Highway Geometric Design

WAVE

WORKFORCE FOR AUTONOMOUS VEHICLE ENGINEERING

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Learning Objectives

1. **Describe** the role of highway geometric design in providing safe and efficient roadways.
2. **Identify** the main components of roadway alignment: horizontal, vertical, and cross-sectional.
3. **Interpret** stationing notation to locate points along a roadway alignment.
4. **Recognize** key terminology and geometry of vertical curves, including PVC, PVI, and PVT.
5. **Explain** the concept of stopping sight distance and how it differs for crest and sag curves.
6. **Identify** common horizontal curve types and their basic geometric elements.

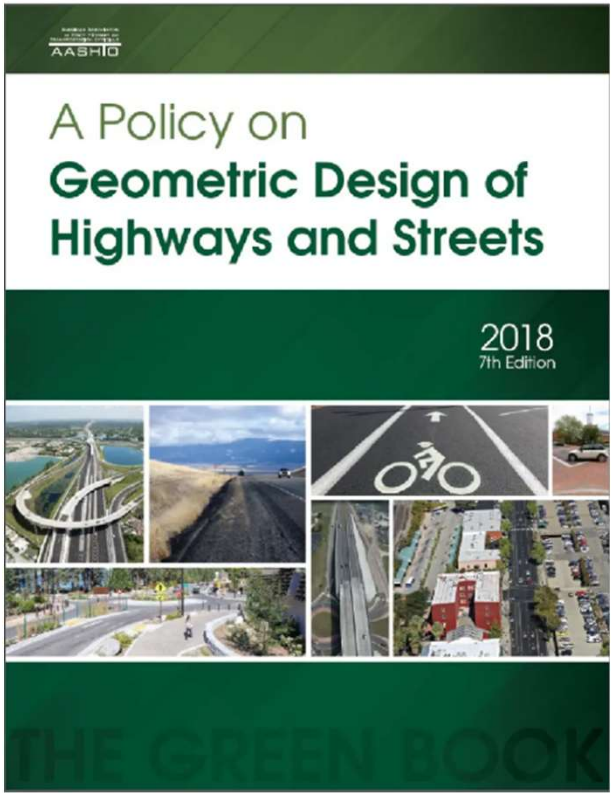
Introduction

- Geometric Design Philosophy:
  - **Safety and Efficiency**
  - Safe roadway features that provide adequate **Stopping Sight Distance** and/or **Passing Sight Distance**

- Geometric Design is based on the following factors:
  - The design **driver**
  - The design **vehicle**
  - The design **environment**

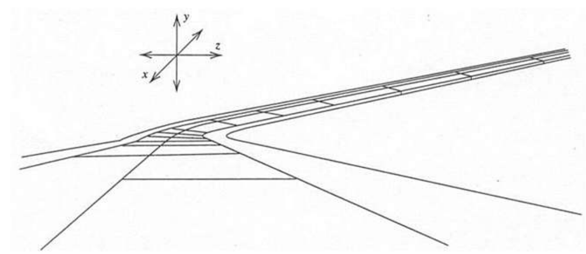
Introduction

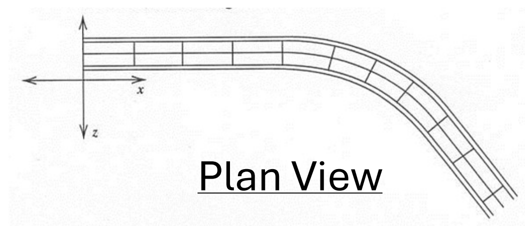
- Current guidelines for highway design are presented in detail in **A Policy on Geometric Design of Highways and Streets**
  - Published by the American Association of State Highway and Transportation Officials (AASHTO)
  - Commonly known as "**The Green Book**"



Principles of Roadway Alignment

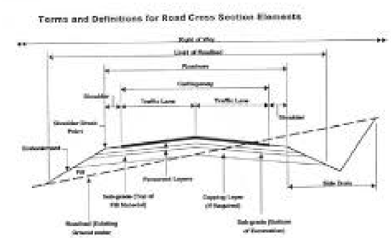
- Alignment of a roadway is a three-dimensional (3-D) problem
- In practice, the design of a roadway is broken down into each of the separate dimensions:
  - Plan View: **Horizontal Alignment**
  - Profile View: **Vertical Alignment**
  - **Cross-Sectional** View





