CHAPTER 3

ROAD DESIGN

3.1 Horizontal and Vertical Alignment

Centerline alignment influences haul cost, construction cost, and environmental cost (e.g., erosion, sedimentation). During the reconnaissance phase and pre-construction survey the preliminary centerline has been established on the ground. During that phase basic decisions regarding horizontal and vertical alignment have already been made and their effects on haul, construction, and environmental costs. The road design is the phase where those "field" decisions are refined, finalized and documented.

3.1.1 Horizontal Alignment Considerations

The preferred method for locating low volume roads discussed in Section 2.3, the so called non-geometric or "free alignment" method, emphasizes the importance of adjusting the road alignment to the constraints imposed by the terrain. The main difference between this and conventional road design methods is that with the former method, the laying out and designing of the centerline offset is done in the field by the road locator while substantial horizontal offsets are often required with the latter method (Figure 25).

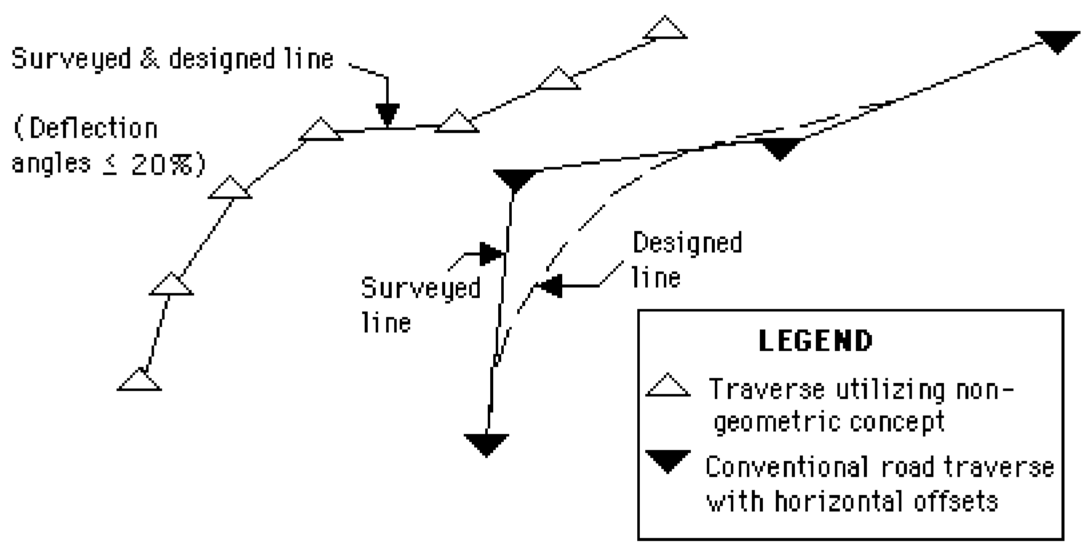


Figure 25. Non-geometric and conventional p-line traverses

Adjustments in horizontal alignment can help reduce the potential for generating roadway sediment. The objective in manipulating horizontal alignment is to strive to minimize roadway cuts and fills and to avoid unstable areas. When unstable or steep slopes must be traversed, adjustments in vertical alignment can minimize impacts and produce a stable road by reducing cuts and fills. The route can also be positioned on more stable ground such as ridgetops or benches. Short, steep pitches used to reach stable terrain must be matched with a surface treatment that will withstand excessive wear and reduce the potential for surface erosion. On level ground, adequate drainage must be provided to prevent ponding and reduce subgrade saturation. This can be accomplished by establishing a minimum grade of 2 percent and by rolling the grade.

Achieving the required objectives for alignment requires that a slightly more thoughtful preliminary survey be completed than would be done for a more conventionally designed road. There are two commonly accepted approaches for this type of survey: the grade or contour location method (used when grade is controlling), or the centerline location method (used when grades are light and alignment is controlling).
Figure 26 illustrates design adjustments that can be made in the field using the non-geometric design concept discussed earlier.

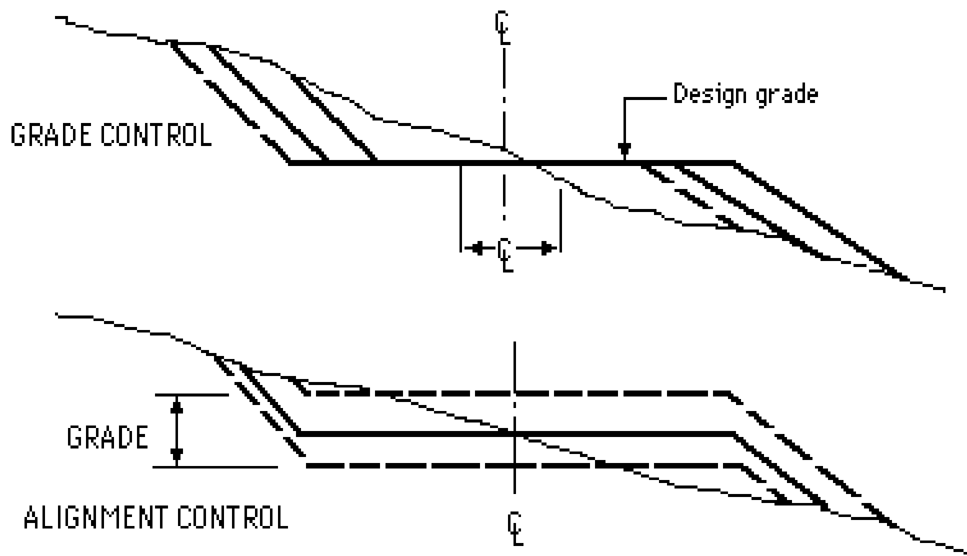


Figure 26. Design adjustments.

Equipment needed for either method may include a staff compass, two Abney levels or clinometers, fiberglass engineer's tape (30 or 50 m), a range rod, engineering field tables, notebook, maps, photos, crayons, stakes, flagging, and pencils. The gradeline or contour method establishes the location of the P-line by connecting two control points with a grade line. A crew equipped with levels or clinometers traverses this line with tangents that follow, as closely as possible, the contours of the ground. Each section is noted and staked for mass balance calculations. Centerline stakes should be set at even 25- and 50-meter stations when practicable and intermediate stakes set at significant breaks in topography and at other points, such as breaks where excavation goes from cut to fill, locations of culverts, or significant obstructions.

On gentle topography with slopes less than 30 percent and grade is not a controlling factor, the centerline method may be used. Controlling tangents are connected by curves established on the ground. The terrain must be gentle enough so that by rolling grades along the horizontal alignment, the vertical alignment will meet minimum requirements. In general, this method may be less practical than the gradeline method for most forested areas.

When sideslopes exceed 50 - 55 percent or when unstable slope conditions are present, it may be necessary to consider full bench construction shown in Figure 27. Excavated material in this case must be end hauled to a safe location. Normally, the goal of the road engineer is to balance earthwork so that the volume of fill equals the volume of cut plus any gain from bulking less any loss from shrinkage (Figure 28).

Road design, through its elements such as template (width, full bench/side cast), curve widening and grade affect the potential for erosion. Erosion rates are directly proportional to the total exposed area in cuts and fills. Road cuts and fills tend to increase with smooth, horizontal and vertical alignment. Conversely, short vertical and horizontal tangents tend to reduce cuts and fills. Erosion rates can be expected to be lower in the latter case. Prior to the design phase it.

