Horizontal and Vertical Alignment

4.1 Introduction

This chapter discusses design considerations and criteria for incorporating horizontal and vertical curves in a roadway’s alignment. All types of roadways are discussed in this chapter - ranging from local low-speed facilities to median divided highways. A horizontal curve in a roadway refers to the alignment, or how “straight” the roadway section is. A vertical curve refers to a roadway’s change in elevation, or the “flatness” of the roadway.

As described in Chapter 3, the operating characteristics of drivers and motor vehicles place the greatest constraints on curvature. In most cases, application of the design controls for motor vehicles satisfies the design controls for bicycles and pedestrians, including those with disabilities. This means that the criteria for vehicles are more restrictive than the criteria for pedestrians and bicyclists – thus incorporating a bend or a grade in a roadway segment that satisfies the design criteria for a motor vehicle will also likely satisfy to design criteria for pedestrians and bicyclists. The goal of the designer in the layout of a roadway is to convey users between their point of origin and their point of destination along a path in a safe and efficient manner that is compatible with the environment and the users’ operational characteristics.

Roadways must respect the existing and developed environment through which they pass while balancing the needs for safety and cost-effectiveness. As a result, roadways are not always flat and straight – they possess vertical and horizontal curves in their alignments to circumvent or be compatible with existing constraints. Alignment constraints typically include topographical variation, natural resource areas, property ownership, land use, cost, and environment. Introduction of curvilinear alignments is necessary when the designer encounters these constraints.
Good alignment design is critical in the effort to balance the needs and safety of the road user with the value of preserving the integrity of the environment.

The designer must use engineering judgment applied to a variety of factors to develop effective and efficient geometry in three dimensions. These factors include:

**Horizontal Curves**
- compatibility between existing and proposed conditions (controls)
- topographical/terrain variations
- vehicle characteristics
- driver limitations
- design speed
- lines of sight
- roadway cross section
- radius of curve
- superelevation (or banking)
- length of curve
- tangent-to-curve transition
- profile
- drainage considerations
- cost

**Vertical Curves**
- compatibility with existing grades and elevations on adjacent land and approaching roads and driveways/entrances adjacent to the new alignment
- design speed
- sight distance
- vertical clearances
- lengths of grade
- entrance considerations associated with acceleration and deceleration
- horizontal alignment
- drainage considerations
- costs

When using a combination of horizontal and vertical curves, it is important to consider the effects of the combination of both. It may be necessary to use more gradual change in each to meet sight distance, acceleration, and other needs safely, as described in Section 4.4

The process of incorporating horizontal and vertical elements into a roadway’s design begins with the identification of the proposed corridor and location of critical constraints that must be considered for preservation throughout the design process. The critical constraints that drive the design process include, but are not limited to:

- project limits
- private property
- pedestrian functions
- accessibility for people with disabilities
- significant cultural (historical/archaeological) areas and features
- regulated wetlands
- natural drainage courses
- endangered species habitat
- intersecting roads and driveways
- underground and overhead utilities
- rail facilities

A balanced design will identify these constraints early in the process and align the vertical and horizontal position of the road to protect, preserve, or meet the requirements of each to the extent practicable.
4.2 Horizontal Alignment

Horizontal alignment, combined with vertical alignment, serves as the primary controlling element associated with the design of all types of public streets and highways. Engineering judgment and experience plays a major role in selecting horizontal geometry that meets desired design criteria. There are a variety of factors that are important in the selection of a horizontal curve or series of curves. In general, the designer should take into account the following considerations:

- Existing environmental and other constraints should be identified on the base mapping to assist the designer in minimizing impacts to wetlands, historical and archaeological features, private and protected property, and permanent structures. To the extent possible, these constraints should serve as boundaries through which the designer must fit the geometry.

- The relationship of the roadway to wetlands and waterways and the interaction of different types of roadway drainage with these resources should be considered.

- For improvements to existing roadways, geometry should be concentric with and/or parallel to the existing roadway layout so that new impacts to the surrounding area are minimized.

- Horizontal alignment should be as smooth and as direct as possible while responsive to the topography. Flatter curvature with shorter tangents is generally preferable to sharp curves connected by long tangents. Angle points should be avoided.

- Curves with small deflection angles (5 degrees or less) should be long enough to avoid the appearance of a kink. Curves should be 500 feet long for a central angle of 5 degrees and increased 100 feet for each degree decrease in central angle.

The minimum length of horizontal curves (Lc) should be:

- Lc desirable = 30V (high speed controlled-access facilities)
- Lc minimum = 15V (other arterials)

(Where V = design speed in miles per hour)
- Broken back curvature (a short tangent between two curves in the same direction) should be avoided because drivers do not expect to encounter this arrangement on typical highway geometry.

- Abrupt reversals in alignment and sharp curvature on long, high fills should be avoided.

- If compound circular curves are required in an effort to fit the highway to the terrain or to other constraints, large differences in radius should be avoided. The radius of the largest curve should not be more than 1.5 times the radius of the smaller curve (except for highway ramps). On ramps, the ratio of the larger curve to the smaller curve should not exceed 2:1.

- The horizontal alignment should be in balance with the vertical profile and cross section rotation associated with superelevation. This is accomplished through the use of a cross sectional analysis. Under this analysis procedure, the alignment is plotted onto the cross section to the lines and grades dictated by the geometry. Should the impacts on the existing topography, private property, environmental areas, etc. be significant for successive cross sections, then modification to the vertical and horizontal geometry should be considered to minimize the impacts, thereby optimizing a balanced geometric design. See Section 4.4 for more information regarding the combination of the design of horizontal and vertical alignments.

- Horizontal curves should be avoided on bridges whenever possible. These cause design, construction, and operational problems. Where a curve is necessary on a bridge, a simple curve should be used on the bridge and any curvature or superelevation transitions placed on the approaching roadway.

4.2.1 Types of Horizontal Curvature

Normally, in the Commonwealth of Massachusetts, simple circular curves are used in design; however, compound or spiral curves may be considered throughout the length of a curve to fit the roadway into a constrained corridor. For circular curves the radius definition is used, with design curves expressed to the nearest 20 feet.
4.2.1.1 Simple Curves

A simple curve has a constant circular radius which achieves the desired deflection without using an entering or exiting transition. This is the most frequently used curve because of their simplicity for design, layout, and construction as shown in Exhibit 4-1.

Exhibit 4-1
Simple Circular Curve

\[
\begin{align*}
R &= \text{Radius} \\
C &= \text{Long Chord} \\
C' &= \text{Any Chord Length} \\
M &= \text{Middle Ordinate} \\
L &= \text{Length of Arc} \\
E &= \text{External Distance} \\
\triangle &= \text{Intersection Angle = Central Angle} \\
X &= \text{Distance Along Tangent}
\end{align*}
\]

\[
\begin{align*}
D &= \text{Deflection Angle for Chord C'} \\
T &= \text{Length of Tangent} \\
P.C. &= \text{Point of Curvature} \\
P.I. &= \text{Point of Intersection} \\
P.T. &= \text{Point of Tangency} \\
\sin \theta &= X/R
\end{align*}
\]

FORMULAS

\[
\begin{align*}
T &= R \tan(\triangle/2) \\
C &= 2R \sin(\triangle/2) \\
L &= \frac{\triangle}{360} (2 \pi R) \\
E &= R (\sec(\triangle/2) - 1) \\
\sin D &= 1/2 + C'R
\end{align*}
\]

TANGENT OFFSET METHODS

\[
\begin{align*}
\theta &= R - \left( R^2 - x^2 \right)^{1.5} \\
Y &= R \cos \theta \\
0 &= R - Y
\end{align*}
\]

Source: MassHighway
Elements of a horizontal curve:

- **Δ**  DELTA (Central Angle). The value of the central angle is equal to the *I* angle. Some authorities call both the intersecting angle and central angle either *I* or *A*.

