Roadway Geometric Design 2

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INTRODUCTION

Geometric design is the assembly of the fundamental three-dimensional features of the highway that are related to its operational quality and safety. Its basic objective is to provide a smooth-flowing, crash-free facility. Geometric roadway design consists of three main parts: **cross section** (lanes and shoulders, curbs, medians, roadside slopes and ditches, sidewalks); **horizontal alignment** (tangents and curves); and **vertical alignment** (grades and vertical curves). Combined, these elements provide a three-dimensional layout for a roadway.

This course is the **second** in a series of five volumes that summarizes and highlights the geometric design process for modern roads and highways. Subjects covered include: *vertical alignments (grades, curves, design controls); and roadway cross-sections (lanes, shoulders, curbs, slopes).* The contents of this document are intended to serve as guidance and not as an absolute standard or rule. The course objective is to give engineers and designers an in-depth look at the principles to be considered when selecting and designing roads.

The *American Association of State Highway and Transportation Officials (AASHTO)* publishes and approves information on geometric roadway design for use by individual state transportation agencies. For this course, AASHTO's **A Policy on Geometric Design of Highways and Streets** (also known as the "Green Book") will be used primarily for fundamental geometric design principles. This text is considered to be the primary guidance for U.S. roadway geometric design.

OFFTRACKING

Offtracking occurs when a vehicle's rear wheels do not precisely follow the same path as the front wheels when turning or traveling through a horizontal curve. Offtracking is dependent on curve/turn radii, number and location of articulation points, and vehicle wheelbase lengths.

Curve without superelevation (low speed)> rear wheels track inside front wheels

Superelevated curve> rear wheels may track inside front wheels (more or less)

High speeds> rear wheels may track outside front wheels

The amount of widening on horizontal curves for offtracking depends on curve radius design vehicle characteristics (track width for passing, lateral vehicle clearance, width of inner lane vehicle front overhang, rear overhang width, curve difficulty allowance width). This amount increases with design vehicle size and decreases with increasing curve radii.

<u>Traveled-Way Widening on Horizontal Curves</u>

Sometimes, roadways with horizontal curves need to be widened in order to obtain operational conditions similar to tangent sections. The primary reasons for widening on certain curves are:

1. Design vehicle offtracks (rear wheels track inside front wheels) when traversing horizontal curves
2. Drivers difficulty in maintaining vehicles in center of lane

The traveled-way width is dependent on many of the same variables as for offtracking: *track width for passing/meeting vehicles; lateral vehicle clearance; width of inner lane vehicle front overhang;* and *curve difficulty allowance width.*

Normally, the design vehicle should be a truck since offtracking is much greater for them versus passenger cars – **WB-62** is considered appropriate for two-lane open highways.

AASHTO recommends a minimum widening of **2.0 feet** due to economic reasons. Widening on a two-lane, one-way riding surface of a divided highway should be equivalent to a two-lane, two-way highway.

Traveled-way widening on horizontal curves should produce gradual transitions to the curve for smooth alignments of the roadway edges and fit the paths of entering /exiting vehicles. The following guidelines are for both ends of highway curves:

- Widening should be only on the inside edge for simple curves.
- For curves with spirals, widening should be applied to the inside edge or equally divided by the centerline.
- Curve widening transitions should be gradual and sufficient for the traveled way to be fully usable.
- Changes in width are transitioned over a distance of 100 to 200 feet.
- The edge of traveled way should have a smooth and graceful appearance throughout the widening transition.
- For roadways without spirals, one-half to two-thirds of the transition length should be based along the tangent section. For roads with spirals, the width increase is distributed along the spiral length.
- Widening sections may be fully detailed on the roadway construction plans.

Turning Roadway Width Criteria (Intersections)

- Vehicle type: based on size and frequency of vehicle expected
- Curve radii: in addition to vehicle track width determine roadway width
- Expected speed

Turning roadways are classified by: *number of lanes; opportunity for passing;* and *one-way or two-way.*

Design Methods for Turning Roadways

Case I One-lane, one-way operation – no passing provision

Used for minor turning movements, moderate turning volumes, short connecting roadway

Remote chance of vehicle breakdown

Case II One-lane, one-way operation – passing provision

Widths are sufficient for all turning movements of moderate to heavy traffic volumes within capacity of single-lane connection

For breakdowns, low traffic can be maintained

Case III Two-lane, either one or two-way

Two lanes needed for traffic volume

Traffic Conditions for Turning Roadway Widths

Traffic Condition A Predominantly Passenger Car (P) vehicles, some Single-Unit Trucks (SU-30)

Traffic Condition B Majority of Single-Unit Trucks (SU-30), some tractor-semitrailer combination trucks (WB-40) 5 to 10%

Traffic Condition C Predominantly tractor-semitrailer combination (WB-40)

For turning roadways, their width includes shoulders or lateral clearance outside the traveled way. Shoulder widths may vary from none (curbed urban streets) to 2 feet or more (highways). For roadways without curbs or with sloping curbs, adjacent shoulders should match those of the approaches.

Table 3-30. Range of Usable Shoulder Widths or Equivalent Lateral Clearances Outside of Turning Roadways, Not on Structure

	Metric		U.S. Customary	
Turning Roadway Condition	Shoulder Width or Lateral Clearance Outside of Traveled-Way Edge (m)		Shoulder Width or Lateral Clearance Outside of Traveled-Way Edge (ft)	
	Left	Right	Left	Right
Short length, usually within channelized intersection	0.6 to 1.2	0.6 to 1.2	2 to 4	2 to 4
Intermediate to long length or in cut or on fill	1.2 to 3.0	1.8 to 3.6	4 to 10	6 to 12

Note: All dimensions should be increased, where appropriate, for sight distance.

If roadside barriers are present, shoulder widths should be measured to the face of barrier (additional graded width of 2.0 feet). For other than low-volume roadways, right shoulders should be stabilized a minimum of 4.0 feet.

Sight Distance – Horizontal Curves

Sight distance across the inside of curves is a crucial design control for any roadway horizontal alignment. For horizontal alignments, the sight line is a chord of the curve. The **stopping sight distance** is along the centerline of the curve's inside lane.

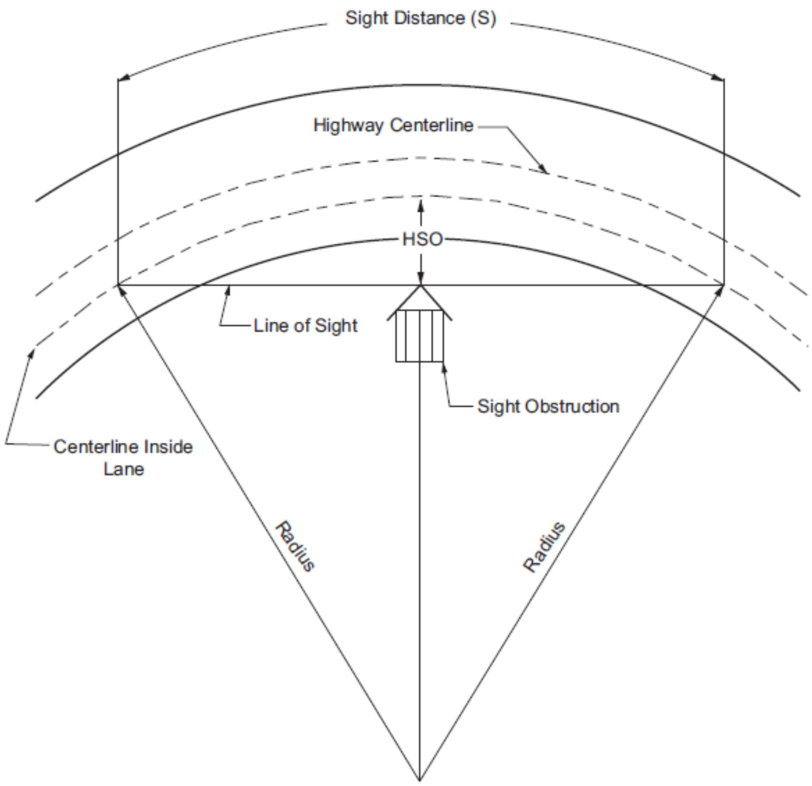


Figure 3-23. Diagram Illustrating Components for Determining Horizontal Sight Distance

Eye Height:	3.50 feet	
Object Height:	2.00 feet	Stopping sight distance
	2.75 feet	Midpoint of sight line where cut slope obstructs sight

Equation 3-36 can be used for circular curve lengths greater than the sight distance for the particular design speed.

$$HSO = R\left[1 - \cos\left(\frac{28.65S}{R}\right)\right]$$

where:

HSO = Horizontal sight line offset, ft

S = Stopping sight distance, ft

R = Radius of curve, ft

At locations where adequate stopping sight distance is not available, the following alternatives may be used: *increase offset to sight obstructions; increase curve radii; or reduce design speed.*

Minimum values for **passing sight distance** (two-lane road) are approximately twice the minimum stopping sight distance.