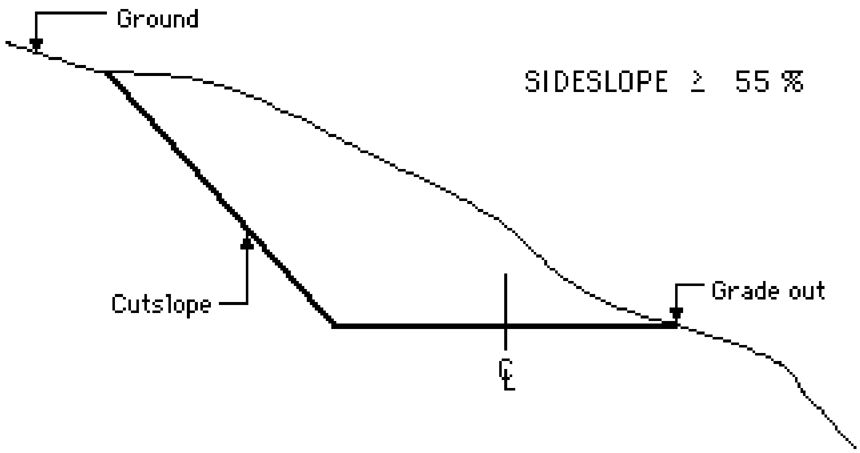


Figure 27. Full bench design.

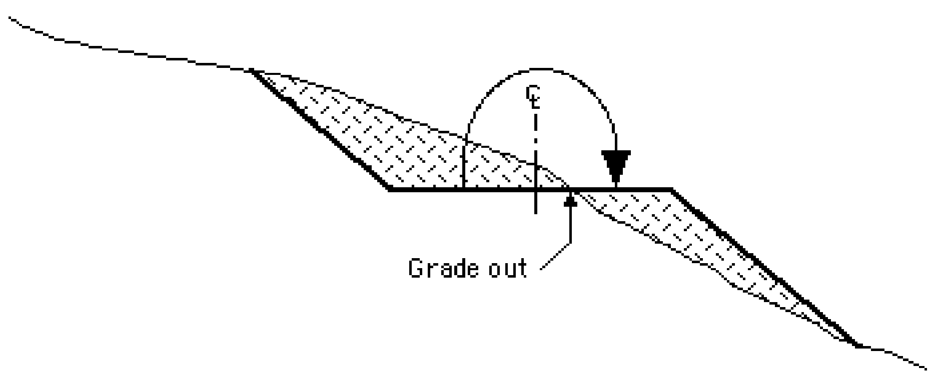


Figure 28. Self-balanced design

should be clearly stated which alignment, horizontal or vertical, takes precedence. For example, if the tag line has been located at or near the permissible maximum grade, the vertical alignment will govern. Truck speeds in this case are governed by grade and not curvature. Therefore, horizontal alignment of the centerline can follow the topography very closely in order to minimize earthwork. Self balancing sections would be achieved by shifting the template horizontally.

3.1.2 Curve Widening

Roadway safety will be in jeopardy and the road shoulders will be impacted by off-tracking wheels if vehicle geometry and necessary curve widening are not considered properly. Continually eroding shoulders will become sedimentation source areas and will eventually weaken the road. On the other hand, over design will result in costly excessive cuts and/or fills.

The main principle of off-tracking and hence curve widening, centers on the principle that all vehicle axles rotate about a common center. Minimum curve radius is vehicle dependent and is a function of maximum cramp angle and wheelbase length (see Figure 29).

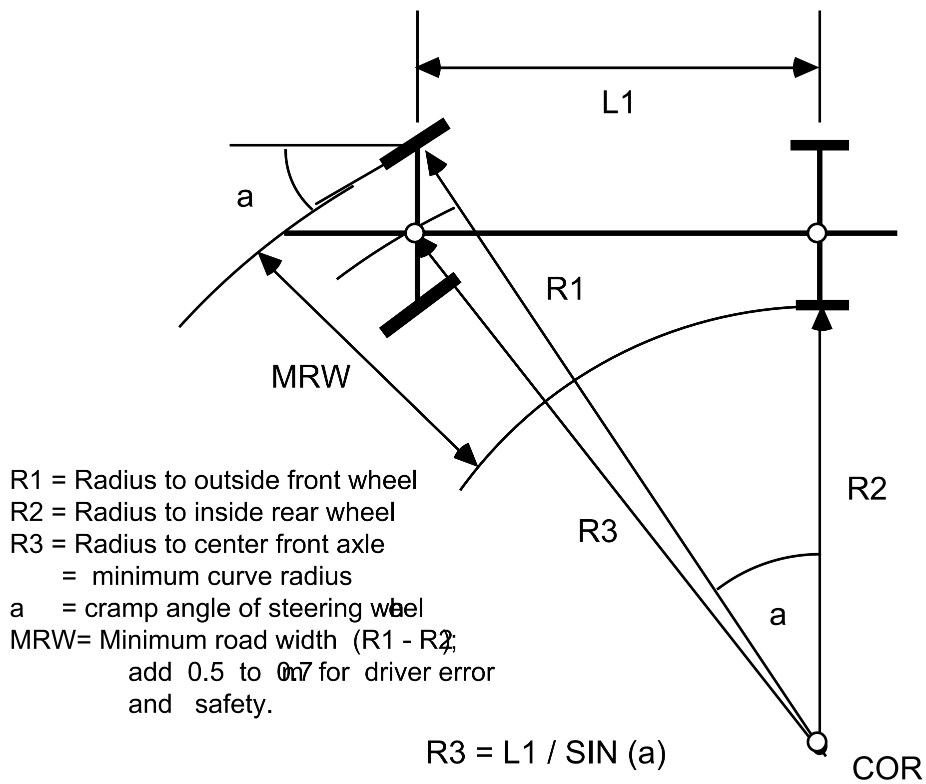


Figure 29. Basic vehicle geometry in off-tracking

Typical vehicle dimensions are shown in Figure 30 for single trucks, truck/ trailers, log truck (pole-type), and tractor/trailer combinations. These dimensions were used to develop Figures 35 to 38 for calculating curve widening in relation to curve radius and central angle.

Several different solutions to determine curve widening requirements are in use. Most mathematical solutions and their simplified versions give the maximum curve widening required. Curve widening is a function of vehicle dimensions, curve radius, and curve length (central angle).

A graphical solution to the problem is provided in Figures 31 to 33. This solution can be used for single trucks, truck-trailer combinations and vehicle overhang situations. This solution provides the maximum curve widening for a given curve radius.

