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Basics in Roadway Geometrics and Design

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Basics of Roadway Geometrics and Design

Credits: 8 PDH

Course Description

This course covers the procedures used to perform a roadway route survey. The course includes the reconnaissance, preliminary, and then the final location survey. Topics commonly found in a construction route survey are also covered.

The geometric design of roads is then addressed; as well as pertinent design principles of geometric roadway design, used by transportation designers.

Topics

- Planning and Preparation for the Proposed Route
- Performing reconnaissance, preliminary, and final location surveys
- Establishing preliminary design criteria and proposed road specs
- Using various existing map sources when establishing road corridor
- Types of data which are collected during a recon survey
- Horizontal Curves, Vertical Curves
- Introduction to the geometric design of roads
- Establishing curve points
- Compound and reverse curves, Transition spirals
- The use of stationing in a roadway route project
- Elements of a simple curve, formulas/solutions of a simple curve
- Degree of curve – Arc and Chord definitions and comparisons
- Layout of a curve; Dealing with terrain restrictions
- Compound, Reverse, spiral curves
- Sag and Crest curve types
- Using high / low points on a vertical curve to establish drainage
- Basic Roadway Design Features; Classification of roads/highways
- Intersections and interchanges; Superelevation of curves
- Stopping, Passing, Intersection sight distances, Design Speeds
- Perception-Reaction/Maneuver time; Level of Service

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Chapter 1: Planning and Preparation for the Proposed Route

Reconnaissance Surveys

Recon Survey

The reconnaissance survey is a preliminary feasibility study for a proposed route that id being considered for a roadway's corridor.

The purpose of this survey is to eliminate any routes which may prove problematic, impractical, non-economical, and non-feasible.

Existing road maps and aerial photography may be very useful, while contour maps such as those found at the USGS, will show the terrain features and the relief of an area. Soil maps are also helpful when laid over a promising road route.

The recon survey should include all potential routes, and the recon survey report should summarize all the collected information, including a description of each route or site, a conclusion on the economic feasibility of each route, and where possible, should include supporting maps and aerial photography.

Design

Characteristics of the roadway design should be taken into consideration during the reconnaissance survey, keeping in mind future expansion considerations for the corridor such as lane additions, intersections, interchanges, and utility right of ways.

Guidelines for Road Design

Design Guidelines:

- Locating portions of the proposed road along existing road routes (see image), or aligned with railroads can reduce the project costs, especially involving excavation, fill, road base, and other earthwork expenses.
- Locate the road on high-bearing-strength soil that is stable and easily drained, avoiding swamps, marshes, and organic soil. This is one area where the soil maps will prove to be of use.
- When the road alignment is established along ridges or streamlines, this will reduce the need for drainage structures.
- Refer to FIRM flood maps to ensure that the grade well remains well above the high waterline when following a stream.
- Keep in mind the need for spoil and borrow areas for excavated earth when selecting a route, and locate the road along contour lines to avoid unnecessary earth work (minimizing cut and fill).
- Avoid areas which require excessive rockwork, clearing and grubbing, and the need to remediate substandard soil conditions.
- Identify regions along the route which may require substantial slope stabilization.
- Avoid sharp curves and locations which involve the need for major bridge projects. When possible consider the potential for the use of culverts in lieu of bridges, as the cost difference between the two is considerable.

Existing secondary gravel road

Data and Maps for the Recon Survey

Data and Maps Needed

Once completed, the reconnaissance survey should support the routes surveyed and provide a basis of study showing the pros and cons of all routes which have been examined.

Collecting Data

Typical data collected in a reconnaissance survey are:

- Sketches and reports of all feasible routes which have been considered
- Data on clearing and grubbing, cut and fill requirements, rock excavation
- Water, pedestrian, railway, or road crossings which may involve bridge spans exceeding 20 feet
- The approximate number of culverts and spans less than 20 feet
- Descriptions and sizes of wetland and marsh areas, or other natural obstacles which are encountered
- Unusual grade and alignment conditions which may pose a problem
- Potential areas of landslide, melting snow, or stormwater hazards
- Soil conditions and stream and substrata conditions at proposed bridge locations
- Discrepancies which have been observed in maps or aerial photography
- Availability of local material sources (such as asphalt, concrete, road base and subbase), equipment, transportation facilities, and skilled labor
- Photographs or sketches of reference points, control points, structure sites, terrain obstacles, and any unusual conditions

Use of Maps to establish a Proposed Route

The procurement and markup of maps is an essential phase of the route recon survey:

- Begin a map study by marking limiting boundaries and specified terminals of the roadway corridor, directly on the map.
- Locate and use existing maps, and verify all land features by using up-to-date aerial photography of the area to be reconnoitered.
- Large-scale topographic maps are preferable, as they depict the terrain in the greatest detail.
- Using maps with overlays will serve as worksheets for plotting out trial alignments, and approximated grades and distances.
- Within the boundaries and specified terminals: observe existing routes, ridge lines, water courses, mountain gaps, and other necessary control features.
- Identify terrain which allows for moderate grades, simplified alignments, and minimized cut and fill.
- The routes which show the most promise will begin to develop.
- Routes to be reconnoitered in the field are marked with contrasting colors to indicate priorities and preferences.
- Take advantage of existing terrain features to minimize excavation.
- Determines grades, estimate the amount of clearing required per route, and mark water and muck crossings for possible ford, bridge, or culvert structure requirements.

Preliminary Survey

Preliminary Survey

The preliminary survey is a detailed study of a potential roadway route which is selected on the basis of the reconnaissance survey's information and recommendations.

The size and scope of the roadway project will determine the nature and extent of the preliminary survey.

In a preliminary survey:

- a traverse is run along the proposed route
- various levels are established
- the topography is recorded
- results are plotted
- then the final location is determined from this plot or preliminary map

The survey effort establishes a traverse with control and reference points, or it may expand to include leveling and topographic detail.

Required Survey Teams

Typically, obtaining traverse, leveling, and topographic data are separate survey efforts. However this does not exclude combining them, to increase the efficient use of personnel and equipment.

Traverse Party

The traverse party will be responsible for establishing the traverse line along the proposed route; by setting and referencing control points, measuring distances, numbering stations, and establishing points of intersection.

Additionally, this party makes the necessary ties to an existing control, when available or needed. When no control is found, the party may establish a starting control monument, which may later be tied to an existing geodetic control point.

Level Party

The level party establishes benchmarks and determines the elevation of selected points along the route to provide control for future surveys; such as those required for the preparation of a topographic map or profile and cross-section leveling.

Rod readings and records elevations should be to a tolerance, to the nearest 0.01 foot or 0.001 meter. Benchmarks are set in a location well away from the area of construction and are marked in such a way, that they will remain stationary throughout the project.

If no established vertical control point is available, then an arbitrary elevation should be established that may be tied to a vertical control point at a later time. The assigned value of the arbitrary elevation must be large enough to avoid negative elevations at any point on the project.

Topographic Party

The topographic party secures enough relief and planimetric detail within the immediate project area to locate any obstacles and allow preparation of rough profiles and cross sections.

Computations made from the data determine the final location. The instruments and personnel combinations used vary with survey purpose, terrain, and available time. A transit-stadia party, plane table party, or combination of both may be used.

Transit-Stadia Party

The transit stadia party is effective in open country where comparatively long, clear sights can be obtained without the need to cut and remove an excessive amount of brush.

Plane Table Party

The plane table party is used where terrain is irregular. For short route surveys, the procedure is similar to the transit-stadia method, except that the fieldwork and the drawing of the map are carried out simultaneously.

Final Location Survey

Final Location Survey

Prior to the final location survey in the field, studies are made back in the office, which are used as guidance for the final location phase.

These consist of:

- preparation of a map from preliminary survey data
- projection of a potential alignment and profile
- preliminary estimates of quantities and costs

The instrument party carefully establishes the final location in the field using the paper location prepared from the preliminary survey.
(No changes should be made without the authority of the officer in charge of the project).

Running the Alignment’s Centerline

The centerline may vary from the location depicted in the plans, due to objects or conditions not previously considered.

The surveyor will determine all of the construction lines based on the final center line, from which they will:

- mark the stations (numbered consecutively at full 100 ft or 30 m stations, beginning with station 0+00)
- then run the levels
- and set the grades

The surveyor also sets stakes at important points along the centerline such as:

- culvert locations
- road intersections
- beginning and ending of curves
- breaks in the grade

Stationing for these points would be labeled as such:

- *English Units:* Station points are numbered from the last full station (n+00), and are called “plus stations.” A station numbered 3+24.75 would be 24.75 feet away from station 3+00 and 324.75 feet from the beginning of the project.
- *Metric Units:* If the total distance from the beginning of a project to a station point was 117.56 meters, it would be numbered 117.56.

Reference Stakes

The control points established by the location survey determine the construction layout; therefore these points must be carefully referenced.

These control point references should be set a reasonable distance from the construction zone, in order to avoid being disturbed by the construction process.

Profile and Cross Sections

Following the staking of the centerline and horizontal curves of the road, will be the elevations along the centerline and lateral points across the road.

These operations, known as *profile leveling* and *cross section leveling*, are performed as separate operations but at the same time as the elevation of points along a centerline or other fixed lines.

The interval usually coincides with the station interval, but shorter intervals may be necessary due to abrupt changes in terrain. The plotting of centerline elevations is known as a *profile*. From this profile, the design engineer determines the grade of the road.

The cross-section elevations make it possible to plot views of the road across the road at right angles. These plotted cross sections will determine the volume of earthwork required.

The surveyor establishes the cross section lines at regular stations, at any plus station, and at intermediate breaks in the ground and lays out the short crosslines by eye and long crosslines at a 90-degree angle to the centerline with an instrument.

Elevations at abrupt changes or breaks in the ground are measured with a rod and level, and distances from the centerline measured with a tape.

In rough terrain, the surveyor uses the hand level to obtain cross sections if the centerline elevations have been determined using the engineer level.

Construction Layout Survey

Construction Layout

The construction layout is an instrument survey, which provides the alignment, grades, and locations that guide the construction operations.

Construction operations include:

- clearing and grubbing of vegetation
- stripping of topsoil
- drainage grading and stormwater structures
- rough grading
- finish grading and surfacing

Keeping ahead of the Construction Activities

The project manager must insure that the surveyor team remains sufficiently in front of the construction activity in both schedule and location, in order to guarantee that the construction effort does not stall.

Survey / Construction Buffer Lengths

Note the following recommended distances:

- Keep the centerline established 1,500 feet (or 450 meters) in front of any clearing and grubbing activity.
- Keep rough grades established and slope stakes set 1,000 feet (or 300 meters) in front of stripping and rough grading activity.
- Set the stakes to exact grade, 500 feet (or 150 meters) in front of finish grading and surfacing activity.

Marking the Alignment

As mentioned above, the centerline alignment survey should be staked or marked ahead of the work crews engaged in the various phases of construction.

A crude but effective alignment, initially marked by flags and rods, is suitable for guiding the clearing and grubbing operations. However, a more precisely staked location of the centerline is required for the final grading and surfacing operations.

Additionally:

- The marking of the curves and minor structures should run concurrently with the layout of the centerline.
- Major structures such as tunnels and bridges involve a site survey.
- The establishment of the site boundaries is performed along with the establishing of the route alignment.

Construction Staking

Setting Grade Stakes

Grade stakes indicate the exact grade elevation for the construction work crews. The construction plans should be consulted to determine the exact elevation of the subgrade, and the offset required from the centerline to the edges of the shoulder.

Preliminary Subgrade Stakes (Cut)

The preliminary subgrade stakes should be set on the centerline and other grade lines, as required.

Initially, the amount of cut or fill required at the centerline station should be determined. (The amount of cut or fill will be equal to the grade rod minus the ground rod).

The grade rod is equal to the height of instrument minus the subgrade elevation at the station. (The ground rod is the foresight reading at the station).

If the result of this computation is a positive value, it indicates the amount of cut required. (If it is negative, it indicates the amount of fill).

Example:

Given a height of instrument (HI) established at 115.5 feet, with a subgrade elevation of 108.6 feet, and a ground rod reading of 3.1 feet, the grade rod = 115.5 feet -108.6 = +6.9 and cut or fill = 6.9 -3.1 = +3.8, indicating a cut of 3.8 feet.

The results are then recorded in the field notes and on the back of the grade stake as C 38 (C for cut, and 38 for 3.8 ft.).

Note: On occasion, it is necessary to mark stakes to the nearest whole or half foot to assist the earthwork crew.

During rough grading operations, the construction crew determines the grades for the edges of the traveled way, roadbed, and ditch lines.

However, if the road is to be superelevated or is in rough terrain, the survey crew must provide stakes for all grade lines.

These would include the centerline, edge of the traveled way, edges of the roadbed, and the centerline of the ditches.

The surveyor sets those stakes by measuring the appropriate distance off the centerline and determines the amount of cut or fill as outlined.

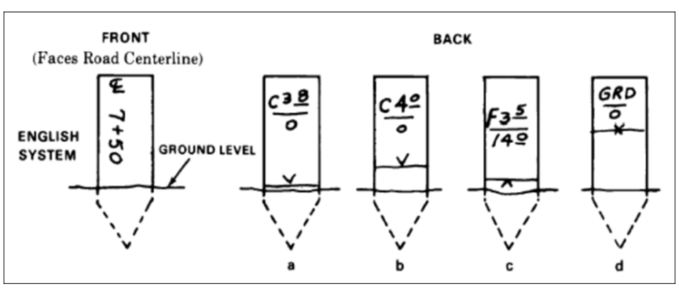
The surveyor offsets the stakes along the traveled way, roadbed, and ditches to avoid their being destroyed during grading operations.

The construction foreman, not the surveyor, makes the decision as to how many and where grade stakes are required.

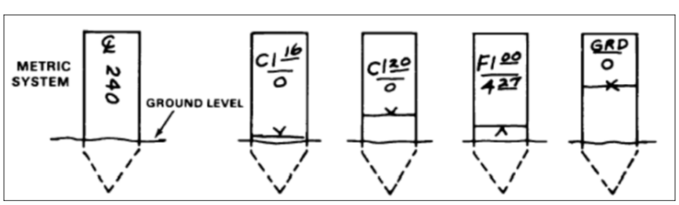
Final Grade Stakes

Once rough grading is finished, the surveyor will set the final grade stakes (blue top stakes):

- The elevation of the final grade is determined and the value of the grade rod reading is computed.
- The surveyor uses a rod target to set the grade rod reading on the rod. The rod is held on the top of the stake.
- The stake is then driven in, until the horizontal crosshair bisects the target and the top of the stake is at final grade.
- The surveyor marks the top of the stake with a blue lumber crayon to distinguish it from other stakes.



Grade Stakes – English Units



Grade Stakes – Metric Units

The surveyor should provide blue tops on all grade lines, or whichever type of stake the construction foreman ultimately decides should be used. In setting the final grade, the surveyor typically makes rod readings and computations within a 0.01 foot or 0.001 meter tolerance.

When staking in Hardened Ground

Where grade stakes cannot be driven due to hardened ground or rocky conditions, the surveyor must set and preserve grade markings on the rock itself with a chisel or a lumber crayon, or some other means which will remain stationary.

Slope Staking

Setting Slope Stakes

Slope stakes indicate the intersection of cut or fill slopes with the natural ground line, indicating the earthwork limits on either side of the centerline.

Level Section

When the ground is level transversely to the centerline of the road, the cut or fill at the slope stake will be the same as at the center, except for the addition of the crown.

- *Fill sections* - the distance from the center stake to the slope stake is determined by multiplying the center cut by the ratio of the slope (for example, horizontal distance to vertical distance) of the side slopes and adding one half the width of the roadbed.
- *Cut sections* - the distance can be found from the center stake to the slope stake by multiplying the ratio of slope by the center cut and adding the distance from the centerline to the outside edge of the ditch.

In either case, if the ground is level, the slope stake on the right side of the road will be the same distance from the centerline as the one on the left side of the road.

- *Superelevated sections* - the widening factor must be added, to determine the distance from the centerline to the slope stake. This is because the widening factor is not the same for both sides of the road, and the slope stakes will not be the same distance from the centerline.

Transversely Sloping Ground

When the ground is not level transversely, the cut or fill will be different for various points depending on their distance from the centerline.

The point must be determined on each side of the centerline, whose distance from the center is equal to the cut or fill at that point multiplied by the slope ratio and added to one half the roadbed width for fills, and the slope ratio multiplied by the distance from the centerline to the outside of the ditches for cuts.

Trial and Error

A trial and error method is needed. Proficiency will improve when approximating the correct position of the slope stake, and the number of trials can eventually be reduced to two or three tries.

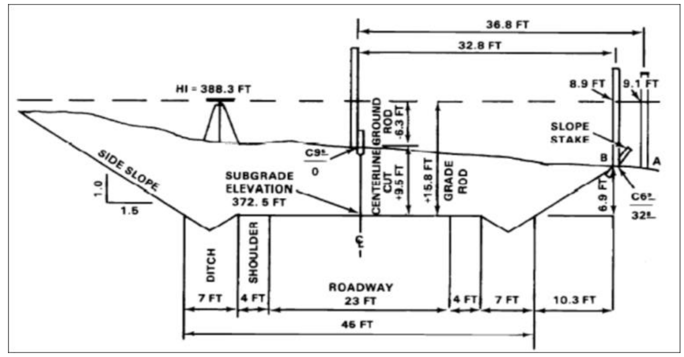
The cut or fill will be marked on the slope stake, and then recorded in the notebook as the numerator of a fraction whose denominator is the distance out from the centerline.

