Chapter 3:
Highway Geometric Design
Horizontal Alignment

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INTRODUCTION
- The design of highways necessitates the determination of specific design elements, which include:
  - the number of lanes,
  - lane width,
  - median type (if any) and width,
  - length of acceleration and deceleration lanes for on- and off-ramps,
  - need for truck climbing lanes for steep grades, curve radii required for vehicle turning, and
  - the alignment required to provide adequate stopping and passing sight distances.
INTRODUCTION

Many of these design elements are influenced by the performance characteristics of vehicles. For example, vehicle acceleration and deceleration characteristics have a direct impact on

- the design of acceleration and deceleration lanes (the length needed to provide a safe and orderly flow of traffic) and
- the highway alignment needed to provide adequate passing and stopping sight distances.

Furthermore, vehicle performance characteristics determine the need for truck climbing lanes on steep grades (where the poor performance of large trucks necessitates a separate lane) as well as the number of lanes required because the observed spacing between vehicles in traffic is directly related to vehicle performance characteristics.

In addition, the physical dimensions of vehicles affect a number of design elements, such as

- the radii required for low-speed turning,
- height of highway overpasses, and
- lane widths.

When one considers the diversity of vehicles' performance and physical dimensions, and the interaction of these characteristics with the many elements constituting highway design, it is clear that proper design is a complex procedure that requires numerous compromises. Moreover, it is important that design guidelines evolve over time in response to changes...

Current guidelines of 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 2001].

This course focuses exclusively on the key elements of highway alignment, which are arguably the most important components of geometric design. As will be shown, the alignment topic is particularly well suited for demonstrating the effect of vehicle performance (specifically braking performance) and vehicle dimensions (such as driver's eye height, headlight height, and taillight height) on the design of highways.

By concentrating on the specifics of the highway alignment problem, the students will develop an understanding of the procedures and compromises inherent in the design of all highway-related geometric elements.
The alignment of a highway is a three-dimensional problem measured in x, y, and z coordinates. This is illustrated, from a driver’s perspective, in Fig. 3.1.

- The actual implementation and construction of a design based on three-dimensional coordinates has been prohibitively difficult.
- As a consequence, the three-dimensional highway alignment problem is reduced to two-dimensional alignment problems, as illustrated in Fig. 3.2.

One of the alignment problems in this figure corresponds roughly to x and z coordinates and is referred to as horizontal alignment.
- The other corresponds to highway length (measured along some constant elevation) and y coordinates (elevation) and is referred to as vertical alignment.

Referring to Fig. 3.2, note that
- The horizontal alignment of a highway is referred to as the plan view, which is roughly equivalent to the perspective of an aerial photo of the highway.
- The vertical alignment is represented in a profile view, which gives the elevation of all points measured along the length of the highway (again, with length measured along a constant elevation reference).
Aside from considering the alignment problem as 2 two-dimensional problems, one further simplification is made. That is, instead of using x and z coordinates, highway positioning and length are defined as the distance along the highway (usually measured along the centerline of the highway, on a horizontal, constant-elevation plane) from a specified point. This distance is measured in terms of stations, with each station consisting of 100 ft (1000 m for metric) of highway alignment distance.

The notation for stationing distance is such that a point on a highway 4250 ft (1295.3 m) from a specified point of origin is said to be at station 42 + 50 (1 + 295.300), that is, 42 stations and 50 ft (1 station and 295.300 m), with the point of origin being at station 0 + 00 (0 + 000 for metric). This stationing concept, combined with the highway’s alignment direction given in the plan view (horizontal alignment) and the elevation corresponding to stations given in the profile view (vertical alignment), gives a unique identification of all highway points in a manner that is virtually equivalent to using true x, y, and z coordinates.