Eye Height: 3.50 feet

Object Height: 3.50 feet Passing sight distance

Due to differences in sight line and stopping sight distance, design for passing sight distance should be limited to tangents and flat curves.

GENERAL CONTROLS

- Any roadway alignment should be directional as possible.
- Minimum radius values should be avoided whenever possible.
- Consistent roadway alignment is desirable.
- Horizontal curves should be long enough for aesthetic purposes.
- Sharp curves should be avoided on lengthy high embankments.
- Exercise caution when using compound circular curves.
- Sudden reversals in alignment should be avoided.
- Avoid “broken-back” or “flat-back” curve arrangements, where possible.
- Horizontal alignment should be carefully coordinated with the roadway profile.
- Avoid changing median widths on tangent alignments.

VERTICAL ALIGNMENT

A roadway’s vertical alignment is comprised of crest and sag curves, and the straight grades connecting them. Geometric design of the proposed roadway profile is related to safety, vehicle operations, drainage, and construction issues. The type of terrain to be traversed also plays a major role in the alignment of roadways – particularly the profile. It can be classified into the following categories:

Level: Both horizontal and vertical sight distances are lengthy without difficulty

Rolling: Natural slopes rise or fall below the roadway with occasional steep slopes

Mountainous: Abrupt changes in ground elevation with respect to the roadway

Tangent Grades

Roadway design should encourage uniform operation throughout the proposed facility. Nearly all passenger cars can readily negotiate grades as steep as 4 to 5 percent without a significant loss in speed. Speeds decrease progressively with grade increases.

Vertical grades have a greater effect on truck speeds as opposed to passenger cars. Tangent grades balance construction costs with desired operations. Lengthy grades greater than 3% start to influence passenger car speeds while shorter, steeper grades affect truck speeds. Although the average speeds of trucks and passenger cars are similar for level roadway sections, trucks usually increase downgrade speeds up to 5% and decrease upgrade speeds by 7%. Their maximum speed is dependent on the length/steepness of the grade and the truck's weight/power ratio (gross vehicle weight divided by the net engine power).

Travel times and speeds for trucks are byproducts of the weight/power ratio. Presently, acceptable values for highway users are approximately **200 lb/hp**. These values have been steadily decreasing over the years resulting in greater power and better climbing ability on upgrades.

Typically, vertical grades should be less than the maximum design grade. Design guidelines for maximum grades have been established from grade controls presently in use – however, these maximum rates should be rarely used, if possible.

Design Speed	Maximum Grade
70 mph	5%
30 mph	7 to 12% (depending on terrain)

On major routes, maximum grade values of 7 to 8 percent are commonly used for 30 mph design speed. In most cases, grades should be less than the maximum design grade. However, for one-way downgrades less than 500 ft long, the maximum grade should be approximately 1% steeper than other locations. The maximum may be 2% steeper for low-volume rural highways.

Maintaining adequate minimum grades is a primary concern in many locations. For roadways with adequate cross slopes for surface drainage, a typical value for minimum grade is 0.5 percent. The vertical profile may affect road drainage by creating very flat roads/sag curves that may have poor drainage, or steep roads with high velocity flows.

0.3 percent	*Minimum control in some states*
0.15 percent	*Practical minimum for flat terrain*
0 percent (flat)	*Should be avoided – relies totally on roadway cross-slope for drainage*

Critical Length of Grade is the maximum length of upgrade on which a loaded truck may operate without an unacceptable speed reduction. Research has shown that the more a vehicle deviates from the average roadway speed, the greater its chances of crashing. The following data may be used to determine values for critical lengths of grade:

– Size , power, and gradeability data for design vehicle
  A typical loaded truck used as a design control has a weight/power ratio of 200 lb/hp

– Entrance speeds to critical length
  The average running speed can be used for vehicle speeds at the beginning of an uphill approach

– Minimum tolerable speeds of trucks on upgrades
  Roadways should be designed to prevent intolerable truck speed reductions for following drivers

A **Climbing Lane** is an added lane for slow-moving vehicles (uphill) so other vehicles may use the normal roadway lanes to pass. These lanes may be used for locations where a level of service or truck speed is much less on an upgrade versus the approach. Climbing lanes are an inexpensive way to overcome capacity reductions, improve operation in truck congestion areas, and reduce crashes.

<u>Justification Criteria for Climbing Lanes</u>

- Upgrade traffic flow rate exceeds 200 vehicles per hour
- Upgrade truck flow rate exceeds 20 vehicles per hour
- One of the following exists:

  10 mph or greater speed reduction expected by heavy trucks

  Level of service of E or F

  Reduction of 2 or more levels of service from approach segment to grade

Successful methods for increasing passing opportunities on 2-lane roads include: passing lanes; turnouts; shoulder driving; and shoulder driving.

A **Passing Lane** is an additional lane to improve traffic operations in low capacity sections. A minimum sight distance of 1000 feet is recommended for taper approaches. The optimal lane length is typically 0.5 to 2 miles with longer lane lengths for higher traffic volumes. Transition tapers at the ends of added-lane sections can be designed from the following equations (Equations 3-37 and 3-38):

$$L = WS$$

45 mph or greater

$$L = \frac{WS^2}{60}$$

Less than 45 mph

where:

L = Length of taper, ft

W = Width, ft

S = Speed, mph

Table 3-31. Optimal Passing Lane Lengths for Traffic Operational Efficiency (*28, 29*)

Metric		U.S. Customary	
One-Way Flow Rate (veh/h)	Passing Lane Length (km)	One-Way Flow Rate (veh/h)	Passing Lane Length (mi)
100–200	0.8	100–200	0.50
201–400	0.8–1.2	201–400	0.50–0.75
401–700	1.2–1.6	401–700	0.75–1.00
701–1200	1.6–3.2	701–1200	1.00–2.00

A **Turnout** is a widened, unobstructed shoulder area for slow-moving vehicles to pull out of traffic (low volume roads, difficult terrain, etc.).

Typical entry & exit taper lengths: *50 to 100 feet*

Minimum turnout width: *12 feet 16 feet (desirable)*

Minimum sight distance: *1000 feet on approach*

Shoulder driving is a practice where slow-moving vehicles move to the shoulder when approached from the rear by another vehicle, and returns to the roadway after being passed. This custom occurs where there are adequate paved shoulders that function as continuous turnouts. Shoulder widths should be a minimum of 10 feet, with 12 feet as a desirable value.

Shoulder use sections are segments where slow vehicles are permitted to use paved shoulders at specific signed sites (similar to shoulder driving). This application is a more limited use of paved shoulders. Lengths typically range from 0.2 to 3 miles with minimum widths of 10 feet (preferably 12 feet).

VERTICAL CURVES

A road's vertical alignment consists of road slopes (grades) connected by vertical curves. Vertical curves (parabolic) provide a gradual change from one grade to another for vehicles to smoothly navigate any grade changes. Normally, a parabolic curve with an equivalent vertical axis is centered on the Vertical Point of Intersection (VPI). These curves are either classified as **sag** or **crest**.

Design guidelines for vertical curve lengths are generally based on providing for sufficient sight distance and driver comfort. Longer stopping sight distances should be used where possible.

The **K value** is the horizontal distance needed to create a one-percent change in gradient. It is a measure of curvature and is expressed as the ratio of the vertical curve length to the algebraic difference in the grades (L/A). This is useful in determining the horizontal distance from the Vertical Point of Curvature (VPC) to the sag or crest points. The K value can also be useful for determining minimum vertical curve lengths.

