation

Defining a factor *f*, side friction factor so that

$$f \equiv \frac{F}{N}$$



Summing forces normal to roadway

$$N = W\cos\theta + \sin\theta\left(\frac{w}{g}\right)\left(\frac{v^2}{R}\right)$$

Derivation of Superelevation equation

The equation can be rewritten as

$$\cos\theta\left(\frac{W}{g}\right)\left(\frac{v^2}{R}\right) = W\sin\theta + fW\cos\theta + f\sin\theta\left(\frac{w}{g}\right)\left(\frac{v^2}{R}\right)$$

Dividing by Wcos θ leads to

$$\frac{v^2}{gR} = \tan\theta + f + f\tan\theta\left(\frac{v^2}{gR}\right)$$

Derivation of Superelevation equation

tan θ is the cross-slope of the roadway, which is same as super-elevation rate e and can be written as

$$\frac{v^2}{gR} = e + f + ef\left(\frac{v^2}{gR}\right)$$

$$\frac{v^2}{gR}(1 + ef) = e + f$$

The term *ef* is small and may be omitted so the equation reduces to

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

or

$$R = \frac{v^2}{g(f + e)}$$

Derivation of Superelevation equation

A commonly used equation is

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

V is in km/hr and
R in m

Alternatively

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

or

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

Superelevation Equation (FPS System)

Where V is in miles/h, and R is in feet

$$R = \frac{V^2}{15(e + f)}$$

- Studies show that the co-efficient of friction (μ) between new tires and wet concrete pavements ranges from about 0.5 at 20 mph (30 Km/h) to approximately 0.35 at 60 mph (100 Km/h).
- For normal, wet, concrete pavement and smooth tires, the value is about 0.35 at 45 mph (70 Km/h). However, curve design cannot be based entirely on available co-efficient of friction (μ). Side friction factor (*f*) is used in the design of curves.

Side Friction Factor *f*

- Values of *f* recommended by AASHTO are conservative relative to actual friction between the tires and road surface.
- Maximum rates of superelevation are limited by the need to prevent
  - slow moving vehicles from sliding to the inside of the curve.
  - to keep the parking lanes relatively level in urban area
  - to keep the difference in slope between roadway and any street or driveways that intersect within reasonable limits.

Side Friction Factor *f* (AASHTO)

Values of side friction recommended by AASHTO

Design speed, km/h	Maximum side friction factor
30	0.17
40	0.17
50	0.16
60	0.15
70	0.14
80	0.14
90	0.13
100	0.12
110	0.11
120	0.09

Minimum Radius of Curve (AASHTO)

Recommended minimum radius of curvature

Design speed, km/h	Manimum curve raidus, m
30	35
40	60
50	100
60	150
70	215
80	280
90	375
100	490
110	635
120	870

Minimum Radius for Limiting values of e and *f* (AASHTO)

Metric

Design Speed (km/h)	Maximum e (%)	Limiting Values of f	Total (e/100 + f)	Calculated Radius (m)	Rounded Radius (m)
20	4.0	0.18	0.22	14.3	15
30	4.0	0.17	0.21	33.7	35
40	4.0	0.17	0.21	60.0	60
50	4.0	0.16	0.20	98.4	100
60	4.0	0.15	0.19	149.1	150
70	4.0	0.14	0.18	214.2	215
80	4.0	0.14	0.18	279.8	280
90	4.0	0.13	0.17	375.0	375
100	4.0	0.12	0.16	491.9	490
20	6.0	0.18	0.24	13.1	15
30	6.0	0.17	0.23	30.8	30
40	6.0	0.17	0.23	54.7	55
50	6.0	0.16	0.22	89.4	90
60	6.0	0.15	0.21	134.9	135
70	6.0	0.14	0.20	192.8	195
80	6.0	0.14	0.20	251.8	250
90	6.0	0.13	0.19	335.5	335
100	6.0	0.12	0.18	437.2	435
110	6.0	0.11	0.17	560.2	560
120	6.0	0.09	0.15	755.5	755
130	6.0	0.08	0.14	950.0	950
20	8.0	0.18	0.28	12.1	10
30	8.0	0.17	0.25	28.3	30
40	8.0	0.17	0.25	50.4	50
50	8.0	0.16	0.24	82.0	80
60	8.0	0.15	0.23	123.2	125
70	8.0	0.14	0.22	175.3	175
80	8.0	0.14	0.22	228.9	230
90	8.0	0.13	0.21	303.6	305
100	8.0	0.12	0.20	393.5	395
110	8.0	0.11	0.19	501.2	500
120	8.0	0.09	0.17	666.6	665
130	8.0	0.08	0.18	831.3	830
20	10.0	0.18	0.28	11.2	10
30	10.0	0.17	0.27	26.2	25
40	10.0	0.17	0.27	46.6	45
50	10.0	0.16	0.26	75.7	75
60	10.0	0.15	0.25	113.3	115
70	10.0	0.14	0.24	160.7	160
80	10.0	0.14	0.24	209.9	210
90	10.0	0.13	0.23	277.2	275
100	10.0	0.12	0.22	357.7	360
110	10.0	0.11	0.21	453.5	455
120	10.0	0.09	0.19	596.5	595
130	10.0	0.08	0.18	738.9	740
20	12.0	0.18	0.30	10.5	10
30	12.0	0.17	0.29	24.4	25
40	12.0	0.17	0.29	43.4	45
50	12.0	0.16	0.28	70.3	70
60	12.0	0.15	0.27	104.9	105
70	12.0	0.14	0.26	148.3	150
80	12.0	0.14	0.26	193.7	195
90	12.0	0.13	0.25	255.0	255
100	12.0	0.12	0.24	327.9	330
110	12.0	0.11	0.23	414.0	415
120	12.0	0.09	0.21	539.7	540
130	12.0	0.08	0.20	665.0	665