- **R**  RADIUS. The radius of the circle of which the curve is an arc, or segment. The radius is always perpendicular to back and forward tangents.

- **PI**  POINT OF INTERSECTION. The point of intersection is the theoretical location where the two tangents meet.

- **PT**  POINT OF TANGENCY. The point of tangency is the point on the forward tangent where the curve ends. It is sometimes designated as EC (end of curve) or CT (curve to tangent).

- **PC**  POINT OF CURVATURE. The point of curvature is the point on the back tangent where the circular curve begins. It is sometimes designated as BC (beginning of curve) or TC (tangent to curve).

- **POC**  POINT ON CURVE. The point on curve is any point along the curve.

- **L**  LENGTH OF CURVE. The length of curve is the distance from the PC to the PT, measured along the curve.

- **T**  TANGENT. The length of tangent is the distance along the tangents from the PI to the PC or the PT. These distances are equal on a simple curve.

- **C**  LONG CHORD. The long chord is the straight-line distance from the PC to the PT. Other types of chords are designated as follows:

  - **c**  The subchord distance between the PC and the first station on the curve.

  - **C’**  Any chord distance between two points along a curve.

  - **E**  EXTERNAL DISTANCE. The external distance (also called the external secant) is the distance from the PI to the midpoint of the curve. The external distance bisects the interior angle at the PI.
- **M** MIDDLE ORDINATE. The middle ordinate is the distance from the midpoint of the curve to the midpoint of the long chord. The extension of the middle ordinate bisects the central angle.

- **D** DEFLECTION ANGLE. The deflection angle for chord C’.

At a minimum, curve data shown on the drawings should include the radius, length of curve, central angle, and tangent length. Plan information should also include the stations at the PC and PT.

### 4.2.1.2 Reverse Curves
A reverse curve consists of two simple curves joined together, but curving in opposite directions. For safety reasons, the use of this curve should be avoided when possible. As with broken back curves, drivers do not expect to encounter this arrangement on typical highway geometry.

### 4.2.1.3 Compound Curves
Compound curves are a series of two or more simple curves with deflections in the same direction immediately adjacent to each other. Compound curves are used to transition into and from a simple curve and to avoid some control or obstacle which cannot be relocated. The following guidelines should be followed when using compound curves:

- Compound curves are appropriate for intersection curb radii, interchange ramps, and transitions into sharper curves.

- As the curvature becomes successively sharper, the radius of the flatter circular arc should not be more than 50 percent greater than that of the sharper arc.

- Superelevating compound curves requires careful consideration. This is discussed in Section 4.2.4.

- Exhibits 4-2 and 4-3 illustrate a typical compound curve layout and design for compound curvature transition.

### 4.2.1.4 Minimum Radius of Horizontal Curvature
The values for horizontal curvature are derived from the design speed, superelevation rate, and side friction factors. The basic equation is:

\[
R_{\text{MIN}} = \frac{V^2}{15(0.01e_{\text{MAX}} + f_{\text{MAX}})}
\]
Where:  \( R_{MIN} = \) minimum radius of curve, feet  
\( e = \) superelevation rate*  
\( f = \) side friction factor (see AASHTO Green Book for values)  
\( V = \) vehicle speed, mph  
*(Note: \( e = 6.0\% \) is the maximum rate used in the Commonwealth of Massachusetts)

The design values derived from the equation above are dependent upon selection of superelevation rates as described in Section 4.2.4.

Exhibit 4-2  
Compound Curve Layout

Formulas

\[
\begin{align*}
PI - PI_1 &= \sin \frac{\triangle_1}{\sin \triangle} (t_1 + t_2) \\
&= \Delta \Delta_1 + \triangle_2 \\
PI - PI_2 &= \sin \frac{\triangle_2}{\sin \triangle} (t_1 + t_2) \\
&= \triangle_2 - \Delta_1 \\
T_1 &= t_1 + PI - PI_1 \\
T_2 &= t_2 + PI - PI_2 \\
L_1 &= (\triangle_1 / 360) (2 \pi R_1) \\
&= C_1 = 2R_1 \sin(\triangle_2) \\
L_2 &= (\triangle_2 / 360) (2 \pi R_2) \\
&= C_2 = 2R_2 \sin(\triangle_2) \\
M_1 &= R_1 (1 - \cos \Delta_2) \\
E_1 &= R_1 (\sec(\triangle_2) - 1) \\
M_2 &= R_2 (1 - \cos \Delta_2) \\
E_2 &= R_2 (\sec(\triangle_2) - 1)
\end{align*}
\]

Source: MassHighway
**Exhibit 4-3**  
Compound Curvature Transition

\[ L_c = \text{The greater of:} \]
\[ a) \quad \text{Three seconds running time at the design speed.} \]
\[ b) \quad \text{The length of runoff plus the length of tangent runout, or} \]
\[ c) \quad \text{The length of runoff plus the length required to superelevate to curve } R. \]

\[ L_c = \text{The greater of:} \]
\[ a) \quad \text{Three seconds running time at the design speed.} \]
\[ b) \quad \text{The length to superelevate curve } R_1 \text{ and } R. \]

\[ L = \text{The greater of:} \]
\[ a) \quad \text{Three seconds running time at the design speed.} \]
\[ b) \quad \text{Two times the length required to superelevate to curve } R, \text{ or} \]
\[ c) \quad \text{A minimum length of 350 ft.} \]

**Minimum Allowable Radii without Transition**

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>70</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius (ft)</td>
<td>3940</td>
<td>4600</td>
<td>6560</td>
<td>6560</td>
<td>8200</td>
</tr>
</tbody>
</table>

Where the horizontal curves are of radii less than “R” shown in table above:
1. Curves \( R_1 \ldots R_n \) are introduced for the purpose of making the transition from the tangent to curve “R”.
2. Curves \( R_1 \ldots R_n \) are compounded with “R”.
3. The radius of curves \( R_1 \ldots R_n \) is to be no more than 1.5 times the radius of the preceding curve, i.e., \( R_1 = 1.5R \), etc., starting from each end of curve “R”.
4. The curves are increased in radius until “\( R_n \)” is at least equal to the values indicated for the respective speeds shown on the table above.
5. Superelevation should be developed as discussed in Section 4.2.3.

Source: MassHighway
4.2.2 **Horizontal Stopping Sight Distance**

Horizontal sight distance on the inside of a curve is limited by obstructions such as buildings, hedges, wooded areas, walls, abutments, cut slopes, headlights, vertical curvature, or other topographic features. A comprehensive field survey should identify these obstructions on the critical cross sections and on the base plans.

Safe sight distance must be provided on the inside of horizontal curves to allow the driver sufficient brake reaction time to bring the vehicle to a stop. Obstructions which interfere with the needed sight distance should be moved or removed, if possible. If the obstruction cannot be removed, consideration should be given to realigning the road (horizontal and/or vertical) or providing appropriate warning signage.

On horizontal curves, a designer must provide a "middle ordinate" between the center of the inside lane and the sight obstruction. The basic equation is:

\[
M = R\left[\frac{28.65S}{R}\right]
\]

Where:
- \(M\) = middle ordinate, or distance from the center of the inside lane to the obstruction, feet.
- \(R\) = radius of curve, feet.
- \(S\) = sight distance, feet.