The critical aspect of horizontal alignment is the horizontal curve with the focus on design of the directional transition of the roadway in a horizontal plane. Stated differently, a horizontal curve provides a transition between two straight (or tangent) sections of roadway. A key concern in this directional transition is the ability of the vehicle to negotiate a horizontal curve. The highway engineer must design a horizontal alignment to accommodate the cornering capabilities of a variety of vehicles.
Vehicle Cornering

Figure 3.12 illustrates the forces acting on a vehicle during cornering.

\[ F_c = \text{centripetal force [lateral acceleration \times mass], in lb (N)}, \]

\[ F_{cp} = \text{centripetal force acting parallel to the roadway surface in lb (N)} , \]

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

\[ R_v = \text{radius defined to the vehicle’s traveled path in ft (m)}, \]

\[ \alpha = \text{angle of incline in degrees}, \]

\[ e = \text{number of vertical ft (m) of rise per 100 ft (m) of horizontal distance}, \]

\[ W = \text{weight of the vehicle in lb (N)}, \]

\[ W_n = \text{vehicle weight normal to the roadway surface in lb (N)}, \]

\[ W_p = \text{vehicle weight parallel to the roadway surface in lb (N)}, \]

\[ F_f = \text{side frictional force [centripetal, in lb (N)}], \]

\[ W_p + F_f = F_{cp} = F_{cn} \]

\[ W \sin \alpha + f_s \left( W \cos \alpha + \frac{WV^2}{gR_v} \sin \alpha \right) = \frac{WV^2}{gR_v} \cos \alpha \]

where

\[ f_s = \text{coefficient of side friction (unitless)}, \]

\[ V = \text{vehicle speed in ft/s (m/s)}, \]

\[ g = \text{gravitational constant, 32.2 ft/s}^2 \text{ (9.807 m/s})^2 \text{ (9.807 m/s)}, \text{and} \]

Other terms are as defined in Fig 3.12.
In the actual design of a horizontal curve, the engineer must select appropriate values of e and $f_s$.

The value selected for superelevation, e, is critical because high rates of superelevation can cause:

- vehicle steering problems on the horizontal curve, and
- 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.

AASHTO provides general guidelines for the selection of e and $f_s$ for horizontal curve design, as shown in Table 3.5.

The values presented in this table are grouped by five values of maximum e. The selection of any one of these five maximum e values is dependent on the type of road (for example, higher maximum e's are permitted on freeways compared with arterials and local roads) and local design practice. Limiting values of $f_s$ are simply a function of design speed. Table 3.5 also presents calculated radii (given V, e, and $f_s$) by applying Eq. 3.34.
In connecting straight (tangent) sections of roadway with a horizontal curve, several options are available. The most obvious of these is the simple circular curve, which is just a curve with a single constant radius. Other options include reverse curves, compound curves, and spiral curves.

Reverse curves generally consist of two consecutive curves that turn in opposite directions. They are used to laterally shift the alignment of a highway. The curves used are usually circular and have equal radii. Reverse curves, however, are not recommended because drivers may find it difficult to stay within their lane as a result of sudden changes in the alignment.

Compound curves consist of two or more curves, usually circular, in succession. Compound curves are used to fit horizontal curves to very specific alignment needs, such as interchange ramps, intersection curves, or difficult topography. In designing compound curves, care must be taken to not have successive curves with widely different radii, as this will make it difficult for drivers to maintain their lane position as they transition from one curve to the next.
Spiral curves are curves with a continuously changing radius. Spiral curves are sometimes used to transition a tangent section of roadway to a circular curve. In such a case, the radius of the spiral curve is equal to infinity where it connects to the tangent section and ends with the radius value of the connecting circular curve at the other end. Because motorists usually create their own transition paths between tangent sections and circular curves by utilizing the full lane width available, spiral curves are not often used. However, there are exceptions.

Horizontal Curve Fundamentals

- Spiral curves are sometimes used on high-speed roadways with sharp horizontal curves and are sometimes used to gradually introduce the superelevation of an upcoming horizontal curve. To illustrate the basic principles involved in horizontal curve design, we will focus only on the single simple circular curve.

Another important term is the degree of curve, which is defined as the angle subtended by a 100-ft (30.5-m) arc along the horizontal curve. It is a measure of the sharpness of the curve and is frequently used instead of the radius in the construction of the curve. The degree of curve is directly related to the radius of the horizontal curve by

\[
D = \frac{180}{\pi} \frac{1}{R} = \frac{18,000}{\pi R} \quad \text{(3.35)}
\]

where

- \(D\) = degree of curve [angle subtended by a 100-ft (30.5-m) arc along the horizontal curve], and

Other terms are as defined in Fig. 3.13.