US Customary

Design Speed (mph)	Maximum e (%)	Limiting Values of f	Total (e/100 + f)	Calculated Radius (ft)	Rounded Radius (ft)
15	4.0	0.175	0.215	70.0	70
20	4.0	0.170	0.210	127.4	125
25	4.0	0.165	0.205	203.9	205
30	4.0	0.160	0.200	301.0	300
35	4.0	0.155	0.195	420.2	420
40	4.0	0.150	0.190	563.3	565
45	4.0	0.145	0.185	732.2	730
50	4.0	0.140	0.180	929.0	930
55	4.0	0.130	0.170	1190.2	1190
60	4.0	0.120	0.160	1505.0	1505
15	6.0	0.175	0.235	64.0	65
20	6.0	0.170	0.230	116.3	115
25	6.0	0.165	0.225	185.8	185
30	6.0	0.160	0.220	273.6	275
35	6.0	0.155	0.215	381.1	380
40	6.0	0.150	0.210	509.6	510
45	6.0	0.145	0.205	660.7	660
50	6.0	0.140	0.200	836.1	835
55	6.0	0.130	0.190	1065.0	1065
60	6.0	0.120	0.180	1337.8	1340
65	6.0	0.110	0.170	1662.4	1660
70	6.0	0.100	0.160	2048.5	2050
75	6.0	0.090	0.150	2508.4	2510
80	6.0	0.080	0.140	3057.8	3060
15	8.0	0.175	0.255	59.0	60
20	8.0	0.170	0.250	107.0	105
25	8.0	0.185	0.245	170.8	170
30	8.0	0.160	0.240	250.8	250
35	8.0	0.155	0.235	348.7	350
40	8.0	0.150	0.230	465.3	465
45	8.0	0.145	0.225	502.0	500
50	8.0	0.140	0.220	760.1	760
55	8.0	0.130	0.210	963.5	965
60	8.0	0.120	0.200	1204.0	1205
65	8.0	0.110	0.190	1487.4	1485
70	8.0	0.100	0.180	1820.9	1820
75	8.0	0.090	0.170	2213.3	2215
80	8.0	0.080	0.160	2675.6	2675
15	10.0	0.175	0.275	54.7	55
20	10.0	0.170	0.270	99.1	100
25	10.0	0.165	0.265	157.8	160
30	10.0	0.160	0.280	231.5	230
35	10.0	0.155	0.255	321.3	320
40	10.0	0.150	0.250	428.1	430
45	10.0	0.145	0.245	552.9	555
50	10.0	0.140	0.240	696.8	695
55	10.0	0.130	0.230	879.7	880
60	10.0	0.120	0.220	1094.6	1095
65	10.0	0.110	0.210	1345.8	1345
70	10.0	0.100	0.200	1838.8	1840
75	10.0	0.090	0.190	1980.3	1980
80	10.0	0.080	0.180	2378.3	2380
15	12.0	0.175	0.295	51.0	50
20	12.0	0.170	0.290	92.3	90
25	12.0	0.165	0.285	146.7	145
30	12.0	0.160	0.280	215.0	215
35	12.0	0.155	0.275	298.0	300
40	12.0	0.150	0.270	396.4	395
45	12.0	0.145	0.265	511.1	510
50	12.0	0.140	0.260	643.2	845
55	12.0	0.130	0.250	809.4	810
60	12.0	0.120	0.240	1003.4	1005
65	12.0	0.110	0.230	1228.7	1230
70	12.0	0.100	0.220	1489.8	1490
75	12.0	0.090	0.210	1791.7	1790
80	12.0	0.080	0.200	2140.5	2140

Note: In recognition of safety considerations, use of e_{max} = 4.0% should be limited to urban conditions.

Superelevation

- Several factors dictate the maximum rates of superelevation: climate conditions, terrain, location (urban or rural), and frequency of very slow-moving vehicles. No single maximum superelevation rate is universally applicable.
- AASHTO recommends maximum superelevation rate of 12% for rural roadways, 8% for rural roadway for which snow or ice is present and 6% or 4% for urban streets.
- To facilitate cross-drainage, a commonly used superelevation rate is 0.12.

Relation between e and *f*

- A variety of methods are practiced in balancing *e* and *f*. One such method uses superelevation at speeds lower than the design speed.
- Average running speed, which is estimated as 80 to 100 percent of design speed, provides superelevation design where all lateral acceleration is sustained by superelevation of curves.
- For flatter curve more rate of superelevation has to be provided to counteract lateral acceleration.

Relation between e and *f* (cont'd)

- Maximum superelevation is reached near the middle of the curve.
- At average running speed, no side friction is needed up to this curvature, and side friction increases rapidly and in direct proportion for sharper curves.
- Considerable side friction is available for higher speeds.
- An alternate method for sustaining centripetal acceleration on curves is to maintain super-elevation and side friction inversely proportional to the radius of the curve.

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* is used).
- Use of sharper curvature for the given design speed would require superelevation beyond the limit considered practicable or for operation with tire friction and lateral acceleration beyond what is considered comfortable by many drivers.

Minimum Radius (cont'd)

- Although based on a threshold of driver comfort, rather than safety, the minimum radius of curvature is a significant value in alignment design.
- The minimum radius of curvature is also an important control value for determination of superelevation rates for flatter curves.
- The minimum radius of curvature, R_{min} can be calculated directly from the simplified curve formula for a given Side Friction Factor.

Minimum Radius

- The formula can be used to determine R_{min} as follows

Metric	US Customary	
$R_{\min} = \dfrac{V^2}{127(0.01e_{\max} + f_{\max})}$	$R_{\min} = \dfrac{V^2}{15(0.01e_{\max} + f_{\max})}$	(3-10)

Problem-1

- A roadway is designed for a speed of 120 km/hr. At one horizontal curve, it is known that the superelevation is 8.0% and side friction factor is 0.09. Determine the minimum radius of the curve (measured to the traveled path) that will provide safe vehicle operating.

Problem-2

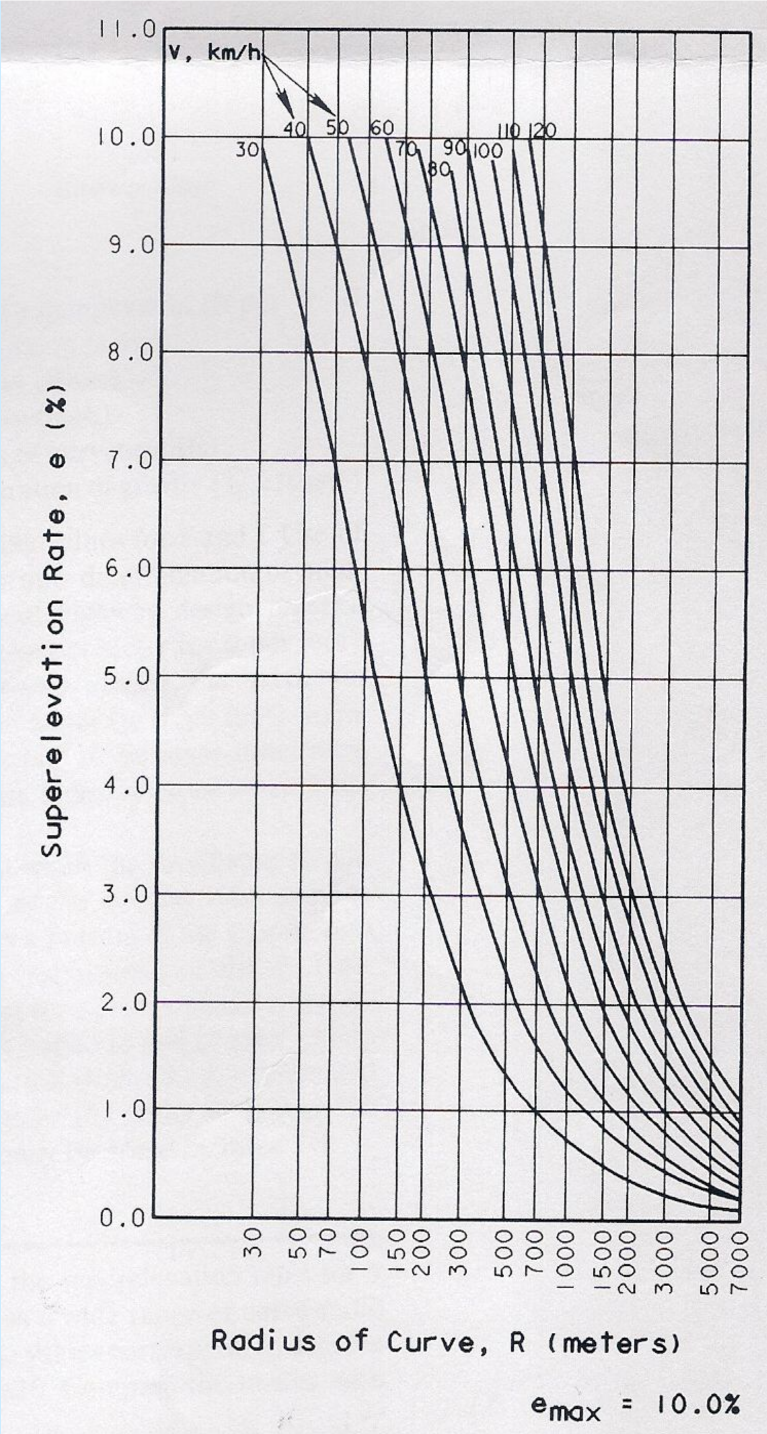
- What is the minimum radius of curvature allowable for a roadway with a 100 km/hr design speed, assuming allowable super elevation rate is 0.12. Compare this with the minimum curve radius recommended by AASHTO.
- What is the actual maximum super elevation rate allowable under AASHTO recommended standards for a 100 km/hr design speed, if the value of *f* is the maximum allowed by AASHTO for this speed.