Terms

A = algebraic difference in grades (percent)

L = vertical curve length

VPC = begin of vertical curve

VPT = end of vertical curve

G1 = initial roadway (tangent) grade

G2 = final roadway (tangent) grade

h_1= Height of eye above roadway

h_2= Height of object above roadway

L = vertical curve length

VPI = point of vertical interception (intersection of initial and final grades)

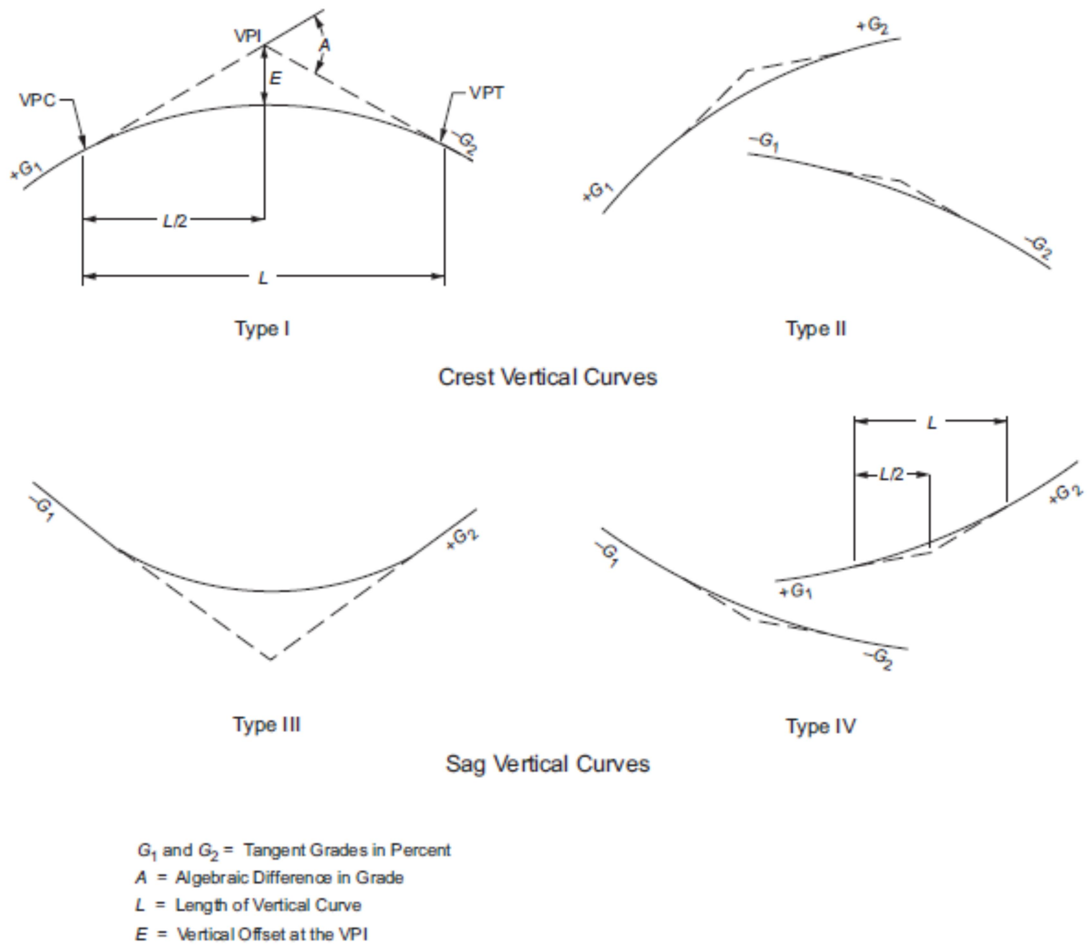


Figure 3-41. Types of Vertical Curves

SAG VERTICAL CURVES

Sag vertical curves have a tangent slope at the end of the curve which is higher than at the beginning. Sag curves appear as valleys by first going downhill, reaching the bottom of the curve, and continuing uphill (resembling an upward concave curve).

Sag Vertical Curve Criteria

Headlight sight distance Passenger comfort Drainage control General appearance

The most important determinant of sag curve length is **headlight sight distance**. When traveling on a sag curve at night, this sight distance is limited by the headlight position and direction. This distance must be adequate for the driver to see a roadway obstruction and stop within the headlight sight distance. The sag curve length should be of sufficient length for the light beam distance to be approximately equal to the stopping sight distance in order for drivers to see the roadway ahead.

Headlight Sight Distance Assumptions

Headlight height: 2 feet

Upward divergence of light beam from longitudinal axis of vehicle: 1 degree

$$L = \frac{AV^2}{46.5}$$

where:

L = length of sag vertical curve, ft

A = algebraic difference in grades, percent

V = design speed, mph

The vertical curve length needed to satisfy passenger comfort is typically 50% of the needed headlight sight distance for normal conditions. A good rule-of-thumb approximation for minimum sag vertical curve length is 100A or K = 100 feet per percent change in grade.

Table 3-36. Design Controls for Sag Vertical Curves

Metric				U.S. Customary			
Design Speed (km/h)	Stopping Sight Distance (m)	Rate of Vertical Curvature, K^a		Design Speed (mph)	Stopping Sight Distance (ft)	Rate of Vertical Curvature, K^a	
		Calculated	Design			Calculated	Design
20	20	2.1	3	15	80	9.4	10
30	35	5.1	6	20	115	16.5	17
40	50	8.5	9	25	155	25.5	26
50	65	12.2	13	30	200	36.4	37
60	85	17.3	18	35	250	49.0	49
70	105	22.6	23	40	305	63.4	64
80	130	29.4	30	45	360	78.1	79
90	160	37.6	38	50	425	95.7	96
100	185	44.6	45	55	495	114.9	115
110	220	54.4	55	60	570	135.7	136
120	250	62.8	63	65	645	156.5	157
130	285	72.7	73	70	730	180.3	181
				75	820	205.6	206
				80	910	231.0	231

[a] Rate of vertical curvature, K, is the length of curve (m) per percent algebraic difference intersecting grades (A), $K = L/A$.

CREST VERTICAL CURVES

Crest vertical curves have a lower tangent slope at the end of the curve than at its beginning. Crest vertical curves are convex upwards and appears as a hill, with vehicles first going uphill, reaching the top of the curve and then continuing downhill. A crucial design criterion for these curves is **stopping sight distance** (the distance a driver can see over the curve crest). This distance is determined by the speed of roadway traffic. The appropriate equation depends on the length of the vertical curve versus the available sight distance. Equations 3-41 and 3-42 are the basic formulas for determining crest vertical curve lengths in terms of algebraic grade difference (A) and sight distance (S).

When S is less than L,

$$L=\frac{AS^2}{100\left(\sqrt{2h_1}+\sqrt{2h_2}\right)^2}$$

When S is greater than L,

$$L=2S-\frac{200\left(\sqrt{h_1}+\sqrt{h_2}\right)^2}{A}$$

where:

L = length of vertical curve, ft

A = algebraic difference in grades, percent

S = sight distance, ft

h_1 = height of eye above roadway surface, ft

h_2 = height of object above roadway surface, ft

Stopping Sight Distance Criteria

Height of Eye:	3.50 feet
Height of Object:	2.00 feet

Using the typical values for eye height and object height, the calculations for crest vertical curve lengths become the following equations (Equations 3-43 and 3-44).