The designer should use the following:

- Exhibit 4-4 illustrates the concept of a middle ordinate and its impact on sight distance around a curve. Exhibit 4-5 is a design chart showing the horizontal sight line offsets (middle ordinate) needed for clear sight areas that satisfy stopping sight distance criteria presented in Exhibit 3-8 for horizontal curves of various radii. The designer should make every practical effort to achieve the stopping sight distance criterion.

The stopping sight distance is based on eye height of 3.5 feet and object height of 2 feet. The line-of-sight intercept with the view obstruction is at the midpoint of the sight line and 2.75 feet above the center of the inside lane.
Exhibit 4-4
Sight Distance on a Curve

Exhibit 4-5
Horizontal Stopping Sight Distance Criteria

If a designer concludes that decision sight distance is needed, greater distance will have to be provided. Chapter 3 discusses those highway conditions where decision sight distance is appropriate and provides procedures for determining the distance. The calculated value would then be used in the basic equation for determining the middle ordinate on the horizontal curve. Also, refer to Chapter 3 in AASHTO’s *A Policy on Geometric Design of Highways and Streets*, for further information.

Normally, it is not practical to provide passing sight distance on horizontal curves. These values yield very large numbers for the middle ordinate. In addition, many drivers will not pass on horizontal curves regardless of the available sight distance. Passing should not be allowed where passing sight distance can not be achieved.

Exhibit 4-6 illustrates the method of ensuring adequate sight distance in cut sections.

**Exhibit 4-6**

**Method of Cutting Slope for Horizontal Sight Distance**

Source: MassHighway
4.2.3 **Superelevation**

Superelevation is the banking of a roadway around a curve as illustrated in Exhibit 4-7. The purpose of employing superelevation of the roadway cross section is to counterbalance the centrifugal force, or outward pull, of a vehicle traversing a horizontal curve. Side friction developed between the tires and the road surface also counterbalances the outward pull of the vehicle. A combination of these two concepts allows a vehicle to negotiate curves safely at higher speeds than would otherwise be possible.

**Exhibit 4-7**
**Superelevation for Left and Right Turning Curves**

Incorporating superelevation into a roadway’s design may help avoid roadside obstacles that might otherwise be impacted by the alignment. In contrast, superelevation may not be desirable for low-speed roadways to help limit excessive speeds or in urban settings to limit impacts to abutting uses or drainage systems and utilities. Moreover,
superelevation may not be desirable when considering pedestrian or bicycle accommodations along the roadway segment. Like other roadway design elements, designers must consider the trade-offs of introducing superelevation in a roadway’s design.

The maximum useable rate for superelevation \( (e_{\text{max}}) \) is controlled by several factors: climate conditions, terrain conditions, type of area, and the frequency of slow moving vehicles. Because of winter snow and icing conditions, the rate of superelevation should not exceed the rate on which a vehicle standing or traveling slowly would slide toward the center of the curve when the pavement is icy; therefore, the maximum rate of superelevation \( (e_{\text{max}}) \) used in Massachusetts is 6.0 percent. On roadways with lower design speeds (less than 45mph), designing without superelevation is often acceptable because the outward pull of a vehicle negotiating a curve is lower.

4.2.4 Maximum Superelevation Rates and Minimum Curve Radii

Exhibit 4-8 provides minimum curve radii for common superelevation rates of 4 percent and 6 percent across a range of design speeds. The values in the exhibit are minimum radii possible with rates of superelevation commonly used in undeveloped or lightly-developed areas (Rural Natural, Rural Developed, Rural Village, and Suburban Low Intensity). The designer should provide flatter curves wherever possible. It may be necessary to provide flatter curvature when the minimum radius will not provide the necessary stopping sight distance due to sight line obstructions along the edges of the roadway (See Section 4.2.3).

Although superelevation is advantageous for traffic operation, various factors often combine to make its use impractical in many built-up areas (such as Suburban High Intensity, Suburban Town Centers and Urban Areas). Such factors include wide pavement areas, the need to meet the grade of adjacent property, surface drainage considerations, and frequency of cross streets, alleys, and driveways. Therefore, horizontal curves on low-speed roadways in urban areas may be designed without superelevation, counteracting the centrifugal force solely with side friction. Designing without superelevation is often a suitable design practice for low-speed roadways (less than 45mph). If site specific conditions allow, designers should avoid using a superelevation to the extent possible for design speeds of 35 mph or less and use a normal crown in the roadway cross-section.
Exhibit 4-8
Minimum Design Radii for Common Superelevation Rates
(e = 4 Percent or e = 6 Percent)

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Minimum Design Radius (ft) with e = 4 %</th>
<th>Minimum Design Radius (ft) with e = 6 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>90</td>
<td>85</td>
</tr>
<tr>
<td>25</td>
<td>155</td>
<td>145</td>
</tr>
<tr>
<td>30</td>
<td>250</td>
<td>235</td>
</tr>
<tr>
<td>35</td>
<td>375</td>
<td>340</td>
</tr>
<tr>
<td>40</td>
<td>535</td>
<td>485</td>
</tr>
<tr>
<td>45</td>
<td>715</td>
<td>645</td>
</tr>
<tr>
<td>50</td>
<td>930</td>
<td>835</td>
</tr>
<tr>
<td>55</td>
<td>1190</td>
<td>1060</td>
</tr>
<tr>
<td>60</td>
<td>1500</td>
<td>1330</td>
</tr>
<tr>
<td>65</td>
<td>Not Permitted</td>
<td>1660</td>
</tr>
<tr>
<td>70</td>
<td>Not Permitted</td>
<td>2040</td>
</tr>
<tr>
<td>75</td>
<td>Not Permitted</td>
<td>2500</td>
</tr>
</tbody>
</table>

Note: For design speeds less than 35 mph, designers should avoid using superelevation to the extent possible. In recognition of safety considerations, use of \( e_{\text{max}} = 4.0\% \) should be limited to developed areas (such as suburban high intensity, suburban town centers, and urban areas). Radii are rounded to the nearest 5 feet.

Source: A Policy on Geometric Design of Highways and Streets, AASHTO, 2004 Chapter 3 Elements of Design

The minimum radius or sharpest curve without superelevation is reached when the side friction factor developed to counteract centrifugal force and adverse cross slope reaches the maximum allowable value based on safety and comfort considerations. For travel on sharper curves or at higher speeds, superelevation is needed. A maximum superelevation rate of 4.0 percent is commonly used. A maximum superelevation rate of 6.0 percent may be justified on sharper curves where adequate transition lengths are available.

For roadways in areas with design speeds of 45 mph and below, Exhibit 4-9 provides the minimum radii for 2.0 percent, 0 percent, and -2.0 percent (no superelevation) rates of superelevation. The 2.0 percent column represents the situation where the normal pavement crown is replaced with a consistent 2.0 percent cross slope.
### Exhibit 4-9
Minimum Radius (ft) with Low or No Superelevation (e of -2.0 Percent, 0 Percent, and 2.0 Percent)

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Percent Superelevation (e)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-2.0 %</td>
</tr>
<tr>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>110</td>
</tr>
<tr>
<td>25</td>
<td>200</td>
</tr>
<tr>
<td>30</td>
<td>335</td>
</tr>
<tr>
<td>35</td>
<td>510</td>
</tr>
<tr>
<td>40</td>
<td>765</td>
</tr>
<tr>
<td>45</td>
<td>1040</td>
</tr>
</tbody>
</table>

Note: Radii are rounded up to the nearest 5 feet

1 For design speeds less than 35 mph, designers should avoid using superelevation to the extent possible.

Source: A Policy on Geometric Design of Highways and Streets, AASHTO, 2004 Chapter 3 Elements of Design

#### 4.2.5 Superelevation Transitioning

The development of superelevation on a horizontal curve requires a transition from a normal crown section, which is accomplished by rotating the pavement. The pavement may be rotated about the centerline or either edge of the travel lanes.