Three level, five-level, and irregular sections present this problem.

The images below illustrate the procedure involved in setting slope stakes on sloping ground for three typical cases.

Case 1: Cut Section

1) The cut section in the image has the level set up with an HI (height of instrument) of 388.3 feet.



Setting Slope Stakes

2) The subgrade elevation at this centerline station is set at 372.5 feet for a 23-foot roadbed with 1.5:1 side slopes, 4-foot shoulders, and 7-foot ditches.

3) The “grade rod” is the difference between these two elevations or 388.3 -372.5 = +15.8 feet.

4) The rodman now holds the rod on the ground at the foot of the center grade stake and obtains a reading of 6.3 feet, a “ground rod.”

5) The recorder subtracts 6.3 from the grade rod of 15.8, which gives +9.5 feet or a center cut of 9.5 feet.

6) On slope stakes, the cut or fill and distance out from the centerline are written on the side of the stake which faces the center of the road. The backs of the slope stakes show the station and the slope ratio to be used.

7) The recorder estimates the trial distance by multiplying the cut at the centerline (9.5) by the slope ratio (1.5) and adding the distance from the centerline to the outside edge of the ditch (22.5). 9.5 x 1.5+ 22.5= 36.8 (to the nearest tenth of a foot). The rodman now moves to the right at right angles to the centerline the trial distance (36.8 feet).

8) The rod is held at A and a reading of 9.1 is obtained, which, when subtracted from the grade rod of 15.8, gives a cut of 6.7 feet.

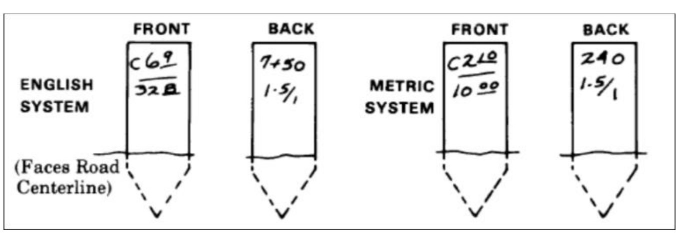
9) The recorder then computes what the distance from the centerline to A should be. This is done by multiplying the cut of 6.7 by the slope ratio and adding one half the roadbed's width, which gives 32.6 feet. However, the distance to A was measured as 36.8 feet instead of 32.6, so the position at A is too far from the centerline.

10) Another trial is made by moving the rod to 32.6 feet from the centerline (B), where a reading of 8.9 is made.

11) The cut at B is now 15.8 - 8.9 = +6.9, and the calculated distance from the center is 6.9 x 1.5 + 22.5 = 32.8 feet. The distance actually measured is 32.8 feet. Therefore, B is the correct location of the slope stake and is marked C6.

12) Since moving the rod one or two tenths of a foot would not materially change its reading, greater accuracy is unnecessary. After a few trials, the rodman locates the slope stake on the left in a similar manner. The instrument operator verifies the figures by computation.

13) When placed in the ground, the stakes will appear as in the image below.

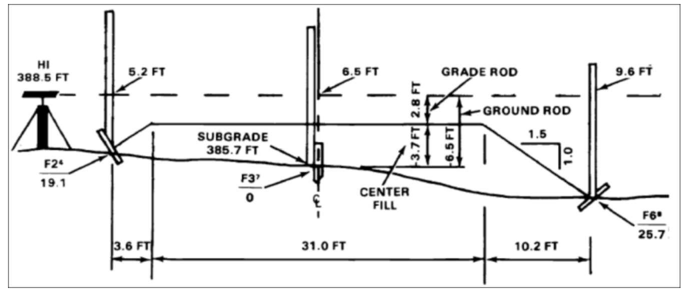


Marking Slope Stakes

Case 2: Fill Section (HI above Grade Elevation)

The image below illustrates a fill with the HI of the level set up above the subgrade elevation of the 31-foot roadbed.

1) In this case, the grade rod will always be less, numerically, than rod readings on the ground.



Slope Stakes, HI above Grade Elevation (English Units)

2) The grade rod in this problem is +2.8; the rod reading at the center stake is 6.5; and the difference is 2.8-6.5 = -3.7 feet. (The minus sign indicates a center fill).

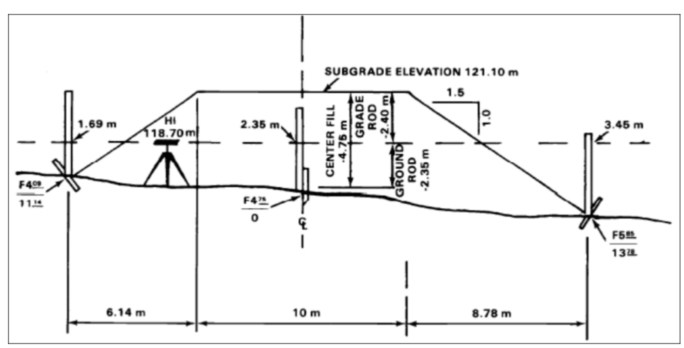
3) The rodman finds the positions of the slope stakes by trial, as previously explained.

Case 3: Fill Section (HI below Grade Elevation)

The image below illustrates a fill with the HI of the level below the grade elevation of the future roadbed. Therefore, the grade rod has a negative value.

1) Adding the negative ground rod to the negative grade rod will give a greater negative value for the fill.

2) For example, at the center stake, the fill equals (-2.40 meters) + (-2.35 meters) or -4.75 meters. (Otherwise, this case is similar to the preceding ones).



Slope Stakes, HI below Grade Elevation (Metric Units)

Laying Out a Culvert

Laying out Culverts

To establish the layout of a site feature such as a culvert, the intersection of the roadway centerline and a line defining the direction of the culvert are located. (Generally, culverts are designed to conform to natural drainage lines).

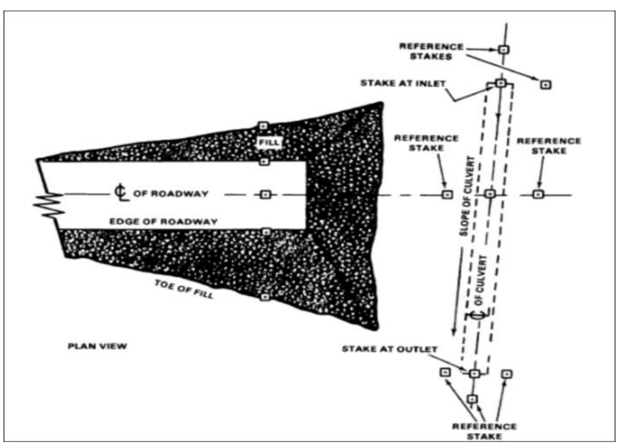
Staking and Marking

Stakes are placed to mark the inlet and outlet points, and any cut or fill requirements are marked on them.

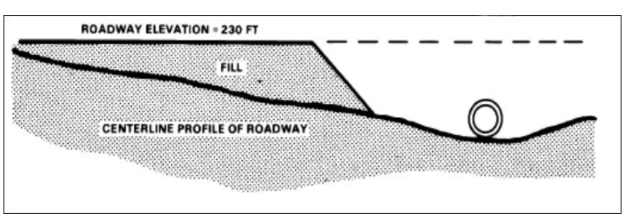
The construction plans for the site are carefully followed, and the alignment and grade stakes are set on the centerlines beyond the work area. Thus, any line stake which is disturbed or destroyed during the work can be easily restored.

A benchmark should be set near the site, but outside of the work area, to lay out the culvert site.

Circumstances may require that certain types of surveys be eliminated or combined. For example, the location and construction surveys may be run simultaneously.



Culvert Layout – Plan View



Culvert Layout – Cross Sectional View

Drainage

Proper Drainage

Maintaining proper drainage throughout the route's corridor is vital when locating, designing, and building any type of road infrastructure.

The surveyor must anticipate potential drainage issues and compile sufficient field data to indicate the best design and location for needed drainage structures.

Proper drainage is of primary importance with respect to the operational requirements and the useful life expectancy of a roadway facility.

Inadequate drainage is a primary cause of many road failures. The surveyor must help to insure that these and similar facilities are well drained to function efficiently during inclement weather conditions.

Providing temporary drainage during construction activities

Rainfall will inevitably be encountered during most roadway projects. Thus providing temporary drainage during the construction phase cannot be emphasized enough.

Properly providing drainage during road construction is essential for:

- preventing construction delays and fines
- reducing muddy, aggravating, and unsafe working conditions
- improving soil compaction process (helps in meeting optimal moisture content in the road base)
- mitigating erosion
- limiting sedimentation transport
- reducing standing water or saturated ground within the construction area

Chapter 2: Horizontal Curves

Geometric Design of Roads

Geometric Road Design

The geometric design of roads (highways and streets), is the branch of transportation engineering which deals with the positioning of the physical elements of the roadway (or railway) according to standardized design principles, standards and policies.

Geometric roadway design consists of three "dimensional" components:

- *Horizontal Alignment* – The horizontal component of a roadway's alignment consists of a series of horizontal tangents (straight roadway sections), circular curves, and spirals.
- *Vertical Alignment or Profile (side view)* – The vertical component of the road alignment, includes the crest (peaks) and sag (valleys) curves, with straight grade lines in between.
- *Cross sections* – This is a slice of the road, usually through a stationing point, which shows crosscut features such as the position and number of lanes, sidewalks, cross slopes or banking, crowning, drainage features, the road structure (base, subbase, and asphalt or concrete pavement with reinforcing).

When properly designed, the horizontal, vertical, and cross sectional elements all contribute to a road's operational quality and safety, providing a smooth-flowing, "predictable" driving experience for the driver.

"Predictability" being a necessary feature in any roadway design, as the driver should always know what to expect of an upcoming road segment.

A roadway's designer must understand how all of the roadway elements go together to contribute to the overall safety and operation of the driving experience.

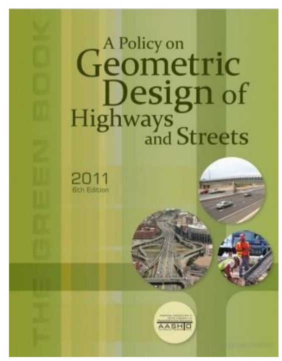
Simply applying pre-established design standards and criteria to a design is not enough, as a roadway's conceptual process can be as much an art as it is a science.

The fundamental objective of any proper geometric design is to produce a road that above all else is safe and predictable to drive; being reasonably economical to build, fitting the terrain, and being functionally sound while taking multiple and often conflicting design concerns into account.

The AASHTO "Green Book"

The commonly accepted guide on geometric roadway design used by most transportation engineers and roadway designers is the AASHTO's Policy on Geometric Design of Highways and Streets or simply the "Green Book".

This guide is technically considered a design policy as opposed to a design standard.



AASHTO's Policy on Geometric Design of Highways and Streets
Image Source: AASHTO

General Design Considerations when Establishing a Roadway Alignment

In general, the use of short curves in the design should be kept to a minimum when possible.

Long tangents are highly suggested on two-lane highways so that sufficient passing sight distance is available on as much of the roadway as possible.

Sharp curves should be avoided near the following:

- elevated structures
- at or near a crest in grade

- at or near a low point in a sag or grade
- at or near intersections
- at or near transit stops
- at or near points of ingress or egress
- at or near decision points

The concepts of stopping sight distance, intersection sight distance, decision sight distance and driver expectancy should be considered when developing the horizontal alignments.

When possible, the horizontal alignments of roadways should be free of curves in and around intersections, interchanges, bridges, railroad crossings, toll plazas, drop lanes and roadside hazards.

To allow proper pavement drainage, alignments should be laid out such that the 0% cross slope flat points which occur when there are superelevation transitions on either end of a horizontal curve, do not correspond to low points in the roadway vertical profile.

The horizontal alignment should be carefully coordinated with the vertical profile design. The design speed of successive horizontal curves on ramps can vary as vehicles are often accelerating or decelerating.

A common rule to apply to the speed design of ramps is that the design speed of the first curve of an exit ramp can be assumed to be 10 mph less than the design speed of the mainline (highway).

With each successive curve on the exit ramp, the design speed of the curve may be reduced based on computed vehicle deceleration.

The process should be reversed for entrance ramps, i.e., the design speed for curves will successively increase until the design speed of the last curve before the mainline is 10 mph less than that of the mainline.

A short horizontal curve with a small deflection angle (less than five degrees) may appear as a kink in the roadway. As a minimum, curves should be at least 100-ft. in length for every one degree of central angle.

Establishing Horizontal Curve Points and Types of Horizontal Curves

Horizontal Curve Points

In the practice of roadway construction surveying, a surveyor must establish the stationing points of the alignment along the circumference line of the many horizontal curves within the roadway project.

In laying out the large arcs of a roadway, measured angles and straight line distances are usually used when locating selected points, (stations), along the circumference of the alignment arc.

Crude (Tape) Method:
In situations involving small curves where a lesser degree of precision is acceptable, and an unobstructed line of sight between the curve and the pivot point is available, a surveyor may establish points along curves of a short radius, (usually less than one tape length), by holding one end of the tape at the center of the circle and swinging the taut tape in an arc, marking the points along each curve, with a rolling measuring device.
However, as the radius and length of curves increase, the tape method becomes impractical, and the surveyor must use more sophisticated surveying methods.

Types of Horizontal Curves

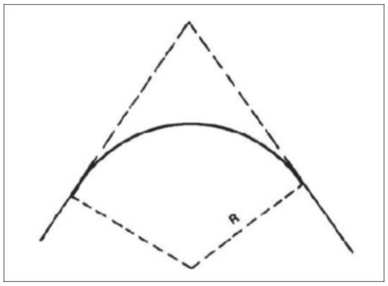
A curve may be simple, compound, reverse, or spiral.

A simple curve is based on a single radius center point, while compound and reverse curves are a combination of two or more simple curves, and the spiral curve is based on a varying radius.

Simple Curve

The simple curve (image below) is no more than an arc segment of a circle.

The radius of the circle determines the "flatness" of the curve. As the radius increases in length, the curve becomes flatter.

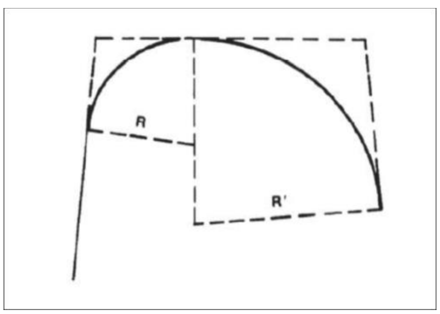


Simple Horizontal Curve

Compound Curve

A compound curve normally consists of two simple curves curving in the same direction and joined together.

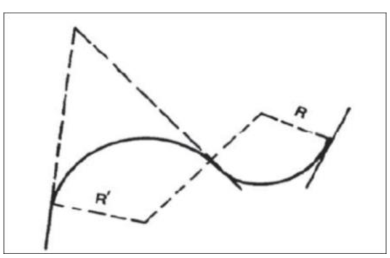
Surveyors often have to use a compound curve (image below) because of the requirements of the alignments terrain.



Compound Curve

Reverse Curve

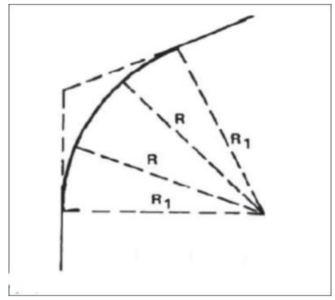
A reverse curve (image) consists of two simple curves joined together, while curving in opposing directions.



Reverse Curves

Spiral Curve

The spiral curve (image) has a varying radius used mainly for rail system alignments, which provides a transition from the tangent to a simple curve or between simple curves in a compound curve.



Spiral Curve

Use of Stationing

Stationing

On route surveys, the surveyor numbers the stations forward from the beginning of the project, measuring along the centerline of the curving alignment.

0+00 would indicate the beginning of the project. A point located at 12+42.46 would indicate a point 1,242.46 feet from the beginning.

Full Station

Each full station is 100 feet in distance (in English units) or 30 meters (in metric design), making 12+00 and 13+00 full stations.

Points in between Full Stations

Points in between single foot measurements are in decimals of a foot, not in inches.

Plus Stations

A plus station indicates a point between full stations. Ex. 15+52.96 is a plus station between the 15 and 16 station.

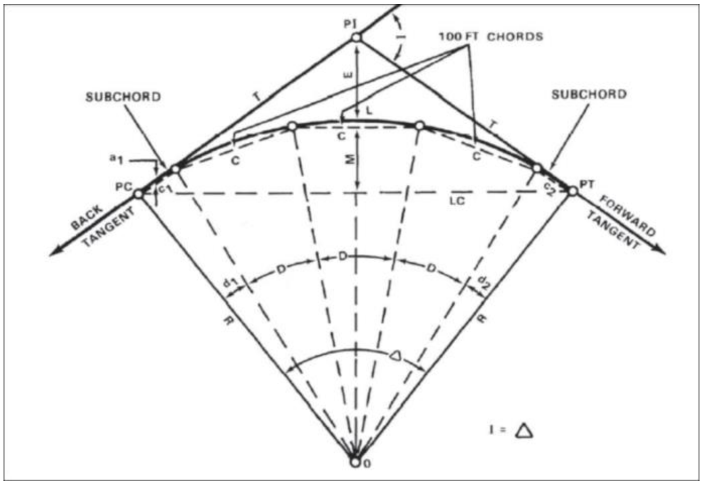
Metric Stationing

When using the metric system, the surveyor does not use the plus system of numbering stations. The station number simply becomes the distance from the beginning of the project.