When S is less than L,

$$L=\frac{AS^2}{2158}$$

When S is greater than L,

$$L=2S-\frac{2158}{A}$$

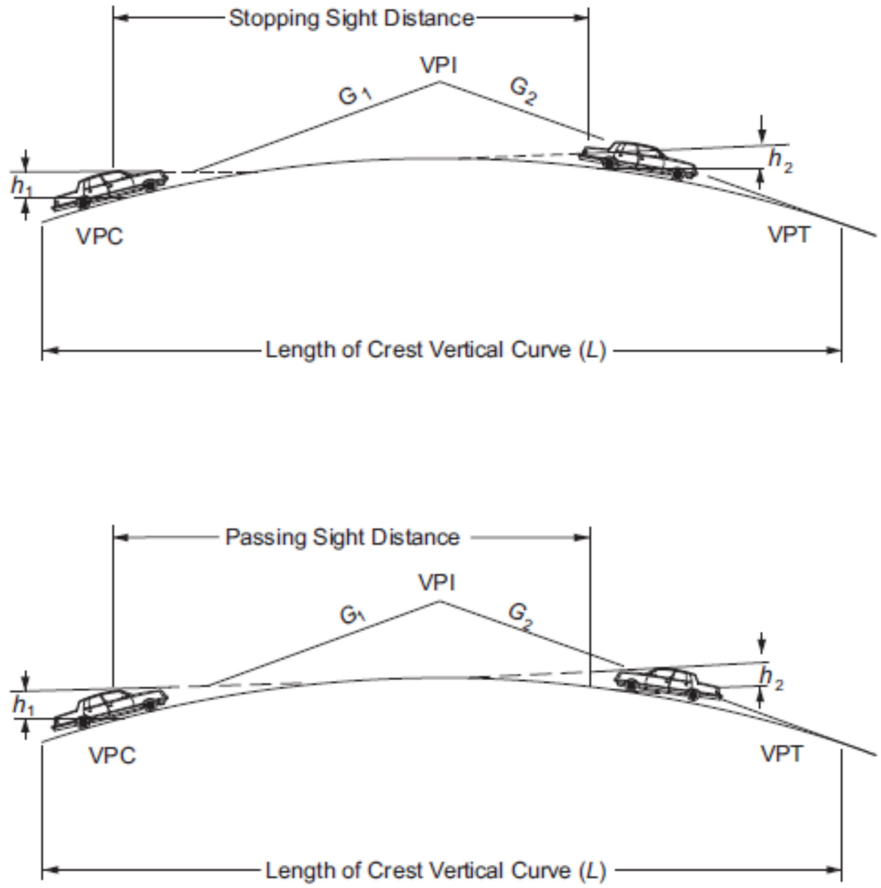


Figure 3-42. Parameters Considered in Determining the Length of a Crest Vertical Curve to Provide Sight Distance

Crest vertical curve design values for **passing sight distance** differ from stopping sight distance due to sight distance and object heights (3.50 feet) and may be determined from the following formulas (Equations 3-45 and 3-46).

When S is less than L,

$$L = \frac{AS^2}{2800}$$

When S is greater than L,

$$L = 2S - \frac{2800}{A}$$

Using passing sight distance criteria, minimum crest curve lengths are much longer than those for stopping sight distance. Typically, it is not realistic to use passing sight distance controls due to high costs of crest cuts and difficulty of integrating long vertical curves to the topography.

Passing sight criteria for crest curves may be appropriate for: *low speed roadways with gentle grades; high speeds with small grade differences;* and *locations not needing significant grading.*

Table 3-35. Design Controls for Crest Vertical Curves Based on Passing Sight Distance

Metric			U.S. Customary		
Design Speed (km/h)	Passing Sight Distance (m)	Rate of Vertical Curvature, K^a Design	Design Speed (mph)	Passing Sight Distance (ft)	Rate of Vertical Curvature, K^a Design
30	120	17	20	400	57
40	140	23	25	450	72
50	160	30	30	500	89
60	180	38	35	550	108
70	210	51	40	600	129
80	245	69	45	700	175
90	280	91	50	800	229
100	320	119	55	900	289
110	355	146	60	1000	357
120	395	181	65	1100	432
130	440	224	70	1200	514
			75	1300	604
			80	1400	700

[a] Rate of vertical curvature, K, is the length of curve per percent algebraic difference in intersecting grades (A), $K = L/A$.

General Controls for Vertical Alignments

- Use a smooth, gradual grade consistent with roadway type and terrain
- Avoid hidden dips/changes in the roadway profile
- Evaluate any proposed profile containing substantial momentum grades with traffic operations
- Avoid "broken back" (consecutive vertical curves in the same direction) gradelines
- Place steep grades at the bottom and flatter grades near the top of ascents
- Reduce grades through at-grade intersections with moderate to steep grades
- Avoid sag curves in cuts, where possible

COORDINATION OF HORIZONTAL AND VERTICAL ALIGNMENTS

Roadway geometry influences its safety performance. Research has shown that roadway factors are the **second** most contributing factor to road accidents. Crashes tend to occur more frequently at locations with sudden changes in road character (example: sharp curves at the end of long tangent roadway sections). The concept of **design consistency** compares adjacent road segments and identifying sites with changes that might appear sudden or unexpected. Design consistency analysis can be used to show the decrease in operating speed at a curve.

The horizontal and vertical geometries are the most critical design elements of any roadway. These alignments should be integrated to enhance vehicle operation, uniform speed, and facility appearance without additional costs (examples: checking for additional sight distance prior to major changes in the horizontal alignment; or revising design elements to eliminate potential drainage problems). Computer-aided design and drafting (CADD) is commonly used to facilitate the iterative three-dimensional design and produce an optimal coordination of horizontal and vertical alignments.

Design speed helps to determine roadway location and keeps all design elements (traffic, topography, geotechnical concerns, culture, future development, project limits, etc.) in balance. It limits many design values (curves, sight distance) and influences others (width, clearance, maximum gradient).

AASHTO provides the following general design guidelines regarding horizontal and vertical alignment combinations:

- Vertical and horizontal elements should be balanced to produce a design which optimizes safety, capacity, operation, and aesthetics within the location's topography.
- Avoid sharp horizontal curves near the top of a crest vertical curve or near the low point of a sag vertical curve. Using higher design values (well above the minimum) for design speed can produce suitable designs and meet driver's expectations.
- Horizontal and vertical curves should be flat as possible for intersections with sight distance concerns.
- For divided roadways, it may be suitable to vary the median width or use independent horizontal/vertical alignments for individual one-way roads.
- Roadway alignments should be designed to minimize nuisances in residential areas. Typical measures may include: depressed facilities (decreases facility visibility and noise); or horizontal adjustments (increases buffer zones between traffic and neighborhoods).
- Horizontal and vertical elements should be used to enhance environmental features (parks, rivers, terrain, etc.). Roadways should lead into outstanding views or features instead of avoiding them where possible.

<u>Exception</u>

Long tangent sections for sufficient passing sight distance may be appropriate for two-lane roads needing passing sections at frequent intervals.

ROADWAY CROSS-SECTIONS

Roadway geometric design consists of the following fundamental three-dimensional features:

Vertical alignment - grades and vertical curves (“profile”)

Horizontal alignment - tangents and horizontal curves (“centerline”)

Cross section - lanes, shoulders, curbs, medians, slopes, ditches, sidewalks

Combined, these elements contribute to the roadway’s operational quality and safety by striving to provide a smooth-flowing, crash-free facility.

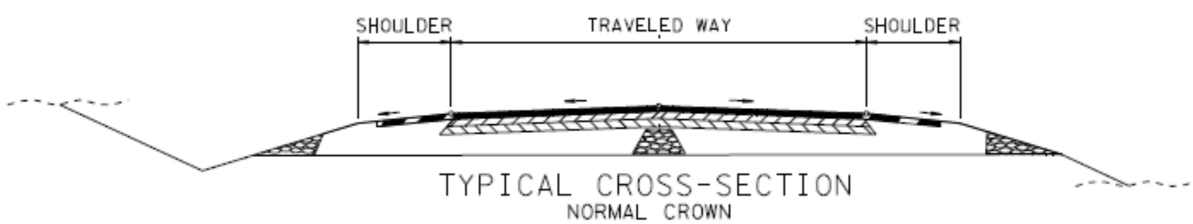
Roadway geometric design is a dynamic process with a multitude of considerations, such as *driver age and abilities; vehicle fleet variety and types; construction costs; maintenance requirements; environmental sensitivity; land use; aesthetics;* and most importantly *societal values.*

Engineers must understand how all of the roadway elements contribute to overall safety and operation. Applying design standards and criteria to ‘solve’ a problem is not enough.

The fundamental objective of good geometric design will remain as it has always been **– to produce a roadway that is safe, efficient, reasonably economic and sensitive to conflicting concerns.**

TRAVELED WAY

AASHTO defines the roadway’s traveled way as *“the portion of the roadway for the movement of vehicles, exclusive of shoulders and bicycle lanes”.* This area usually contains two or more lanes for roadway traffic.



(Ref: TDOT, Standard Roadway Drawings)

Surface Type Criteria

Initial cost	Traffic volume & composition
Soil characteristics	Climate
Maintenance cost	Pavement performance
Availability of materials	Energy conservation
Service-life cost	

Important geometric design considerations include the effect on driver behavior, surface resiliency, drainage ability, and skid resistance (see *AASHTO Mechanistic-Empirical Pavement Design Guide).* The number of required roadway lanes is typically determined by the analysis procedures in the *Highway Capacity Manual* for the level of service desired.