Problem-3

- Determine a proper superelevation rate for a low volume, gravel surface road with a design speed of 50 mph and a degree of curvature of 8 degrees.

Problem-4

- Calculate the super elevation rates for a roadway with a design speed of 100 km/hr that has a wide range of curve radii; i.e R= 1750, 875, 585, 440, 350 and 295 m. These values corresponds to degrees of curve, D = 1, 2, 3, 4, 5 and 6. Use maximum super elevation rate = 0.10. Compare the results obtained from figure.
- Assuming *f is 0.12.*

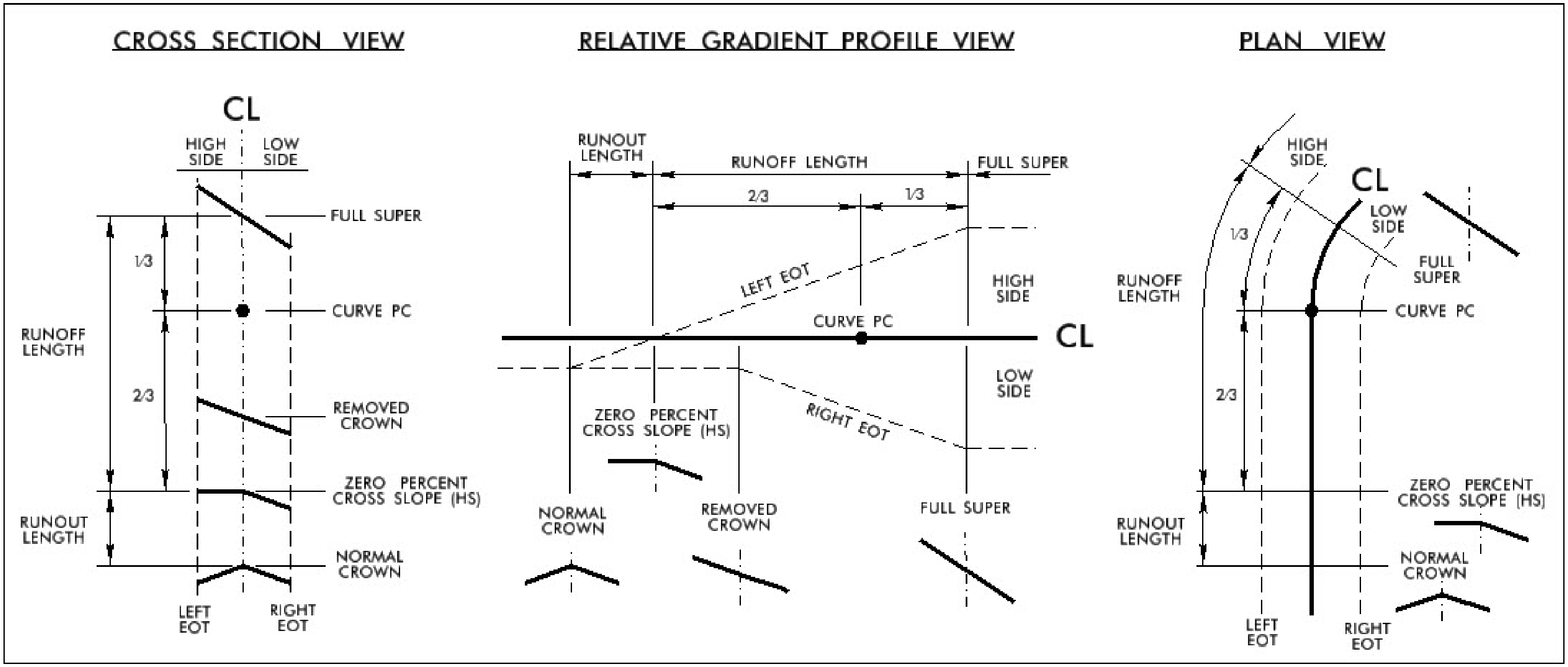


V, km/h
30
40
50
60
70
80
90
100
110
120
Superelevation Rate, e (%)
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
30
50
70
100
150
200
300
500
700
1000
1500
2000
3000
5000
7000
Radius of Curve, R (meters)
emax = 10.0%