Note that the quantity \(\frac{180}{\pi}\) converts from radians to degrees.
Geometric and trigonometric analyses of Fig. 3.13 reveal the following relationships:

- It is important to note that horizontal curve stationing, curve length, and curve radius \( R \) are usually measured to the centerline of the road.
- In contrast, the radius determined on the basis of vehicle forces \( R_v \) in Eq. 3.34) is measured from the innermost vehicle path, which is assumed to be the midpoint of the innermost vehicle lane. Thus, a slight correction for lane width is required in equating the \( R_v \) of Eq. 3.34 with the \( R \) in Eqs. 3.35 to 3.39.

\[
\begin{align*}
T &= R \tan \frac{\Delta}{2} \quad (3.36) \\
E &= R \left[ \frac{1}{\cos(\Delta/2)} - 1 \right] \quad (3.37) \\
M &= R \left( 1 - \cos \frac{\Delta}{2} \right) \quad (3.38) \\
L &= \frac{\pi}{180} R \Delta \quad (3.39)
\end{align*}
\]

**EXAMPLE 3.14**

- A horizontal curve is designed with a 2000-ft (609.600-m) radius. The curve has a tangent length of 400 ft (121.920 m) and the PI is at station 103 + 00 (3 + 139.440). Determine the stationing of the PT.

**SOLUTION**

Equation 3.36 is applied to determine the central angle, \( \Delta \).

\[
T = R \tan \frac{\Delta}{2}
\]

\[
400 = 2000 \tan \frac{\Delta}{2}
\]

\[
\Delta = 22.62^\circ
\]
SOLUTION

So, from Eq. 3.39, the length of the curve is

\[ L = \frac{\pi R \Delta}{180} \]
\[ L = \frac{3.1416 \times 200}{180} = 789.58 \text{ ft} \]

Given that the tangent length is 400 ft,

stationing \( PC = 103 + 00 \) minus 4 + 00 = 99 + 00

Since horizontal curve stationing is measured along the alignment of the road,

stationing \( PT = \) stationing \( PC + L \)

\[ = 99 + 00 \text{ plus } 7 + 89.58 = 106 + 89.58 \]

Stopping Sight Distance and Horizontal Curve Design

- Adequate stopping sight distance must be provided in the design of horizontal curves.
- Sight distance restrictions on horizontal curves occur when obstructions are present, as shown in Fig. 3.14.
- Such obstructions are frequently encountered in highway design due to the cost of right-of-way acquisition or the cost of moving earthen materials, such as rock outcroppings.

When such an obstruction exists, the stopping sight distance is measured along the horizontal curve from the center of the traveled lane (the assumed location of the driver's eyes).

As shown in Fig. 3.14, for a specified stopping distance, some distance \( Ms \) (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 stopping sight distance is available.

Fig. 3.14. Stopping Sight Distance Considerations for Horizontal Curves

\[ L = \text{length of curve in ft (m)}, \]
\[ SSD = \text{stopping sight distance in ft (m)}, \]
\[ R = \text{radius measured to the centerline of the road in ft (m)}, \]
\[ R_c = \text{radius to the vehicle's traveled path (usually measured to the center of the innermost lane of the road) in ft (m)}, \]
\[ PC = \text{point of curve (the beginning point of the horizontal curve)}, \]
\[ PT = \text{point of tangent (the ending point of the horizontal curve)} \]
Fig. 3.14. Stopping Sight Distance Considerations for Horizontal Curves

Stopping Sight Distance and Horizontal Curve Design

- Equations for computing stopping sight distance (SSD) relationships for horizontal curves can be derived by first determining the angle, $\Delta_s$, for an arc length equal to the required stopping sight distance (see Fig. 3.14 and note that this is not the central angle, $\Delta_c$, of the horizontal curve whose arc length is equal to $L$). Assuming that the length of the horizontal curve exceeds the required SSD (as shown in Fig. 3.14), we have (as with Eq. 3.39)

$$SSD = \frac{\pi}{180} R \Delta_s$$  \hspace{1cm} (3.40)

- Rearranging terms,

$$\Delta_s = \frac{180 \text{ (SSD)}}{\pi R}$$  \hspace{1cm} (3.41)

- Substituting this into the general equation for the middle ordinate of a simple horizontal curve (Eq. 3.38) to get an expression for $M_s$ gives

$$M_s = R \left(1 - \cos \frac{\Delta_s}{2}\right)$$  \hspace{1cm} (3.42)

- Solving Eq. 3.42 for SSD gives

$$SSD = \frac{\pi R}{90} \cos^{-1} \left(\frac{R - M_s}{R}\right)$$  \hspace{1cm} (3.43)

- Note that Eqs. 3.40 to 3.43 can also be applied directly to determine sight distance requirements for passing. If these equations are to be used for passing, distance values given in Table 3.4 would apply and SSD in the equations would be replaced by PSD.
A horizontal curve on a two-lane highway is designed with a 2000-ft (609.600-m) radius, 12-ft (3.6-m) lanes, and a 60-mi/h (96-km/h) design speed. Determine the distance that must be cleared from the inside edge of the inside lane to provide a sufficient stopping sight distance.