Signalized intersections are also an important factor controlling the capacity of an urban roadway.

Cross Slope

Cross slopes on **undivided** roads have a high point (crown) in the center and slope downward toward the roadway edges. These downward slopes can be plane, rounded, or a combination of both.

Plane - *Slope break at crown line*

Uniform slope on each side

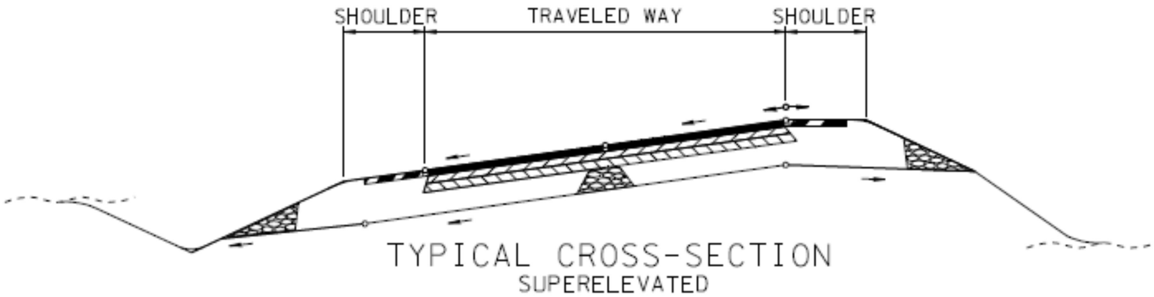
Rounded - *Parabolic cross-section*

Rounded surface at crown line

Increasing slope toward edges

The rounded section is beneficial for roadway drainage due to its steepening cross slope toward the edge of traveled way. However, disadvantages include: difficult construction; excessive outer lane cross slopes; and pavement transitions at intersection areas.

Pavement cross slopes on **divided** roadways can be unidirectional or crowned separately (i.e. undivided road). Roadways with separate crowns may be advantageous for their drainage ability but may require more drainage facilities for stormwater runoff. Unidirectional cross slopes provide more driver comfort for lane changing and drain toward or away from the roadway median. Drainage toward the median helps free the outer lanes from surface water. Drainage away from the median minimizes drainage (savings in structures) and simplifies intersection treatment.



(Ref: TDOT, Standard Roadway Drawings)

The rate of roadway cross slope is a crucial design element for cross-sections. For curved locations, the outside edge of the road is **superelevated** above the centerline. Since the road is banked toward the inside of the curve, gravity forces the vehicle down near the inside of the curve and provides some of the centripetal force needed to go around the curve.

Cross slopes over 2 percent are perceptible to motorists and may require a conscious effort in terms of vehicle steering. Steep cross slopes increase the chances of lateral skidding on wet or icy roadways or when making emergency stops on dry pavement.

The accepted range of cross slope for paved two-lane roadways (**normal crown**) is *1.5 to 2 percent*. Any effect on steering is barely perceptible for vehicles operating on crowned pavements. Cross slopes should not exceed 3% on tangent alignments – unless there are three or more lanes in one direction. Cross slope rates over 2 percent are unsuited for high-speed roadways (crowned in the center) due to a total rollover rate over 4 percent. Heavy vehicles with high centers of gravity would have difficulty in maintaining control when traveling at high speeds over steep slopes.

Steeper cross slopes (2.5 percent) may be used for roads subject to intense rainfall that need increased surface drainage. Reasonably steep lateral slopes are desirable to minimize ponding on flat roadway sections due to imperfections or unequal settlement. Completely level sections can drain very slowly and create problems with hydroplaning and ice. Open-graded pavements or pavement grooving may be used to help water drain from the roadway surface.

Greater cross slope rates need to be used for unpaved roadways. Due to surface materials, increased cross slope rates on tangent sections are needed to prevent water absorption into the road surface.

A minimum cross slope of 1.5% is suggested for curbed pavements. Steeper gutter sections may permit lower cross slope rates.

AASHTO provides tables from which desired superelevation rates can be determined based on design speed and curve radius. These tables are incorporated into many state roadway design guides and manuals.

Skid Resistance

With skidding incidents being a major safety concern, roadways need to have adequate skid resistance for typical braking and steering maneuvers. Crashes due to skidding cannot be written off simply as *driver error* or *driving too fast for conditions.*

Vertical and horizontal geometric design should incorporate skid reduction measures (pavement types, textures, etc.) for all new and reconstruction roadway projects.

Causes of Poor Skid Resistance

Rutting – causes water accumulation in wheel tracks

Polishing – reduces pavement surface microtexture

Bleeding – covers pavement surface microtexture

Dirty pavements – loses skid resistance when contaminated

Skid resistance corrective actions should produce high initial durability, long term resistance (traffic, time) and minimum resistance decrease with increasing speeds.

LANE WIDTH

The selection of a roadway lane width can affect the facility's cost as well as its performance. Lane widths are influenced by: driver comfort; operational characteristics; crash probability; and level of service.

Rivers typically increase their speeds with wider traffic lanes - so it may be appropriate to use narrower lane widths that are compatible with the alignment and intended speed at locations with low design speeds and restricted alignments. Using a **typical lane width of 12 feet** reduces maintenance costs and provides adequate clearance between heavy vehicles on two-lane, two-way rural highways with high commercial vehicle traffic.

Typical Lane Widths

Range: *9 to 12 feet*

High speed, high volume highways: *12 feet (predominant)*

Urban areas with lane width controls: *11 feet*

Low-speed facilities: *10 feet (acceptable)*

Rural low-volume roads & residential areas: *9 feet (acceptable)*

Narrow lanes and restricted clearances make vehicles operate closer laterally than normal – affecting the roadway's level of service. The capacity is impacted by the reduced effective width of the traveled way due to restricted lateral clearance. The *Highway Capacity Manual* provides further information regarding the effect of lane width on capacity and level of service.

Although the total roadway width is a critical design decision, pavement marking

(stripes) actually determines lane widths. For locations with unequal-width lanes, outside (right) wider lanes provide more space for heavy vehicles, bicycles, and lateral clearance.

At intersections and interchanges, auxiliary lanes (10-ft minimum) should be wide enough to facilitate traffic. An optimal lane width of 10 to 16 feet is appropriate for continuous left-turn lanes.

AASHTO Guidelines for Geometric Design of Very Low-Volume Local Roads provides alternative design criteria for local roads and collectors with less than 400 vehicles per day. It may not be cost-effective to design low-volume roadway cross-sections using the same criteria for high volume roads. *NCHRP Report 362 – Roadway Widths for Low-Traffic Volume Roads* contains additional details for low-volume rural and residential roadways.