Attainment of Superelevation

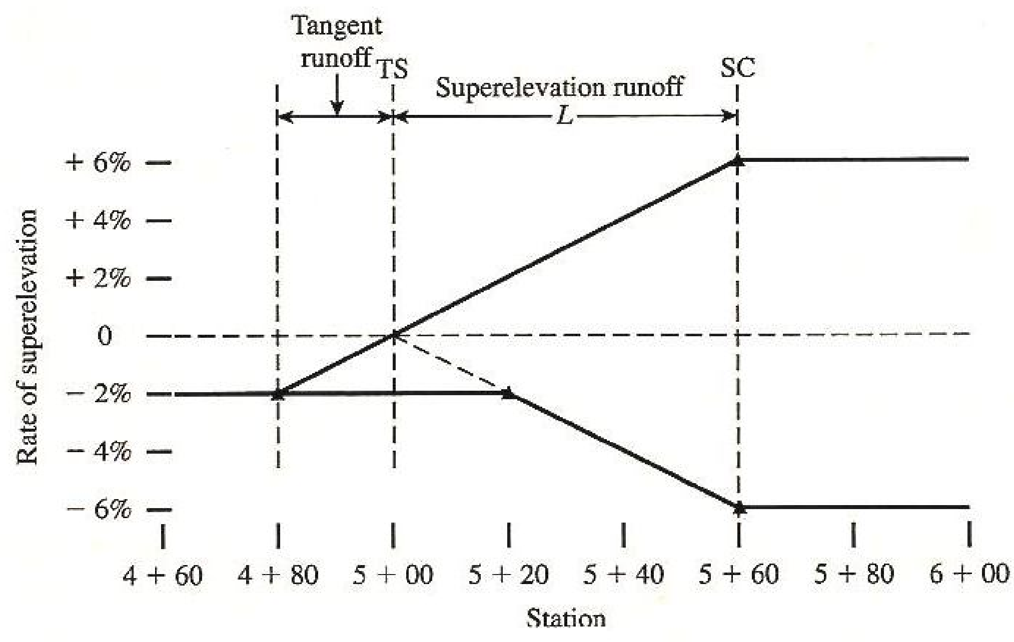
- Superelevation transitions involve modification of the roadway cross-section from normal crown to full superelevation, at which point the entire roadway width has a cross-slope of *e*.
- The manner in which this transition is accomplished is expressed by a superelevation diagram, which is a graph of superelevation (cross-slope) versus distance measured in stations.
- As an alternative, the diagram may show the difference in elevation between the profile grade and the edge versus distance.

Attainment of Superelevation



Superelevation Transition

- Figure is an example of superelevation diagram, showing the transition from normal crown with 2 percent cross-slopes to 6 percent superelevation for a roadway with a spiral transition curve.

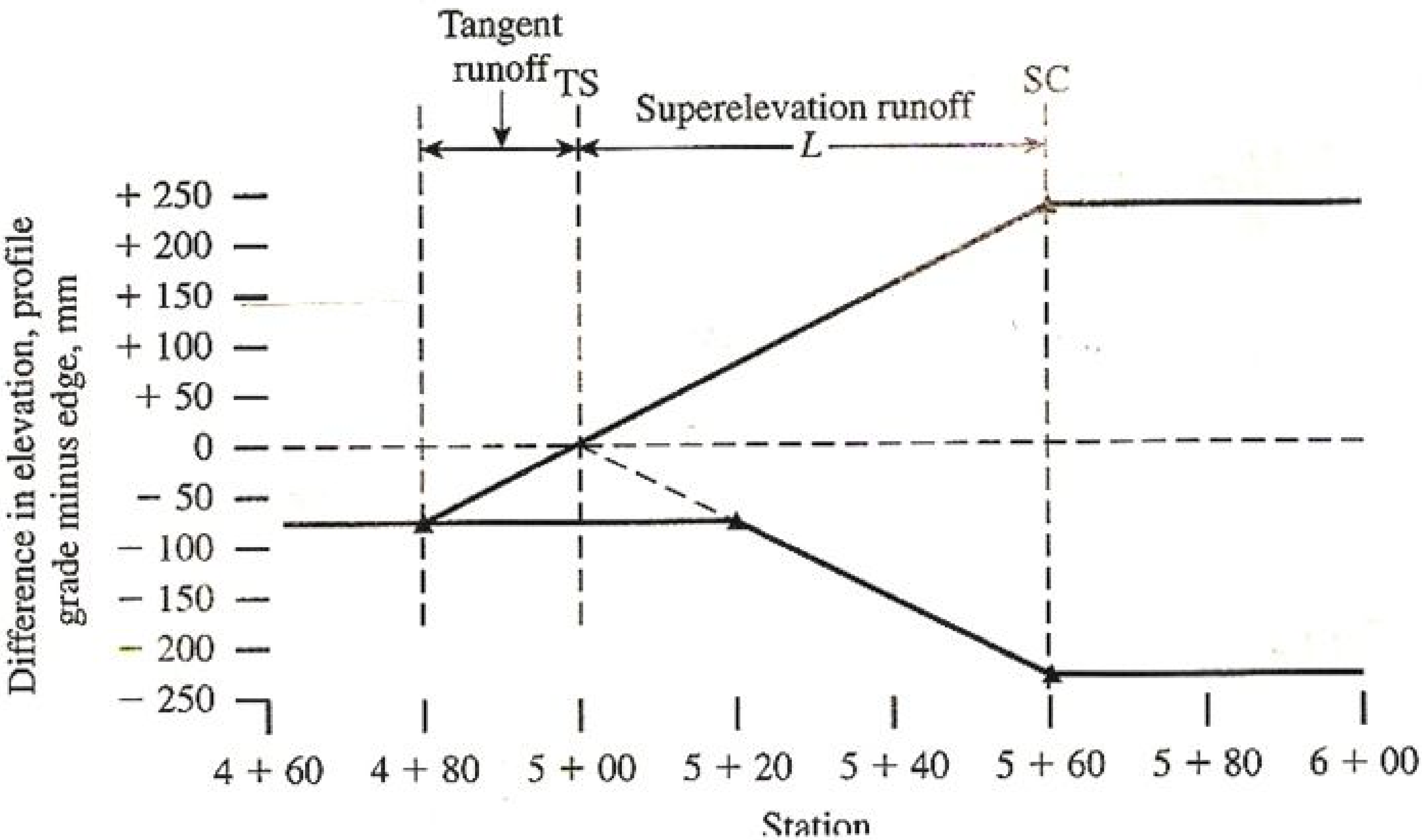


Superelevation diagram, showing rate of superelevation.