Plan View

Profile View

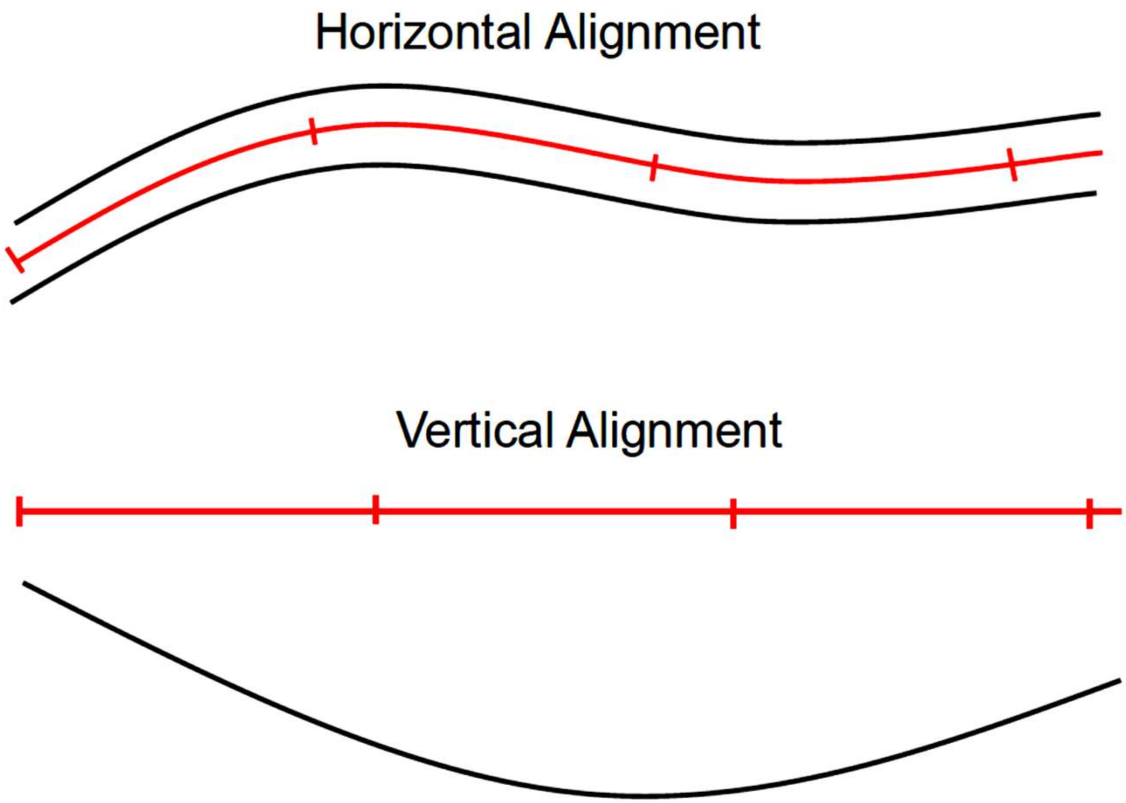


Cross-Section

Principles of Roadway Alignment

- **Stationing**
  - To locate an alignment (Horizontal or Vertical)
- In **U.S. customary** units, each station consists of 100 ft. of horizontal distance:
  - Origin station denoted as 0 + 00.00
  - A point 685.3 ft. from the origin would be at station 6 + 85.30 (six stations and 85.3 ft.)
- In **metric** units, each station consists of 1000 m of horizontal distance:
  - Origin station denoted as 0 + 000.000
  - A point 2213.5 m from the origin would be at station 2 + 213.500 (two stations and 213.5 m)

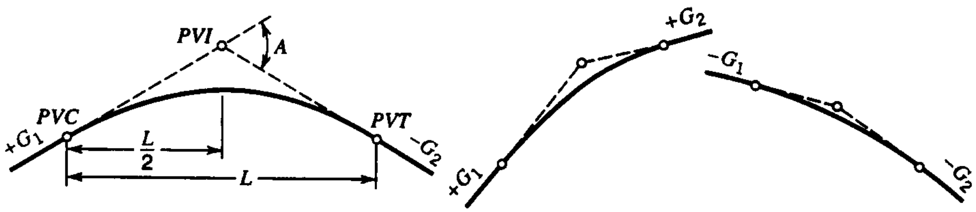
Principles of Roadway Alignment



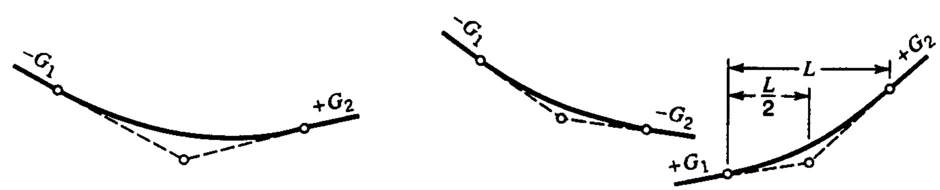
Vertical Alignment

Notation

- Curve Points
  - PVC: Point of Vertical Curvature (beginning of curve)
  - PVI: Point of Vertical Intersection (intersection of tangents)
  - PVT: Point of Vertical Tangent (ending point of curve)