There are five basic cross section controls — (-a-) through (-e-) — involved in transitioning the pavement to obtain full superelevation illustrated in Exhibit 4-10.

- **Cross section (-a-)** is the normal crown section where the transitioning begins.
- **Cross section (-b-)** is reached by rotating half the pavement until it is level.
- **Cross section (-c-)** is attained by continuing to rotate the same half of pavement until a plane section is attained across the entire pavement section, at a cross slope equal to the normal crown slope.
- **Cross section (-d-)** is the rate of the cross slope at any intermediate cross section between (-c-) and (-e-) is proportional to the distance from Cross section (-e-).
- **Cross section (-e-)** is achieved by further rotation of the planar section, the entire pavement section, to attain the full superelevation at a cross slope equal to (e).
Exhibit 4-10
Methods of Attaining Superelevation

A. Crowned Pavement Revolved About Centerline

B. Crowned Pavement Revolved About Inside Edge

C. Crowned Pavement Revolved About Outside Edge

D. Straight Cross Slope Pavement Revolved About Outside Edge


NOTE:
Angular breaks to be appropriately rounded as shown by dotted line.
Superelevation runoff is the general term denoting the length of highway needed to accomplish the change in cross slope from a section with adverse crown removed (−b−) to a fully superelevated section (−e−), or vice versa.

Tangent runout is the general term denoting the length of highway needed to accomplish the change in cross slope from a normal section (−a−) to a section with the adverse crown removed (−b−), or vice versa.

4.2.5.1 Design Considerations

■ Superelevation is introduced or removed uniformly over the lengths required for comfort and safety.

■ Place approximately two-thirds of the runoff on the tangent section and one-third on the horizontal curve.

■ Angular breaks occur in the vertical profile in the superelevation transition areas. To smooth these breaks, when the vertical angle points are greater than 1%, short vertical curves are required. The minimum vertical curve length in feet can be used as numerically equal to the 5.3 times the design speed in mph. Greater lengths should be used where possible.

■ On compound curves the following criteria should be met:
  - Full superelevation for the sharpest curve should be attained at the PCC.
  - If the flatter entering curve is less than or equal to 500 feet, a uniform longitudinal gradient should be used throughout the transition.
  - If the flatter entering curve is longer than 500 feet, it may be preferable to consider the two curves separately. Superelevation for the entering curve would be developed by the 2/3-1/3 distribution method. This rate would be maintained until it is necessary to develop the remaining superelevation for the sharper curve.

Exhibit 4-11 illustrates the two transition methods for compound curves.
The minimum superelevation runoff lengths for roadways wider than two lanes should be as follows:

- Three-lane traveled ways; 1.25 times the corresponding length for two-lane traveled ways.
- Four-lane undivided traveled ways; 1.5 times the corresponding length for two-lane highways.
- Six-lane undivided traveled ways; 2.0 times the corresponding length for two-lane traveled ways.

4.2.5.2 Axis of Rotation

To attain superelevation an axis must be selected about which the pavement is rotated. In general there are four methods that may be selected:

- **Rotation about the centerline profile of traveled way.** This is generally the preferred method for two lane and undivided multilane roadways and when the elevations of the outside of
roadway must be held within critical limits, such as in an urban area to minimize the impact on adjacent properties. This is also the method that distorts the edge line profiles the least. Exhibit 4-12 graphically demonstrates how the roadway superelevation is developed for this method.

- **Rotation about the inside-edge profile of traveled way.** This is generally the preferred method when the lower edge profile is of concern, such as when the profile is flat and the inside edge of the roadway needs to be controlled for drainage purposes. Exhibit 4-13 graphically demonstrates how the roadway superelevation is developed for this method. This method is suitable for ramps.

- **Rotation about the outside-edge profile of traveled way.** This method is similar to inside edge rotation except that the change is effected below the outside-edge profile instead of above the inside edge profile. This method is used when the higher edge profile is critical, such as on divided highways where the median edge profiles are held. Exhibit 4-14 graphically demonstrates how the roadway superelevation is developed for this method.

- **Rotation about the outside-edge profile of traveled way when the roadway has a straight cross-slope at the beginning of transition (-a-).** The outside-edge rotation is shown because this point is most often used for rotation of two-lane one-way roadways, with profile along the median edge of traveled way or for the traveled way having a typical straight cross-slope. Exhibit 4-15 graphically demonstrates how the roadway superelevation is developed for this method.
Exhibit 4-12
Banking Undivided Highways - Rotation Around Centerline

Crowned Pavement Revolved About Centerline

Equations:

\[
\begin{align*}
H_c &= 8 \times W \\
H_a &= 8 \times W \\
H_{ae} &= e \times W \\
P &= \left(\frac{e \times W}{L}\right) \\
\text{Tangent Runout} &= \frac{H_a}{P} \\
X &= 2 \times \text{Tangent runout}
\end{align*}
\]

Where:

\[
\begin{align*}
W &= \text{Width of travel lane(s) from } C_l \\
S &= \text{Normal cross slope} \\
e &= \text{Superelevation rate at full bank} \\
L &= \text{Length of runoff} \\
P &= \text{Rate of transition}
\end{align*}
\]

Exhibit 4-13
Banking Undivided Highways - Rotation About Inside Edge

Crowned Pavement Revolved About Inside Edge

Equations:
- \( H_a = 8 \times W \)
- \( H_o = 8 \times W \)
- \( H_e = 2 \times e \times W \)
- \( P = (e \times W) / L \)
- \( \text{Tangent Runout} = H_a / P \)
- \( 2P = 2 \times P \)
- \( X = 2 \times \text{tangent runout} \)

Where:
- \( W \) = Width of travel lane(s) from \( C_L \)
- \( S \) = Normal cross slope
- \( e \) = Superelevation rate at full bank
- \( L \) = Length of runoff
- \( P \) = Rate of transition

Exhibit 4-14
Banking Undivided Highways - Rotation about Outside Edge

Crowned Pavement Revolved About Outside Edge

Equations:
- \( Ha = 8 \times W \)
- \( Ho = 8 \times W \)
- \( He = 2 \times e \times W \)
- \( P = \frac{(e \times W)}{L} \)
- \( 2P = 2 \times X \)

Where:
- \( W = \) Width of travel lane(s) from \( C_L \)
- \( S = \) Normal cross slope
- \( e = \) Superelevation rate at full bank
- \( L = \) Length of runoff
- \( P = \) Rate of transition

Exhibit 4-15
Undivided Highways - Straight Cross Slope, Rotation
About Outside Edge

**Equations:**
- \( Ha = 8 \times W \)
- \( Ho = 8 \times W \)
- \( He = 2 \times e \times W \)
- \( P = (e \times W) / L \)
- Tangent Runout = \( Ha / P \)
- \( 2P = 2 \times P \)
- \( X = 2 \times \text{tangent runout} \)

**Where:**
- \( W \) = Width of travel lane(s) from CL
- \( S \) = Normal cross slope
- \( e \) = Superelevation rate at full bank
- \( L \) = Length of runoff
- \( P \) = Rate of transition

Source: A Policy on Geometric Design of Highways and Streets, AASHTO, 2004, Chapter 3 Elements of Design
On a divided highway with a wide median, rotate each road separately and provide a compensating slope in the median. When using the centerline profile or the outside-edge as axis of rotation, the designer should evaluate the resulting edge profile of the low edge of sag and crest curves to ensure that positive drainage is preserved.