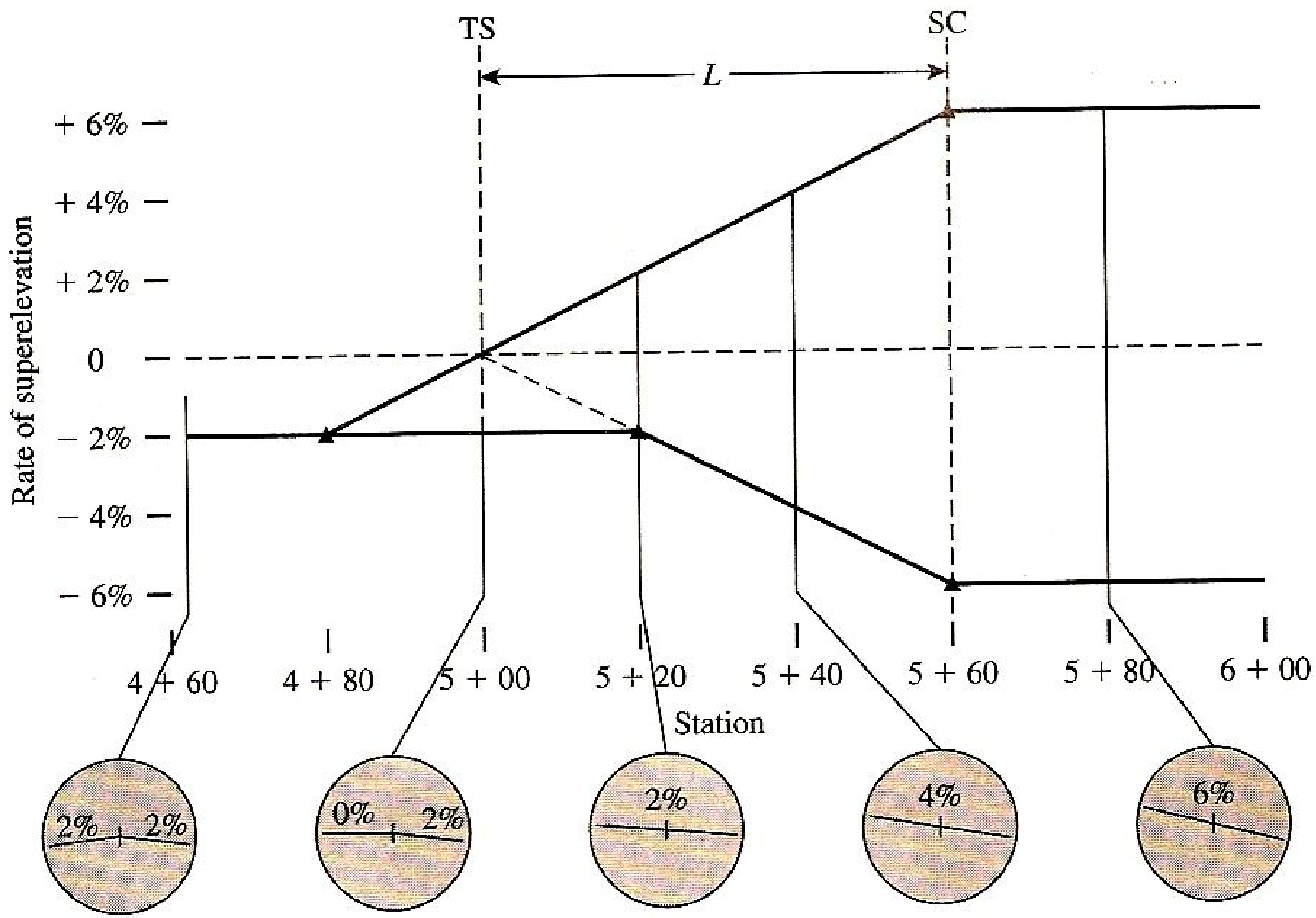
Superelevation Transition

- Figure on next slide is the alternative form of the diagram, assuming a two-lane highway with 3.6 m lanes.
- Figure "c" on next slide presents an interpretation of the superelevation diagram, showing the appearance of the cross section at intervals through the transition.

Superelevation Transition



Superelevation Transition



Superelevation Runoff

- As shown in Figure “a”, the superelevation transition is normally linear; that is, the rate of rotation of the cross section is constant with respect to distance through the transition.
- The distance marked *L*, which runs from the point at which the outside half of the roadway (that is, the half on the outside of the curve) is at zero cross-slope to the full superelevation (or from the tangent -to-spiral point TS to the spiral-to-curve point SC), is called *superelevation runoff*

Tangent Runoff

- The distance from the point at which the outside half of the roadway first begins to rotate to the TS is referred to as *tangent runoff*.

Superelevation Transition

- The superelevation transition section consists of the superelevation runoff and tangent runoff sections.
- Superelevation runoff section consists of the length of roadway needed to accomplish a change in outside-lane cross slope from zero (flat) to full superelevation, or vice versa.
- Tangent runoff section consists of the length of roadway needed to accomplish a change in outside-lane cross slope from the normal cross slope rate to zero (flat), or vice versa.

Superelevation Transition

- For reasons of safety and comfort, the pavement rotation in the superelevation transition section should be effected over a length that is sufficient to make such rotation imperceptible to drivers. To be pleasing in appearance, the pavement edges should not appear distorted to the driver.

Example

- A two lane highway goes from 2% normal crown to 6% superelevation. Sketch Superelevation diagram for the following data:

Superelevation, e = 6%

L = 60 m

B = 7 m (two lane)