TYPICAL TRUCK / TRAILER DIMENSIONS

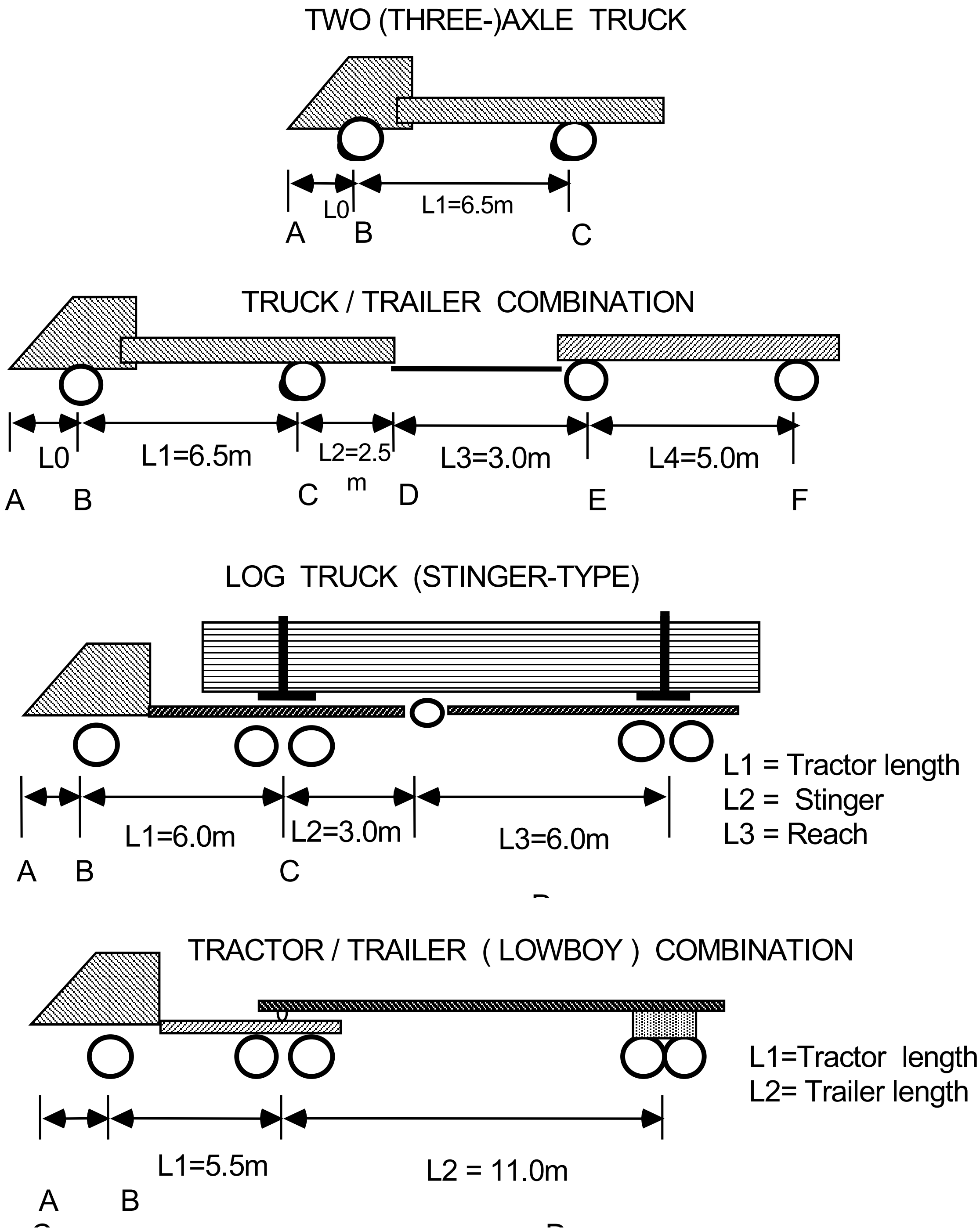
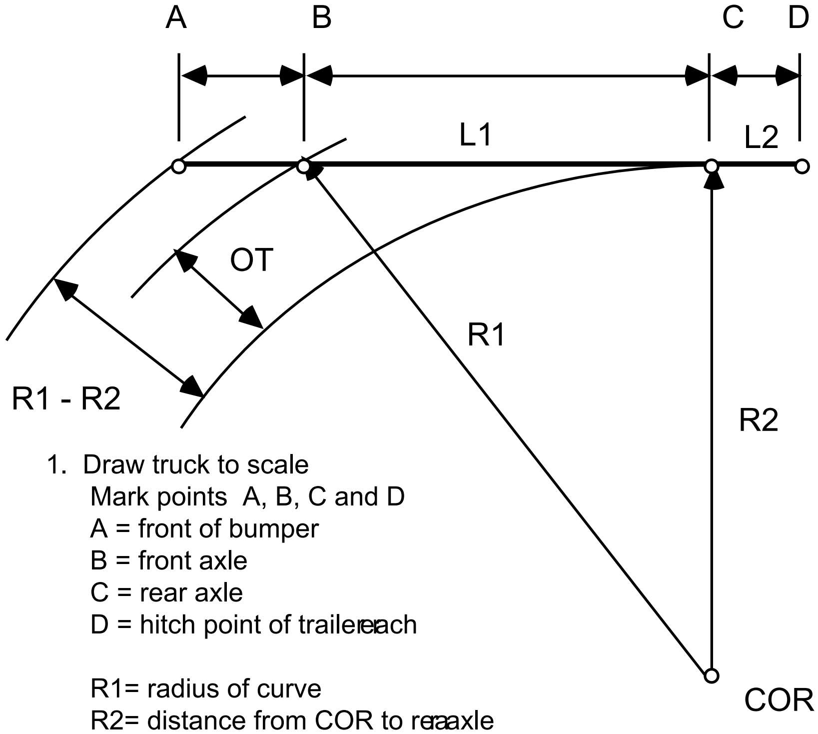


Figure 30. Example of truck-trailer dimensions.

Graphical Solution for
Off-Tracking
Truck / Trailer

STEP 1



1. Draw truck to scale
   Mark points A, B, C and D
   A = front of bumper
   B = front axle
   C = rear axle
   D = hitch point of trailer each

   R1= radius of curve
   R2= distance from COR to rear axle
   OT= off-tracking, front- to rear wheel
   COR= center of rotation