4.2.5.3 Shoulder Superelevation

All shoulders of 4.0 feet or greater should slope away from the travel lanes on superelevated curves. The maximum algebraic difference between the travel lane slope and shoulder slope ("rollover") is 0.09 ft/ft. Shoulders less than 4.0 feet wide should slope in the same direction as the travel lane as illustrated in Exhibit 4-16.

In the Commonwealth of Massachusetts, the grade break for shoulders occurs 1.0 feet outside the lane line; therefore an additional 1.0 foot must be added to the outside travel lane dimension to calculate shoulder edge profiles.

Exhibit 4-16
Highway with Paved Shoulders

Source: MassHighway
Note: Shoulder treatments are typical for all methods of superelevation. Shoulder less than 4.0 ft. should slope in the same direction as the travel lane.
"Roll-over" between travel lane and shoulder cannot exceed 0.09.
Divided Highways with Medians

Divided highways with medians require special consideration.

- **Medians of less than 10 feet** – To minimize the distortion between the two outside edges of the median, the center of the cross section may be used as the axis, with the whole roadway rotated about the center line of the median as a plane section. This method is limited to moderate superelevation rates.

- **Medians wider than 10 feet** – Where both roadways are crowned separately, the axis of rotation should be at the median edges for each side of the roadway, or the gutter lines where applicable. In this case the median is held in a horizontal plane. This method is illustrated in Exhibit 4-17.

- **Medians wider than 40 feet** – It may be preferable to develop the superelevation on each roadway independently with medians greater than 40 feet. The rotation may be made for each side of the roadway using any of the methods illustrated in Exhibits 4-12 to 4-16 as considered appropriate by the designer.
Exhibit 4-17
Banking Divided Highways - Rotation About Median Edge

Equations:
- \( H_a = 8 \times W \)
- \( H_o = 8 \times W \)
- \( H_e = 2 \times e \times W \)
- \( P = (e \times W) / L \)
- \( \text{Tangent Runout} = H_a / P \)
- \( X = 2 \times \text{tangent runout} \)
- \( 2P = 2 \times P \)

Where:
- \( W \) = Width of travel lane(s) from CL
- \( S \) = Normal cross slope
- \( e \) = Superelevation rate at full bank
- \( L \) = Length of runoff
- \( P \) = Rate of transition

Superelevation Design and Runoff Lengths

As it is desirable to select a curve radius larger than the minimum, the design superelevation rate needs to be selected for the actual radius used and the selected design speed. Exhibit 4-18 provides the design superelevation rates (for an undivided highway banked around the centerline) for a range of curve radii and design speeds with maximum superelevation of 6.0 percent. The formula related to this exhibit can be found in Exhibit 4-12.

Exhibit 4-19 provides superelevation runoff lengths for a variety of design superelevations and design speeds, both for two lane and four-lane cross-sections.

Exhibit 4-18 may also be used to calculate the minimum desirable length of tangent between two reversing curves of minimum radii. The superelevation rate of zero may be used to determine the intervening length of tangent between reversing curves even if neither is superelevated. Because two-thirds of the maximum superelevation should be provided at the PC and PT of the curves, the minimum tangent length is two-thirds of the sum of the superelevation runoff lengths.

Superelevation runoff lengths should be long enough so that the rate of change (slopes) of the edges of pavement relative to the centerline does not exceed empirically developed controls. These maximum relative gradients, (which provide a minimum length of runoff) are given in Exhibit 4-20.
Exhibit 4-18
Minimum Radii for Design Superelevation Rates, Design Radius and Design Speeds
\( (e_{\text{max}} = 6\%) \)

<table>
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<tr>
<th>Design Speed (Vd)</th>
<th>15 mph R (ft)</th>
<th>20 mph R (ft)</th>
<th>25 mph R (ft)</th>
<th>30 mph R (ft)</th>
<th>35 mph R (ft)</th>
<th>40 mph R (ft)</th>
<th>45 mph R (ft)</th>
<th>50 mph R (ft)</th>
<th>55 mph R (ft)</th>
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Note: Based on banking an undivided highway (2 or 4 lanes) around the centerline. See Exhibit 4-12.
### Exhibit 4-19
**Superelevation Runoff Length for Design Superelevation and Design Speed**

<table>
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<th>Design Speed $V_d$</th>
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<th>25 mph</th>
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<tbody>
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<td>Number of Lanes Rotated. Note that 1 lane rotated is typical for a 2-lane highway, 2 lanes rotated is typical for a 4-lane highway, etc.</td>
<td>e (%)</td>
<td>Lᵣ (ft)</td>
<td>Lᵣ (ft)</td>
<td>Lᵣ (ft)</td>
<td>Lᵣ (ft)</td>
<td>Lᵣ (ft)</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5.4</td>
<td>21</td>
<td>13</td>
<td>8</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5.6</td>
<td>22</td>
<td>14</td>
<td>8</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5.8</td>
<td>23</td>
<td>14</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6.0</td>
<td>24</td>
<td>15</td>
<td>9</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Exhibit 4-20
**Maximum Relative Gradients**

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Maximum Relative Gradient (%)</th>
<th>Equivalent Maximum Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.78</td>
<td>1:128</td>
</tr>
<tr>
<td>20</td>
<td>0.74</td>
<td>1:135</td>
</tr>
<tr>
<td>25</td>
<td>0.70</td>
<td>1:143</td>
</tr>
<tr>
<td>30</td>
<td>0.66</td>
<td>1:152</td>
</tr>
<tr>
<td>35</td>
<td>0.62</td>
<td>1:161</td>
</tr>
<tr>
<td>40</td>
<td>0.58</td>
<td>1:172</td>
</tr>
<tr>
<td>45</td>
<td>0.54</td>
<td>1:185</td>
</tr>
<tr>
<td>50</td>
<td>0.50</td>
<td>1:200</td>
</tr>
<tr>
<td>55</td>
<td>0.47</td>
<td>1:213</td>
</tr>
<tr>
<td>60</td>
<td>0.45</td>
<td>1:222</td>
</tr>
<tr>
<td>65</td>
<td>0.43</td>
<td>1:233</td>
</tr>
<tr>
<td>70</td>
<td>0.40</td>
<td>1:250</td>
</tr>
<tr>
<td>75</td>
<td>0.38</td>
<td>1:263</td>
</tr>
</tbody>
</table>

*Source: A Policy on Geometric Design of Highways and Streets, AASHTO, 2004 Chapter 3 Elements of Design*

### 4.3 Vertical Alignment

Roadway vertical alignment is controlled by design speed, topography, traffic volumes and composition, highway functional classification, safety, sight distance, typical sections, horizontal alignment, climate, vertical clearances, drainage, economics, and aesthetics. In general, the designer should consider the following:

- In level terrain, the designer’s ability to efficiently satisfy the design controls can be accomplished without construction difficulty or extraordinary expense; however, as the terrain becomes more challenging, as in rolling or mountainous terrain and developed areas, significantly more complicated construction techniques must be employed to achieve compatibility between the road alignment and the surrounding ground. Introducing vertical curves to minimize the disruption to the existing environment may result in sight distance or clearance issues and may require truck climbing lanes for higher-speed facilities. The designer must balance these factors when introducing vertical curves into a roadway alignment.

- Where a highway crosses a waterway the profile of the highway must be consistent with the design flood frequency and elevation. (See Chapter 8 Drainage and Erosion Control).
The roadway elevation must provide sufficient clearance and cover for construction of culverts and other components of the drainage system.

When a highway is located where environmental resources exist the vertical alignment should be designed to minimize impacts.