Cross slopes = 2%

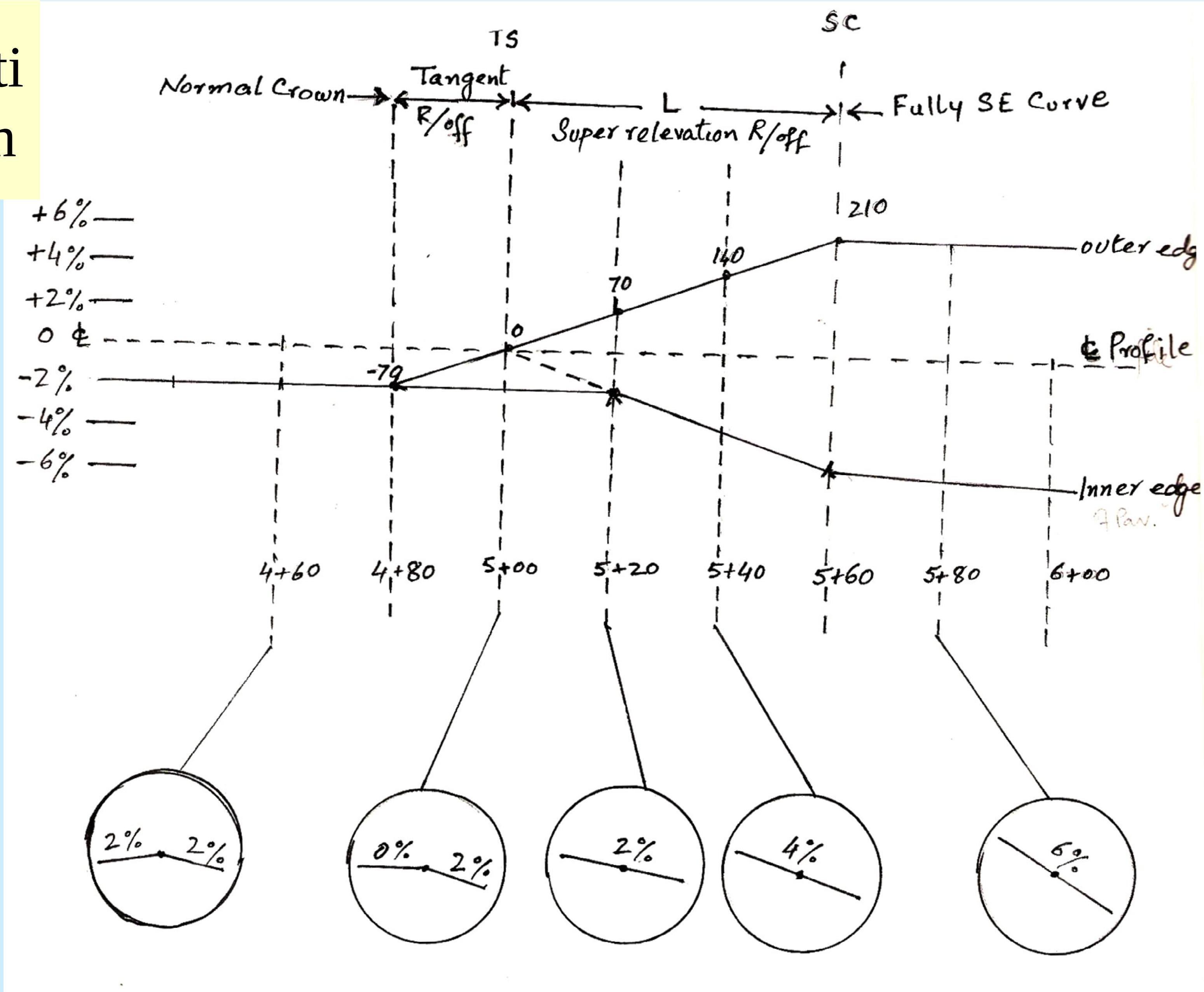
Solution

- Elevation difference between C/L and edge at TS = 0
- Elevation difference between C/L and edge at SC

  = De = (width of lane x e) = 3.5 x 0.06

  = 0.21 m = 210 mm

Superelevation Diagram



Determination of Length of Superelevation Runoff

- The length of the superelevation runoff *L* is determined by either vehicle dynamics or appearance criteria.
- More commonly, superelevation transition lengths for highways are based on appearance or comfort criteria. One such criterion is a rule that the difference in longitudinal slope (grade) between the centerline and edge of traveled way of a two-lane highway should not exceed 1/200.
- .

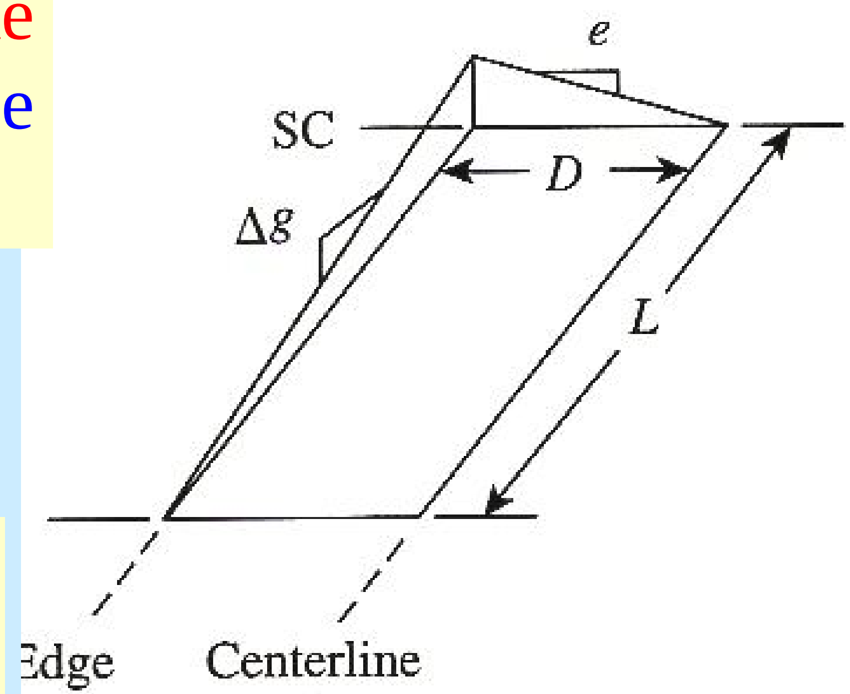
Determination of Length of Superelevation Runoff

- Figure on next slide illustrates the application of this rule. *L* is measured from the TS to the SC, as in the superelevation diagram.
- At the TS, the difference in elevation between the centerline and edge is zero.
- At the SC, it is the superelevation rate *e* times the distance *D* from the centerline to the edge.

Determination of Length of Superelevation Runoff

- Thus, the difference in grade between the centerline and the edge is

$$\Delta g = \frac{De}{L}$$



Since the criterion that the difference in grade not exceed 1/200 implies that

$$\frac{De}{L} \leq \frac{1}{200}$$

Superelevation Transition

L is given by

$$L \geq 200De$$

L is normally rounded up to some convenient length, such as a multiple of 20 m.

Superelevation Transition

- The transition from a tangent, normal crown section to a curved superelevation section must be accomplished without any appreciable reduction in speed and in such a manner as to ensure safety and comfort to the occupants of the traveling vehicle.
- In order to effect this change, the normal crown road section will have to be tilted or banked as a whole to provide superelevation cross section required for a given design speed.

Attainment of Superelevation

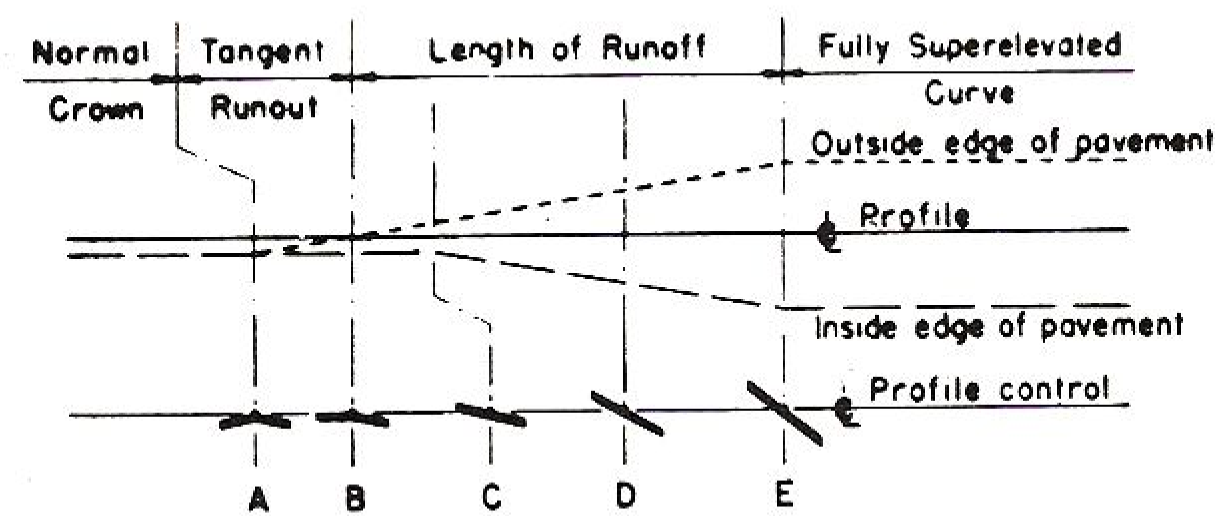
- This attainment of superelevation is accomplished by the following methods
  - Rotate about the centerline of the pavement
  - Rotate about the inner edge of the pavement
  - Rotation about the outside edge of the pavement

Rotation about centerline Axis

- The effect of this rotation is to lower the inside edge of pavement and, at the same time, to raise the outside edge without changing the centerline grade. Rotation about the centerline is most widely used because the change in elevation of edge of the pavement is made with less distortion than other methods.
- However, for flat grades too much sag is created in the ditch grades by this method.