Elements of a Simple Curve

Simple Curve

In the image below, is illustrated the basic elements of a simple curve as used in the geometric design of roads.



Elements of a Simple Curve
Image Source: USACE TM-5-232

Radius (R)

This is the radius of the circle, of which the curve is an arc.

Point of Curvature (PC)

The point of curvature is the point where the circular curve begins, (the back tangent being tangent to the curve at this point).

Point of Intersection (PI)

The point of intersection is the point where the back and forward tangents intersect. (The surveyor indicates it as one of the stations on the preliminary traverse).

Length of Curve (L)

The length of curve is the distance from the PC to the PT measured along the curve.

Intersecting Angle (I)

The intersecting angle is the deflection angle at the PI. The surveyor may compute its value from either the preliminary traverse station angles or from measurements in the field.

Point of Tangency (PT)

The point of tangency is the end of the curve. (The forward tangent is tangent to the curve at this point).

Tangent Distance (T)

This is the distance along the tangents; from the PI to the PC or PT. (These distances are equal on a simple curve).

Central Angle (Δ)

The central angle is the angle formed by two radii drawn from the center of the circle (0) to the PC and PT. The central angle is equal in value to the (I) angle.

Long Chord (LC)

The long chord is the chord which runs from the PC to the PT.

External Distance (E)

The external distance is the distance from the PI to the midpoint of the curve. (The external distance bisects the interior angle at the PI).

Middle Ordinate (M)

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).

Degree of Curve (D)

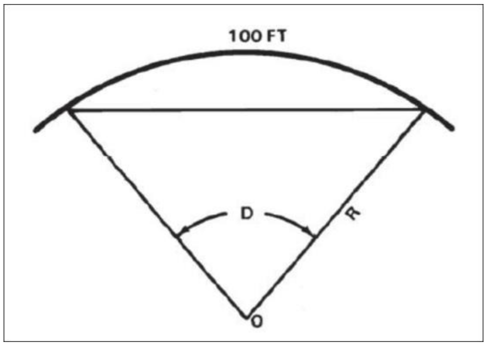
The degree of curve defines the “flatness” of the curve.

Degree of Curve - Arc and Chord Definitions

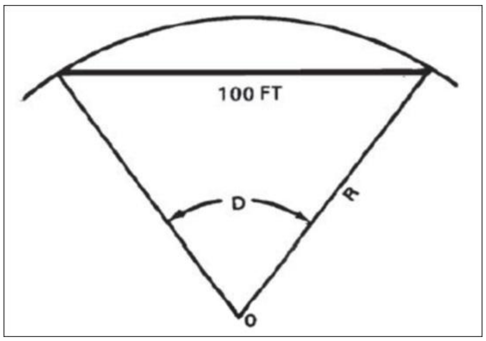
Degree of Curve (D)

The degree of curve (D) defines the amount of the “sharpness” or the “flatness” in a roadway curve.

There are two definitions commonly used for the degree of curve, the *arc definition* (image) and the *chord definition* (image):



Arc Definition



Chord Definition

Arc Definition

This definition states that the degree of curve (D) is the angle formed by two radii drawn from the center of the circle (point O, in the image above) to the ends of an arc 100 feet or 30.48 meters long.

In the arc definition:
The degree of curve and radius are inversely proportional; as the degree of curve increases, the radius decreases.

$$\frac{\text{Degree of Curve}}{360°} :: \frac{\text{Length of Arc}}{\text{Circumference}}$$

$$\text{Circumference} = 2\,\pi\,\text{Radius}$$
$$\pi = 3.141592654$$

Equation 2.1 - Arc Definition

Note:
When using the arc definition, for a given intersecting angle or central angle, all of the elements of the curve are inversely proportioned to the degree of curve. (This definition is primarily used by civilian engineers in highway construction).

English System

Substituting into Equation 2.1, D (Degree of Curve) = 1° and the length of arc = 100 feet; solving for R:

$$\frac{1°}{360°} :: \frac{100}{2\pi R} = \frac{1}{360} :: \frac{100}{6.283185308\ R}$$

$$\text{Therefore, } R = 36{,}000 \text{ divided by } 6.283185308$$
$$R = 5{,}729.58 \text{ ft}$$

Example - English

Metric System

Substituting into Equation 2.1, D = 1° with a length of arc = 30.48 meters; and solving for R:

$$\frac{1°}{360°} :: \frac{30.48}{2\pi R} = \frac{1}{360} :: \frac{30.48}{6.283185308\ R}$$

$$\text{Therefore, } R = 10{,}972.8 \text{ divided by } 6.283185308$$
$$R = 1{,}746.38 \text{ m}$$

Example - Metric

Chord Definition

The chord definition states that the degree of curve is the angle formed by two radii drawn from the center of the circle (point O, previous image) to the ends of a chord 100 feet or 30.48 meters long.

The radius is computed by the following formula:

$$R = \frac{50 \text{ ft}}{\text{Sin } ½ \text{ D}} \text{ or } \frac{15.24 \text{ m}}{\text{Sin } ½ \text{ D}}$$

Equation 2.2 - Chord Definition

With the chord definition, the radius and the degree of curve are not inversely proportional; even though, as in the arc definition, the larger the degree of curve the “sharper” the curve and the shorter the radius.

(The chord definition is used primarily on railroads in civilian practice and for both roads and railroads by the military).

English System

Substituting into Equation 18, D = 1° and given that sin ½ 1 = 0.0087265355, Solving for R:

$$R = \frac{50 \text{ ft}}{\text{Sin } ½ \text{ D}} \text{ or } \frac{50}{0.0087265355}$$

$$R = 5{,}729.65 \text{ ft}$$

Example - English

Metric System

Using a chord 30.48 meters long, the surveyor computes R by the formula; substituting D = 1° and given that sin ½ 1° = 0.0087265335; solving for R:

$$R = \frac{15.24}{0.0087265355}$$

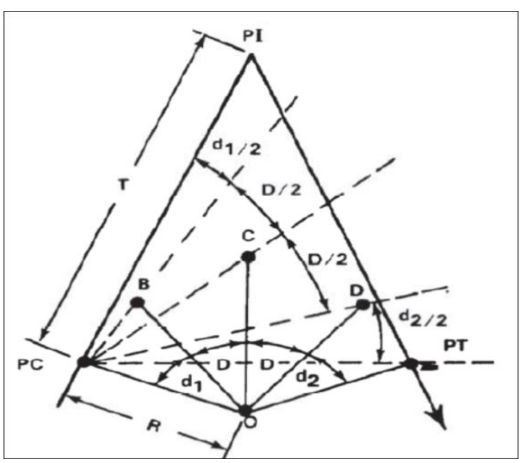
$$R = 1{,}746.40 \text{ m}$$

Example - Metric

Chords

On curves with a long radius, it's impractical to stake the curve by locating the center of the circle and swinging the arc with a tape.

The surveyor lays these curves out by staking the ends of a series of chords (as illustrated in the image below).



Deflection Angles

Since the ends of the chords lie on the circumference of the curve, the surveyor defines the arc in the field. The length of the chords will vary with the degree of curve.

To reduce the discrepancy between the arc distance and chord distance, the surveyor uses the following chord lengths (in Table below):

Degree of Curve	Radius Feet	Radius Meters	Chord Feet	Lengths Meters
from 1 - 3	5,730 - 1,910	1,745 - 585	100	30.0
3 - 8	1,910 - 720	585 - 220	50	15.0
8 - 16	720 - 360	220 - 110	25	7.5
over 16	360 - 150	110 - 45	10	3

Chord Lengths Table

The chord lengths above are the maximum distances in which the discrepancy between the arc length and chord length will fall within the allowable error for taping, which is 0.02 foot per 100 feet on most construction surveys.

Depending upon the terrain and the needs of the project foremen, the surveyor may stake out the curve with shorter or longer chords than recommended.

Deflection Angles

The deflection angles are the angles between a tangent and the ends of the chords from the PC. The surveyor uses them to locate the direction in which the chords are to be laid out.

The total of the deflection angles is always equal to one half of the (I) angle. This total serves as a check for the computed deflection angles.

Simple Curve Formulas

Simple Curve Formulas

The following formulas are used in the computation of a simple curve.

All of these formulas, with the exception of those noted, apply to both the arc and chord definitions:

$$R = \frac{5729.58 \text{ ft}}{D} \text{ or } \frac{1746.38 \text{ m}}{D} \quad \text{(arc definition)}$$

$$D = \frac{5729.58 \text{ ft}}{R} \text{ or } \frac{1746.38 \text{ m}}{R} \quad \text{(arc definition)}$$

$$R = \frac{50 \text{ ft}}{\text{Sin } ½ \text{ D}} \text{ or } \frac{15.24 \text{ m}}{\text{Sin } ½ \text{ D}} \text{ (chord definition)}$$

$$\text{Sin } ½ \text{ D} = \frac{50 \text{ ft}}{R} \text{ or Sin } ½ \text{ D} = \frac{15.24 \text{ m}}{R} \text{ (chord definition)}$$

$$T = R \text{ (Tan } ½ \text{ I)}$$

$$L = \left(\frac{I}{D}\right) 100 \text{ ft or } L = \left(\frac{I}{D}\right) 30.48\text{m}$$

L is the distance around the arc for the arc definition, or the distance along the chords for the chord definition.

$$PC = PI - T$$

$$PT = PC + L$$

$$E = R\left(\frac{1}{\text{Cos } ½ \text{ I}} - 1\right) \text{ or } E = T \text{ (Tan } ¼ \text{ I)}$$

$$M = R \text{ (1-COs } ½ \text{ I)}$$

$$LC = 2 R \text{ (Sin } ½ \text{ I)}$$

In the following formulas, C equals the chord length and d equals the deflection angle.

All the formulas are exact for the arc definition and approximate for the chord definition.

$$d = \left(\frac{D}{2}\right)\left(\frac{C}{100 \text{ ft}}\right) \text{ or } d = \left(\frac{D}{2}\right)\left(\frac{C}{30.48 \text{ m}}\right)$$

For the formula below, the answer is in degrees:

$$d = \left(\frac{D}{2}\right)\left(\frac{C}{100 \text{ ft}}\right) \text{ or } d = \left(\frac{D}{2}\right)\left(\frac{C}{30.48 \text{ m}}\right)$$

$$d = 0.3 \text{ (C)(D) in the English system or } \frac{(0.3 \times D) \text{ (C)}}{.3048}$$

(Note: In the metric system, the answer will be in minutes).

Solution of a Simple Curve

In solving a simple curve, the surveyor must know three elements:

- The PI station value
- The (I) angle
- The degree of curve

The surveyor normally determines the (PI) and (I) angle on the preliminary traverse for the road. This may also be done through triangulation when the PI is inaccessible (discussed later in this course).

Example using the Chord Definition (English Units)

Note: The six-place natural trigonometric functions used in this example are based on empirical tables. When a calculator is used to obtain the trigonometric functions, the results may vary slightly.

Chord Example

Given the following known elements:

PI = 18+00

(I) = 45

D = 15°

Solution:

1) As the degree of curve is 15 degrees, the chord length will be 25 feet.
2) The first stake is customarily placed after the PC, at a plus station divisible by the chord length.
3) The centerline of the road is staked at intervals of 10, 25, 50 or 100 feet between curves, to avoid confusion for the level party when profile levels are run on the centerline.
4) The first stake after the PC for this curve will be at station 16+50. (Therefore, the first chord length or subchord is 8.67 feet).
5) Similarly, there will be a subchord at the end of the curve from station 19+25 to the PT. (This subchord will be 16,33 feet).
6) The surveyor designates the subchord at the beginning, C1, and at the end, C2 (as

shown in the diagram on page 4 of this chapter, "elements of a simple curve").

$$R = \frac{50\ ft}{\text{Sin } ½\ D} = \frac{50}{0.130526} = 383.07\ ft$$

$$T = R\ (\text{Tan } ½\ I) = 383.07 \times 0.414214 = 158.67\ ft$$

$$L = \left(\frac{I}{D}\right) 100\ ft = \frac{45}{15} \times 100 = 300.00\ ft$$

$$PC = PI - T = 1{,}800 - 158.67 = 1{,}641.33 \text{ or station } 16+41.33$$

$$PT = PC + L = 1{,}641.33 + 300 = 1{,}941.33 \text{ or station } 19+41.33$$

$$E = R\left(\frac{1}{\text{Cos } ½\ I} - 1\right) = 383.07\left(\frac{1}{0.923880} - 1\right) = 31.56\ ft$$

$$M = R\ (1 - \text{Cos } ½\ I) = 383.07\ (1 - 0.923880) = 29.16\ ft$$

$$LC = 2\ R\ (\text{Sin } ½\ I) = 2 \times 383.07\ (0.382683) = 293.19\ ft$$

Chord Definition (English Units)

(Chord definition) Deflection Angles

Computing Deflection Angles

After the subchords have been determined, the deflection angles are computed using the "simple curve" formulas found on the previous page of this chapter.

Technically, the formulas for the arc definitions are not exact for the chord definition, however, when a one-minute instrument is used to stake the curve, they may be used for either definition.

The deflection angles are:

- d = 0.3' x C x D
- dstd = 0.3 x 25 x 15° = 112.5' or 1°52.5'
- d1 = 0.3X 8.67X 15° = 0°39.015'
- d2 = 0.3 x 16.33 x 15° = 73.485' or 1°13.485'

1) The number of full chords is computed by subtracting the first plus station divisible by the chord length from the last plus station divisible by the chord length and dividing the difference by the standard (std) chord length.

2) Thus, we have (19+25 - 16+50) - 25 = 11 full chords.

3) Since there are 11 chords of 25 feet, the sum of the deflection angles for 25 ft. chords is 11 x 1°52.5' = 20°37.5'.

4) The sum of d1, d2, and the deflections for the full chords is:
   - d1= 0°39.015'
   - d2= 1°13.485'
   - dstd= 20°37.500'
   - Total = 22°30.000'

5) *Note: The total of the deflection angles is equal to one half of the (I) angle. (If the total deflection does not equal one half of (I), a mistake has been made in the calculations).*

6) After the total deflection has been decided, the surveyor determines the angles for each station on the curve. In this step, they are rounded off to the smallest reading of the instrument to be used in the field. (For this problem, the surveyor must assume that a one-minute instrument is to be used).

7) The curve station deflection angles are listed in the following table.

STATION	CHORD LENGTH	DEFLECTION ANGLES
PC 16+41.33		
+50	C_1 8.67	d_1 0° 39.015′ or 0° 39′ d_{std} + 1° 52.500′
+75	C_{std} 25	2° 31.515′ or 2° 32′ + 1° 52.500′
17+00	25	4° 24.015′ or 4° 24′ + 1° 52.500′
+25	25	6° 16.515′ or 6° 17′ + 1° 52.500′
+50	25	8° 9.015′ or 8° 09′ + 1° 52.500′
+75	25	10° 1.515′ or 10° 02′ + 1° 52.500′
18+00	25	11° 54.015′ or 11° 54′ + 1° 52.500′
+25	25	13° 46.515′ or 13° 47′ + 1° 52.500′
+50	25	15° 39.015′ or 15° 39′ + 1° 52.500′
+75	25	17° 31.515′ or 17° 32′ + 1° 52.500′
19+00	25	19° 24.015′ or 19° 24′ + 1° 52.500′
+25	25	21° 26.515′ or 21° 27′ d_2 + 1° 13.485′
PT 19+41.33	C_2 16.33	22° 30.000′ or 22° 30′

Curve Station Deflection Angles

Angles which consist of Minutes

Situation: When the (I) angle and the degree of curve consist of both degrees and minutes

For simplification, this curve example had an (I) angle and degree of curve whose values were whole degrees.

When the (I) angle and degree of curve consist of degrees and minutes, the procedure in solving the curve does not change, but care must be taken when substituting these values into the formulas for length and deflection angles.

Example

1) Given the known values:
   - I = 42° 15’
   - D = 5° 37’

2) Change the minutes in each angle to a decimal part of a degree, or D = 42.25000°, I = 5.61667°.
3) To obtain the required accuracy, values must be converted to five decimal places.
4) An alternate method for computing the length is to convert the (I) angle and degree of curve to minutes; thus, 42° 15’ = 2,535 minutes and 5° 37’ = 337 minutes.
5) Substituting into the length formula gives:

$$L = \frac{2{,}535}{337} \times 100 = 752.23 \text{ feet.}$$

6) This method gives an exact result. (By converting the minutes to a decimal part of a degree to the nearest five places, this will provide the same results).
7) Since the total of the deflection angles should be one half of the (I) angle, a problem arises when the (I) angle contains an odd number of minutes the instrument used is a one-minute instrument.
8) Since the PT is normally staked prior to running the curve, the total deflection will be a check on the PT.
9) Therefore, the surveyor should compute to the nearest 0.5 degree. If the total deflection checks to the nearest minute in the field, it can be considered correct.

Curve Tables

The surveyor can simplify the computation of simple curves by the use of tables: A-5 and A-6, from the USACE Field Manual: FM 5-233, (available by searching online).

Table A-5 “Functions of 1° Curves” - lists long chords, middle ordinates, externals, and tangents for an l-degree curve with a radius of 5,730 feet for various angles of intersection (example for angles 0° and 1° is shown below in the image below). To find the corresponding functions of any other curve, divide the tabular values by the degree of curve.