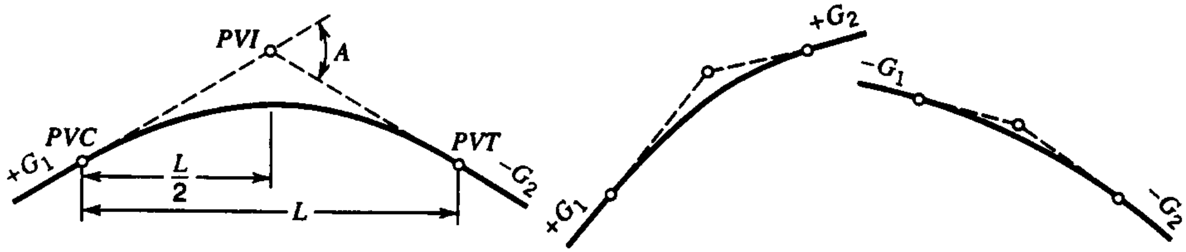
Crest Vertical Curves



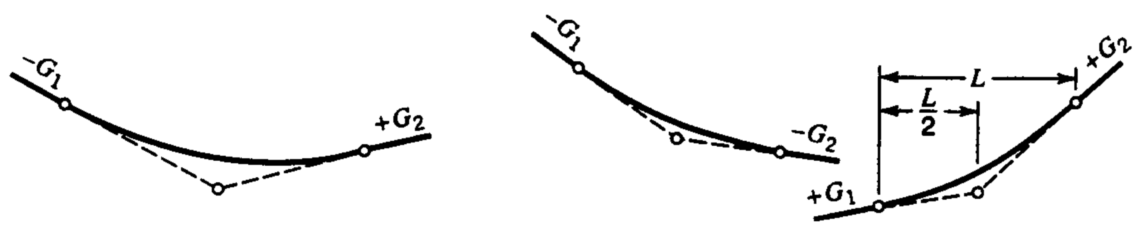
Sag Vertical Curves

Terminology

- Sag vs. Crest Vertical Curves



Crest Vertical Curves



Sag Vertical Curves

Vertical Curve Equations

- Elevations along a **Vertical Curve** is generally given by a **Parabolic** Curve.
  - Parabolic function → $\boldsymbol{y = ax^2 + bx + c}$
  - where y is the elevation of a point on the curve from the PVC and x is a horizontal distance from the PVC.

y = roadway elevation
x = distance from PVC
c = elevation of PVC

$$a = \frac{(G_2 - G_1)}{2L}$$

$$b = \frac{dy}{dx} = G_1$$

$$c = \text{PVC elevation}$$

- Equal Tangent Vertical Curves
  - PVI is always L/2 from PVC

Stopping Sight Distance (SSD)

- It is necessary, when designing vertical curves, to provide adequate **Stopping Sight Distance (SSD)**

- curve construction is expensive, we want to minimize curve length, subject to adequate SSD

- The **minimum stopping distance** is the distance required to bring a vehicle traveling at a give speed to a stop after an object on the road becomes visible.

Stopping Sight Distance (SSD)

- Stopping Sight Distance is a function of distance travelled during perception/reaction time and distance travelled to bring the vehicle to a stop.

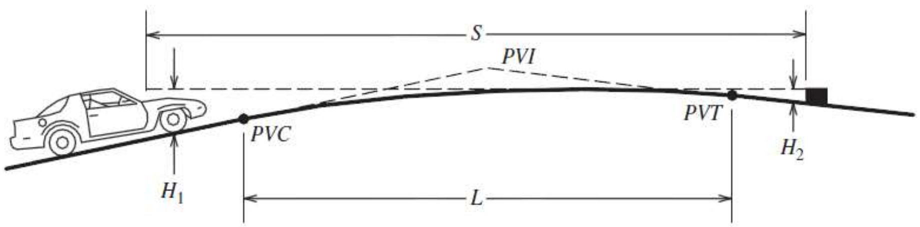
$$SSD = \frac{V_1^{\,2}}{2g\left(\frac{a}{g} \pm G\right)} + V_1 t_r$$

where

SSD is the stopping sight distance in feet.
V_1 is the initial vehicle speed in ft/s.
g is gravitational constant, 32.2 ft/s^2.
a is deceleration in ft/s^2. (**Assume 11.2 ft/s^2**).
G is roadway grade (+ uphill, – downhill) in decimals (% / 100)
t_r is driver perception/reaction time in sec (**Assume 2.5 sec.**)
[1.0 sec if expected; 2.5 sec if unexpected]

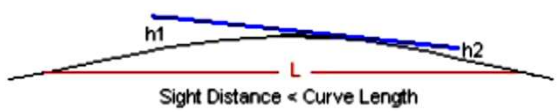
SSD on Crest Curves

- The curve length is critical to proving ample stopping distance to avoid hitting an object.