**SOLUTION**

Because the curve radius is usually taken to the centerline of the roadway, \( R_c = R - \frac{2000}{12} = 1994 \) ft, which gives the radius to the middle of the inside lane (the critical driver location). From Table 3.1, the SSD for a 60-mi/h design speed is 570 ft, so applying Eq. 3.42 gives

\[
M_s = R \left(1 - \cos \left(\frac{570}{R}\right)\right)
\]

\[
= 1994 \left(1 - \cos \left(\frac{570}{1994}\right)\right) = 20.33 \text{ ft}
\]

Therefore, 20.33 ft must be cleared, as measured from the center of the inside lane, or 14.33 ft as measured from the inside edge of the inside lane.
EXAMPLE 3.16

A two-lane highway (two 12-ft (3.6-m) lanes) has a posted speed limit of 50 mi/h (80 km/h) and, on one section, has both horizontal and vertical curves, as shown in Fig. 3.15. A recent daytime crash (driver traveling eastbound and striking a stationary roadway object) resulted in a fatality and a lawsuit alleging that the 50-mi/h (80-km/h) posted speed limit is an unsafe speed for the curves in question and was a major cause of the crash. Evaluate and comment on the roadway design.

SOLUTION

Begin with an assessment of the horizontal alignment. Two concerns must be considered: the adequacy of the curve radius and superelevation, and the adequacy of the sight distance on the eastbound (inside) lane. For the curve radius, note from Fig. 3.15 that

\[ L = \text{station of } PT - \text{station of } PC \]
\[ L = 32 + 75 \text{ minus } 16 + 00 = 1675 \text{ ft} \]

Rearranging Eq. 3.39, we get

\[ R = \frac{180}{\pi \Delta} \cdot \frac{180}{\pi (80)} (1675) = 1199.63 \text{ ft} \]

Using the posted speed limit of 50 mi/h with \( \epsilon = 8.0\% \), we find that Eq. 3.34 can be rearranged to give (with the vehicle traveling in the middle of the inside lane, \( R_v = R - \frac{1}{2} \text{ the lane width, or } R_v = 1199.63 - 6 = 1193.63 \text{ ft} \)

\[ f_v = \frac{V^2}{gR_v} = \frac{(50 \times 1.467)^2}{32.2(1193.63)} = 0.08 = 0.060 \]
SOLUTION

From Table 3.5, the maximum $f_e$ for 50 mi/h is 0.14. Since 0.060 does not exceed 0.14, the radius and superelevation are sufficient for the 50-mi/h design speed.

For sight distance, the available $M_f$ is 18 ft plus the 6-ft distance to the center of the eastbound (inside) lane, or 24 ft. Application of Eq. 3.43 gives

$$SSD = \frac{\pi R_e}{90} \left[ \cos^{-1} \left( \frac{R_e - M_f}{R_e} \right) \right]$$

$$= \frac{\pi (1193.63)}{90} \left[ \cos^{-1} \left( \frac{1193.63 - 24}{1193.63} \right) \right]$$

$$= 479.5 \text{ ft}$$

From Table 3.1, the required SSD at 50 mi/h is 425 ft, so the 479.5 ft of SSD provided is sufficient. Turning to the sag vertical curve, the length of curve is

$$L = \text{station of PVT} - \text{station of PVC}$$

$$L = 18 + 80 \text{ minus } 14 + 00 = 480 \text{ ft}$$

Using $A = 6\%$ (from Fig. 3.15) and applying Eq. 3.10, we obtain

$$K = \frac{L}{A} = \frac{480}{6} = 80$$

For the 50-mi/h design speed, Table 3.3 indicates a necessary $K$-value of 96. Thus the $K$-value of 80 reveals that the curve is inadequate for the 50-mi/h speed. However, because the crash occurred in daylight and sight distances on sag vertical curves are governed by nighttime conditions, this design did not contribute to the crash.