	74°				75°				
	LC	M	E	T	LC	M	E	T	
0	6896.8	1153.8	1444.7	4317.8	6976.4	1184.1	1492.5	4396.7	0
2	6899.4	1154.8	1446.2	4320.5	6979.0	1185.1	1494.1	4399.4	2
4	6902.1	1155.8	1447.8	4323.1	6981.7	1186.1	1495.7	4402.1	4
6	6904.8	1156.8	1449.4	4325.7	6984.3	1187.1	1497.3	4404.7	6
8	6907.4	1157.8	1451.0	4328.3	6986.9	1188.1	1499.0	4407.4	8
10	6910.1	1158.8	1452.6	4330.9	6989.6	1189.2	1500.6	4410.0	10
12	6912.7	1159.8	1454.1	4333.6	6992.2	1190.2	1502.2	4412.7	12
14	6915.4	1160.8	1455.7	4336.2	6994.9	1191.2	1503.8	4415.3	14
16	6918.0	1161.8	1457.3	4338.8	6997.5	1192.2	1505.4	4418.0	16
18	6920.7	1162.8	1458.9	4341.4	7000.1	1193.2	1507.0	4420.7	18
20	6923.3	1163.9	1460.5	4344.0	7002.8	1194.3	1508.7	4423.3	20
22	6926.0	1164.9	1462.0	4346.7	7005.4	1195.3	1510.3	4426.0	22
24	6928.6	1165.9	1463.6	4349.3	7008.0	1196.3	1512.0	4428.6	24
26	6931.3	1166.9	1465.2	4351.9	7010.7	1197.3	1513.6	4431.3	26
28	6933.9	1167.9	1466.8	4354.5	7013.3	1198.3	1515.3	4434.0	28
30	6936.6	1168.9	1468.4	4357.1	7015.9	1199.4	1516.9	4436.6	30
32	6939.2	1169.9	1469.9	4359.8	7018.6	1200.4	1518.5	4439.3	32
34	6941.9	1170.9	1471.5	4362.4	7021.2	1201.4	1520.2	4442.0	34
36	6944.6	1171.9	1473.1	4365.1	7023.9	1202.4	1521.8	4444.6	36
38	6947.2	1172.9	1474.7	4367.7	7026.5	1203.4	1523.5	4447.3	38
40	6949.9	1174.0	1476.4	4370.3	7029.1	1204.5	1525.1	4450.0	40
42	6952.5	1175.0	1478.0	4373.0	7031.8	1205.5	1526.7	4452.7	42
44	6955.2	1176.0	1479.6	4375.6	7034.4	1206.5	1528.4	4455.3	44
46	6957.8	1177.0	1481.2	4378.3	7037.0	1207.5	1530.0	4458.0	46
48	6960.5	1178.0	1482.8	4380.9	7039.7	1208.5	1531.7	4460.7	48
50	6963.1	1179.0	1484.4	4383.5	7042.3	1209.6	1533.3	4463.4	50
52	6965.8	1180.0	1486.0	4386.2	7045.0	1210.6	1534.9	4466.0	52
54	6968.4	1181.0	1487.7	4388.8	7047.6	1211.6	1536.6	4468.7	54
56	6971.1	1182.0	1489.3	4391.5	7050.2	1212.6	1538.2	4471.4	56
58	6973.7	1183.0	1490.9	4394.1	7052.9	1213.6	1539.9	4474.1	58
60	6976.4	1184.1	1492.5	4396.7	7055.5	1214.7	1541.5	4476.7	60

Example of Table A-5 from the USACE Field Manual: FM-233 (Appendix Section)

Note: Values obtained from this table can be converted to the metric system by multiplying by 0.3048.

Table A-6 lists the tangent, external distance corrections (chord definition) for various angles of intersection and degrees of curve, (example of Table A-6 is shown below).

Table A-6. Corrections for tangent and external distances

(This table is to convert tabular values in table A-5 to the chord definition.)

Example

Required are the tangent, external distance, and length of curve for a curve of 18° 20′ and an I angle of 9° 46′.

Tangent: $T = \frac{\text{Tabluar Entry}}{\text{Degree of Curve}} = \frac{489.56}{18.333} = 26.70$

+ (correction to be added from table A-6 for 18° 20′ and 9° 46′) 0.12′ = 26.82′

External Distance $= \frac{\text{Tabluar Entry}}{\text{Degree of Curve}} = \frac{20.88}{18.333} = 1.139$

+ (correction to be added from table A-6 for 18° 20′ and 9° 46′) 0.005 = 1.14′

Excerpt from USACE's Field Manual: FM-233

Table A-6. Corrections for tangent and external distance (continued)

Angle	Curve 5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°
5°	.02	.03	.05	.06	.08	.10	.11	.13	.15	.16	.18	.20	.21
10°	.03	.06	.09	.13	.16	.19	.22	.25	.28	.31	.34	.38	.42
15°	.04	.10	.14	.19	.24	.29	.34	.39	.45	.51	.53	.58	.63
20°	.06	.13	.19	.26	.32	.39	.45	.51	.58	.65	.72	.79	.84
25°	.08	.16	.24	.33	.40	.49	.58	.67	.75	.83	.90	.99	1.06
30°	.10	.19	.29	.39	.49	.59	.69	.79	.89	.99	1.09	1.20	1.29
35°	.11	.22	.34	.47	.58	.69	.80	.93	1.05	1.17	1.29	1.42	1.54
40°	.13	.26	.40	.53	.67	.80	.93	1.06	1.20	1.34	1.49	1.64	1.79
45°	.15	.30	.44	.60	.76	.91	1.06	1.21	1.37	1.52	1.70	1.87	2.04
50°	.17	.34	.51	.68	.85	1.02	1.19	1.36	1.54	1.72	1.91	2.10	2.29
55°	.19	.38	.57	.76	.95	1.14	1.32	1.52	1.72	1.92	2.14	2.35	2.56
60°	.21	.42	.63	.84	1.05	1.27	1.49	1.71	1.92	2.17	2.38	2.60	2.83
65°	.23	.46	.69	.93	1.16	1.40	1.64	1.88	2.13	2.38	2.63	2.88	3.13
70°	.25	.51	.76	1.02	1.28	1.54	1.80	2.06	2.33	2.60	2.88	3.16	3.44
75°	.27	.56	.83	1.12	1.40	1.69	1.98	2.27	2.57	2.87	3.16	3.47	3.78
80°	.30	.61	.91	1.22	1.53	1.84	2.15	2.46	2.78	3.10	3.44	3.78	4.12
85°	.33	.66	1.00	1.33	1.68	2.02	2.36	2.70	3.05	3.40	3.77	4.14	4.55
90°	.36	.72	1.09	1.45	1.83	2.20	2.57	2.94	3.32	3.70	4.10	4.50	4.91
95°	.39	.79	1.19	1.55	2.00	2.40	2.80	3.20	3.61	4.02	4.49	4.98	5.38
100°	.43	.86	1.30	1.74	2.18	2.62	3.06	3.50	3.95	4.40	4.88	5.37	5.85
105°	.46	.94	1.42	1.90	2.38	2.87	3.34	3.84	4.35	4.84	5.35	5.87	6.40
110°	.50	1.03	1.55	2.08	2.60	3.14	3.66	4.21	4.76	5.31	5.86	6.43	7.01
115°	.54	1.13	1.70	2.29	2.86	3.45	4.03	4.63	5.23	5.83	6.44	7.07	7.70
120°	.61	1.25	1.89	2.52	3.16	3.81	4.44	5.11	5.78	6.44	7.11	7.80	8.51

Example of Table A-6 from the USACE Field Manual: FM-233

Arc Definition using Tables

Since the degree of curve by arc definition is inversely proportional to the other functions of the curve, the values for a one-degree curve are divided by the degree of curve to obtain the element desired.

For example, table A-5 lists the tangent distance (T) and external distance (E), for an (I) angle of 74 degrees to be:

- T= 4,396.7 feet
- E=1,492.5 feet

Dividing by 15 degrees, the degree of curve, the surveyor obtains a tangent distance of 293.11 feet and an external distance of 99.50 feet.

Chord Definition using Tables

To convert these values to the chord definition, the surveyor uses the values in table A-5:

1) From table A-6, a correction of 0.83 feet is obtained for the tangent distance and external distance, 0.29 ft.
2) The surveyor adds the corrections to the tangent distance and external distance obtained from table A-5.
3) This gives a tangent distance of 293.94 feet and an external distance of 99.79 feet for the chord definition.

4) After the tangent and external distances are extracted from the tables, the surveyor computes the remainder of the curve.

Comparison of Arc and Chord Definitions

Arc or Chord Definition?

Misunderstandings often occur between surveyors in the field concerning the arc and chord definitions. It must be remembered that neither definition is recommended over the other.

Two different circles are involved in comparing two curves with the same degree of curve. The difference is that one is computed by the arc definition and the other by the chord definition. Since the two curves have different radii, the other elements are also different.

5,730-Foot Definition

Some roadway designers prefer to use a value of **5,730** feet for the radius of a l-degree curve, and the arc definition formulas.

When compared with the pure arc method using 5,729.58, the 5,730 method produces discrepancies of less than one part in 10,000 parts.

This is much better than the accuracy of the measurements made in the field and is acceptable in all but the most extreme cases.

Note: Table A-5 mentioned in the previous page, is based on this definition.

Curve Layout

Laying out Curves

The following is the procedure to lay out a curve using a one-minute instrument with a horizontal circle that reads to the right.

Setting PC and PT

1) With the instrument at the PI, the instrument operator sights on the preceding PI and keeps the head tapeman on line while the tangent distance is measured.
2) A stake is set on line and marked to show the PC and its station value.
3) The instrument operator now points the instrument on the forward PI, and the tangent distance is measured to set and mark a stake for the PT.

Laying out a Curve from the PC point

The procedures for laying out a curve from the PC are described as follows:

Situation 1: Laying Out Curve from PC (When the Road Curves to Right)

1) The instrument is set up at the PC with the horizontal circle at 0°00' on the PI.

2) The angle to the PT is measured if the PT can be seen. (This angle will equal one half of the (I) angle if the PC and PT are located properly).

3) Without touching the lower motion, the first deflection angle, d1 (0° 39'), is set on the horizontal circle.

4) The instrument operator keeps the head tapeman on line while the first subchord distance, C1 (8.67 feet), is measured from the PC to set and mark station 16+50.

5) The instrument operator now sets the second deflection angle, d1 + dstd (2° 32'), on the horizontal circle.

6) The tapemen measure the standard chord (25 feet) from the previously set station (16+50) while the instrument operator keeps the head tapeman on line to set station 16+75.

7) The succeeding stations are staked out in the same manner. If the work is done correctly, the last deflection angle will point on the PT, and the last distance will be the subchord length, C2 (16.33 feet), to the PT.

Situation 2: Laying Out Curve from PC (When the Road Curves to Left)

1) As in the procedures noted, the instrument occupies the PC and is set at 0°00’ pointing on the PI.
2) The angle is measured to the PT, if possible, and subtracted from 360 degrees. The result will equal one half the (I) angle if the PC and PT are positioned properly.
3) The first deflection, dl (0° 39’), is subtracted from 360 degrees, and the remainder is set on the horizontal circle.
4) The first subchord, Cl (8.67 feet), is measured from the PC, and a stake is set on line and marked for station 16+50.
5) The remaining stations are set by continuing to subtract their deflection angles from 360 degrees and setting the results on the horizontal circles. The chord distances are measured from the previously set station.
6) The last station set before the PT should be C2 (16.33 feet from the PT), and its deflection should equal the angle measured in the first step (described above) plus the last deflection, d2 (1° 14’).

Laying Out Curve from Intermediate Setup

When it is impossible to stake the entire curve from the PC, an adaptation of the above procedure must be used:

1) Stake out as many stations from the PC as possible.
2) Move the instrument forward to any station on the curve.
3) Pick another station already in place, and set the deflection angle for that station on the horizontal circle.
4) Sight that station with the instruments telescope in the reverse position.
5) Plunge the telescope, and set the remaining stations as if the instrument was set over the PC.

Laying Out Curve from PT (Backing-in Method)

If a setup on the curve has been made and it is still impossible to set all the remaining stations due to some obstruction, the surveyor can “back in” the remainder of the curve from the PT.

Although this procedure has been set up as a method to avoid obstructions, it is widely used for laying out curves.

When using the “backing in method,” the surveyor sets approximately one half the curve stations from the PC and the remainder from the PT.

With this method, any error in the curve is in its center where it is less noticeable.

Situation 1: Laying Out Curve from PT When the Road Curves to Right

1) Occupy the PT, and sight the PI with one half of the (I) angle on the horizontal circle.
2) The instrument is now oriented so that if the PC is sighted, the instrument will read 0°00’.
3) The remaining stations can be set by using their deflections and chord distances from the PC or in their reverse order from the PT.

Situation 2: Laying Out Curve from PT When the Road Curves to Left

1) Occupy the PT and sight the PI with 360 degrees minus one half of the (I) angle on the horizontal circle.
2) The instrument should read 0° 00’ if the PC is sighted.
3) Set the remaining stations by using their deflections and chord distances as if computed from the PC or by computing the deflections in reverse order from the PT.

Chord Corrections

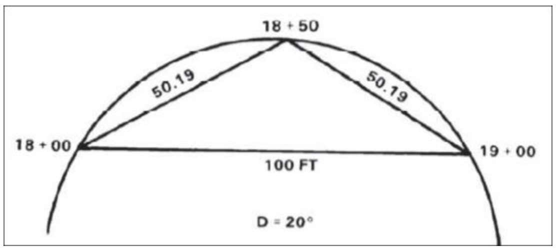
Frequently, curves must be laid out more precisely than is possible using the chord lengths previously described.

To eliminate the discrepancy between chord and arc lengths, the chords must be corrected using the values taken from the nomograph in Table A-11.

Chord Corrections:

- *Arc* - Table A-11 (found in USACE FM-233) provides the corrections to be applied if the curve were computed by the arc definition.
- *Chord* - Table A-10 (found in USACE FM-233) provides the corrections to be applied if the curve were computed by the chord definition.

The length of a curve computed by the chord definition is the length along the chords. (see image below, which illustrates the example given in Table A-9.) (found in USACE FM-233)



Subchord Corrections

- The chord distance from station 18+00 to station 19+00 is 100 feet.
- The nominal length of the subchords is 50 feet.

Intermediate Stake (Applying a correction to maintain 100 ft. chord length)

To place an intermediate stake at station 18+50, a correction must be applied to the subchords, since the distance from 18+00 through 18+50 to 19+00 is greater than the chord from 18+00 to 19+00.

Therefore, a correction must be applied to the subchords to keep station 19+00 100 feet from 18+00.

In the image above, if the subchord length is nominally 50 feet, then the correction is 0.19 feet. Thus the subchord distance from 18+00 to 18+50 and 18+50 to 19+00 would be 50.19.

Chapter 3: Obstacles to Curve Location

Dealing with Terrain Restrictions

Terrain Restrictions

To solve a simple curve, the surveyor must know these three values:

- (PI)
- angle
- The degree of curve

However, terrain features may occasionally limit the size of various elements of the curve. If this happens, the surveyor must determine the degree of curve from the limiting factor.

Inaccessible Points on a Curve

The following pages in this chapter (pages 2 through 5), will explain and illustrate the methods used to deal with inaccessible PC, PI, and PT points, as well as dealing with sizable obstacles along the curve.

Curve through a Fixed Point

Because of topographic features or other obstacles, the surveyor may find it necessary to determine the radius of a curve which will pass through, or bypass a fixed point and connect two given tangents. (The method used to accomplish this is found on page 6 of this chapter).

Limiting factors other than the radius

Additionally, in certain cases, a surveyor may be required to use elements other than the radius of the curve, as the limiting factor in determining the size of the curve. (The method for dealing with this is explained later in this chapter).

Laying out a Curve, when the PI is Inaccessible

PI Inaccessible

Under certain conditions, it may be impossible or impractical for a surveyor to occupy the PI, due to various obstructing factors.

In such a case, the surveyor locates the curve elements by using the following steps:

1) Mark two inter-visible points A and B, one on each of the tangents, so that line AB (a random line connecting the tangents) will clear the obstruction.
2) Measure angles a and b by setting up at both A and B.
3) Measure the distance AB.

Compute inaccessible distances AV and BV as follows:

$$I = a + b$$

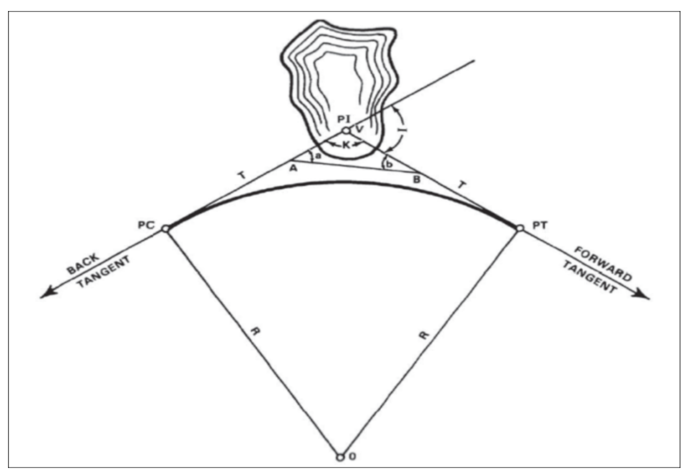
$$K = 180° - I$$

$$AV = \frac{AB \text{ Sin } b}{\text{Sin } K}$$

$$BV = \frac{AB \text{ Sin } b}{\text{Sin } K}$$

$$PI = \text{Sta } A + AV$$

4) Determine the tangent distance from the PI to the PC, based on degree of curve or other given limiting factor.
5) Locate the PC at a distance T minus AV from the point A and the PT at distance T minus BV from point B.
6) Proceed with the curve computation and layout.