Rotation about centerline Axis

- Used for highways with narrow medians and moderate superelevation rates. Since large difference in elevation can occur between extreme pavement edges if median is wide.



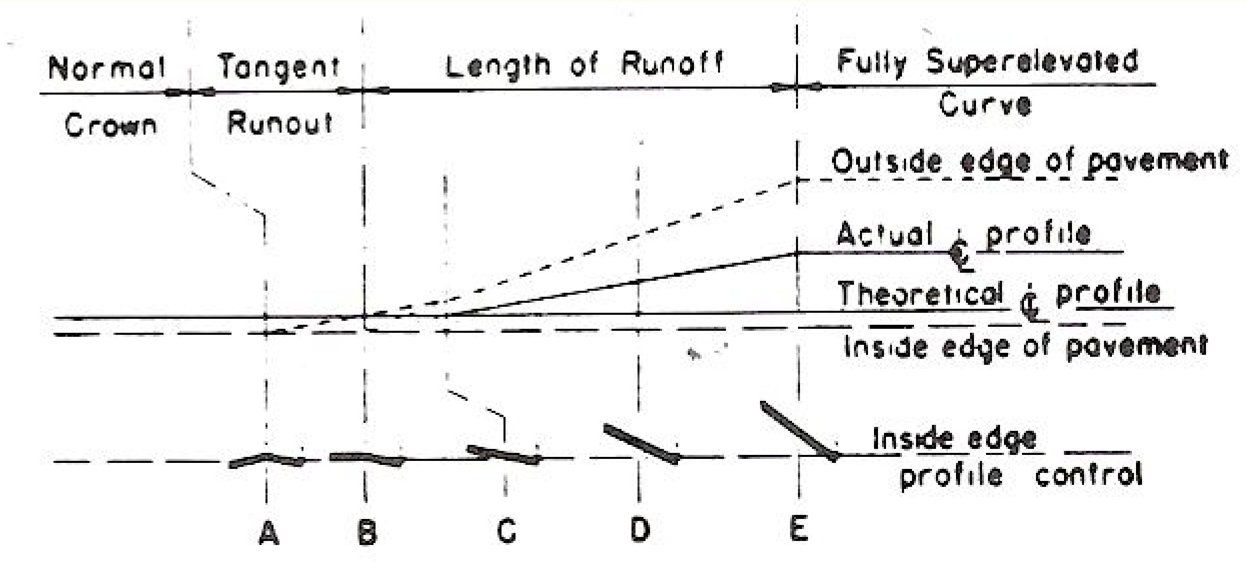
A - PAVEMENT REVOLVED ABOUT CENTER LINE

Rotation about inner edge of the pavement

- Rotate about the inner edge of the pavement as an axis so that the inner edge retains its normal grade but the centerline grade is varied, or rotation may be likewise about the outside edge.
- Half of the required change in cross slope is made by raising center line profile with respect to inner edge and other half by raising out side pavement edge with respect to to the actual center line profile.

Rotation about inner edge of the pavement

- On grades below 2 percent, rotation about the inside edge is preferred.
- Used for pavements with median width 30 ft. or less.

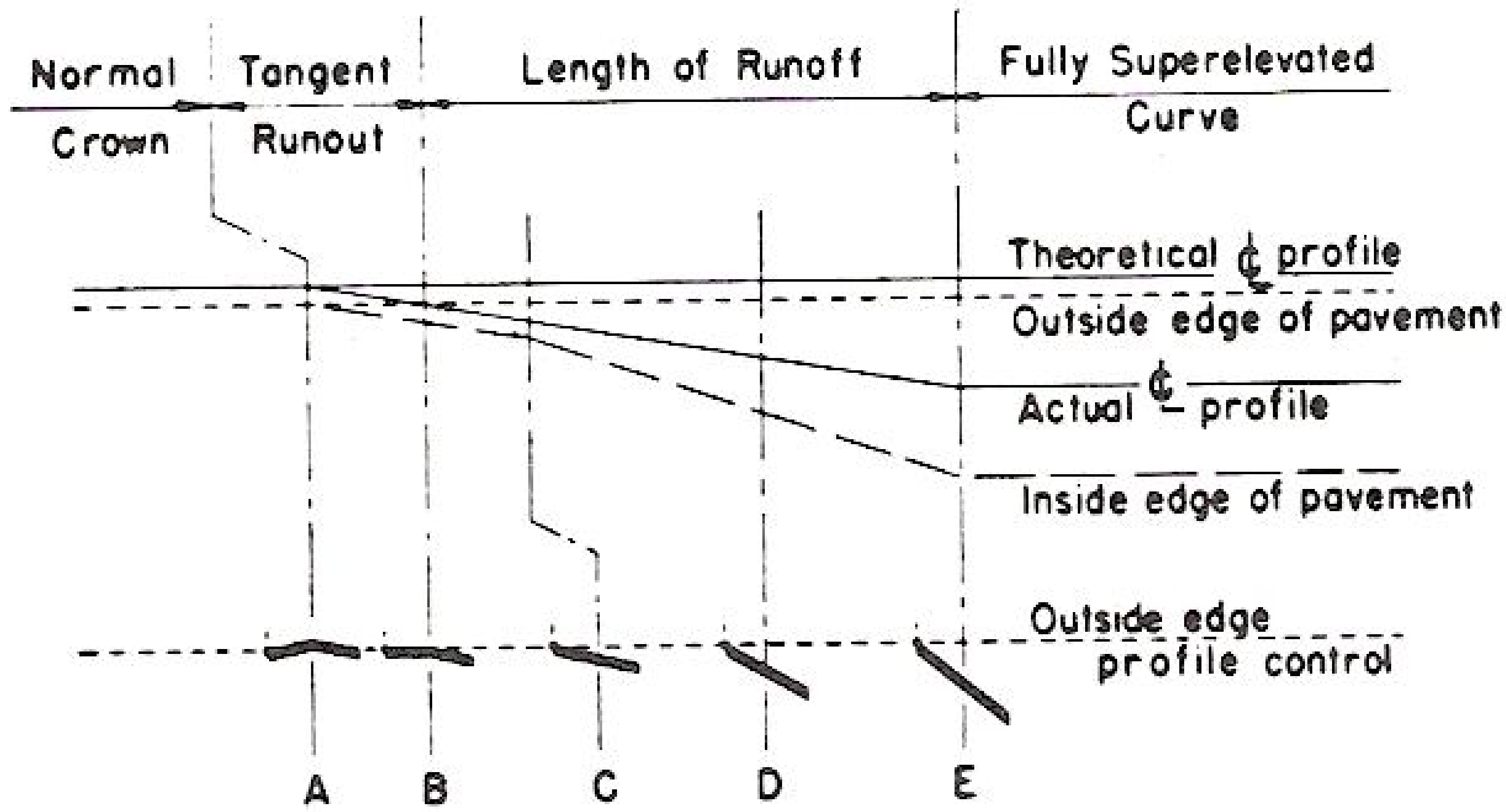


B - PAVEMENT REVOLVED ABOUT INSIDE EDGE

Rotation about outside edge of the pavement

- Same geometry as rotation about the inner edge of the pavement except that the elevation change is accomplished below the outside edge profile instead of about the inside edge profile.
- Used for pavements with median width 40 ft. or greater.