Vertical alignment should be properly coordinated with the natural topography, available right-of-way, utilities, roadside development, and natural and man-made drainage patterns.

4.3.1 Grades

Roadway grades have a direct correlation to the uniform operation of vehicles. Vehicle weight and the steepness of the roadway grade have a direct relationship on the ability of the driver to maintain uniform speed. Exhibit 4-21 presents the recommended maximum highway grades in an effort to achieve uniform vehicular operation for various design speeds. Flatter grades should be used where possible.

On a long ascending grade it is preferable to place the steepest grade at the bottom and flatten the grade near the top. In order to facilitate positive highway drainage, the highway must have a minimum longitudinal tangent gradient of 0.4% and preferably 0.5%.

Maximum grade recommendations are presented for the area types described in Chapter 3 and vary depending upon the terrain in which the facility is located. For most locations in Massachusetts, the level or rolling terrain category is applicable.

Where pedestrian or bicycle facilities follow a roadway alignment, these facilities should follow the prevailing grade of the adjacent roadway. See Chapter 11 for design guidance on facilities in separate rights-of-way. If bicycles share the roadway with motor vehicles, consideration should be given to providing extra width or a bicycle climbing lane on the uphill side. A designated bicycle lane may not be necessary on a downgrade where bicyclists travel as fast (or nearly as fast) as motor vehicles.

In addition to the maximum grade, the designer must consider the length of the grade. The gradient in combination with its length will determine the truck speed reduction on upgrades. Exhibit 4-22 shows how a typical heavy truck, approaching a grade at a given speed, loses speed as it travels along the length of the grade. For general design purposes, a 10 mph speed reduction should be used.
### Exhibit 4-21

**Recommended Maximum Grades**

<table>
<thead>
<tr>
<th>Freeways (All Areas)</th>
<th>Percent Grade for Selected Design Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain</td>
<td>50</td>
</tr>
<tr>
<td>Level</td>
<td>4</td>
</tr>
<tr>
<td>Rolling</td>
<td>5</td>
</tr>
<tr>
<td>Mountainous</td>
<td>6</td>
</tr>
</tbody>
</table>

*Grades 1% steeper than the value shown may be provided in mountainous terrain or in urban areas with crucial right-of-way controls.*

<table>
<thead>
<tr>
<th>Arterials and Highways (Rural Villages, Suburban High-Intensity, Suburban Town Center, and Urban Areas)</th>
<th>Percent Grade for Selected Design Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain</td>
<td>30</td>
</tr>
<tr>
<td>Level</td>
<td>8</td>
</tr>
<tr>
<td>Rolling</td>
<td>9</td>
</tr>
<tr>
<td>Mountainous</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Arterials and Highways (Rural Natural, Rural Developed, and Suburban Low Intensity Areas)</th>
<th>Percent Grade for Selected Design Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain</td>
<td>40</td>
</tr>
<tr>
<td>Level</td>
<td>5</td>
</tr>
<tr>
<td>Rolling</td>
<td>6</td>
</tr>
<tr>
<td>Mountainous</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Collectors and Local Roads (Rural Villages, Suburban High Intensity, Suburban Town Center, and Urban Areas)</th>
<th>Percent Grade for Selected Design Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain</td>
<td>20</td>
</tr>
<tr>
<td>Level</td>
<td>7</td>
</tr>
<tr>
<td>Rolling</td>
<td>10</td>
</tr>
<tr>
<td>Mountainous</td>
<td>12</td>
</tr>
</tbody>
</table>

*Note: Short lengths of grade in urban areas, such as grades less than 500 ft in length, one-way downgrades, and grades on low-volume urban collectors may be up to 2 percent steeper than the grades shown above.*

<table>
<thead>
<tr>
<th>Collectors (Rural Natural, Rural Developed, and Suburban Low Intensity Areas)</th>
<th>Percent Grade for Selected Design Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain</td>
<td>20</td>
</tr>
<tr>
<td>Level</td>
<td>7</td>
</tr>
<tr>
<td>Rolling</td>
<td>10</td>
</tr>
<tr>
<td>Mountainous</td>
<td>12</td>
</tr>
</tbody>
</table>

*Note: Short lengths of grade in urban areas, such as grades less than 500 ft in length, one-way downgrades, and grades on low-volume urban collectors may be up to 2 percent steeper than the grades shown above.*

<table>
<thead>
<tr>
<th>Local Roads (Rural Natural, Rural Developed, and Suburban Low Intensity Areas)</th>
<th>Percent Grade for Selected Design Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain</td>
<td>15</td>
</tr>
<tr>
<td>Level</td>
<td>9</td>
</tr>
<tr>
<td>Rolling</td>
<td>12</td>
</tr>
<tr>
<td>Mountainous</td>
<td>17</td>
</tr>
</tbody>
</table>

*Note: Short lengths of grade in urban areas, such as grades less than 500 ft in length, one-way downgrades, and grades on low-volume urban collectors may be up to 2 percent steeper than the grades shown above.*

Source: A Policy on Geometric Design of Highways and Streets, AASHTO, 2004. Chapter 4 Rural and Urban Arterials; Chapter 5 Freeways
Exhibit 4-22
Speed-Distance Curves for a Typical Heavy Truck for Deceleration on Upgrades

Note: Curves are for grades between 0 and 9%.
For starting speeds other than 70mph, distance is interpolated along the grade curve for the desired speed reduction.

Where an upgrade is preceded by a downgrade, trucks will often increase speed to make the climb. A speed increase of 5 mph on moderate downgrades (3-5%) and 10 mph on steeper grades (6-8%) of sufficient length are reasonable adjustments. These can be used in design to allow the use of a higher speed reduction curve. However, these speed increases may not be attainable if traffic volumes are high enough that a truck is likely to be behind a passenger vehicle when descending the grade.

4.3.2 Truck Climbing Lanes
If a critical length of grade in Exhibit 4-21 is exceeded, then a truck climbing lane may be warranted provided the construction costs and environmental impact are reasonable. The Highway Capacity Manual and AASHTO’s A Policy on Geometric Design of Highways and Streets presents the detailed methodology for truck climbing lanes on two-lane highways. On freeways and expressways, the Highway Capacity Manual presents the accepted methodology.

When determining if a truck climbing lane is warranted, the designer must select a level of service. Preferably, the level of service should
not be allowed to fall below that desired for the project as determined through the parameters described in Chapter 3 and determined in the project development process. At restricted locations, the ascending roadway facility may be operating below these guidelines before a truck climbing lane is warranted. If a truck climbing lane is warranted and the costs are reasonable, the following criteria should be followed for designing the lane:

- Lane width should be the same as the adjacent lane, but not less than 12 feet. The useable shoulder width should be at least 4 feet.
- The full width of the climbing lane should be achieved at the point where a truck will have reduced its speed by 10 mph.
- The full width of the climbing lane should, when feasible, extend to the point where the truck speed has returned to within 10 mph of the typical auto speed. At a minimum it should extend to a point where full passing sight distance becomes available.
- The entering taper should preferably be 25:1 and at least 150 feet long.
- An exiting or merging taper not sharper than 50:1 is preferred. It should be 200 feet or more in length.

4.3.3 Vertical Curves
Vertical curves are employed to effect gradual change between roadway grades. Vertical curves should be simple in application and should result in a design that is safe and comfortable in operation, pleasing in appearance, and adequate for drainage. The design of vertical curves should comply with the following general considerations:

- All vertical crest and sag curves are in the shape of a parabola. The computations for vertical curves are shown in Exhibits 4-23, 4-24, and 4-25. Design controls for vertical curves are generally based on the formula \( K = \frac{L}{A} \) where \( L \) is the length of curve in feet and \( A \) is the algebraic difference in grades expressed as a percent. The designer's use of \( K \) values facilitates geometric design. The tables are calculated to provide the minimum sight distances for the corresponding design speed.
- \( K \) is the horizontal distance required to effect a 1% change in grade.
- Vertical alignment should use a smooth grade line with gradual changes, consistent with the type of highway and character of terrain. Grades with break points and short tangent lengths should be avoided.