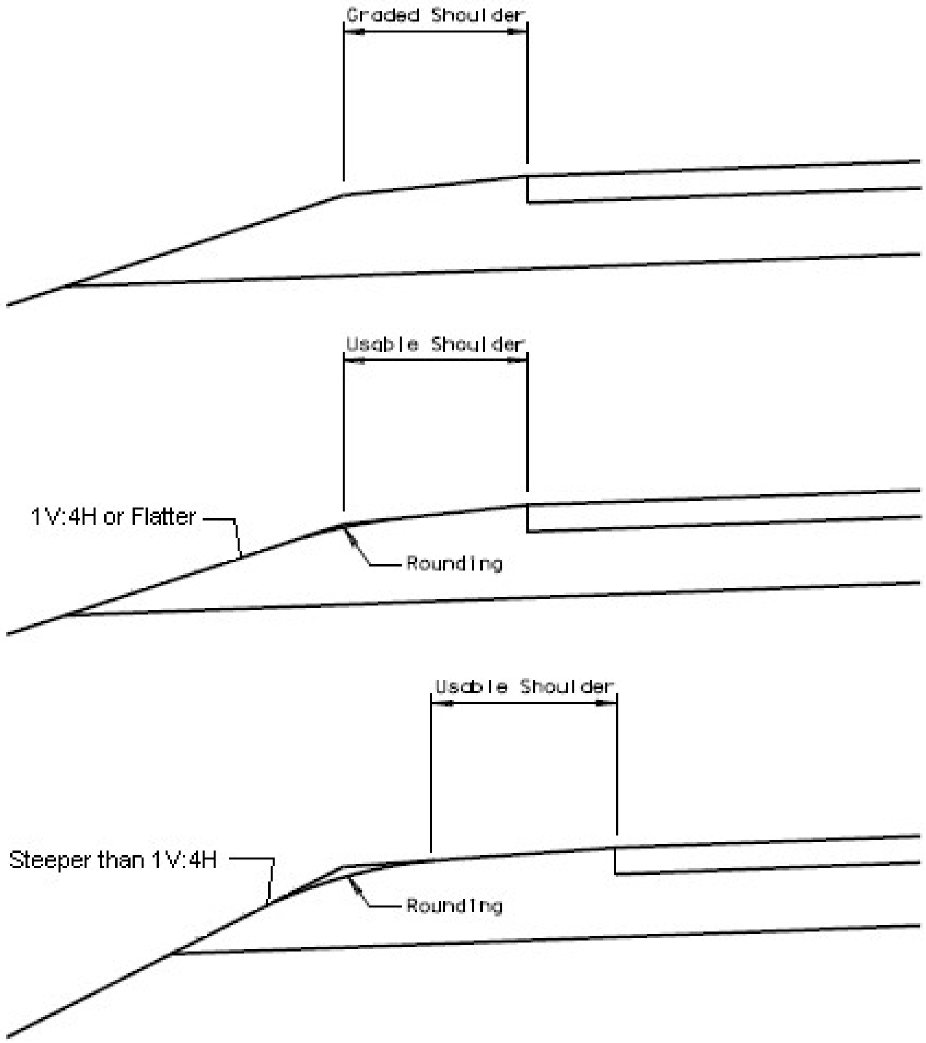
SHOULDERS

Roadway shoulders are defined by AASHTO as "the portion of the roadway contiguous with the traveled way that accommodates stopped vehicles, emergency use, and lateral support of subbase, base, and surface courses". Shoulders are one of the most important safety features for roadways.

Type of Roadway	Shoulder Width
Minor rural roads (with or without surface)	2 feet
Major roads (with stabilized or paved shoulder)	12 feet

The limits of **graded** shoulders are from the edge of traveled way to the intersection of the shoulder slope and foreslopes. The **usable** shoulder width is the actual shoulder for parking and emergencies. This width is equal to the graded shoulder for sideslopes of 1V:4H or flatter.

Shoulder surfacing provides better all-weather load support versus soil. Typical shoulder surface materials include: *gravel; mineral/chemical additives; shell; asphaltic/concrete paving; crushed rock; and bituminous surface treatments.*



Shoulder Width

Design guidelines for roadway shoulder widths vary by design speed, functional class, and traffic volume. AASHTO recommends a minimum lateral clearance of 1 foot (preferably 2 feet) between a stopped vehicle on a roadway shoulder and the edge of the traveled way.

Facility	Shoulder Width	
High speed, high volume roadways	10 feet	normal width
Low volume highways	2 feet	6 to 8 ft preferable
High speed, high volume roadways w/trucks	10 feet	12 feet preferable
Bicycles and pedestrians	4 feet	no rumble strips

For roadsides with *barriers, walls, or vertical elements*, the graded shoulder should have a minimum offset of 2 feet (measured from outer shoulder edge to vertical element). Vertical elements on *low-volume roads* can be used on the outer edge of shoulder with a minimum clearance of 4 feet (traveled way to barrier).

Roadway shoulders should be continuous along the route. Benefits include: providing driver refuge areas; fostering motorist security; and furnishing an area for bicyclists. Intermittent shoulder sections should be avoided – their use can result in driver stops in the traveled way and increased opportunities for potential collisions.

Shoulder Cross-section

Roadway shoulders need to be flush and adjoin the edge of traveled way in order to help drainage. They should have sufficient slope to drain surface water but not restrict vehicle usage. The cross slope for curb locations should be designed to prevent ponding.

Shoulder Surface	Cross Slope
Bituminous/Concrete	2 to 6%
Gravel/Crushed rock	4 to 6%
Turf	6 to 8%

The maximum algebraic difference between the traveled way and shoulder grades should range from *6 to 7 percent* (tangent sections with normal crown and turf shoulders). This range is adequate due to the resulting gains for pavement stability by preventing stormwater detention on the pavement.

Shoulders that drain away from the pavement should be designed without a significant cross slope break. The shoulder should be sloped at a rate comparable to the superelevated traveled way. For locations with stormwater, snow, and ice drainage on the road surface, the maximum grade break should be limited to 8 percent (by flattening the outside shoulder).

Shoulders with curb or gutter on the outer edge may be installed to keep runoff on the paved shoulder and serve as a longitudinal gutter. All of the roadway runoff is handled by these curbs as part of the drainage system that drains at designated outlets. Significant advantages of this shoulder type include: keeping stormwater off the travel lanes; and not deterring motorists from leaving the traveled way.

Shoulder Stability

Roadway shoulders need to be able to support various vehicle loads in different kinds of weather without rutting. Regular maintenance is crucial for all types of shoulders to perform as intended.

Unstabilized shoulders consolidate over time producing a drop-off at the edge of the traveled way. This difference can affect driver control of speeding vehicles, and reduce the operational advantage of driving close to the pavement edge.

Stabilized shoulders help to prevent erosion and moisture penetration which enhances the pavement's strength and durability. They provide emergency vehicle refuges; prevent drop-off & rutting prevention; furnish adequate roadway drainage cross slope; reduce maintenance; and provide lateral roadway base/surface support.

Some rural highway designs use surfacing over the entire roadway width (including shoulders). This surfacing may range from *28 to 44 feet* for two-lane roads. Edge line pavement markings are typically installed to delineate the edge of traveled way.

RUMBLE STRIPS

Rumble strips are raised or grooved designs that are intended to alert drivers of potential dangers through vibration and audible rumbling. These strips are applied in the direction of travel as part of the edge line or centerline to alert motorists when they drift from their lane. While rumble strips are effective (and cost effective) in reducing crashes due to inattention, they may also have issues pertaining to noise levels, bicyclists, motorcycles, and roadway maintenance.

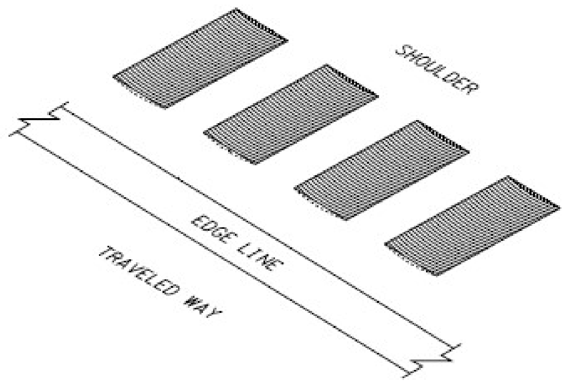
Basic Rumble Strip Designs

Milled-in: cut into existing hardened asphalt or concrete

Rolled-in: applied to malleable freshly laid asphalt paving

Formed: corrugated form pressed into new pavement

Raised: prefabricated units connected to asphalt or concrete pavement



Typical Rumble Strip

<u>Uses of Rumble Strips</u>

- Continuous Shoulder Rumble Strip (most common)
  Installed on shoulders to prevent potential run-off-road (ROR) collisions
- Centerline Rumble Strips
  Used on two-lane rural highways to reduce potential head-on collisions
- Transverse Rumble Strips
  Placed in travel lanes where the majority of traffic will cross

  Installed on intersection approaches, toll plazas, horizontal curves, work zones

Rumble stripes combine rumble strips with pavement markings to provide increased visibility in inclement weather or nighttime conditions. These may be installed using raised plastic pavement markers or conventional pavement markings.

ROADSIDE DESIGN

Roadsides are a crucial component for safe highways by providing a recovery zone for errant drivers, and reducing vehicle crash severity. The fundamental design considerations for roadsides are **clear zones** and **lateral offsets.**

The **clear zone** concept is defined in the *AASHTO Roadside Design Guide* as "the unobstructed, transversable area provided beyond the edge of the through traveled way for the recovery of errant vehicles. The clear zone includes shoulders, bikes lanes, and auxiliary lanes, except those auxiliary lanes that function like through lanes". This area needs to be as free of objects or hazards as practical, and sufficiently flat (1V:4H or flatter) to enable driver recovery.