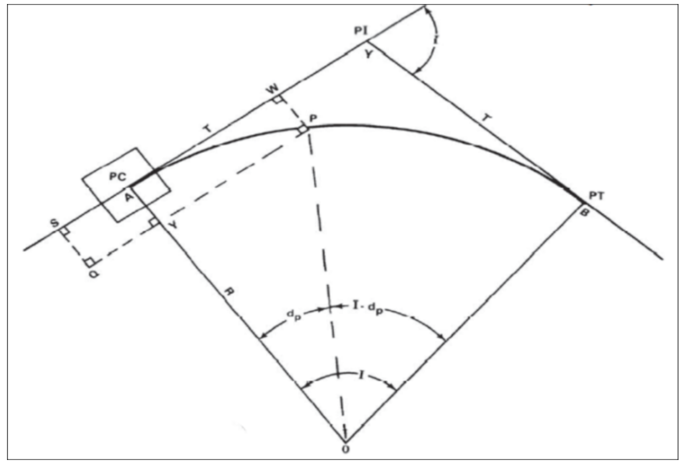
Inaccessible PI

Laying out a Curve, when the PC is Inaccessible

PC Inaccessible

When the PC point is not accessible, and both the PI and PT are set and readily accessible, the surveyor must establish the location of an offset station at the PC (see image, below):

1) Place the instrument on the PT and back the curve in as far as possible.
2) Select one of the stations (for example, “P”) on the curve, so that a line PQ, parallel to the tangent line AV, will clear the obstacle at the PC.
3) Compute and record the length of line PW so that point W is on the tangent line AV and line PW is perpendicular to the tangent. The length of line PW = R (l - Cos dp), where dp is that portion of the central angle subtended by AP and equal to two times the deflection angle of P.
4) Establish point W on the tangent line by setting the instrument at the PI and laying off angle V (V = 180° - I). This sights the instrument along the tangent AV. Swing a tape using the computed length of line PW and the line of sight to set point W.
5) Measure and record the length of line VW along the tangent.
6) Place the instrument at point P. Backsight point W and lay off a 90-degree angle to sight along line PQ, parallel to AV.
7) Measure along this line of sight to a point Q beyond the obstacle. Set point Q, and record the distance PQ.
8) Place the instrument at point Q, backsight P, and lay off a 90-degree angle to sight along line QS. Measure, along this line of sight, a distance QS equals PW, and set point S. Note that the station number of point S = PI - (line VW + line PQ).
9) Set an offset PC at point Y by measuring from point Q toward point P a distance equal to the station of the PC minus station S.
10) To set the PC after the obstacle has been removed, place the instrument at point Y, backsight point Q, lay off a 90-degree angle and a distance from Y to the PC equal to line PW and QS.
11) Carefully set reference points for points Q, S, Y, and W to insure points are available to set the PC after clearing and construction have begun.



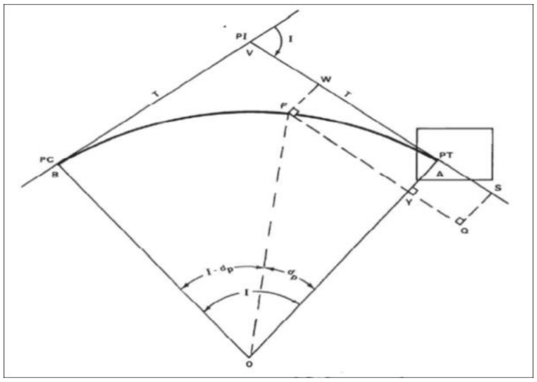
Inaccessible PC point

Laying out a Curve, when the PT is Inaccessible

PT Inaccessible

When the PT is inaccessible, as illustrated below, and both the PI and PC are readily accessible, the surveyor must establish an offset station at the PT using the method for inaccessible PC with the following exceptions.

1) Letter the curve so that point A is at the PT instead of the PC (see image, below).
2) Lay the curve in as far as possible from the PC instead of the PT.
3) Angle dp is the angle at the center of the curve between point P and the PT, which is equal to two times the difference between the deflection at P and one half of I.
4) Follow the steps for inaccessible PC to set lines PQ and QS. Note that the station at point S equals the computed station value of PT plus YQ.
5) Use station S to number the stations of the alignment ahead.



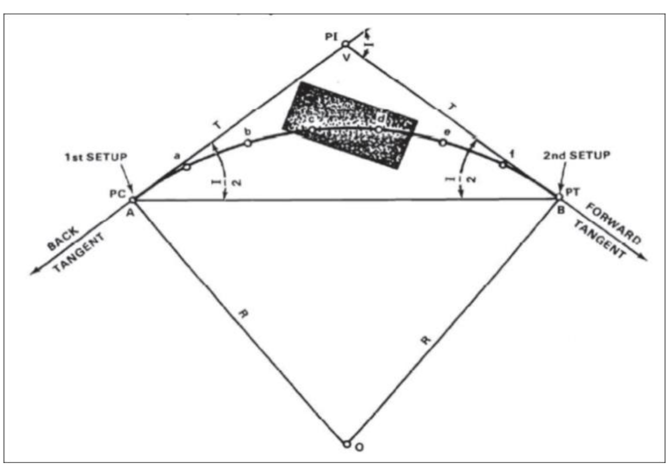
Inaccessible PT point

When there is an Obstacle on the Curve

Obstacles on Curve

Some curves have obstacles large enough to interfere with the line of sight and taping. Normally, only a few stations are affected, (see image, below which illustrates a method of bypassing an obstacle on a curve).

1) Set the instrument over the PC with the horizontal circle at 0˚ 00’, and sight on the PI. Check (I)/2 from the PI to the PT, if possible.
2) Set as many stations on the curve as possible before the obstacle, point b.
3) Set the instrument over the PT with the plates at the value of (I)/2.
4) Sight on the PI.
5) Back in as many stations as possible beyond the obstacle, point e.
6) After the obstacle is removed, the obstructed stations c and d can be set.



Obstacle on a Curve

Laying out a Curve through a Fixed Point

Curve on a Fixed Point

Because of topographic features or other obstacles, the surveyor may find it necessary to determine the radius of a curve which will pass through or bypass a fixed point and connect two given tangents (image).

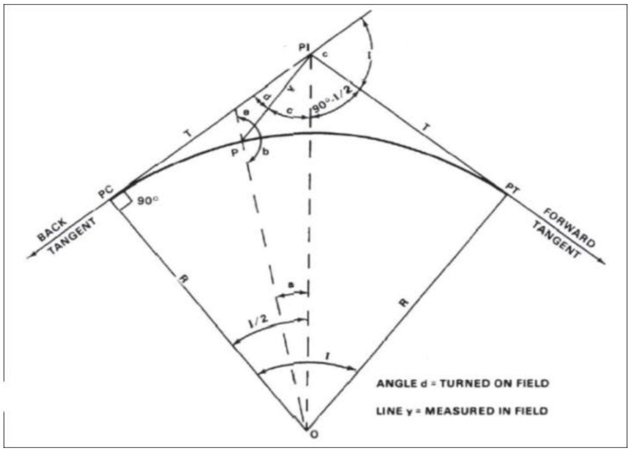
This may be accomplished as follows:

1) Given the PI and the I angle from the preliminary traverse, place the instrument on the PI and measure angle d, so that angle d is the angle between the fixed point and the tangent line that lies on the same side of the curve as the fixed point.
2) Measure line y, the distance from the PI to the fixed point.
3) Compute angles c, b, and a in triangle COP: c = 90 - (d + I/2)
4) To find angle b, first solve for angle e: Sin e = Sin c / Cos (I)/2
   - b = 180°- angle e
   - a = 180° - (b + c)
5) Compute the radius of the desired curve using the formula:

$$R = \frac{y \text{ Sin } c}{\text{Sin } a}$$

6) Compute the degree of curve to five decimal places, using the following formulas:
   - (arc method - english units)
     D = 5,729.58 ft/R
   - (arc method - metric units)
     D = 1,746.385 meters/R
   - (chord method – english units)
     Sin D = 2(50 feet/R)
   - (chord method – metric units)
     Sin D = 2(15.24 meters/R)

7) Compute the remaining elements of the curve and the deflection angles, and stake the curve.



Curve through a fixed point

Other Limiting Factors for Curve Sizing

Limiting Factors

In some cases, the surveyor may have to use elements other than the radius as the limiting factor in determining the size of the curve; which are usually the tangent T, external E, or middle ordinate M.

When any limiting factor is given, it will usually be presented in the form of T equals some value x, (T ≥ x or T ≤ x).

Determine R

The first step is to determine the radius using one of the following formulas:

- (T) Tangent; then R = T / (Tan ½ I)
- (E) External; then R = E/[(l / Cos ½ I) - 1]
- (M) Middle Ordinate; then R = M/(l - Cos ½I)

Determine D

The surveyor next determines D:

If the limiting factor is presented in the form T equals some value x, the surveyor must compute D, hold to five decimal places, and compute the remainder of the curve.

If the limiting factor is presented ≥, then D is rounded down to the nearest ½ degree.

For example:

If E ≥ 50 feet, the surveyor would round down to the nearest ½ degree, re-compute E, and then compute the rest of the curve data using the rounded value of D. (The new value of E will be equal to or greater than 50 feet).

If the limiting factor is ≤ the D is rounded to the nearest ½ degree.

For example:

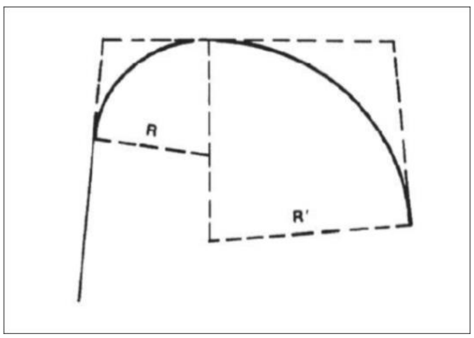
If M ≤ 45 feet, then D would be rounded up to the nearest ½ degree, M would be recomputed, and the rest of the curve data computed using the rounded value of D. The new value of M will be equal to or less than 45 feet.

Chapter 4: Compound and Reverse Curves

Compound Curves

A compound curve is two or more simple curves which have:

- different centers
- bend in the same direction
- lie on the same side of their common tangent
- connect to form a continuous arc



Compound Curve

The PCC (point of compound curvature)

The point where the two curves connect (the point at which the PT of the first curve equals the PC of the second curve) is referred to as the point of compound curvature (PCC).

More hazardous

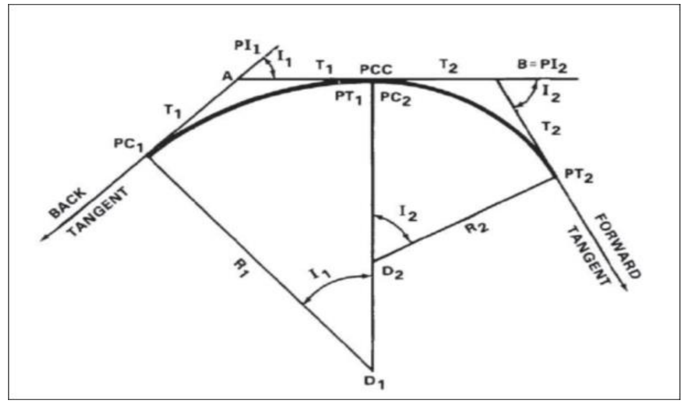
Since their tangent lengths vary, compound curves fit the topography much better than simple curves.

These curves easily adapt to mountainous terrain or areas cut by large, winding rivers. However, compound curves are more hazardous by design than simple curves, and should never be used where a simple curve would suffice.

Computation of Compound Curves

The computation of compound curves presents two basic problems:

- The first is where the compound curve is to be laid out between two successive PIs on the preliminary traverse.
- The second is where the curve is to be laid in between two successive tangents on the preliminary traverse.



Between Successive PI's

Compound Curve between Successive PIs

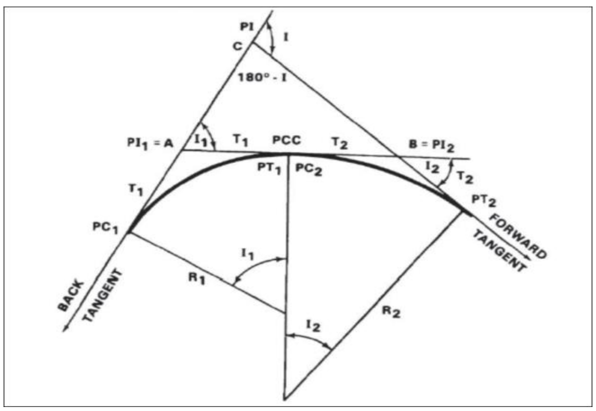
The calculations and procedure for laying out a compound curve between successive PIs are outlined in the following steps. (This procedure is illustrated in the image above).

1) Determine the PI of the first curve at point A from field data or previous computations.
2) Obtain I1, I2, and distance AB from the field data.
3) Determine the value of D1, the D for the first curve.
4) This may be computed from a limiting factor based on a scaled value from the road plan or furnished by the project engineer.
5) Compute R1, the radius of the first curve.
6) Compute T1, the tangent of the first curve:
7) T1 = R1 (Tan ½ I)
8) Compute T2, the tangent of the second curve: T2 = AB - T1
9) Compute R2, the radius of the second curve.
10) Compute D2 for the second curve. As the tangent for the second curve must be precisely located, the value of D2 requires five decimal places.
11) Comparing D1 and D2, the difference should not exceed 3 degrees. A variance of more than 3 degrees may require a change be made in the configuration of the curve.

12) If the two Ds are acceptable, then compute the remaining data and deflection angles for the first curve.
13) Compute the PI of the second curve. Since the PCC is at the same station as the PT of the first curve, then PI2 = PT1 + T2.
14) Compute the remaining data and deflection angles for the second curve, and lay in the curves.

Compound Curve between Successive Tangents

The procedure for laying out a compound curve between successive tangents is illustrated in the image below.



Between Successive Tangents

The following steps explain the laying out of a compound curve between successive tangents:

1) Determine the PI and I angle from the field data and/or previous computations.
2) Determine the value of I1 and distance AB. (This may be done by using field measurements or by scaling the distance and angle from the plan and profile sheet.)
3) Compute angle C: C = 180 - I
4) Compute I2: I2 =180-(Il+C)
5) Compute line AC.
6) Compute line BC.
7) Compute the station of PI1. PI1 = PI - AC
8) Determine D1 and compute R1 and T1 for the first curve.
9) Compute T2 and R2.
10) Compute D2 (according to the simple curve formulas found on Page 6 of Chapter 2).
11) Compute the station at PC: PC1 = PI - (AC + T1)
12) Compute the remaining curve data and deflection angles for the first curve.
13) Compute PI2: PI2 = PT1 + T2
14) Compute the remaining curve data and deflection angles for the second curve, and stake out the curves.

Staking Compound Curves

Two procedures for staking compound curves are described:

Situation 1: Compound Curve between Successive (PI) points

1) Stake the first curve, as previously described in Chapter 2, on Page 13), then:
2) Verify the PCC and PT2 by placing the instrument on the PCC, sighting on PI2, and laying off I2/2.
3) The resulting line of sight should intercept PT2.
4) Stake the second curve in the same manner as the first.

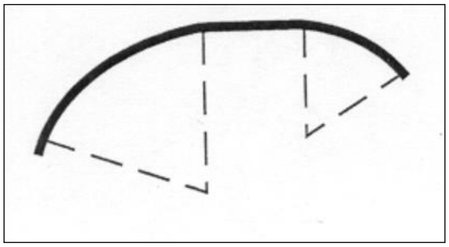
Situation 2: Compound Curve between Successive Tangents

1) Place the instrument at the PI and sight along the back tangent.
2) Lay out a distance AC from the PI along the back tangent, and set PI1.
3) Continue along the back tangent from PI2 a distance T1, and set PC1.
4) Sight along the forward tangent with the instrument still at the PI.
5) Lay out a distance BC from the PI along the forward tangent, and set PI2.
6) Continue along the forward tangent from PI a distance T2, and set PT2.
7) Check the location of PI1 and PI2 by measuring the distance between the two PIs, and comparing the measured distance to the computed length of line AB.
8) Or check the location of PI1 and PI2 by placing the instrument at PI1, sighting the PI, and laying off I1.
9) The resulting line-of-sight should intercept PI2.
10) Stake the curves (as previously outlined in Chapter 2, Page 13).

Broken-Back Curves

Broken Back Curves

A broken back curve consists of successive curves bending in the same direction that are separated by a short tangent (see image below).



Broken Back Curve

These short tangents are defined as one with a length less than:

- 15*V for design speeds less than 50 mph, or
- 30*V for design speeds greater than or equal to 50 mph.

Where: V is the design speed in mph

Broken-back curves are not recommended in roadway design, from both an operational and an appearance standpoint.

While it may not be feasible or practical in some situations to completely eliminate broken-back curves, every effort should be made to avoid this type of alignment if possible by separating, combining, or compounding curves in the same direction.

Reverse Curves

Reverse Curve

A reverse curve is composed of two or more simple curves which turn in opposite directions.

Their points of intersection lie on opposite ends of a common tangent, and the PT of the first curve coincides with the PC of the second.

This coincidental point is called the *point of reverse curvature* (PRC).