2. Extend rear axle (Pt. C); swing arc R1 from Pt.B
   Intersection of R1 and R2 locates COR (center of rotation)

3. The difference R1 - R2 is the off tracking of the rear axle

Figure 31. Step 1. Graphical solution of curve widening

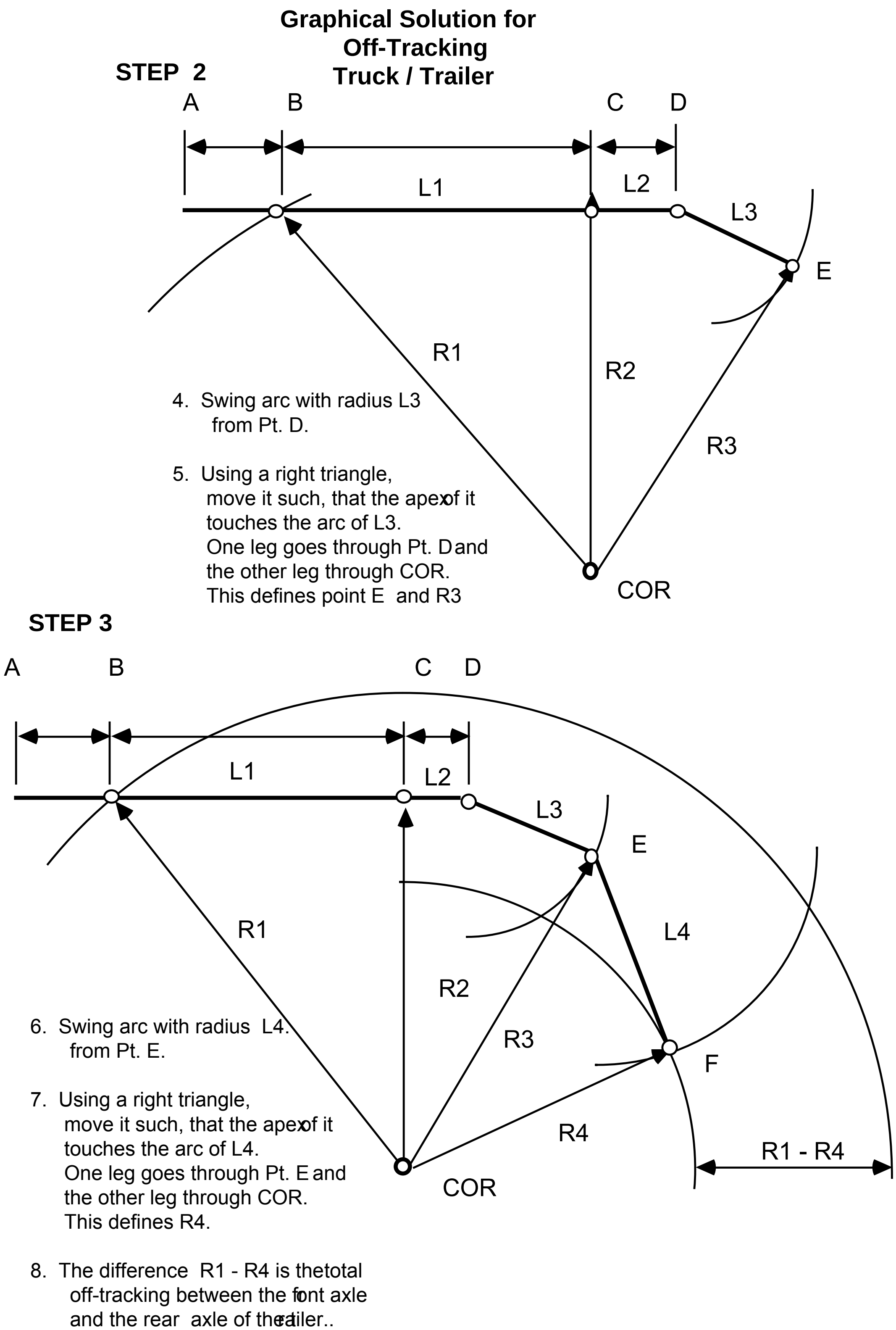


Figure 32. Steps 2 and 3; Graphical solution for curve widening.

The graphical solution for a stinger type log truck is shown in Figure 33. Here, an arc with the bunk length L2 plus L3 is drawn with the center at C. The log load swivels on the bunks, C and E and forms line C - E, with the trailer reach forming line D - E.

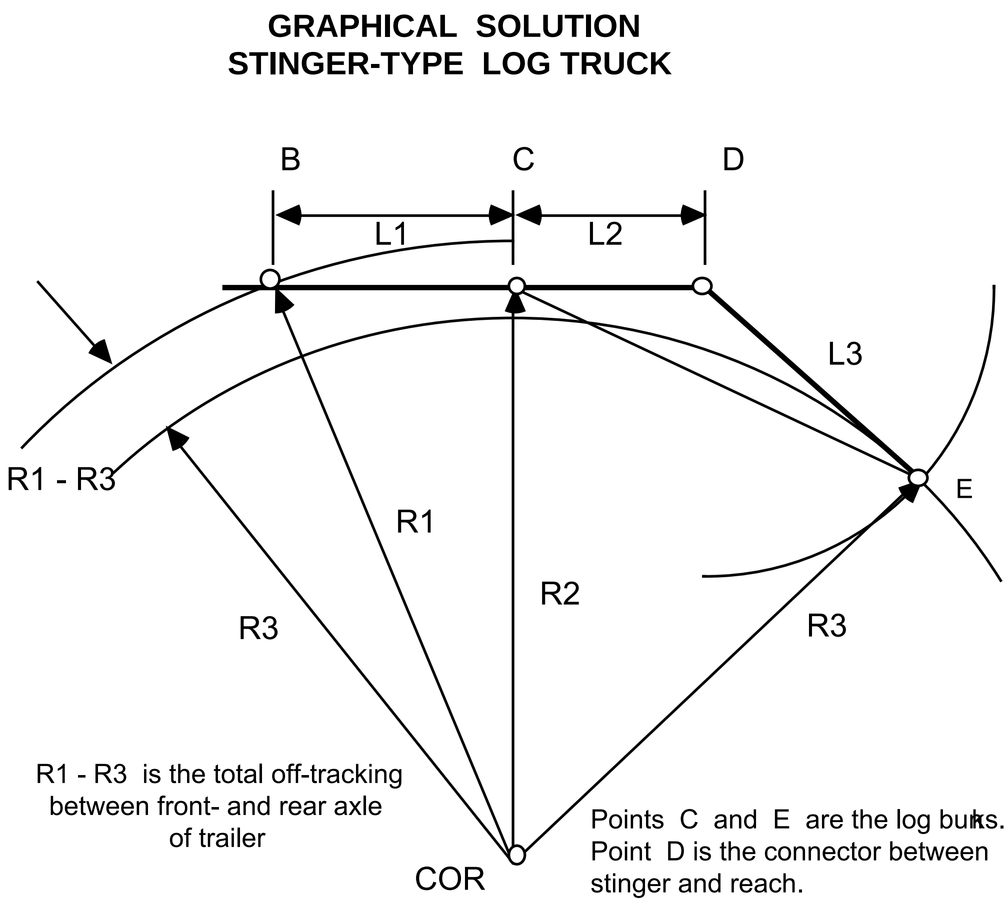


Figure 33. Graphical solution for off-tracking of a stinger-type log truck

Simple, empirical curve widening formulae have been proposed by numerous authors and government agencies. A common method used in North America is:

CW = 37/R For Tractor-trailer (low boy; units in meters)

CW =18.6/R For log-truck (units in meters)

The above equations are adapted for the typical truck dimensions used in the United States and Canada. In Europe, curve widening recommendations vary from 14/R to 32/R. Curve widening recommendations in Europe are given by Kuonen (1983) and Dietz et al. (1984). Kuonen defines the curve widening requirement for a two-axle truck (wheelbase = 5.5m) as

$$CW = 14/R$$

and a truck-trailer combination where

$$CW = 26/R$$

Dietz, et. al. (1984) recommend CW=32/R for any truck combination.

The approximation methods mentioned above are usually not satisfactory under difficult or critical terrain conditions. They typically overestimate curve widening requirements for wide curves (central angle < 45^{o}) and under estimate them for tight curves (central angle > 50^{o}).

Vehicle tracking simulation provides a better vehicle off-tracking solution because it considers vehicle geometry and curve elements, in particular the deflection angle (Kramer, 1982, Cain & Langdon, 1982). The following charts provide off-tracking for four common vehicle configurations--a single or two-axle truck, a truck-trailer combination, a stinger-type log-truck and a tractor-trailer (lowboy) combination. The charts are valid for the specified vehicle dimensions and are based on the following equation (Cain and Langdon, 1982):

$$OF = (R - (R2 - L2)\ 1/2) * (1 - e^{X})$$

where $x = (-0.015 * D * R/L + 0.216)$

- OF = Off tracking (m)
- R = Curve radius (m)
- D = Deflection angle or central angle
- e = Base for natural logarithm (2.7183)
- L = Total combination wheelbase of vehicle
- L = (Summation of $L_i^2)^{1/2}$

For a log-truck:

$$L= (L1^2 + L2^2 + L3^2)^{1/2}$$

where L1-3 are defined in Figure 30.

The maximum off-tracking for a given vehicle, radius and deflection angle occurs when the vehicle leaves the curve. Since vehicles travel both directions, the required curve widening, which consists of off-tracking (OT) plus safety margin (0.5 - 0.6m), should be added to the full curve length. One half of the required curve widening should be added to the inside and one half to the outside of the curve (Figure 34).