Rotation about outside edge of the pavement

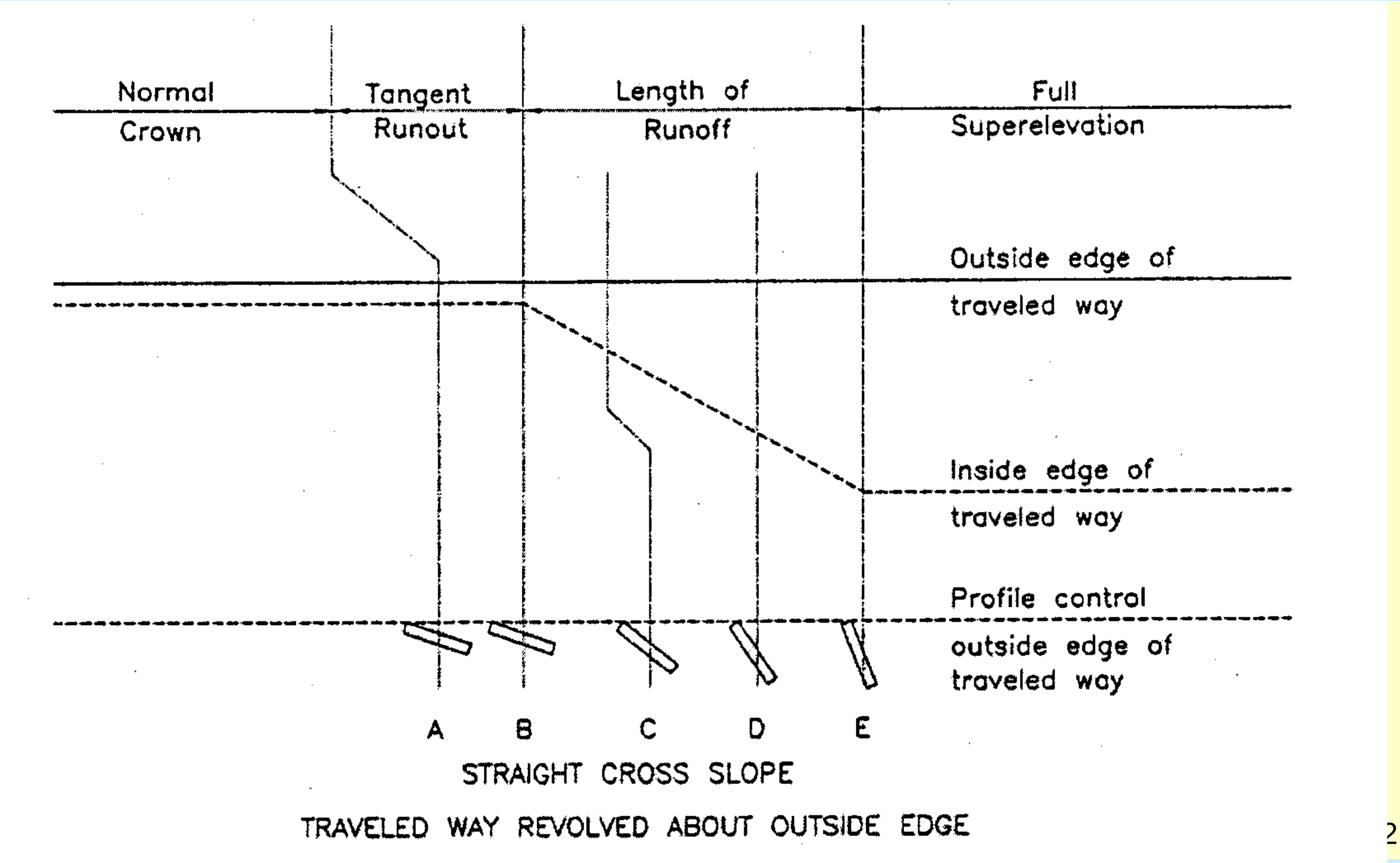


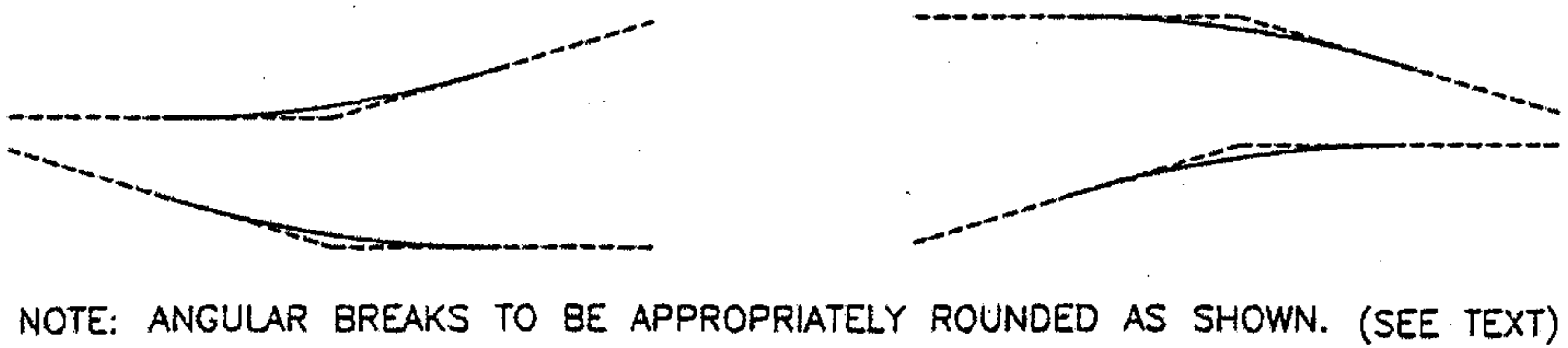
C-PAVEMENT REVOLVED ABOUT OUTSIDE EDGE

Rotation about outside edge of the pavement

- Revolves the traveled way about the outside edge profile.
- In this case, section is not crowned.
- This method is often used for two-lane one way road where the axis of rotation coincides with the edge of the road adjacent to the highway median.

Rotation about outside edge of the pavement





Axis of Rotation for undivided highways

General Consideration for Attainment of Superelevation

- Regardless of which method is utilized, care should be exercised to provide for drainage in ditch sections and adjacent gutters all along the length in superelevated areas.
- The roadway on full SE sections should be a uniform inclined section perpendicular to the direction of travel.
- When a crowned surface is rotated to the desired SE, the change from a crowned section to a uniformly inclined section would be accomplished gradually at a consistent rate along a length measured along the centerline.