Historically, most roadway agencies have tried to maintain a **30-foot clear zone** for high-volume, high-speed rural roads. This is the result of studies that showed that using this minimum width permitted 80% of vehicles leaving the roadway to recover (*Highway Design and Operational Practices Related to Highway Safety*, 1974). Past obstacle treatments within clear zones have included: *removal, relocation, redesign, or shielding (barriers or crash cushions)*. However, for low-volume, urban, or low-speed highways, clear zone distances of 30-feet may be excessive or unjustified due to engineering, environmental, or economic reasons.

The *AASHTO Roadside Design Guide* supplies specific details regarding the clear zone concept and provides design procedures based on vehicle encroachment frequency, collision severity with roadside obstacles, and costs of providing greater clear recovery areas. The optimal roadside design solution is to balance engineering judgment with current roadside safety practices.

Lateral Offsets

The Federal Highway Administration (FHWA) defines the **lateral offset** to an obstruction as "the distance from the edge of traveled way, shoulder, or other designated point to a vertical roadside element". These offsets are typically considered to be *operational* offsets – providing adequate roadside clearance without affecting vehicle performance. Lateral offsets are generally suitable (in lieu of a full-width clear zone) for urban environments with lower operating speeds that have limited right-of-way or constraints (on-street parking, sidewalks, curb & gutter, drainage structures, frequent traffic stops, and fixed roadside objects).

Advantages of Lateral Offsets

- Improves sight distances
- Minimizes contact between obstructions & vehicles
- Improves travel lane capacity
- Reduces lane encroachments from parked/disabled vehicles
- Avoids adverse lane position impacts & lane encroachments

For sites with curbs, the offset should be measured from the curb face. Any traffic barriers should be placed in front or at the face of the curb. The *AASHTO Roadside Design Guide* provides further guidance for using lateral offsets.

CURBS

Roadway curbs may use raised or vertical elements to influence driver behavior, and therefore → roadway utility and safety.

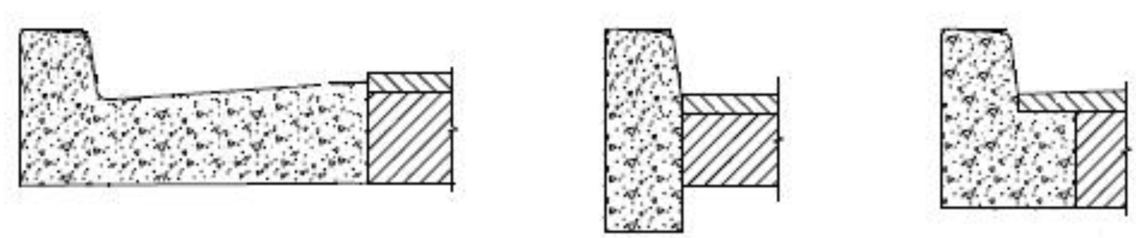
Purposes of Curbs

Drainage control	*Roadway edge delineation*	*Right-of-way reduction*
Aesthetics	*Walkway delineation*	*Maintenance reduction*
	Roadside development	

Curbs can influence the trajectory of errant vehicles and affect a driver's ability to control a vehicle after impact. The extent of this effect is due to vehicle speed, impact angle on the curb, curb configuration, and vehicle type.

The main curb configurations are **vertical** and **sloping**. These designs may be separate or integrated units that include gutters.

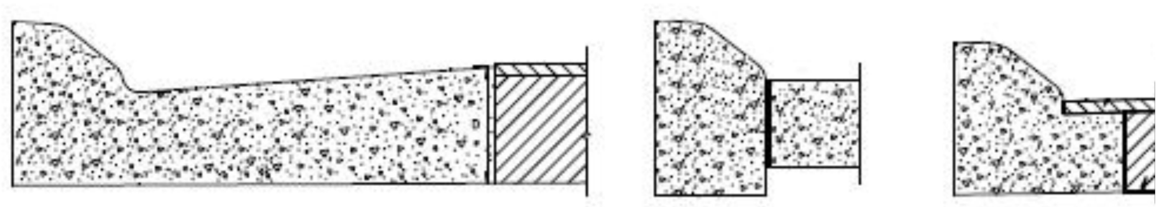
The purpose of **vertical (non-mountable)** curbs is to discourage errant vehicles from leaving the road. These types of curbs are not suitable for high-speed roadways due to vehicle tendencies to overturn or become airborne from curb impact. Vertical curbs (typically range from 6 to 8 inches) can also be used along tunnels or long walls to discourage close vehicle proximity and reduce risks to pedestrians.



VERTICAL CURBS (Non-mountable)

Sloping curbs (mountable) are designed to be easily crossed by vehicles when needed. These are well-rounded, low curbs with flat sloping faces.

Slope of Curb Face	Curb Height	
>1V:1H	4 inches (maximum)	easily mountable
1V:1H to 1V:2H	6 inches (maximum)	



SLOPING CURBS (Mountable)

- **4-inch Sloping Curb:** Suitable for high-speed facilities with drainage issues, restricted right-of-way, or access control

- **6-inch Sloping Curb:** Appropriate for high-speed urban/suburban roadway sections with multiple access points

Some sloping curbs are created with small vertical sections (2 inch maximum for 6 inch curbs) on the lower curb face for future resurfacing. If this vertical section exceeds 2 inches, it may be treated as a vertical curb instead of a sloping one.

Typical Uses of Sloping Curbs

Median edges

Islands at intersections

Shoulder outer edges

Sloping curbs at outer shoulder edges are used for drainage control, delineation, access control, and erosion reduction. These curbs should be easily mountable for vehicle parking clear of the traveled way for constricted sections. There should also be adequate clearance to prevent conflicts between bicycles and motorists.

Gutters may be combined with vertical or sloping curbs for roadway drainage systems. Typical gutter sections are 1 to 6 feet wide on a 5 to 8% cross slope to increase hydraulic capacity. Typically, this cross slope is limited to the 2 to 3 feet adjacent to the curb. It is unrealistic to expect gutter sections to contain all drainage – overflow is typical.

Research has shown that drivers tend to shy away from curbs with significant height or steepness – reducing effective lane width. Sloping curbs may be placed at the edge of the traveled way for low-speed urban sections (with preferred offsets of 1 to 2 feet). If used intermittently along streets, vertical curbs should be offset 2 feet from the edge of traveled way. For medians or islands, the offset for vertical curbs should be a minimum of 1 foot (preferably 2 feet).

High visibility treatments may include: *reflectorized markers on curb tops*

reflectorized paints

reflectorized surfaces

Periodic maintenance (cleaning or repainting) is typically required to keep the curbs fully effective.

DRAINAGE CHANNELS AND SIDESLOPES

Drainage design considerations (safety, aesthetics, pollution control, maintenance) are an essential part of modern roadway geometric design. By using flat sideslopes, broad drainage channels, and liberal transitions, highway drainage facilities can be used to intercept and remove stormwater from the roadway. The drainage channel -sideslope interface is also important for reducing potential crash severity (vehicles leaving the road).

Types of highway drainage facilities include: bridges; culverts; *channels; curbs; gutters;* and *drains.* The location and hydraulic capacities of these drainage facilities should consider the likelihood of upstream/downstream damage, and potential flooding impacts on roadway traffic . Any **new** culverts should meet the minimum *HL-93* design loads. **Existing** culverts that are considered appropriate to remain in place must have a structural capacity that meets *HS-15* for live loads.

Stream crossings and flood plains can impact both roadway horizontal and vertical alignments. These crossings and encroachments should be located and aligned to retain the natural flood flow properties (distribution and direction). Any roadway design should also address stream stability and environmental concerns.

Drainage inlets are used to limit the spread of surface water on the traveled way. These inlets need to be located as such as to prevent silt/debris deposits on the roadway. Additional inlets may be used near vertical sag points for any overflow. All pipes need to have sufficient capacity to avoid ponding on the roadway and facilities.

Urban drainage design is typically more expensive and more complex than rural facilities. Potential urban drainage impacts may include *rapid runoff rates, larger volumes of runoff, costly flood damage, higher overall costs, greater restrictions – urban development, lack of receiving waters,* and *high vehicular/pedestrian traffic.*

Drainage Channels

Drainage channels intercept and remove surface water by providing adequate capacity, and a smooth transition for stormwater. These channels can be lined with vegetation, or rock/paved linings at locations where erosion cannot be controlled by normal vegetation. Roadway runoff typically drains down grass slopes to roadside and median channels. Various measures (curbs, dikes, inlets, chutes, flumes, etc.) can be used to prevent slope erosion from roadway runoff.