Reverse curves are useful when laying out such things as:

- pipelines
- flumes
- levees
- low-speed roads and railroads

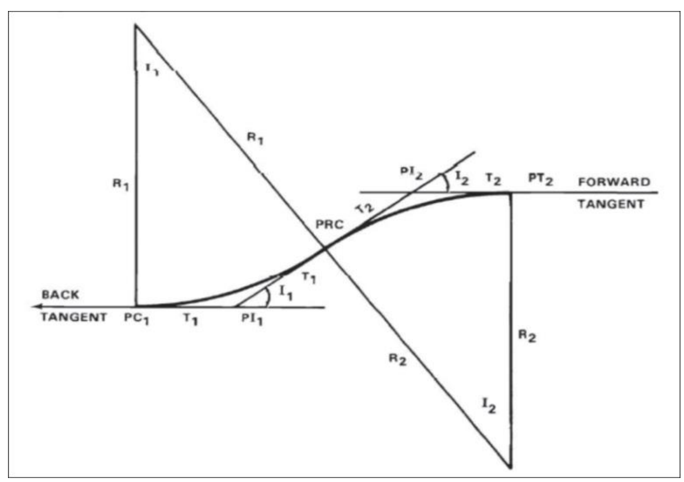
Because they cannot be properly superelevated at the PRC, they should not be used on high-speed roads or railroads.

They may occasionally be used on canals, but only with extreme caution, as they make the canal difficult to navigate and contribute to erosion.

Reverse Curve Data

The computation of reverse curves presents three basic problems:

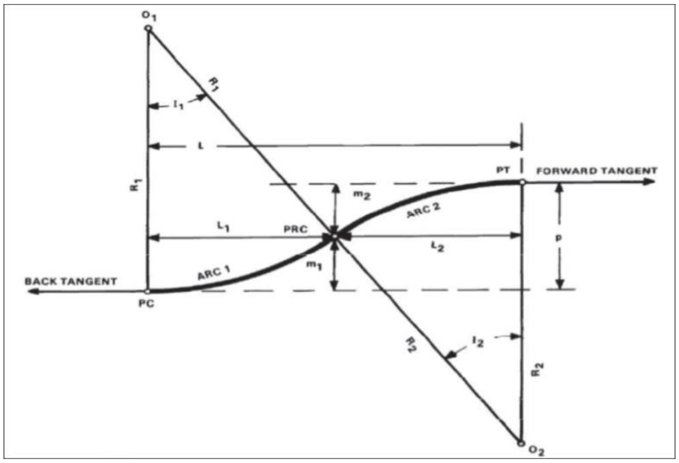
1.) Where the reverse curve is to be laid out between two successive PI's. (See image, below) In this case, the computations are performed in exactly the same manner as a compound curve between successive PIs.
2.) Where the curve is to be laid out so it connects two parallel tangents (see image on next page).
3.) Where the reverse curve is to be laid out so that it connects diverging tangents (see image, page after next).



Reverse Curve between Successive PI's

Connecting Parallel Tangents

The image below, illustrates a reverse curve connecting two parallel tangents.



Reverse Curve connecting Parallel Tangents

The PC and PT are located as follows:

1.) Measure p, the perpendicular distance between tangents.
2.) Locate the PRC and measure m1 and m2. (If conditions permit, the PRC can be at the midpoint between the two tangents. This will reduce computation, since both arcs will be identical.)
3.) Determine R1.
4.) Compute I1.

$$\text{Cos } I_1 = \frac{R_1 - m_1}{R_1}$$

5.) Compute L1 from: L1 = R1 Sin I1 (R2 ,I2 ,and L2 are determined in the same way as R1, I1, and L1. If the PRC is to be the midpoint, the values for arc 2 will be the same as for arc 1.)
6.) Stake each of the arcs the same as a simple curve. If necessary, the surveyor can easily determine other curve components. (For example, a reverse curve to connect two parallel tangents is required.)
7.) No obstructions exist so it can be made up of two equal arcs. The degree of curve for both must be 5°.
8.) The distance p is measured and found to be 225.00 feet.

$$m_1 = m_2 \text{ and } L_1 = L_2$$
$$R_1 = R_2 \text{ and } I_1 = I_2$$

$$R_1 = \frac{50 \text{ ft}}{\text{Sin } ½ \text{ D}} = \frac{50 \text{ ft}}{0.043619} = 1{,}146.29 \text{ ft}$$

$$\text{Cos } I_1 = \frac{R_1 - m_1}{R_1} = \frac{1{,}033.79}{1{,}146.29} = 0.901857$$

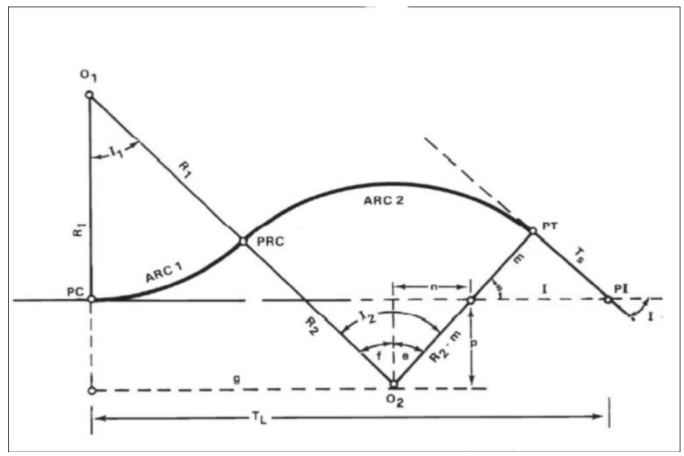
$$I_1 = 25° \, 36'$$

$$L_1 = R_1 \text{ Sin } I_1 = 1{,}146.29 \times 0.432086 = 495.30 \text{ ft}$$

9.) The PC and PT are located by measuring off L1 and L2.

Connecting Diverging Tangents

The connection of two diverging tangents by a reverse curve is illustrated in image, below. Due to possible obstruction or topographic considerations, one simple curve could not be used between the tangents.



Reverse Curve connecting Diverging Tangents

The PT has been moved back beyond the PI. However, the (I) angle still exists as in a simple curve. The controlling dimensions in this curve are the distance Ts to locate the PT and the values of R1 and R2, which are computed from the specified degree of curve for each arc.

1.) Measure (I) at the PI.
2.) Measure Ts to locate the PT as the point where the curve is to join the forward tangent. (In some cases, the PT position will be specified, but Ts must still be measured for the computations).

Perform the following calculations:

3.) Determine R1 and R2. If practical, have R1 equal R2.
4.) Angle s = 180 - (90+I) = 90 - I
5.) m = Ts (Tan I)
6.) angle e = I1 (by similar triangles)
7.) angle f = I1 (by similar triangles)
8.) Therefore, I2 = I + I1
    - n = (R2 - m) Sin e
    - p = (R2 - m) Cos e

1.) Determine g by establishing the value of I1.
2.) Knowing Cos I1, determine Sin I1.
3.) g = (R1 + R2) Sin I1
4.) TL = g + n + L
5.) Measure TL from the PI to locate the PC.
6.) Stake arc 1 to PRC from PC.
7.) Set instrument at the PT and verify the PRC (invert the telescope, sight on PI, plunge, and turn angle I2/2).
8.) Stake arc 2 to the PRC from PT. For example (in image), a reverse curve is to connect two diverging tangents with both arcs having a 5-degree curve.
9.) Locate the PI; measuring the (I) angle is 41 degrees. The PT location is specified and the Ts is measured as 550 feet. The PC is located by measuring TL. The curve is staked using 5-degree curve computations.

$$R_1 = R_2 = \frac{50 \text{ ft}}{\text{Sin } ½ \text{ D}} = \frac{50}{0.043619} = 1{,}146.29 \text{ ft}$$

$$n = (R_2 - m) \text{ Sin I} = (1{,}146.29 - 478.11)\ 0.656059$$
$$= 438.37 \text{ ft}$$

$$p = (R_2 - m) \text{ Cos I} = (1{,}146.29 - 478.11)\ 0.754710$$
$$= 504.28 \text{ ft}$$

$$\text{Cos } I_1 = \frac{R_1 + p}{R_1 + R_2} = \frac{1{,}146.29 + 504.28}{1{,}146.29 + 1{,}146.29} = 0.719962$$

$$I_1 = 43° 57'$$

$$g = (R_1 + R_2) \sin I_1 = (2{,}292.58)\ 0.694030 =$$
$$1{,}591.12 \text{ ft}$$

$$T_L = g + n + L = 1{,}591.12 + 438.37 + 728.76 =$$
$$2{,}758.25 \text{ ft}$$

Chapter 5: Transition Spirals

Spiral Curves

Spiral Curves

In engineering construction, the surveyor often inserts a transition curve (also known as a spiral curve), between a circular curve and the tangent to that curve.

This spiral curve varies in radius to gradually increase the curvature of a road or railroad.

Spiral curves are used primarily to reduce skidding and steering difficulties by gradual transition between a straight-line (tangent) and the turning motion encountered in a curve.

Transitioning into a Superelevated Curve

Spiral transition curves also provide a method to properly transition into a fully superelevated or banked curve.

The spiral curve is designed to provide for a gradual superelevation of the outer pavement edge of the road to counteract the centrifugal force of vehicles as they pass.

The best spiral curve is one in which the superelevation increases uniformly with the length of the spiral from the TS (or the point where the spiral curve leaves the tangent).

The curvature of a spiral must increase uniformly from beginning to end:

- At the beginning, where it leaves the tangent, its curvature is zero.
- At the end, where it joins the circular curve, it has the same degree of curvature as the circular curve it intercepts.

Theory of the A.R.E.A. 10-Chord Spiral

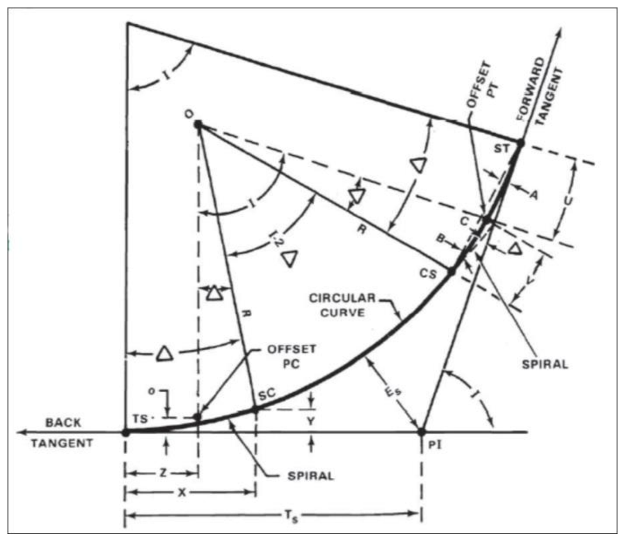
The spiral of the American Railway Engineering Association (known as the A.R.E.A. spiral), retains nearly all of the characteristics of the cubic spiral. In the cubic spiral, the lengths have been considered as measured along the spiral curve itself, but measurements in the field must be taken by chords.

With the A.R.E.A. spiral, the length of spiral is measured by 10 equal chords, so that the theoretical curve is brought into harmony with field practice. This 10-chord spiral closely approximates the cubic spiral. Basically, the two curves coincide up to the point where Δ = 15 degrees.

The exact formulas for this A.R.E.A. 10-chord spiral, when Δ does not exceed 45 degrees, are given on page 2 of this chapter.

Spiral Elements

The image below show the notations applied to elements of a simple circular curve with spirals connecting it to the tangents.



Simple Curve connected to its tangents with spirals

- TS = the point of change from tangent to spiral
- SC = the point of change from spiral to circular curve
- CS = the point of change from circular curve to spiral
- ST = the point of change from spiral to tangent
- SS = the point of change from one spiral to another (not shown in the image above)

Note: symbols PC and PT, TS and ST, and SC and CS become transposed when the direction of stationing is changed.

- a = angle between the tangent at the TS and the chord from the TS to any point on the spiral
- A = angle between the tangent at the TS and the chord from the TS to the SC
- b = angle at any point on the spiral between the tangent at that point and the chord from the TS
- B = angle at the SC between the chord from the TS and the tangent at the SC
- c = chord from any point on the spiral to the TS
- C = chord from the TS to the SC
- d = degree of curve at any point on the spiral
- D = degree of curve of the circular arc
- f = angle between any chord of the spiral (calculated when necessary) and the tangent through the TS
- I = angle of the deflection between initial and final tangents; the total central angle of the circular curve and spirals
- k = increase in degree of curve per station on the spiral
- L = length of the spiral in feet from the TS to any given point on the spiral
- Ls = length of the spiral in feet from the TS to the SC, measured in 10 equal chords
- = the ordinate of the offset PC; the distance between the tangent and a parallel tangent to the offset curve
- r = radius of the osculating circle at any given point of the spiral
- R = radius of the central circular curve
- s = length of the spiral in stations from the TS to any given point
- S = length of the spiral in stations from the TS to the SC
- u = distance on the tangent from the TS to the intersection with a tangent through any given point on the spiral
- U = the distance on the tangent from the TS to the intersection with a tangent through the SC; the longer spiral tangent
- v = the distance on the tangent through any given point from that point to the intersection with the tangent thru the TS
- V = the distance on the tangent through the SC from the SC to the intersection with the tangent through the TS; the shorter spiral tangent
- x = the tangent distance from the TS to any point on the spiral
- X = the tangent distance from the TS to the SC
- y = the tangent offset of any point on the spiral
- Y = the tangent offset of the SC
- Z = the tangent distance from the TS to the offset PC (Z = X/2, approximately)
- δ = the central angle of the spiral from the TS to any given point
- Δ= the central angle of the whole spiral
- Ts = the tangent distance of the spiraled curve; distance from TS to PI, the point of intersection of tangents
- Es = the external distance of the offset curve

Spiral Formulas

The following formulas are for the exact determination of the functions of the 10- chord spiral when the central angle (Δ), does not exceed 45 degrees.

These are suitable for the compilation of tables and for accurate fieldwork.

$$d = ks = \frac{kL}{100}$$

$$D = kS = \frac{kL_s}{100}$$

$$\delta = \frac{ks^2}{2} = \frac{d_s}{2} = \frac{kL^2}{20{,}000} = \frac{dL}{200}$$

$$\frac{ks^2}{2} = \frac{DS}{2} = \frac{kL_s}{20,000} = \frac{DL_s}{200}$$

$$A = (\Delta/3) - 0.00297\ \Delta^3 \text{ seconds}$$

$$B = \Delta - A$$

$$C = L_s\ (\text{Cos } 0.3\ \Delta + 0.004 \text{ Exsec } ¾\ \Delta)$$

$$(\text{Exsec } \Delta = 1 \text{ Tan } ½\ (\Delta)$$

$$X = C \text{ Cos } A$$

$$Y = C \text{ Sin } A$$

$$U = C\left(\frac{\text{Sin } B}{\text{Sin } \Delta}\right)$$

$$V = C\left(\frac{\text{Sin } A}{\text{Sin } \Delta}\right)$$

$$R = \frac{50 \text{ ft}}{\text{Sin } ½\ D} \quad \text{(chord definition)}$$

$$Z = X - (R \text{ Sin } \Delta)$$

$$o = Y - (R \text{ Vers } \Delta)$$

$$(\text{Vers } \Delta = 1 - \text{Cos } \Delta)$$

$$T_s = (R + o) \text{ Tan } (½\ I) + Z$$

$$Es = (R + o) \text{ Exsec } (½\ I) + o$$

$$(\text{Exsec } (½\ I) = \text{Tan } (½\ I)\ (\text{Tan } (¼\ I))$$

Empirical Formulas

For use in the field, the following formulas are sufficiently accurate for practical purposes, when Δ does not exceed 15 degrees.

$$a = \delta/3 \quad \text{(degrees)}$$

$$A = \Delta/3\ \text{(degrees)}$$

$$a = 10\ ks^2 \text{(minutes)}$$

$$S = 10\ kS^2 \text{(minutes)}$$

Spiral Lengths

Different factors must be taken into account when calculating spiral lengths for highway and railroad layout.

Highways

Spirals applied to highway layout must be long enough to permit the effects of centrifugal force to be adequately compensated for by proper superelevation.

Minimum transition spiral length

The minimum transition spiral length for any degree of curvature and design speed is obtained from the relationship:

Ls= 1.6V3/R

Where:

- Ls = minimum spiral length in feet
- V = design speed in miles per hour
- R = radius of curvature of the simple curve

The above equation is not mathematically exact but an approximation based on years of observation and road tests.

Note: Table 3-1 in the addendum, is compiled from the above equation for multiples of 50 feet.

Spirals between arcs of a compound curve

When spirals are inserted between the arcs of a compound curve, use this equation:

Ls= 1.6V3/Ra

Where:

- Ra = radius of a curve of a degree equal to the difference in degrees of curvature of the circular arcs

Railroads Spirals

Applied to railroad layout spiral curves must be long enough to permit an increase in superelevation not exceeding 1¼ inches per second for the maximum speed of train operation.

The minimum length is determined from this equation:

$$Ls = 1.17\ EV$$

Where:

- E is the full theoretical superelevation of the curve in inches
- V is the speed in miles per hour
- Ls is the spiral length in feet

This length of spiral provides the best riding conditions by maintaining the desired relationship between the amount of superelevation and the degree of curvature. The degree of curvature increases uniformly throughout the length of the spiral.

This equation is also used to compute the length of a spiral between the arcs of a compound curve. In such a case, E is the difference between the superelevations of the two circular arcs.

Spiral Calculations

Spiral elements are easily computed from the formulas given previously under the "Spiral Formulas" heading.

To use these formulas, certain data must be known which is usually normally obtained from location plans or by field measurements.