– **Sight distance (S)**
– Driver's eyes (H_1)
– Height of an object (H_2)
– Equal tangent curve (use parabola properties)

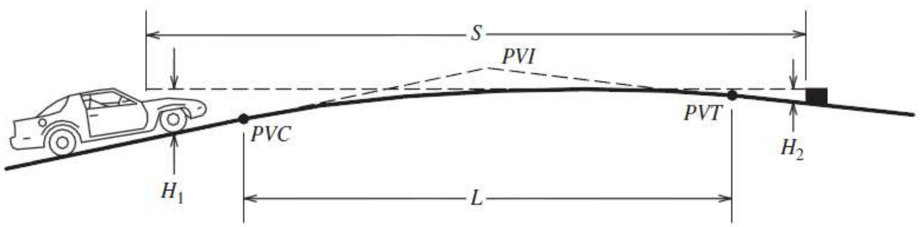
- If S < L (you can't see the end of the curve):



$$L_m = \frac{A \times SSD^2}{200\left(\sqrt{H_1} + \sqrt{H_2}\right)^2}$$

SSD on Crest Curves

- The curve length is critical to proving ample stopping distance to avoid hitting an object.



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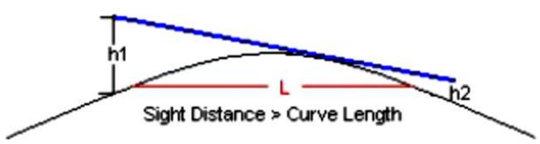
- If S > L (you can see the end of the curve):



$$L_m = 2 \times SSD - \frac{200\left(\sqrt{H_1} + \sqrt{H_2}\right)^2}{A}$$

SSD on Crest Curves

- AASHTO Guideline
  - Sight distance (S = SSD)
  - Driver's eyes (H_1= 3.5 ft)
  - Height of an object (H_2= 2.0 ft)
  - Equal tangent curve (use parabola properties)
  - A= $|G_1 – G_2|$

For SSD < L

$$L_m = \frac{A \times \text{SSD}^2}{2158}$$

For SSD > L

$$L_m = 2 \times \text{SSD} - \frac{2158}{A}$$

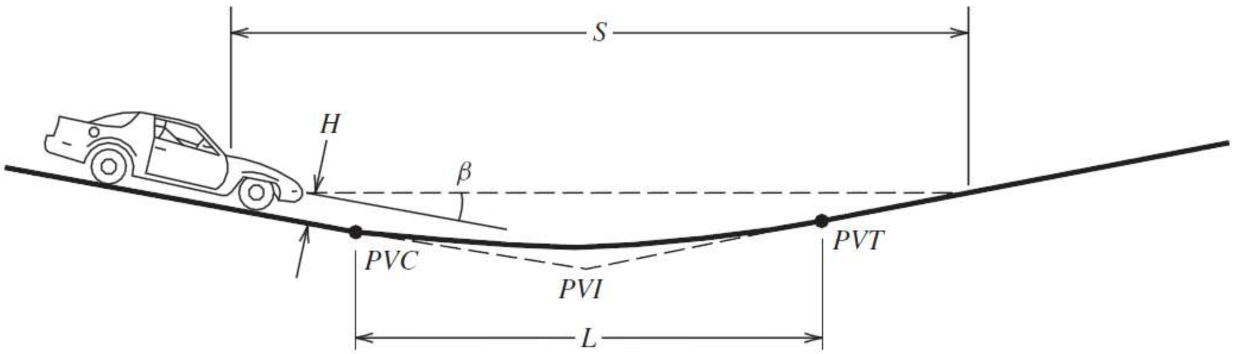
SSD on Sag Curves

- Since SSD is unrestricted on sag curves during daylight hours, **nighttime conditions** govern design.

- Thus, the critical concern for sag curves is the **headlight sight distance** (i.e., the length of road illuminated by the vehicle's headlights).

- Which is a function of the **height of the headlight** above the roadway, H, and the **inclined upward angle of the headlight beam**, relative to the horizontal plane of the car, β

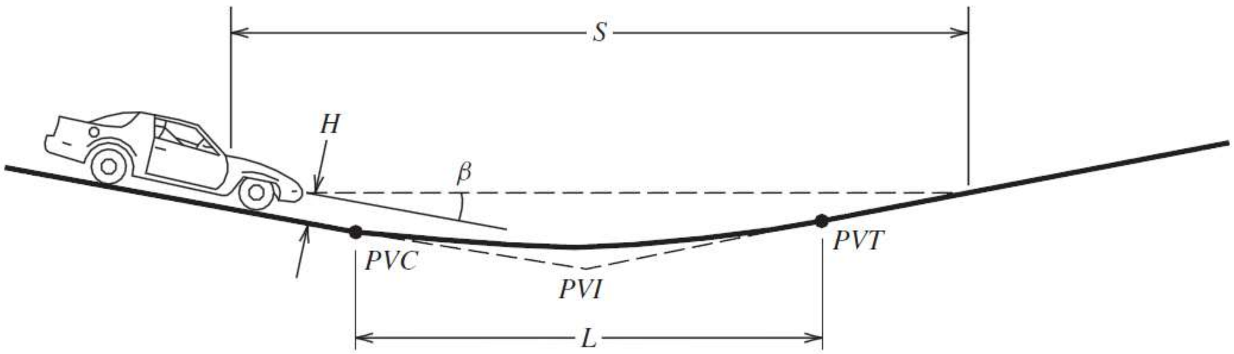
SSD on Sag Curves



- If S < L (you can't see the end of the curve):