- On long ascending grades, it is preferable to place the steepest grade at the bottom and flatten the grade near the top. It is also preferable to break a sustained grade with short intervals of flatter grades.

- Maintain moderate grades through intersections to facilitate starting and turning movements. See Chapter 6, (Intersections) for specific information pertaining to vertical alignment at intersections.

- Roller Coaster type profiles, where the roadway profile closely follows a rolling natural ground line along a relatively straight horizontal alignment, should be avoided. This type of profile is aesthetically undesirable and may be more difficult to drive.

- As with horizontal alignment, broken back curvature (short tangent between two curves in same direction) should be avoided because drivers do not expect to encounter this arrangement on typical highway geometry.

- Avoid using sag vertical curves in a cut section unless adequate drainage can be provided.
Exhibit 4-23
Parabolic Vertical Curves

To Find Low Point or High Point on a Curve

\[ X = \frac{L (G_1)}{G_1 - G_2} \]

\[ L = \text{Length of curve in feet} \]

\[ X = \left\{ \begin{array}{l}
\text{Distance of high point of a crest curve from P.V.C. in feet.} \\
\text{Distance of low point of a sag curve from P.V.C. in feet.}
\end{array} \right. \]

\[ G_1, G_2 = \text{Rates of grades expressed in } \% \text{ with proper sign} \]

Note: In all of the above formulas, \((G_1 - G_2)\) is the algebraic difference in percent grade.

Source: MassHighway
Exhibit 4-24
Parabolic Vertical Curves

\[ G_1, G_2 = \text{Rate of grade expressed in percent, with proper sign} \]
\[ A = (G_1 - G_2) \text{ algebraic difference of rates of grades expressed in percent} \]
\[ L = \text{Length of curve in stations (The length is measured on a horizontal plane)} \]
\[ M = \text{Middle ordinate in feet} \]
\[ d, d_1 = \text{Corrections (offsets) from grade line to curve in feet} \]
\[ t, t_1 = \text{Distance in stations from P.V.C. or P.V.T. that points } k, k_1 \text{ on the curve are located} \]
\[ a = \text{Corrector factor, constant for any one curve} \]
\[ M = \frac{L (G_1 - G_2)}{8} \text{ or } M = \frac{1}{2} \left( \text{Elev. Point } I - \frac{\text{Elev. at P.V.C. + Elev. at P.V.T.}}{2} \right) \]
\[ a = \frac{M}{\left( \frac{L}{2} \right)^2} = \frac{A}{2L} \]
\[ d = at^2, d_1 = at_1^2 \text{ etc.} \]

\[ \text{Elev of } k = \text{Elev. of } P_1 \pm d, \text{Elev. of } k_1 = \text{Elev. of } P_1 \pm d_1, \text{ etc. When the algebraic difference of grades is positive,} \]

the offsets of \( d, d_1 \) … are subtracted from the elevations \( P, P_1 \) … on the tangent.

When the algebraic difference of grades is negative, the offsets \( d, d_1 \) … are added to the elevations \( P, P_1 \) … on the tangent.

Source: MassHighway
Exhibit 4-25
Parabolic Vertical Curves

TO FIND SLOPE OF CURVE AT ANY POINT

$G_1, G_2 = \text{Rate of grade expressed in percent, with proper sign}$

$(G_1 - G_2) = \text{Algebraic difference in rates of grades}$

$S_1$ and $S_2 = \text{Slope in percent of a tangent drawn at points 01, 02 \ldots at distances, D_1, D_2 \ldots from P.V.C. of vertical curve}$

$D_1, D_2 \ldots = \text{Distance in stations}$

$L = \text{Length of vertical curve in stations}$

$S_1 = \frac{|G_1 - G_2|}{L}$, $S_2 = \frac{|G_1 - G_2|}{L}$

The sign of $|G_1 - G_2|$ is always positive (absolute value)

* Assign the proper sign to $G_1$
  ± Becomes a plus (+) for sag curves
  ± Becomes a minus (−) for crest curves

Note: The above formula may be used to find the rate of grade of a tangent at any point on a vertical curve and to check slopes of curves for drainage purposes.

Source: MassHighway
4.3.3.1 Crest Vertical Curves

The primary control for crest vertical curves is providing adequate stopping sight distance as described in Chapter 3. Exhibit 4-26 shows computed K values for lengths of vertical curves as required for the value of stopping sight distance for each design speed.

Exhibit 4-26
Design Control for Stopping Sight Distance for Crest Vertical Curves

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Stopping Sight Distance (ft)</th>
<th>Rate of Vertical curvature, Ka</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>80</td>
<td>3.0</td>
</tr>
<tr>
<td>20</td>
<td>115</td>
<td>6.1</td>
</tr>
<tr>
<td>25</td>
<td>155</td>
<td>11.1</td>
</tr>
<tr>
<td>30</td>
<td>200</td>
<td>18.5</td>
</tr>
<tr>
<td>35</td>
<td>250</td>
<td>29.0</td>
</tr>
<tr>
<td>40</td>
<td>305</td>
<td>43.1</td>
</tr>
<tr>
<td>45</td>
<td>360</td>
<td>60.1</td>
</tr>
<tr>
<td>50</td>
<td>425</td>
<td>83.7</td>
</tr>
<tr>
<td>55</td>
<td>495</td>
<td>113.5</td>
</tr>
<tr>
<td>60</td>
<td>570</td>
<td>150.6</td>
</tr>
<tr>
<td>65</td>
<td>645</td>
<td>192.8</td>
</tr>
<tr>
<td>70</td>
<td>730</td>
<td>246.9</td>
</tr>
<tr>
<td>75</td>
<td>820</td>
<td>311.6</td>
</tr>
</tbody>
</table>

Note: Rate of vertical curvature, K, is the length of curve per percent algebraic difference in intersection grades (A). K = L/A
Source: A Policy on Geometric Design of Highways and Streets, AASHTO 2004, Chapter 3 Elements of Design

Crest vertical curves must be balanced with the horizontal alignment. The beginning of the horizontal curve should not be positioned beyond the crest curve in a way that does not allow the advancing driver the ability to see the upcoming change in the horizontal alignment.

For the design of crest vertical curves, the following shall apply:

- **Stopping Sight Distance** —should be available on crest vertical curves. A height of eye of 3.5 feet and a height of object of 2 feet are used. A minimum length curve should be used for driver comfort and vehicular control. The line-of-sight intercept is 2.75 feet or above when the view obstruction is at the midpoint of the sight line.
Where: \[ L_{\text{min}} = 3V \]
\[ L_{\text{min}} \text{ is in feet, } V \text{ is in mph} \]

Flat vertical curves of less than 0.3% for distances of 50 feet or greater from the crest require careful drainage design. This equates to a \( K \) value of 167 or greater.

4.3.3.2 Sag Vertical Curves
Headlight sight distance (see Chapter 7 for additional detail at underpasses) is the primary design control for sag vertical curves on non-illuminated roadways. The height of the headlights is assumed to be 2 feet. The upward divergence of the beam is 1 degree from the longitudinal axis of the vehicle. The curvature of the sag should be such that the headlights will illuminate the pavement sufficiently to provide adequate stopping sight distance.