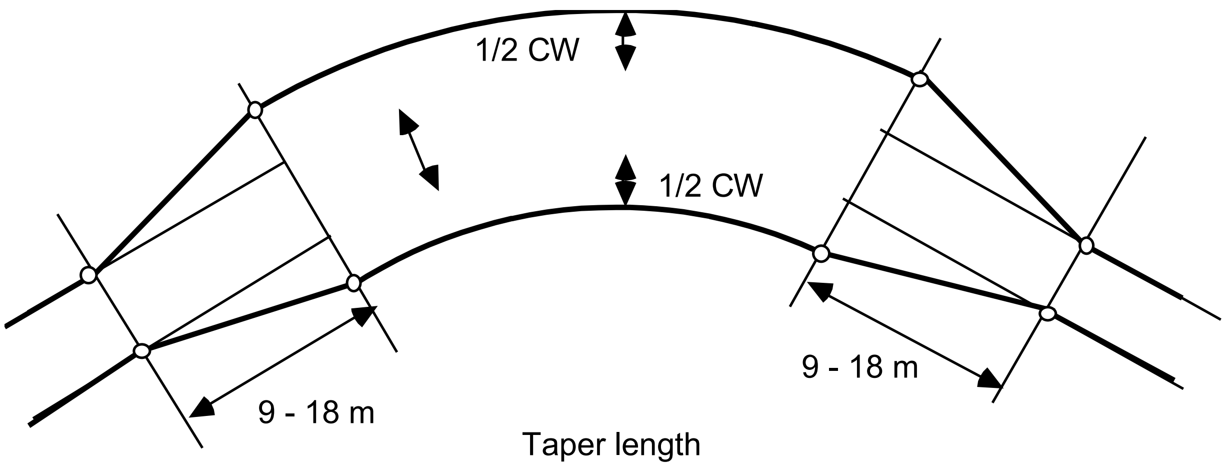


Figure 34. Curve widening and taper lengths.

Figures 35 through 38 provide vehicle off-tracking for a given vehicle, radius, and deflection (or central angle). To this value, 0.5 to 0.6m should be added to allow for formula and driver's error, grade, and road or super elevation variations.

Transition or taper length from tangent to curve vary from 9 to 18 m depending on curve radius. Recommended length of transition before and after a curve are as follows (Cain and Langdon, 1982):

Curve Radius (m)	Length of Taper (m)
20	18
20 - 25	15
25 - 30	12
30	10

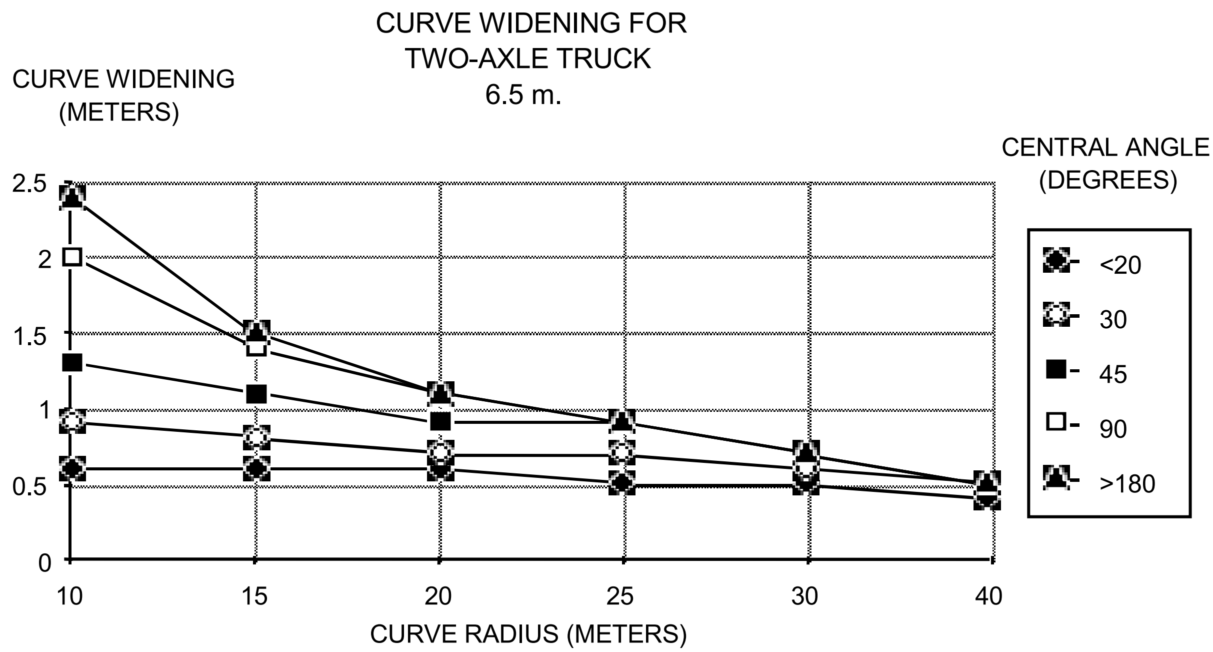
Example: Standard road width is 3.0 m. Design vehicle is a stinger-type log-truck with dimensions as shown in Figure 30. Curve radius is 22m, deflection angle equals 60^o.

From Figure 37 locate curve radius on the x-axis (interpolate between 20 and 25), go up to the corresponding 60^o- curve (interpolate between 45^o and 90^o), go horizontally to the left and read the vehicle off-tracking equal to 1.8 m.

The total road width is 4.80 m (3.0 m + 1.8 m).

Depending on conditions, a safety margin of 0.5 m could be added. The current 3.0 m road width already allows for safety and driver's error of 0.30 m on either side of the vehicle wheels (truck width = 2.40

m). Depending on the ballast depth, some additional shoulder width may be available for driver's error. Taper length would be 15 m.



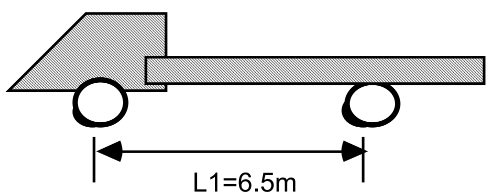


Figure 35. Curve widening guide for a two or three axle truck as a function of radius and deflection angle. The truck dimensions are as shown.