$$L_m = \frac{A \times SSD^2}{200\left(H + SSD \tan \beta\right)}$$

SSD on Sag Curves



- If S > L (you can see the end of the curve):

$$L_m = 2 \times SSD - \frac{200(H + SSD\tan\beta)}{A}$$

SSD on Sag Curves

- AASHTO Guideline
  - Assuming a headlight height (H= 2.0 ft) and an upward headlight angle(β= 1°)
  - SSD = S

$$\text{SSD} < L$$

$$L_m = \frac{A \times \text{SSD}^2}{400 + 3.5 \times \text{SSD}}$$

$$\text{SSD} > L$$

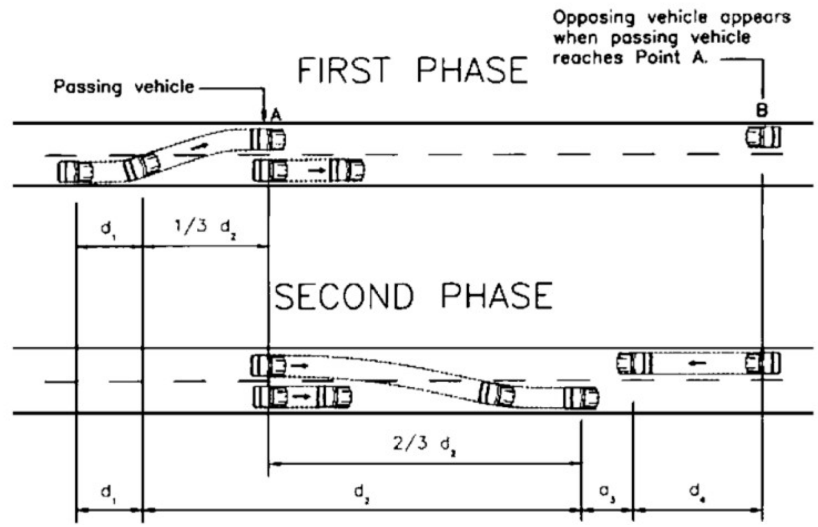
$$L_m = 2 \times \text{SSD} - \frac{400 + 3.5 \times \text{SSD}}{A}$$

Passing Sight Distance (PSD)

- Passing sight distance is important in 2-lane highway design
- Sight distance required for passing is generally much longer than required for stopping
- Assumptions
  - Constant speeds
  - Passing veh. speed > 10 mph from vehicle passing
  - H_2= 3.5 ft.

Passing Sight Distance (PSD)

- d_1: The distance the passing vehicle travels while contemplating the passing maneuver, and while accelerating to the point of encroachment on the left lane.
- d_2:The length of roadway that is traversed by the passing vehicle while it occupies the left lane.
- d_3:The clearance distance between the passing vehicle and the opposing vehicle when the passing vehicle returns to the right lane.
- d_4:The distance that the opposing vehicle travels during the final 2/3 of the period when the passing vehicle is in the left lane.