Types of Drainage Channels

Roadside channels in cut sections

Toe-of-slope channels

Intercepting channels

Flumes

The purpose of roadside channels is to control surface drainage. These are typically built as open-channel ditches that are cut into the natural terrain. Roadside channels containing **steep sides** are usually preferred due to their hydraulic efficiency. Slope steepness may be restricted by soil stability, construction, maintenance, and right-of-way factors.

Roadside designs need to consider the impact of slope combinations on vehicles leaving the roadway. The effects of traversing roadside channels with widths less than **4 to 8 feet** are similar for slope combinations despite channel shape. Flatter foreslopes allow greater vehicle recovery distance, and better flexibility in choosing backslopes for safe traversal. Foreslopes greater than **1V:4H** seriously limit the types of backslopes for use. The channel depth depends on soil characteristics and should be able to remove surface water without subgrade saturation.

Roadway channel grades do not have to mimic that of the roadway's vertical alignment. The minimum grade should be developed from drainage velocities that avoid sedimentation. Depths, widths, and lateral offsets for roadside channel designs can vary to meet runoff amounts, channel slopes, lining types, and distances between discharge points. Measures should be taken to avoid violating driver expectancy, or major channel grade changes that produce scouring/siltation.

Intercepting channels are typically the result of a dike built to prevent disturbing the existing ground surface. These usually have a flat cross section with substantial capacity that follow natural contours, when possible.

Median drainage channels are formed near the center of the median by flat sideslopes and are typically very shallow. Drainage is intercepted by inlets or channels and discharged by culverts.

Flumes may be either **open (channels)** or **closed (culverts)** to transport water from intercepting channels down cut slopes, and release water from curbs. Open channels are ill-suited for higher velocities or sharp turns, and may need some type of energy dissipation. Culverts are generally preferred for preventing settlement and soil erosion.

Channel linings *(vegetation, concrete, asphalt, stone, and nylon)* are designed to prevent channel erosion by resisting storm runoff velocities.

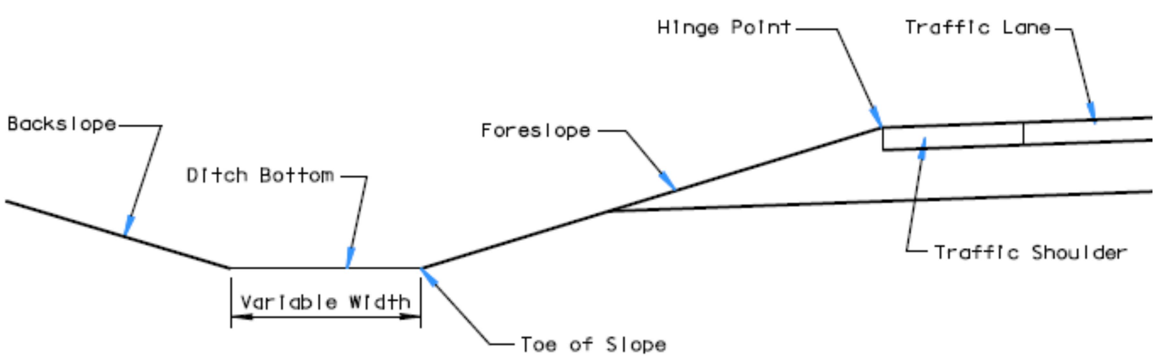
Roadside Channel Lining Criteria

- Velocity of flow
- Type of soil
- Grade of channel
- Channel geometry

Vegetation provides the most economical lining but is unsuitable for steep slopes or high velocities. Smooth linings create high-velocity flows that need some sort of energy dissipation before releasing.

Sideslopes

Sideslopes adjoin the roadway shoulder - located between the edge of shoulder and the right-of-way boundary. Any sideslope design needs to improve road stability and provide adequate recovery space for errant vehicles.



Regions of the Roadside

Hinge Point (top of slope) - contributes to loss of steering control

- vehicles may become airborne at this point

- rounding may increase general roadside safety

Foreslope - provides area for recovery maneuver or speed reduction prior to impact

Toe of Slope - intersection of foreslope with level ground or backslope

- usually within clear zone and impacted by vehicle

Reducing crash severity at intersections is a major concern for designers. Potential design solutions include: flatter slopes between the shoulder edge and ditch bottom; longer lateral offset from the roadway; and enclosed drainage facilities.

Foreslopes

Steeper than 1V:4H	*Not desirable – limits choices of backslopes*
1V:3H or steeper	*For locations where flatter slopes cannot be used*
	May require roadside barriers

Backslopes

1V:3H or flatter	*Typically used – accommodates equipment*
Steeper than 1V:3H	*Needs evaluation for soil stability & crash impacts*
Steeper than 1V:2H	*Retaining walls may be required*
1V:2H or flatter	*May be determined by soil characteristics*

For major roadways (freeways, arterials) with wide roadsides, sideslopes should provide an adequate area to avert potential crashes and for out-of-control vehicles to recover. Embankment slopes of 1V:6H or flatter are traversable, recoverable, and ought to be used when practical. Flat, rounded recovery areas adjacent to the roadway need to be provided as far as conditions permit.

Embankment Slope

1V:6H or flatter	*Good chance of vehicle negotiation & recovery*
1V:3H or flatter	*Possibly traversable – possibly recoverable*

The use of turf may be suitable for flat, well-rounded sideslopes (1V:2H favorable climates, 1V:3H semiarid climates). Steeper slopes (2V:3H or steeper) make it difficult for grass to be established – even with sufficient water. Slopes of 1V:3H or flatter are easier to mow and maintain.

Flat, well-rounded sideslopes are recommended for creating a natural roadside appearance. Rounded landforms are a stable, natural result of erosion – so using rounded sideslopes should result in greater stability. A **streamlined cross section** is the resulting combination of flat and rounded slopes. This produces roadways that operate with fewer severe crashes, and need minimal maintenance/operating costs.

Rock cuts depend on the material and may involve bench construction for deep cuts. These slopes may range from 2V:1H (typical) to 6V:1H (good-quality rock).

Vegetation may be used to enhance slope stability and aesthetics of poor-quality rock. Any rock outcroppings within the clear roadside recovery area should either be removed or shielded by a roadside barrier.

REFERENCES

A Policy on Geometric Design of Highways and Streets, 6th Edition.

AASHTO. Washington, D.C. 2011.

Note: All figures, illustrations, tables, etc. contained within this course are from this text unless noted otherwise.

Civil Engineering Reference Manual, 8th Edition.

Michael R. Lindeburg. Professional Publications, Inc. Belmont, CA 2001.

Design of Stable Channels with Flexible Linings, 3rd Edition.

FHWA. Washington, D.C. 2005.

Flexibility in Highway Design.

Federal Highway Administration. Washington, D.C. 1997.

Guide for the Design of High-Occupancy Vehicle (HOV) Facilities, 3rd Edition.

AASHTO. Washington, D.C. 2004.

Guide for the Design of Park-and-Ride Facilities, 2nd Edition.

AASHTO. Washington, D.C. 2004.

Guide for the Planning, Design, and Operation of Pedestrian Facilities.

AASHTO. Washington, D.C. 2004.

Handbook of Simplified Practice for Traffic Studies.

Center for Transportation Research & Education – Iowa State University.

Ames, Iowa. 2002.

Manual on Uniform Traffic Control Devices, 2009 Edition.

Federal Highway Administration. Washington, D.C. 2009.

Mini-Roundabouts Technical Summary.

FHWA. Washington, D.C. 2010.

NCHRP Report 672 Roundabouts: An Informational Guide, 2nd Edition.

FHWA. Washington, D.C. 2010.

Roadside Design Guide, 4th Edition.

AASHTO. Washington, D.C. 2011.

Roundabouts: An Informational Guide.

FHWA. Washington, D.C. 2000.

Standard Roadway Drawings.

Tennessee Department of Transportation.

TCRP Report 19 Guidelines for the Location and Design of Bus Stops.

Transportation Research Board. Washington, D.C. 1996.

Traffic Engineering Handbook, 5th Edition.

Institute of Transportation Engineers. Washington, D.C. 1999.

Traffic Engineering Handbook, 6th Edition.

Institute of Transportation Engineers. Washington, D.C. 2009.

Urban Drainage Design Manual, 3rd Edition.

FHWA. Washington, D.C. 2009.