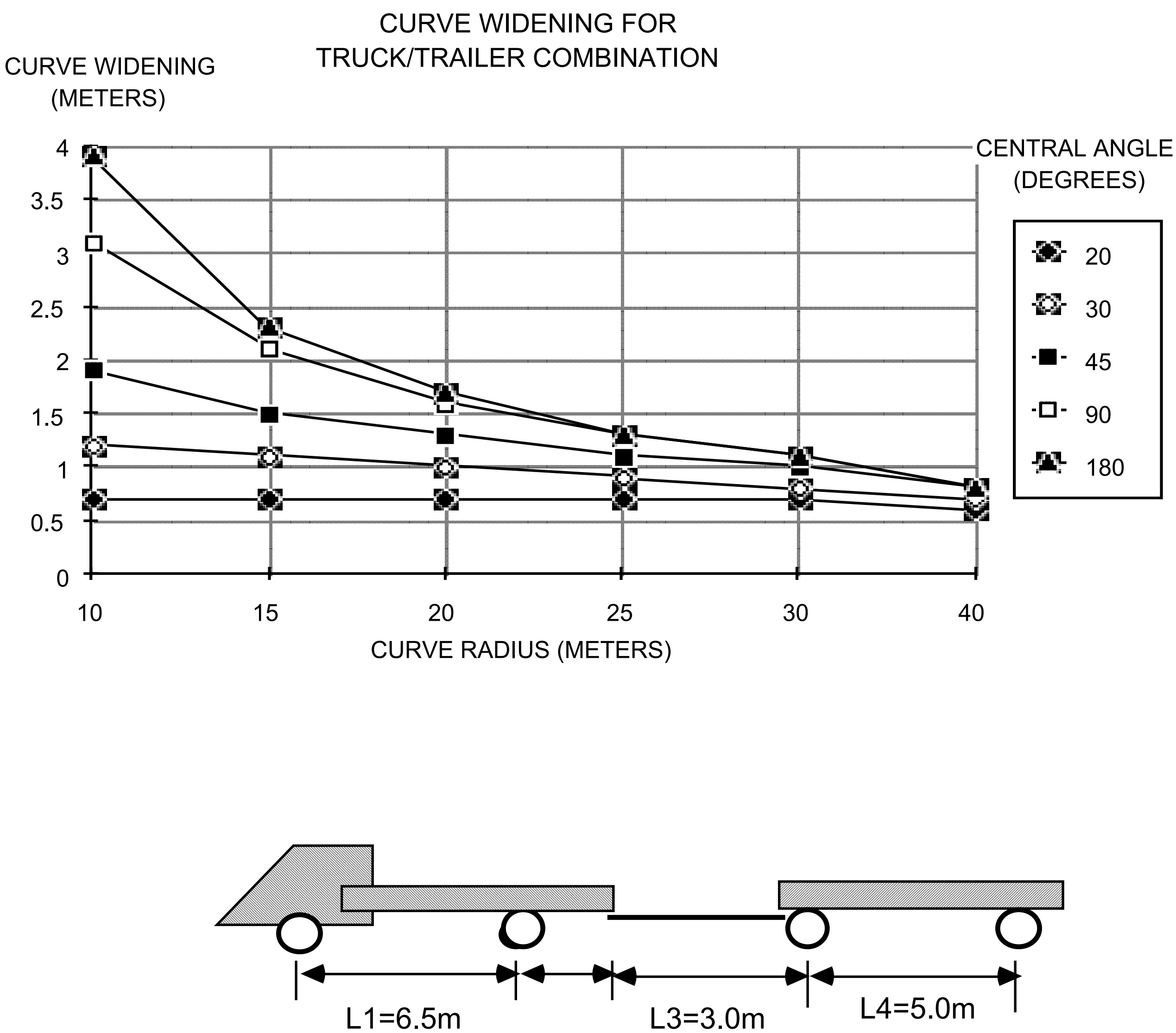
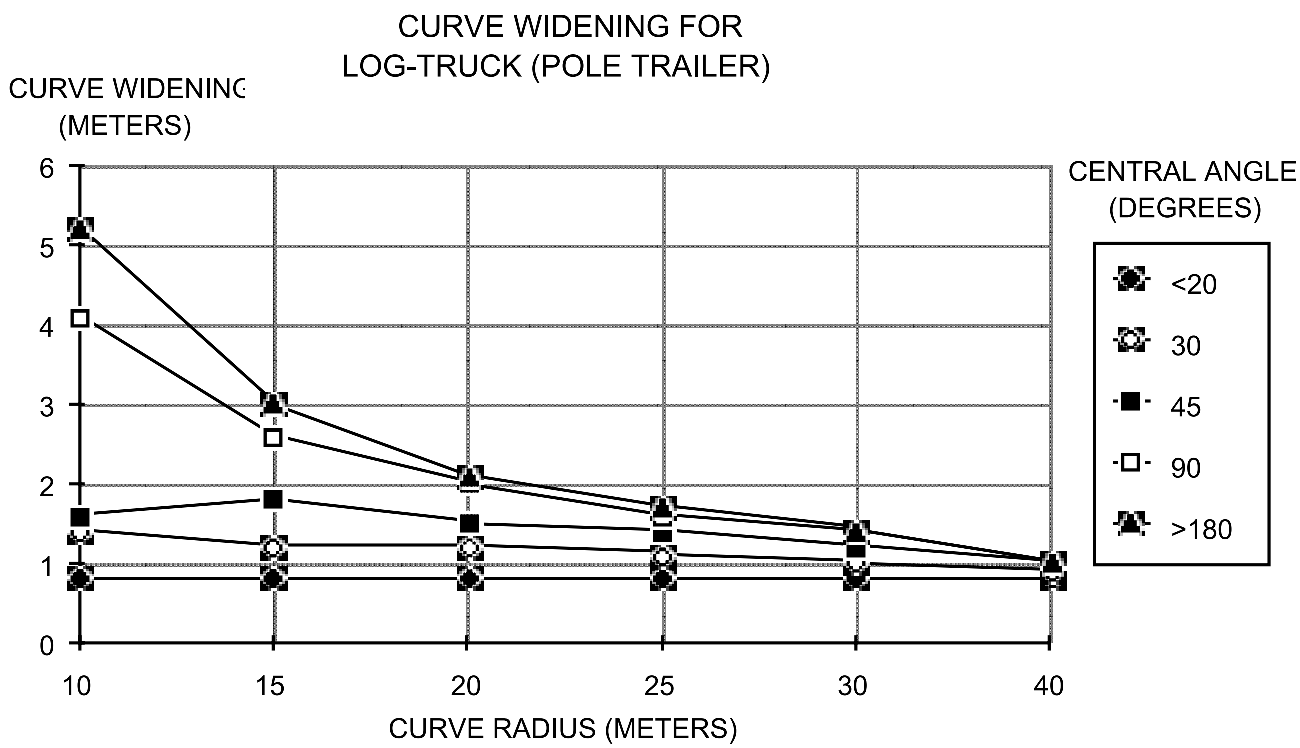


Figure 36. Curve widening guide for a truck-trailer combination as a function of radius and deflection angle. The dimensions are as shown.



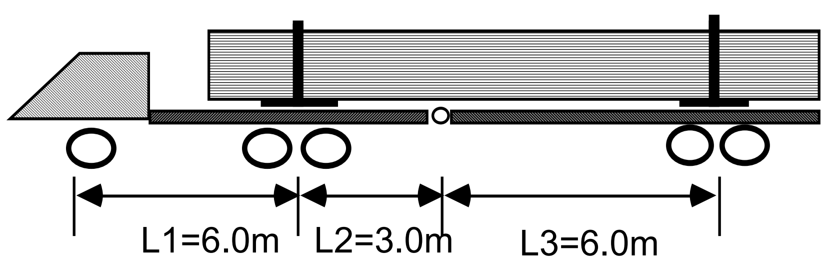
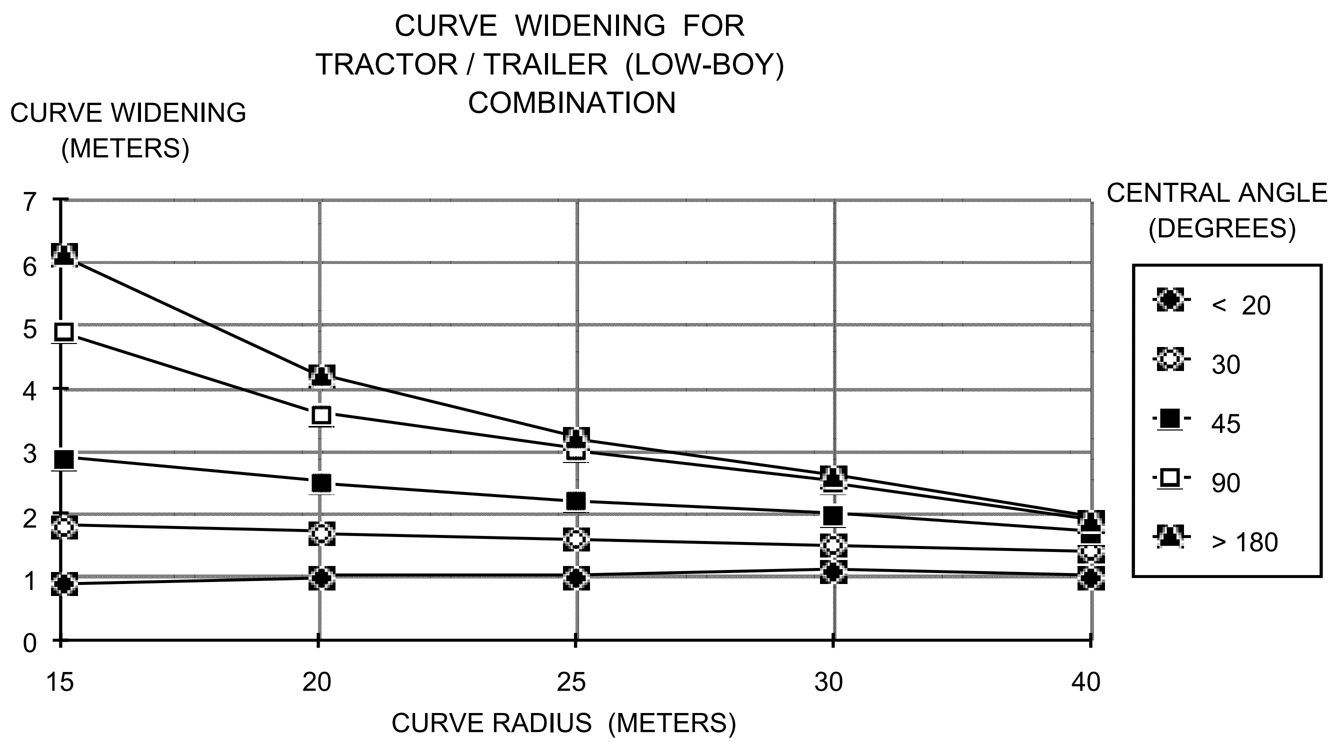