Exhibit 4-27 shows the range of rounded values of \( K \) selected as design controls which provide for minimum headlight sight distance. Minimum lengths of vertical curves for flat gradients are equal to 3 times the design speed in mph.

As for crest curves careful drainage design must be made for \( K \) values of greater than or equal to 167.

Designer should check the sight distance under bridges.

4.3.4 Vertical Clearances
Exhibit 4-28 provides the required vertical clearances for all highway types and other clearance criteria. The location of the critical clearance generally occurs where the highest point on the crown line and/or runoff line of the road underpass falls directly under the lowest elevation of the bottom overpass superstructure support member. Refer to the MassHighway Bridge Manual for the method of determining clearances.
### Exhibit 4-27
**Design Control for Sag Vertical Curves**

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Stopping Sight Distance (ft)</th>
<th>Rate of Vertical Curvature, $K_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Calculated</td>
</tr>
<tr>
<td>15</td>
<td>80</td>
<td>9.4</td>
</tr>
<tr>
<td>20</td>
<td>115</td>
<td>16.5</td>
</tr>
<tr>
<td>25</td>
<td>155</td>
<td>25.5</td>
</tr>
<tr>
<td>30</td>
<td>200</td>
<td>36.4</td>
</tr>
<tr>
<td>35</td>
<td>250</td>
<td>49.0</td>
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<td>40</td>
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<td>45</td>
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<tr>
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<td>55</td>
<td>495</td>
<td>114.9</td>
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<tr>
<td>60</td>
<td>570</td>
<td>135.7</td>
</tr>
<tr>
<td>65</td>
<td>645</td>
<td>156.5</td>
</tr>
<tr>
<td>70</td>
<td>730</td>
<td>180.3</td>
</tr>
<tr>
<td>75</td>
<td>820</td>
<td>205.6</td>
</tr>
</tbody>
</table>

Note: Rate of vertical curvature, $K_a$ is the length of curve per percent algebraic difference in intersection grades.  

### Exhibit 4-28
**Vertical Clearances**

<table>
<thead>
<tr>
<th>Minimum1-4 (ft)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.5</td>
<td>Bridges over expressways/freeways</td>
</tr>
<tr>
<td>16.5</td>
<td>Bridges over arterial</td>
</tr>
<tr>
<td>16.5</td>
<td>Freeway Tunnels</td>
</tr>
<tr>
<td>16.5</td>
<td>Tunnels for all other roadway classes</td>
</tr>
<tr>
<td>16.5</td>
<td>Bridges over collector</td>
</tr>
<tr>
<td>16.5</td>
<td>Bridges over local road</td>
</tr>
<tr>
<td>See Note 2</td>
<td>Roadway bridge over railroad</td>
</tr>
<tr>
<td>17.0</td>
<td>Sign bridge or pedestrian bridge over roadway</td>
</tr>
<tr>
<td>See Note 3</td>
<td>Highway in vicinity of an airport</td>
</tr>
</tbody>
</table>

1. The Chief Engineer shall approve any clearance less than the minimum clearance in writing.  
2. The MassHighway Bridge Engineer will coordinate clearance over railroads with the railroads.  
3. Clearance in the vicinity of an airport will be coordinated with the FAA through the FHWA.  
4. Minimum values allow 4 inches for paving overlays in all cases.  
5. New or reconstructed structures should provide 16.5 ft clearance over entire roadway width. In a highly urbanized area a minimum clearance of 14.5 ft may be provided where an alternate route with 16.5 ft clearance is provided. Existing structures that provide 14.5 ft clearance may be retained, if allowed by local statute.  
6. Provisions must be made for lighting, overhead signs and pavement overlays.  
4.3.5 Establishing Profiles
When establishing the vertical profile, use the following criteria:

- On freeways, a minimum distance of 1,500 feet should be provided between points of intersection. On other major highways, 1,200 feet is the minimum distance.

- The vertical profile should be in balance with the horizontal alignment (See Section 4.4).

- On divided highways with a median less than 30 feet, including shoulders, the median edges should be at the same elevation. For wider medians, the profiles for the two roadways should be established independently.

- Vertical profiles of urban and local roads are determined considering the existing topography, construction costs, safety, and the abutting properties. The evaluation should establish the critical abutting locations. Buildings, driveways, and steps are especially important when establishing profiles.

4.4 Combination of Horizontal and Vertical Alignment
Horizontal and vertical alignments should be designed concurrently. Their designs complement each other and poorly designed combinations can reduce the quality of both.

Coordinate the horizontal and vertical alignment to obtain safety, uniform speed, pleasing appearance, and efficient traffic operation. Coordination can be achieved by plotting the location of the horizontal curves on the working profile to help visualize the highway in three dimensions.

Horizontal and vertical alignments are among the most important of the permanent design elements. Quality in their design and in their combined design increases usefulness and safety, encourages uniform speed, and improves appearance. The following general controls should be considered in balancing horizontal and vertical alignments:

- Balance curvature and grades. Use of steep grades to achieve long tangent and flat curves, or excessive curvature to achieve flat grades, are both poor designs.
Vertical curvature superimposed on horizontal curvature generally results in a more pleasing facility. Successive changes in profile not in combination with horizontal curvature may result in a series of dips not visible to the driver.

A horizontal curve should not begin or end at or near the top of a crest vertical curve. This condition can be unsafe, especially at night, if the driver does not recognize the beginning or ending of the horizontal curve. Safety is improved if the horizontal curve leads the vertical curve, that is, the horizontal curve is made longer than the vertical curve in both directions.

Curvature in the horizontal plane should be accompanied by comparable length of curvature in the vertical plane.

Awkward combinations of curves and tangents in both the horizontal and vertical planes should be avoided (i.e., "broken back" curves).

Horizontal and vertical curvatures should be coordinated to avoid combinations that appear awkward when viewed from a low angle.

Ideally the vertices of horizontal curves (PI) and vertical curves (PVI) should coincide or be within 1/4 phase of each other.

Horizontal curvature should lead vertical curvature. i.e., the horizontal curve should be longer than the vertical curve and the PVT and PC should not be at the same point.

The alignment designs should enhance attractive scenic views of the natural and manmade environment, such as rivers, rock formations, parks, and outstanding man-made structures.

In residential areas, the alignment design should minimize nuisance factors to the neighborhood. Generally, a depressed facility makes a highway less visible and less noisy to adjacent residents. Minor horizontal adjustments can sometimes be made to increase the buffer zone between the highway and clusters of homes.

Horizontal curvature and profile should be as flat as feasible at intersections where sight distance along both roads is important and vehicles may have to slow or stop.

On divided highways, consideration of variation in the width of the median and the use of independent alignments is needed to derive the design and operational advantages of one-way roadways.
On two-lane roads, the need for safe passing sections (at frequent intervals and for an appreciable percentage of the length of the roadway) often supersedes the general desirability for combination of horizontal and vertical alignment. Passing zones with long tangent sections are needed to secure sufficient passing sight distance.

Avoidance of a sharp horizontal curve at or near the low point of a pronounced sag vertical curve is important. The road ahead is foreshortened and any horizontal curve that is not flat assumes an undesirably distorted appearance. Further, vehicular speeds, particularly of trucks, often are high at the bottom of grades and erratic operation may result, especially at night.

To maintain drainage, vertical and horizontal curves should be designed so that the flat profile of a vertical curve will not be located near the flat cross slope of the superelevation transition.

The designer is directed to use the guidelines found in the AASHTO Policy on Geometric Design of Highways and Streets, Chapter 3: "Elements of Design, and other applicable publications.

4.5 For Further Information

- Practical Highway Esthetics, ABCE, 1977.