For PSD $< L$

$$L_m = \frac{A \times \text{PSD}^2}{2800}$$

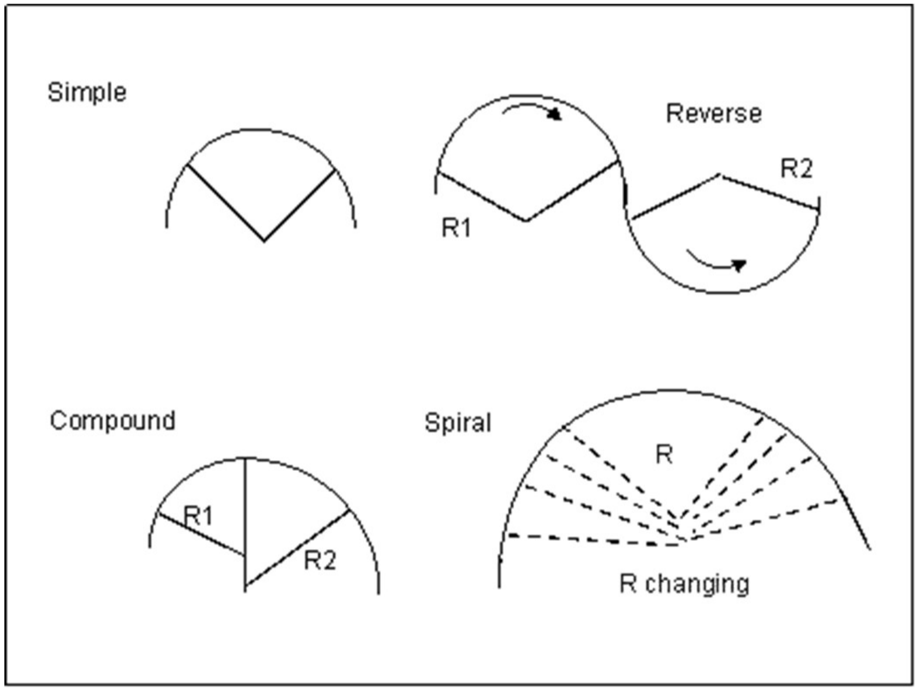
For PSD $> L$

$$L_m = 2 \times \text{PSD} - \frac{2800}{A}$$

Horizontal Alignment

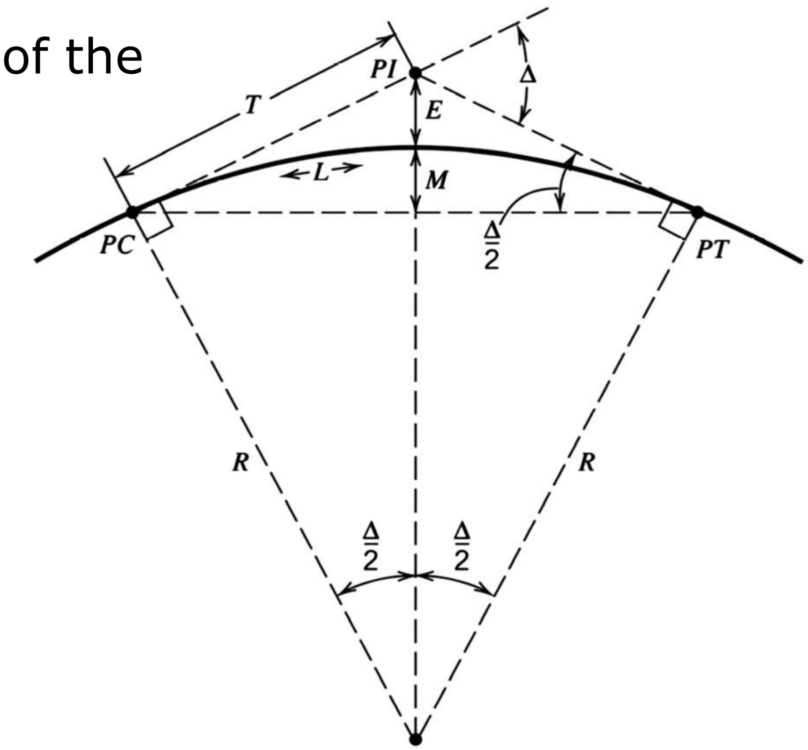
Curve Options

- Types of horizontal curves
  - **Simple circular curve**
  - Reverse curves
  - Compound curves
  - Spiral curves



Simple Circular Curve

R = radius, usually measured to the centerline of the road, in ft (m),
Δ = central angle of the curve in degrees,
PC = point of curve (the beginning point of the horizontal curve),
PI = point of tangent intersection,
PT = point of tangent (the ending point of the horizontal curve),
T = tangent length in ft (m),
M = middle ordinate in ft (m),
E = external distance in ft (m), and
L = length of curve in ft (m).



Simple Circular Curve

$$D = \frac{100\left(\frac{180}{\pi}\right)}{R} = \frac{18000}{\pi R}$$

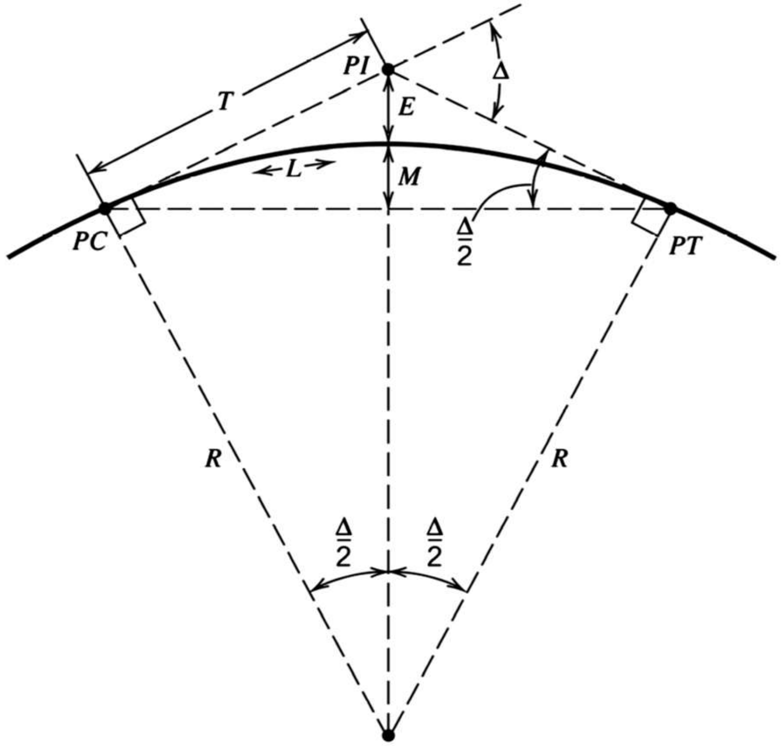
$$T = R\tan\frac{\Delta}{2}$$

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

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

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

<u>Degree of curve</u>: Angle subtended by a 100-ft arc along the horizontal curve.