The following computations are for a spiral when D, V, PI station, and I are known:

- D = 4°
- I = 24°10'
- PI station = 42 + 61.70
- V = 60 mph

Determining Ls

Assuming that this is a highway spiral, use either the equation for Ls found on the previous page, or search the table below.

1.) From this Table, when D = 4° and V = 60 mph, the value for Ls is 250 feet.

D	30 mph		40 mph		50 mph		60 mph		70 mph	
	θLs		θLs		θLs		θLs		θLs	
1-00	0	0	0	0	0	0	0	0	0	0
1-30	.01	150	.02	150	.02	150	.04	150	.05	150
2-00	.01	150	.02	150	.03	150	.05	150	.06	200
2-30	.01	150	.03	150	.04	150	.06	150	.08	250
3-00	.02	150	.03	150	.05	150	.07	200	.09	300
3-30	.02	150	.04	150	.06	150	.08	200	.10	350
4	.02	150	.04	150	.06	150	.09	250	.10	400
5	.03	150	.05	150	.08	150	.10	300		
6	.03	150	.06	150	.10	200	.10	350		
7	.04	150	.07	150	.10	250				
8	.05	150	.08	150	.10	300				
9	.05	150	.09	150	.10	300				
10	.06	150	.10	200						
11	.06	150	.10	200						
12	.07	150	.10	200						
13	.07	150	.10	250						
14	.08	150	.10	250						
15	.09	150								
16	.09	150								
17	.10	150								
18	.10	150								
19	.10	150								
20	.10	150								
21	.10	150								
22	.10	150								
23	.10	150								
24	.10	200								
25	.10	200								

Table for Recommended Superelevation and Minimum Transition Lengths

2.) Determine Δ

Δ = D x Ls / 200

Δ = 4 x 250 / 200 = 50

3.) Determining o

o = Y - (R Vers Δ)

4.) From previous page (spiral formulas):

$$R = \frac{50\ ft}{\text{Sin } ½\ D°}$$

- R = 50 ft. / .0348994
- R = 1,432.69 ft.

5.) Using Δ = 5˚, (see table A-9 in the addendum)

- Y = 0.029073 x Ls
- Y = 0.029073 x 250
- Y = 7.27 ft.

6.) = Y - (R Vers Δ)

- (Vers Δ = 1 - Cos Δ)

- = 7.27 - (1,432.69 x 0.00381)
- = 1.81 ft

7.) Determining Z
8.) Z = X - (R Sin A)
9.) From table A-9,
    - X = .999243 x Ls
    - X = .999243 x 250
    - X = 249.81 ft.
    - R = 1,432.69 ft.
    - Sin 5° = 0.08716
    - (3) Z = 249.81- (1,432.69 x 0.08716)
    - Z = 124.94 ft.

Next:

1.) Determining Ts
    - Ts= (R + o) Tan (½ I) + Z

2.) Where, from the previous steps:
    - R = 1,432.69 ft.
    - = 1.81 feet, and Z = 124.94 ft.

3.) Ts = (1,432.69 + 1.81) (0.21408) + 124.94
    - Ts = 432.04 ft

4.) Determining Length of the Circular Arc (La)

$$L_a = \frac{I - 2\Delta}{D} \times 100$$

Where:

- I = 24° 10'= 24.16667°
- Δ =5"
- D=4°

$$L, = \frac{24.16667 - 10}{4} \times 100 = 354.17 \text{ ft}$$

Determining Chord Length

$$\text{Chord length} = \frac{L_s}{10}$$

$$\text{Chord length} = \frac{\text{length} = 250 \text{ ft}}{10}$$

Determining Station Values

With the data above, the curve points are calculated as follows:

Station PI	=	42 + 61.70		
Station TS	=	-4 + 32.04	=	T_s
Station TS	=	38+ 29.66		
		+2 + 50.()()	=	L,
Station SC	=	40 + 79.66		
		+3 + 54.17	=	L_a
Station CS	=	44+ 33.83		
		+2 + 50.()()	=	L_s
Station ST	=	46+ 83.83		

Determining Deflection Angles

One principal characteristic of the spiral: the deflection angles vary relative to the square of the distance along the curve.

$$\frac{a}{A} :: \frac{L^2}{L_s^2}$$

From this relationship, the following are obtained:

$$a_1 = \frac{(1)^2}{(10)^2} A,\ a_2 = 4a_1,\ a_3 = 9a, = 16a_1, \ldots a_9 = 81a_1, \text{ and } a_{10} = 100a_1 = A.$$

The deflection angles to the various points along the spiral from the TS or ST are a1 through a10.

Using these relationships, the deflection angles for the spirals and the circular arc are computed for the example spiral curve.

Based on the following equation:

$$D = \frac{kL_s}{100}$$

Solving for k:

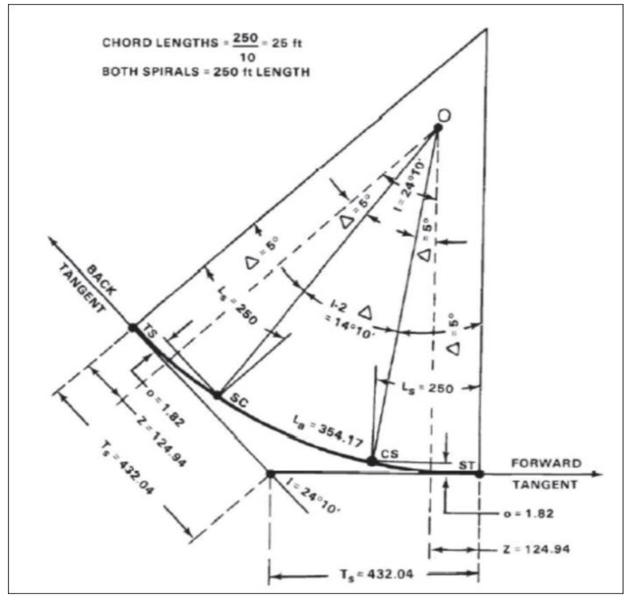
$$k = \frac{D\,(100)}{L_s} = \frac{D\,(100)}{250} = 1.6$$

Stations	Deflection Angles	
38 + 29.66 (TS)	a_o	= 0° 00′
+ 54.66	$a_1 = 10ks^2 = 10\ (1.6)\ (0.25)^2$	= 0° 01′
+ 79.66	$a_2 = 4a_1$	= 0° 04′
39 + 04.66	$a_3 = 9a_1$	= 0° 09′
+ 29.66	$a_4 = 16a_1$	= 0° 16′
39 + 54.66	$a_5 = 25a_1$	= 0° 25′
+ 79.66	$a_6 = 36a_1$	= 0° 36′
40 + 04.66	$a_7 = 49a_1$	= 0° 49′
+ 29.66	$a_8 = 64a_1$	= 1° 04′
+ 54.66	$a_9 = 81a_1$	= 1° 21′
40 + 79.66 (SC)	$a_{10} = 100a_1 = A = \Delta/3$	= 1° 40′
41 + 00.00	$d_1 = 0.3c_1\ D = 0.3'\ (20.34)\ (4)$	= 0° 24.4′
42	$d_2 = d_1 + D/2$	= 2° 24.4′
43	$d_3 = d_2 + D/2$	= 4° 24.4′
44	$d_4 = d_3 + D/2$	= 6° 24.4′
+ 33.83 (CS)	$d_5 = d_4 + 0.3c_2\ D$	
	$= 6°\ 24.4' + 0.3\ (33.83)\ (4)$	
	$= \frac{I-2\Delta}{2}$	
	$= \frac{24°\ 10' - 10°}{2}$	= 7° 05′
+ 33.83 (CS)	$a_{10} = A = \frac{\Delta}{3} = \frac{5}{3}$	= 1° 40′
+ 58.83	$a_9 = 81a_1$	= 1° 21′
+ 83.83	$a_8 = 64a_1$	= 1° 04′
45 + 08.83	$a_7 = 49a_1$	= 0° 49′
+ 33.83	$a_6 = 36a_1$	= 0° 36′
+ 58.83	$a_5 = 25a_1$	= 0° 25′
+ 83.83	$a_4 = 16a_1$	= 0° 16′
46 + 08.83	$a_3 = 9a_1$	= 0° 09′
+ 33.83	$a_2 = 4a_1$	= 0° 04′
+ 58.83	$a_1 = 10ks^2 = 10\ (1.6)\ (0.25)^2$	= 0° 01′
+83.83 (ST)	a_0	= 0° 00′

Spiral Curve Layout

The following is the procedure to lay out a spiral curve, using a one-minute instrument with a horizontal circle that reads to the right.

The image below, illustrates the required procedures:



Staking a Spiral Circular Curve

Setting TS and ST

With the instrument at the PI, the instrument operator:

1.) Sights along the back tangent and keeps the head tapeman on line while the tangent distance (Ts) is measured.
2.) A stake is set on line and marked to show the TS, along with the corresponding station value.
3.) The instrument operator now sights along the forward tangent to measure and set the ST.

Laying Out First Spiral from TS to SC

Set up the instrument at the TS, pointing on the PI, with 0°00′ on the horizontal circle:

1.) Check the angle to ST, if possible. The angle should equal one half of the (I) angle, if the TS and ST were located properly.
2.) The first deflection (a1/ 0˚ 01′) is subtracted from 360 degrees, and the remainder is set on the horizontal circle.
3.) Measure the standard spiral chord length (25 feet) from TS, and set the first spiral station (38 + 54.66) on line.
4.) The remaining spiral stations are set by subtracting their deflection angles from 360 degrees and measuring 25 feet from the previously set station.

Laying Out Circular Arc from SC to CS

Set up the instrument at the SC with a value of A minus A (5° 00'- 1°40' = 3° 20') on the horizontal circle:

1.) Sight the TS with the instrument telescope in the reverse position.
2.) Plunge the telescope. Rotate the telescope until 0° 00' is read on the horizontal circle. The instrument is now sighted along the tangent to the circular arc at the SC.
3.) The first deflection (dl /0° 24') is subtracted from 360 degrees, and the remainder is set on the horizontal circle. The first subchord (c1 / 20.34 feet) is measured from the SC, and a stake is set on line and marked for station 41+00.
4.) The remaining circular arc stations are set by subtracting their deflection angles from 360 degrees and measuring the corresponding chord distance from the previously set station.

Laying Out Second Spiral from ST to CS

1.) Set up the instrument at ST, pointing on PI, with 0° 00' on the horizontal circle.
2.) Check the angle to the CS. The angle should equal 1° 40' if the CS is located properly.
3.) Set the spiral stations using their deflection angles in reverse order and the standard spiral chord length (25 ft).
4.) Correct any error encountered by adjusting the circular arc chords from the SC to the CS.

Intermediate Setup

When the instrument must be moved to an intermediate point on the spiral, the deflection angles computed from the TS cannot be used for the remainder of the spiral.

In this respect, a spiral differs from a circular curve.

Calculating Deflection Angles

The following are the procedures for calculating the deflection angles and staking the spiral:

Where:

- D = 4°
- Ls = 250 ft. (for highways)
- V =60 mph
- I = 24° 10'
- Point 5 = intermediate point

Steps:

1.) Calculate the deflection angles for the first five points. These angles are: a1 = 0° 01', a2 = 0˚ 04', a3 = 0˚ 09', a4 = 0° 16', and a5 = 0° 25'.
2.) The deflection angles for points 6, 7, 8, 9, and 10, with the instrument at point 5, are calculated with the use of Table 5.4.2 below.
3.) Table 5.4.2 is read as follows: with the instrument at any point, coefficients are obtained which, when multiplied by a1, give the deflection angles to the other points of the spiral.
4.) Therefore, with the instrument at point 5, the coefficients for points 6, 7, 8, 9, and 10 are 16, 34, 54, 76, and 100, respectively.
5.) Multiply these coefficients by a1 to obtain the deflection angles. These angles are a6 = 16a1 = 0° 16', a7 = 34a1 = 0˚ 34', a8 = 54a1 = 0° 54', a9 = 76a1 = 1° 16', and a10 = 100a1= 1˚ 40'.
6.) The Table below is also used to orient the instrument over point 5 with a backsight on the TS.
7.) The angular value from point 5 to point zero (TS) equals the coefficient from the Table times a1. This angle equals 50a1= 0° 50'.

Deflection angle to chord-point number	Transit at chord-point number 0 TS	1	2	3	4	5	6	7	8	9	10 SC
OTS	0	2	8	18	32	50	72	98	128	162	200
1	1	0	5	14	27	44	65	90	119	152	189
2	4	4	0	8	20	36	56	80	108	140	176
3	9	10	7	0	11	26	45	68	95	126	161
4	16	18	16	10	0	14	32	54	80	110	144
5	25	28	27	22	13	0	17	38	63	92	125
6	36	40	40	36	28	16	0	20	44	72	104
7	49	54	55	52	45	34	19	0	23	50	81
8	64	70	72	70	64	54	40	22	0	26	56
9	81	88	91	90	85	76	63	46	25	0	29
10SC	100	108	112	112	108	100	88	72	52	28	0

Table of Coefficients of a1 for deflection angles to chord-points

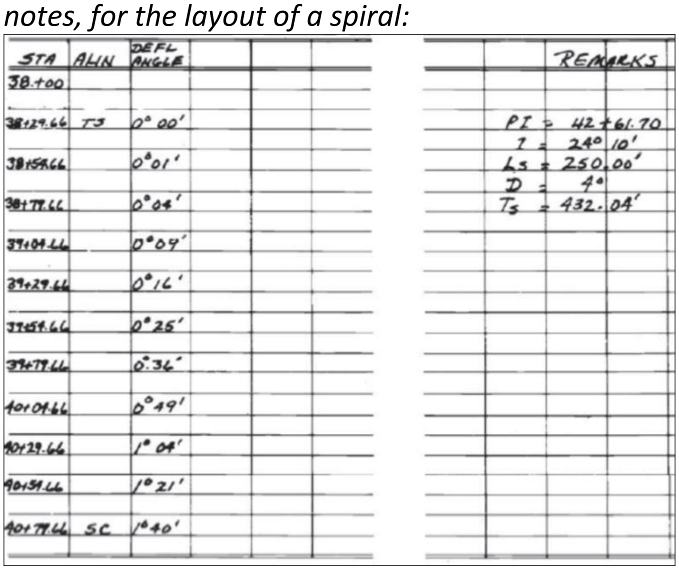
Staking

Stake the first five points according to the procedures shown previously:

1.) Check point 5 by repetition to insure accuracy.
2.) Set up the instrument over point 5.
3.) Set the horizontal circle at the angular value determined above.
4.) With the telescope inverted, sight on the TS (point zero).
5.) Plunge the telescope, and stake the remainder of the curve (points 6, 7, 8, 9, and 10) by subtracting the deflection angles from 360 degrees.

Field Notes for Spirals

The image, below, shows a typical page of field notes, for the layout of a spiral:



STA	ALIN	DEFL ANGLE	REMARKS
38+00			
38+29.66	TS	0° 00'	PI = 42+61.70
			I = 24° 10'
38+54.66		0° 01'	Ls = 250.00'
			D = 4°
38+79.66		0° 04'	Ts = 432.04'
39+04.66		0° 09'	
39+29.66		0° 16'	
39+54.66		0° 25'	
39+79.66		0° 36'	
40+04.66		0° 49'	
40+29.66		1° 04'	
40+54.66		1° 21'	
40+79.66	SC	1° 40'	

Sample of spiral field notes

Chapter 6: Vertical Curves

Function and Types of Vertical Curves

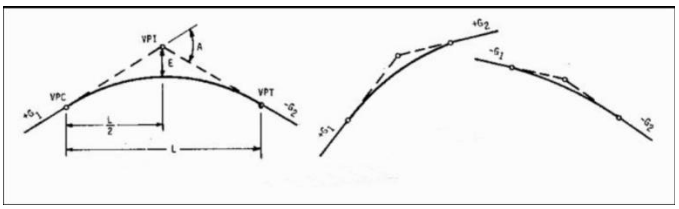
Change in Grade

When there is a vertical change of direction or change in grade (where two grade lines intersect), the roadway designer will round off the intersection by inserting a vertical parabolic curve.

This parabolic curve provides a gradual directional transition from one grade to the next.

Crest Curve

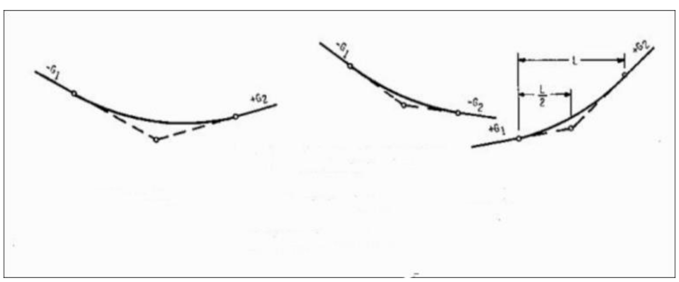
An ascending grade followed by a descending grade (Type I), or one ascending less sharply (Type II), is joined by a crest, summit, or curve.



Crest, Summit, or Overt Curve

Sag Curve

A vertical curve connecting a descending grade with an ascending grade (Type III), or with one descending less sharply (Type IV), is called a sag or invert curve.