Figure 37. Curve widening guide for a log-truck as a function of radius and deflection angle. The dimensions are as shown.



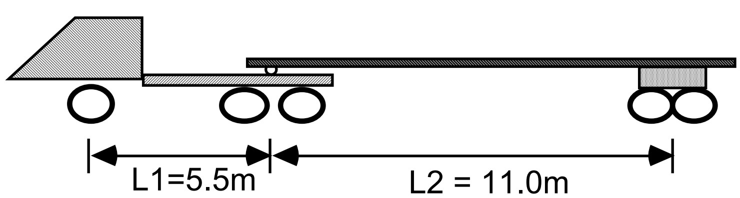


Figure 38. Curve widening guide for a tractor/trailer as a function of radius and deflection angle. The tractor-trailer dimensions are as shown.

3.1.3 Vertical Alignment

Vertical alignment is often the limiting factor in road design for most forest roads. Frequently grades or tag lines are run at or near the maximum permissible grade. Maximum grades are determined by either vehicle configuration (design/critical vehicle characteristic) or erosive conditions such as soil or precipitation patterns. Depending on road surface type, a typical logging truck can negotiate different grades. Table 16 lists maximum grades a log truck can start from. It should be noted that today's loaded trucks are traction limited and not power limited. They can start on grades up to 25 % on dry, well maintained, unpaved roads. Once in motion they can typically negotiate steeper grades.

Vertical curves or grade changes, like horizontal curves, require proper consideration to minimize earthwork, cost, and erosion damage. Proper evaluation requires an analysis of vertical curve requirements based on traffic characteristics (flow and safety), vehicle geometry, and algebraic difference of intersecting grades.

Vertical curves provide the transition between an incoming grade and an outgoing grade. For convenience in design, a parabolic curve (Figures 39 and 40) is used because the grade change is proportional to the horizontal distance. The grade change is the difference between incoming grade and outgoing grade. The shorter the vertical curve can be kept, the smaller the earthwork required.

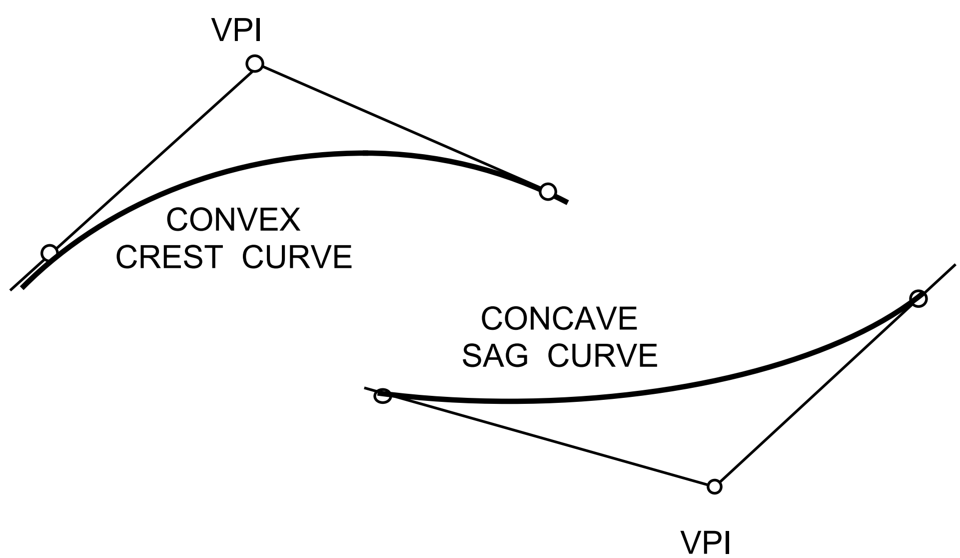


Figure 39. Typical vertical curves(VPI = Vertical Point of Intersection).

The grade change per unit length is defined as

$$(G1 - G2) / L \qquad (\% / \text{meter})$$

or more commonly its inverse, where the grade change is expressed in horizontal distance (meters) to effect a 1% change in grade.

(1) Surface	(2) Traction Coef. (f)	(3 Rolling Res. (r)	(4)* Starting Res. (s)	Maximum Starting Grades** (5) TR = .435 Loaded Truck[a]		(6) TR = .64 Empty Truck Piggyback[b]		(7) TR = .32 Empty Truck Trailer Extended[b]	
				From	To	From	To	From	To
Concrete-dry	.75-.90	.018	.10	21.6	28.1	47.0	61.4	17.6	24.8
Concrete-wet	.55-.70	.015	.10	13.1	19.6	29.6	42.5	9.0	15.5
Asphalt-dry	.55-.70	.020	.10	12.8	19.3	28.4	42.3	8.7	15.2
Asphalt-wet	.40-.70	.018	.10	6.4	19.4	17.4	42.4	2.8	15.3
Gravel-packed, oil, & dry	.50-.85	.022	.10	10.5	25.7	26.2	56.3	6.5	22.0
Gravel-packed, oil, & wet	.40-.80	.020	.10	6.3	23.7	17.4	51.6	2.7	19.8
Gravel-loose, dry	.40-.70	.030	.10	5.7	19.8	17.0	42.0	2.0	14.5
Gravel-loose, wet	.36-.75	.040	.10	3.4	20.4	13.6	46.2	-0.2	16.1
Rock-crushed, wet or dry	.55-.75	.030	.10	12.2	20.9	29.0	46.5	8.0	16.8
Earth-dry	.55-.65	.022-.03	.10	12.2	17.0	29.0	37.8	8.0	12.8
Earth-wet (excludes some clays)	.40-.50	.022-.03	.10	5.7	10.5	17.0	25.2	2.0	6.5
Dry packed snow	.20-.55	.025	.10	-2.7	12.5	2.5	29.2	-5.0	8.4
Loose snow	.10-.60	.045	.10	-8.2	13.6	-5.1	32.7	-9.8	9.1
Snow lightly sanded	29-.31	.025	.10	1.2	2.1	8.9	10.4	-1.8	-1.0
Snow lightly sanded with chains	.34	.035	.10	2.8		12.3		0.6	
Ice without chains	.07-.12	.005	.10	-7.2	-5.1	-5.6	-2.3	-6.1	-6.4

Example

Given: earth surface road
Req'd: maximum adverse grades for the following:

1) landings
2) loaded log truck to start from rest
3) moving loaded log trucks

Assume hauling will be done during wet weather, but not ice or snow

Solution: Under Column (1), find earth-wet:

1) for landing, go across to Col. (7) truck, trailer extended, and read from 2.0 to 6.5 %.
2) for loaded log trucks starting from rest, go across to Col. (5) and read from 5.7 to 10.5 %.
3) add 10 % to part 2, which means a moving loaded log truck will 'spin out' somewhere between 16.7 to 20.5 %.