Horizontal Curves

- **Vehicle cornering** capability is thus a key concern in horizontal curve design

R_v = radius defined to the vehicle's traveled path in ft (m),

α = angle of incline in degrees,

e = number of vertical ft (m) of rise per 100 ft (m) of horizontal distance,

W = weight of the vehicle in lb (N),

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

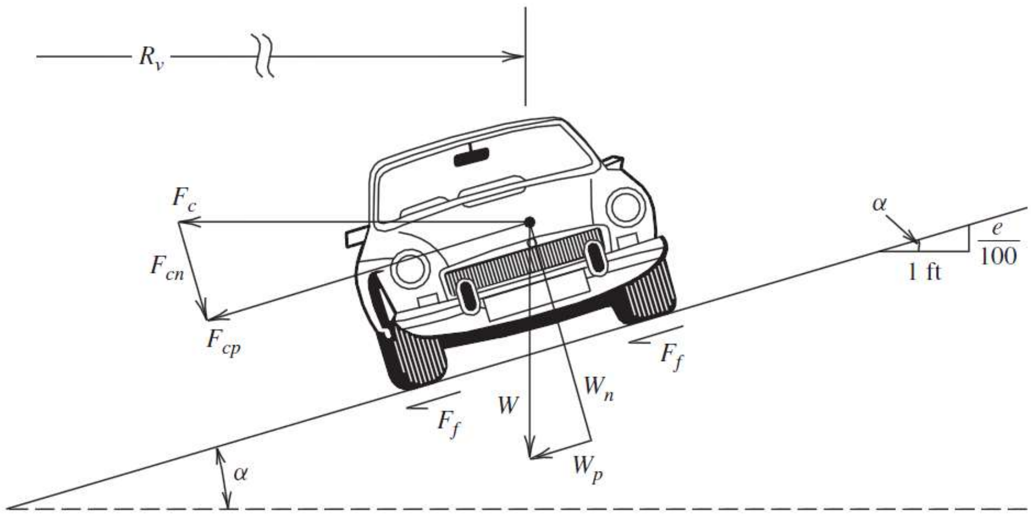
W_p = vehicle weight parallel to the roadway surface in lb (N),

F_f = side frictional force (centripetal, in lb (N)),

F_c = centripetal force (lateral acceleration x mass, in lb (N)),

F_{cp} = centripetal force acting parallel to the roadway surface in lb (N), and

F_{cn} = centripetal force acting normal to the roadway surface in lb (N).



Minimum Radius

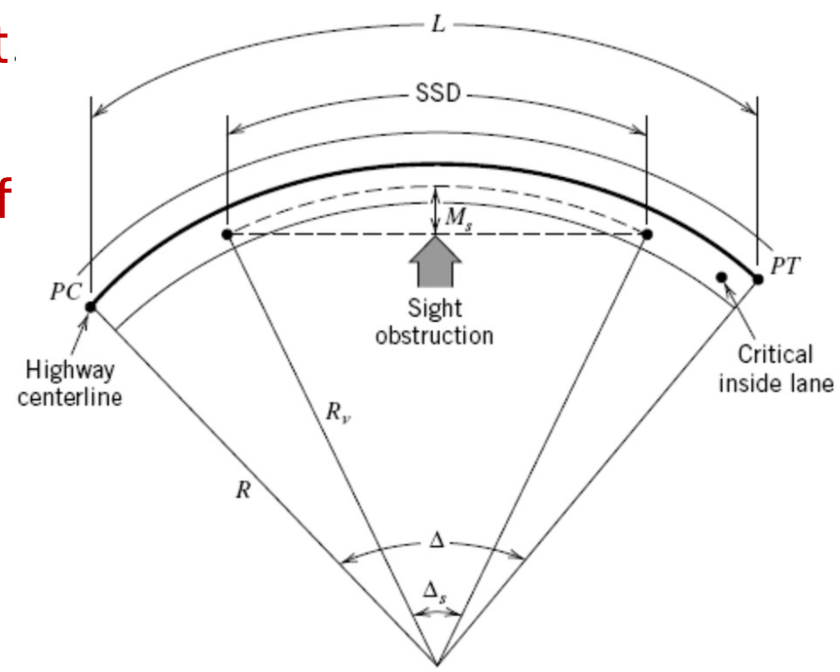
$$R_v = \frac{V^2}{g(f_s + \frac{e}{100})}$$

Table 3.5 Minimum Radius Using Limiting Values of e and f_s

Design speed (mi/h)	Maximum e (%)	Limiting values of f_s	Total $(e/100+f_s)$	Calculated radius, R_v (ft)	Rounded radius, R_v (ft)
10	4.0	0.38	0.42	15.9	16
15	4.0	0.32	0.36	41.7	42
20	4.0	0.27	0.32	86.0	86
25	4.0	0.23	0.27	154.3	154
30	4.0	0.20	0.24	250.0	250
35	4.0	0.18	0.22	371.2	371
40	4.0	0.16	0.20	533.3	533
45	4.0	0.15	0.19	710.5	711
50	4.0	0.14	0.18	925.9	926
55	4.0	0.13	0.17	1186.3	1190
60	4.0	0.12	0.16	1500.0	1500
10	6.0	0.38	0.44	15.2	15
15	6.0	0.32	0.38	39.5	39
20	6.0	0.27	0.33	80.8	81
25	6.0	0.23	0.29	143.7	144
30	6.0	0.20	0.26	230.8	231
35	6.0	0.18	0.24	340.3	340
40	6.0	0.16	0.22	484.8	485
45	6.0	0.15	0.21	642.9	643
50	6.0	0.14	0.20	833.3	833
55	6.0	0.13	0.19	1061.4	1060
60	6.0	0.12	0.18	1333.3	1330
65	6.0	0.11	0.17	1656.9	1660
70	6.0	0.10	0.16	2041.7	2040
75	6.0	0.09	0.15	2500.0	2500
80	6.0	0.08	0.14	3047.6	3050
10	8.0	0.38	0.46	14.5	14
15	8.0	0.32	0.40	37.5	38
20	8.0	0.27	0.35	76.2	76
25	8.0	0.23	0.31	134.4	134
30	8.0	0.20	0.28	214.3	214
35	8.0	0.18	0.26	314.1	314
40	8.0	0.16	0.24	444.4	444
45	8.0	0.15	0.23	587.0	587
50	8.0	0.14	0.22	757.6	758
55	8.0	0.13	0.21	960.3	960
60	8.0	0.12	0.20	1200.0	1200
65	8.0	0.11	0.19	1482.5	1480
70	8.0	0.10	0.18	1814.8	1810
75	8.0	0.09	0.17	2205.9	2210
80	8.0	0.08	0.16	2666.7	2670
10	10.0	0.38	0.48	13.9	14
15	10.0	0.32	0.42	35.7	36
20	10.0	0.27	0.37	72.1	72
25	10.0	0.23	0.33	126.3	126
30	10.0	0.20	0.30	200.0	200
35	10.0	0.18	0.28	291.7	292
40	10.0	0.16	0.26	410.3	410
45	10.0	0.15	0.25	540.0	540
50	10.0	0.14	0.24	694.4	694
55	10.0	0.13	0.23	876.8	877
60	10.0	0.12	0.22	1090.9	1090
65	10.0	0.11	0.21	1341.3	1340
70	10.0	0.10	0.20	1633.3	1630
75	10.0	0.09	0.19	1973.7	1970
80	10.0	0.08	0.18	2370.4	2370
10	12.0	0.38	0.50	13.3	13
15	12.0	0.32	0.44	34.1	34
20	12.0	0.27	0.39	68.4	68
25	12.0	0.23	0.35	119.0	119
30	12.0	0.20	0.32	187.5	188
35	12.0	0.18	0.30	272.2	272
40	12.0	0.16	0.28	381.0	381
45	12.0	0.15	0.27	500.0	500
50	12.0	0.14	0.26	641.0	641
55	12.0	0.13	0.25	806.7	807
60	12.0	0.12	0.24	1000.00	1000
65	12.0	0.11	0.23	1224.6	1220
70	12.0	0.10	0.22	1484.8	1480
75	12.0	0.09	0.21	1785.7	1790
80	12.0	0.08	0.20	2133.3	2130

Stopping Sight Distance (SSD)

- Sight distance restrictions on horizontal curves occur when obstructions are present.
- When obstruction exists, SSD is measured along the horizontal curve from the center of the traveled lane (the assumed location of the driver's eyes).
- for a specified stopping distance, some distance, M_s (the middle ordinate of a curve that has an arc length equal to the stopping sight distance), must be visually cleared so that the line of sight is such that sufficient SSD is available.



Stopping Sight Distance (SSD)

$$\text{SSD} = \frac{\pi}{180} R_v \Delta_s \qquad \rightarrow \qquad \Delta_s = \frac{180 \times \text{SSD}}{\pi R_v}$$

Substituting into the general equation for the middle ordinate of simple horizontal curve (Eq. 3.38) gives

$$M_s = R_v \left(1 - \cos \frac{90 \times \text{SSD}}{\pi \text{R}_\text{v}} \right)$$

Solving the above equation for SSD gives

$$\text{SSD} = \frac{\pi \text{R}_\text{v}}{90} \left[\cos^{-1} \left(\frac{R_v - M_s}{R_v} \right) \right]$$

References

- Mannering, F., and S. Washburn (2020). Principles of Highway Engineering and Traffic Analysis, Seventh Edition, John Wiley & Sons

- American Association of State Highway and Transportation Officials (AASHTO). (2018). A Policy on Geometric Design of Highways and Streets (7th ed.). Washington, D.C.: AASHTO