NOTE
Extreme caution is recommended in the use of steep grades, especially over 20 %. They may be impractical because of construction and maintenance problems and may cause vehicles that travel in the downhill direction to lose control.

*For vehicles with manual transmissions. Factor for wet clutches, hydraulic torque converters, freeshaft turbines, or hydrostatic transmissions would be .03 to .05.
**Add 10 % to these values to obtain the maximum grade a log truck may negotiate when moving.
[a]Based upon = f(TR) - r(1 - TR) - S
[b]Based upon = f(TR)/(1-(f(h)/b)) - r(1 - TR) - S
h = height of trailer coupling or center of gravity (1.2 m)
b = wheel base (5.5 m) formulas from source 2 values in Col. 2 & 3 are composite.

table 21 Maximum grades log-trucks can start on from rest (Cain, 1981).

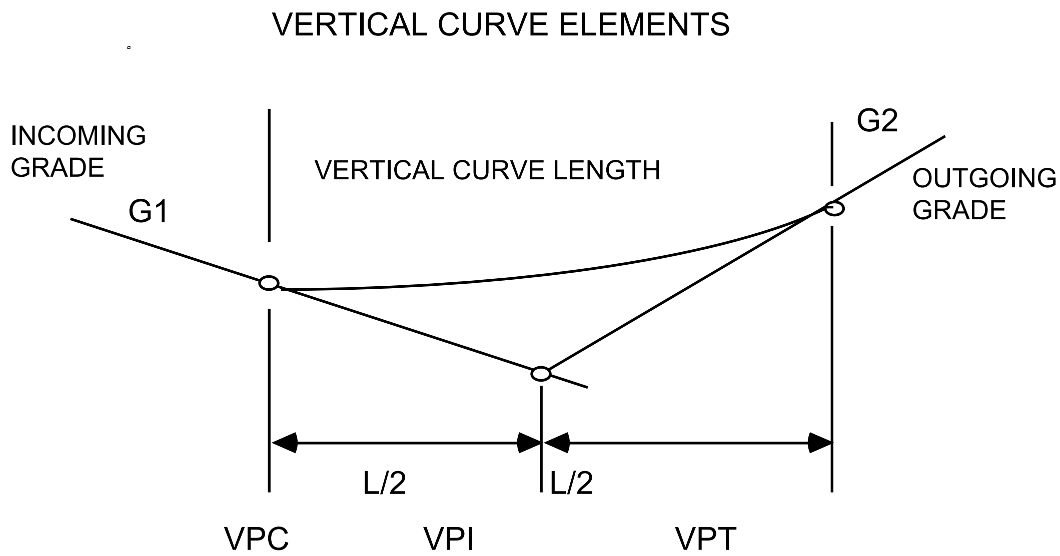


Figure 40. Vertical curve elements (VPC = Vertical Point of Curvature; VPT = Vertical Point of Tangency).

Factors to be considered in the selection of a vertical curve are:

Stopping Sight distance S: On crest curves, S is a function of overall design speed of the road and driver's comfort. On most forest roads with design speeds from 15 km/hr to 30 km/hr, the minimum stopping sight distance is 20 and 55 meters respectively (see Ch. 2.1.2.7). Kuonen(1983) provides an equation for minimal vertical curve length based on stopping distance:

$$L_{min} = S_{min}^2 / 800$$

Where L_{min} = minimum vertical curve length for each 1% change in grade (m/%)
S_{min} = minimum safe stopping sight distance (m).

Example: Determine the minimum vertical curve length for a crest curve that satisfies the safe stopping sight distance.

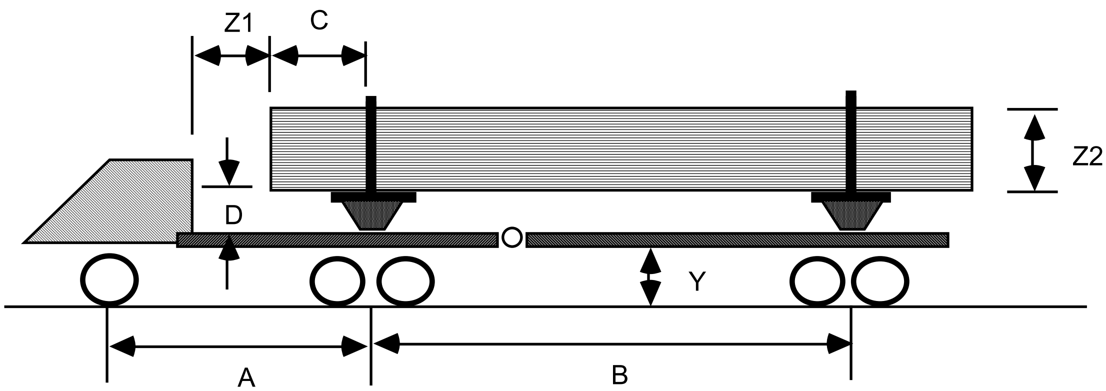
Design speed of road: 25 km/hr
Grade change (G1 - G2): 20 %

Solution: Stopping sight distance for 25 km/hr equals approximately 37 meters (from Ch. 2.1.2.7).

$L_{min} = (37^2 / 800)\ 20 = 34.2$ m

Vehicle geometry: Vehicle clearance, axle spacing, front and rear overhang, freedom of vertical movement at articulation points are all factors to be considered in vertical curve design.

Passage through a sag curve requires careful evaluation of the dimensions as illustrated in Figure 41.



D = Clearance between top of the frame of the truck and the bottom of the logs at the front
Y = Distance between the ground and the bottom of the trailer reach or stinger
Z1= Distance between the front of the logs and the cab of the truck which depend on C and Z2
Z2= Height of log load

Figure 41. Log truck geometry and dimensions for vertical curve analysis

The critical dimensions of a log truck when analyzing crest vertical curves are the length of the stinger and the vertical distance between the stinger and the bottom of the logs, x. A log truck as shown in Figure 41 with dimensions

A - Tractor length	=	4.8 m
B - Bunk to Bunk	=	7.2 m
C - Log overhang front	=	2.4 m
D - Clearance log - frame	=	0.39 m

could negotiate a grade change of 30% over a vertical curve length of 12 m without damage to the truck (Ohmstede, 1976).

As shown in the previous example, safety considerations typically require significantly longer, vertical curves than physical truck dimensions do. With the exception of special or critical vehicles, vertical curves can be kept very short, even for large grade changes. Road maintenance considerations are more important in such situations. Vehicle dimension considerations do become important, however, in special cases such as fords in creek crossings.