Sag or Invert Curve

Elements of Vertical Roadway Design:

- BVC = Beginning of Vertical Curve
- EVC = End of Vertical Curve
- PVI = point of vertical interception (intersection of initial and final grades)
- G1 = initial roadway grade, expressed in percent
- G2 = final roadway grade, expressed in percent
- H1 = Height of eye above roadway, measured in meters or feet
- H2 = Height of object above roadway, measured in meters or feet
- A = absolute value of the difference in grades (initial minus final), expressed in percent
- L = curve length (along the x-axis)
- tangent elevation = elevation of a point along the initial tangent
- x = horizontal distance from BVC
- Y (offset) = vertical distance from the initial tangent to a point on the curve
- Y' = curve elevation = tangent elevation - offset

Safe Design of a Sag Curve

The most critical design aspect of a sag curve is the headlight sight distance. When a driver is traveling on a sag curve at night, the sight distance is limited by the higher grade ahead.

This distance must be long enough that the driver can see an obstruction on the road and stop the vehicle within the headlight sight distance.

Headlight sight distance (S) - is determined by the angle of the headlight and angle of the tangent slope at the end of the curve.

By first finding the headlight sight distance (S) and then solving for the curve length (L) in each of the equations below, the correct curve length can be determined.

Units	Sight Distance < Curve Length (S<L)	Sight Distance > Curve Length (S>L)
Metric	$L = \frac{AS^2}{120 + 3.5S}$	$L = 2S - \frac{120 + 3.5S}{A}$
US Customary	$L = \frac{AS^2}{400 + 3.5S}$	$L = 2S - \frac{400 + 3.5S}{A}$

Headlight Sight Distance Equations

- *If the S<L curve length is greater* - than the headlight sight distance, then this number can be used. If it is smaller, this value cannot be used.

- *If the S>L curve length is smaller* - than the headlight sight distance, then this number can be used. If it is larger, this value cannot be used.

Safe Design of a Crest Curve

The most critical design aspect of a crest curve is stopping sight distance. This is the distance a driver can see over the crest of the curve.

If the driver cannot see an obstruction in the roadway, such as a stalled vehicle or an animal, the driver may not be able to stop the vehicle in time to avoid a crash.

Headlight Sight Distance (S)

The desired stopping sight distance (S) is determined by the speed of traffic on a road.

By first finding the stopping sight distance (S) and then solving for the curve length (L) in each of the equations below, the correct curve length can be determined.

The proper equation depends on whether the vertical curve is shorter or longer than the available sight distance. Normally, both equations are solved, and then the results are compared to the curve length.

Sight Distance > Curve Length (S>L)

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

Sight Distance S>L

Sight Distance < Curve Length (S<L)

$$L = \frac{AS^2}{200(\sqrt{h_1} + \sqrt{h_2})^2}$$

Sight Distance S<L

US standards specify the height of the driver's eye is defined as 3.5 ft (1080 mm) above the pavement, and the height of the object the driver needs to see as 2.0 ft (600 mm), which is equivalent to the taillight height of most passenger cars.

Vertical Curve Computations

Xx

In order to achieve a smooth change of direction when laying out vertical curves, the grade must be brought up through a series of elevations.

The surveyor normally determines elevations on a vertical curve for:

- the beginning (point of vertical curvature or PVC)
- the end (point of vertical tangency or PVT)
- all full stations
- various additional points, (depending on construction requirements)

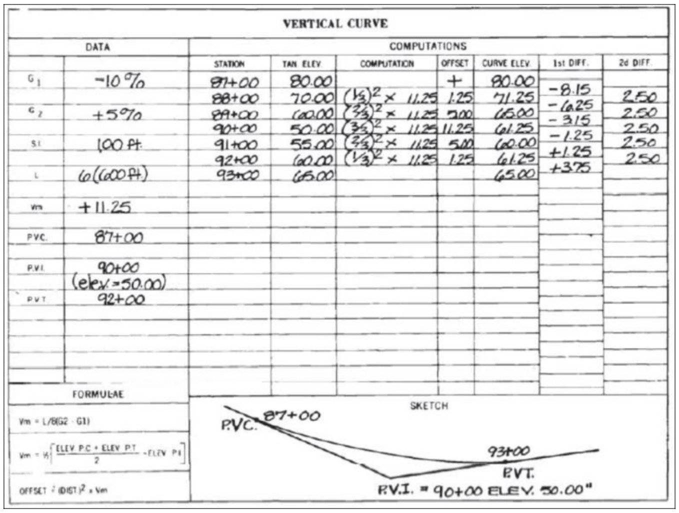
Length of Curve

The elevations are vertical offsets to the tangent (straight-line design grade) elevations.

- Grades G1 and G2 are given as percentages of rise for 100 feet of horizontal distance.
- Grades are identified as plus or minus, (depending on whether they are ascending or descending in the direction of the survey).
- The length of the vertical curve (L) is the horizontal distance (in 100-foot stations) from PVC to PVT.
- Usually, the curve extends ½ L stations on each side of the point of vertical intersection (PVI) and is most conveniently divided into full station increments.

Example (Sag Curve)

A sag curve is illustrated in the figure below, with the field notes and sketch.



VERTICAL CURVE

DATA		STATION	TAN ELEV.	COMPUTATION	OFFSET	CURVE ELEV.	1st DIFF.	2d DIFF.
G_1	-10%	87+00	80.00		+	80.00	-8.15	
		88+00	70.00	$(1/3)^2 \times 11.25$	1.25	71.25	-6.25	2.50
G_2	+5%	89+00	60.00	$(2/3)^2 \times 11.25$	5.00	65.00	-3.15	2.50
		90+00	50.00	$(3/3)^2 \times 11.25$	11.25	61.25	-1.25	2.50
S.I.	100 ft.	91+00	55.00	$(2/3)^2 \times 11.25$	5.00	60.00	+1.25	2.50
		92+00	60.00	$(1/3)^2 \times 11.25$	1.25	61.25	+3.75	2.50
L	6(600 ft)	93+00	65.00			65.00		
Vm	+11.25							
P.V.C.	87+00							
P.V.I.	90+00 (elev=50.00)							
P.V.T.	92+00							

FORMULAE

Vm = L/8(G2 - G1)

$Vm = 1/2\left[\frac{ELEV\ P.C + ELEV\ P.T}{2} - ELEV\ P.I\right]$

OFFSET = (DIST)^2 x Vm

Sag Curve Layout

The curve data is derived as follows:
Determine values of G1 and G2, the original grades.

To arrive at the minimum curve length (L) in stations, divide the algebraic difference of G1 and G2 (AG) by the rate of change (r), which is normally included in the design criteria.

When the rate of change (r) is not given, use the following formulas to compute L:

(Summit Curve)

$$L = 125\text{ ft}\frac{(G_2\text{-}G_1)}{4} \text{ or } L = 38.10\text{ m}\ \frac{(G_2\text{-}G_1)}{4}$$

(Sag Curve)

$$L = 100\text{ ft}\frac{(G_2\text{-}G_1)}{4} \text{ or } L = 30.48\text{ m}\ \frac{(G_2\text{-}G_1)}{4}$$

If the answer for L is not a whole number of stations from the above formula, it is usually extended to the nearest whole number. Note that this reduces the rate of change.

Thus, L = 4.8 stations would be extended to 5 stations, and the value of r computed from r = Δ G/L. (These formulas are for road design only; not railroad).

Station Interval (SI)

Once the length of curve (L) is determined, an appropriate station interval (SI) will be selected.

The first factor to be considered is the terrain. As the terrain becomes rougher, the station interval will decrease.

The second consideration is to select an interval which will place a station at the center of the curve with the same number of stations on both sides of the curve.

(For example, a 300-foot curve could not be staked at 100-foot intervals but could be staked at 10-, 25-, 30-, 50-, or 75-foot intervals).

The same intervals as those recommended for horizontal curves are often used: (10, 25, 50, and 100 ft).

As PVI is the only fixed station, next compute the station value of the PVC, PVT, and all stations on the curve:

- *PVC* = PVI - L/2
- *PVT* = PVI + L/2
- *Other Stations* - determined by starting at the PVI, adding the SI, and continuing until the PVT is reached.

Tangent Elevations of PVC, PVI, and All Stations on Curve

Compute tangent elevations PVC, PVT, and all stations along the curve.

As PVI is the fixed point on the tangents, next compute the station elevations as follows:

- *Elev PVC* = Elev PVI + (-1 x L/2 x G1)
- *Elev PVT* = Elev PVI + (L/2 x G2)

The elevation of the stations along the back tangent may be found as follows:

- *Elev of Stations* = Elev of PVC + (distance from the PVC x G1)

The elevation of the stations along the forward tangent is found as follows:

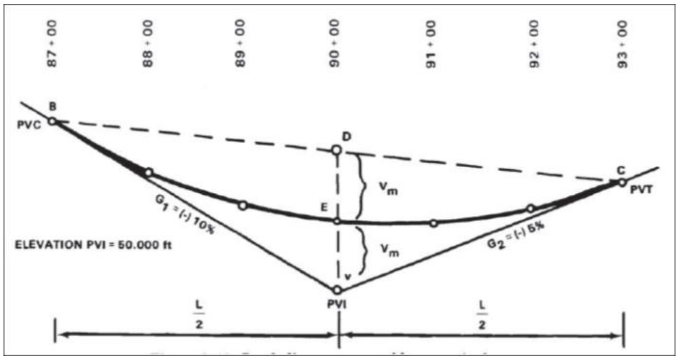
- *Elev of Stations* = Elev of PVI + (distance from the PVI x G2)

Vertical Curve Computations (continued)

Vertical Maximum

The parabola bisects a line joining the PVI and the midpoint of the chord drawn between the PVC and PVT.

In the image below, line VE = DE and is referred to as the vertical maximum (Vm):



Grade lines connected by a vertical curve

The value of Vm is computed as follows:

$$Vm = L/8\ (G2 - G1)$$

or

$$Vm = \frac{1}{2}\left(\left(\frac{\text{Elev PVC} + \text{Elev PVT}}{2}\right) - \text{Elev PVI}\right)$$

- L = length in 100-foot stations
- *In a 600-foot curve*, L = 6

Note: In practice the value of Vm should be computed using both formulas, since working both provides a check on the Vm, the elevation of the PVC, and the elevation of the PVT.

Vertical Offset

The value of the vertical offset is the distance between the tangent line and the road grade.

This value varies as the square of the distance from the PVC or PVT and is computed using the formula:

- *Vertical Offset* = (Distance) 2 x Vm

A parabolic curve presents a mirror image. This means that the second half of the curve is identical to the first half, and the offsets are the same for both sides of the curve.

Station Elevation

Next, compute the elevation of the road grade at each of the stations along the curve.

The elevation of the curve at any station is equal to the tangent elevation at that station plus or minus the vertical offset for that station,

The sign of the offset depends upon the sign of Vm (plus for a sag curve and minus for a crest curve).

First and Second Differences

Finally, determine the values of the first and second differences:

- *First differences* - are the differences in elevation between successive stations along the curve, namely, the elevation of the second station minus the elevation of the first station, the elevation of the third station minus the elevation of the second, etc.
- *Second differences* - are the differences between the differences in elevation (the first differences), and they are computed in the same sequence as the first differences.

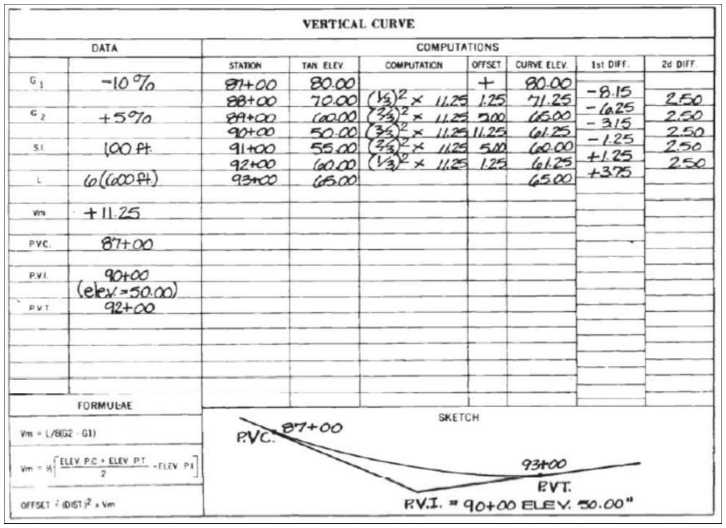
Care must be taken to observe and record the algebraic sign of both the first and second differences.

The second differences provide a check on the rate of change per station along the curve and a check on the computations.

The second differences should all be equal; however, they may vary by one or two in the last decimal place due to rounding off in the computations. When this occurs, they should form a pattern.

If they vary too much and/or do not form a pattern, an error has been made in the computation.

The vertical offsets for each station are computed (as in image, below). The first and second differences are determined as a check.



VERTICAL CURVE

DATA	
G_1	-10%
G_2	+5%
SI	100 ft
L	6 (600 ft)
Vm	+11.25
PVC	87+00
PVI	90+00 (elev.=50.00)
PVT	92+00

STATION	TAN ELEV	COMPUTATION	OFFSET	CURVE ELEV	1st DIFF	2d DIFF
87+00	80.00		+	80.00		
88+00	70.00	(1/3)² × 11.25	1.25	71.25	-8.15	2.50
89+00	60.00	(2/3)² × 11.25	5.00	65.00	-6.25	2.50
90+00	50.00	(3/3)² × 11.25	11.25	61.25	-3.15	2.50
91+00	55.00	(2/3)² × 11.25	5.00	60.00	-1.25	2.50
92+00	60.00	(1/3)² × 11.25	1.25	61.25	+1.25	2.50
93+00	65.00			65.00	+3.75	

FORMULAE

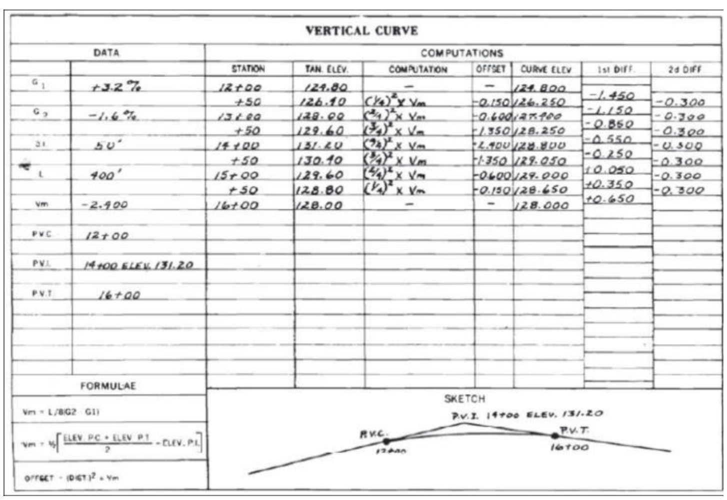
Vm = L/8(G2 - G1)

Vm = ½[(ELEV PC + ELEV PT)/2 - ELEV. PI]

OFFSET = (DIST)² × Vm

Example 1 - Typical Solution of a Sag Curve

The image below illustrates the solution of a crest curve with offsets for 50-foot intervals:



VERTICAL CURVE

DATA	
G_1	+3.2%
G_2	-1.6%
SI	50'
L	400'
Vm	-2.400
PVC	12+00
PVI	14+00 ELEV. 131.20
PVT	16+00

STATION	TAN. ELEV.	COMPUTATION	OFFSET	CURVE ELEV	1st DIFF	2d DIFF
12+00	124.80	–	–	124.800		
+50	126.40	(1/4)² × Vm	-0.150	126.250	-1.450	-0.300
13+00	128.00	(2/4)² × Vm	-0.600	127.400	-1.150	-0.300
+50	129.60	(3/4)² × Vm	-1.350	128.250	-0.850	-0.300
14+00	131.20	(4/4)² × Vm	-2.400	128.800	-0.550	-0.300
+50	130.40	(3/4)² × Vm	-1.350	129.050	-0.250	-0.300
15+00	129.60	(2/4)² × Vm	-0.600	129.000	+0.050	-0.300
+50	128.80	(1/4)² × Vm	-0.150	128.650	+0.350	-0.300
16+00	128.00	–	–	128.000	+0.650	

FORMULAE

Vm = L/8(G2 - G1)

Vm = ½[(ELEV PC + ELEV PT)/2 - ELEV. PI]

OFFSET = (DIST)² × Vm

Example 2 - Typical Solution of a Crest Curve

High and Low Points on a Vertical Curve

High and Low Points

The high or low points of a vertical curve are used to determine the direction and amount of runoff, (in the case of crest curves), and to locate the low point for drainage:

- When the tangent grades are equal, the high or low point will be at the center of the curve.
- When the tangent grades are both plus, the low point is at the PVC and the high point at the PVT.
- When both tangent grades are minus, the high point is at the PVC and the low point at the PVT.
- When unequal plus and minus tangent grades are encountered, the high or low point will fall on the side of the curve that has the flatter gradient.

Horizontal Distance

Determine the distance (x, expressed in stations) between the PVC or PVT and the high or low point by the following formula:

$$x = G \frac{L}{(G_2 - G_1)}$$

Where:

- G is the flatter of the two gradients
- L is the number of curve stations
- G1 and G2 are the tangent grades

Vertical Distance

Compute the difference in elevation (y) between the PVC or PVT and the high or low point by the formula:

$$y = \frac{-(G_2 - G_1)}{2L}(x^2) + Gx$$

Example:

From the curve in Example 2, (found in the previous section):

- G1 = +3.2%
- G2 = -1.6%
- L = 4 (400)

Note: Since G2 is the flatter gradient, the high point will fall between the PVI and the PVT.

$$x = G \frac{L}{G_2 - G_1} = -1.6 \frac{4}{-1.6 - (+3.2)} = 1.3333 \text{ sta}$$

$$= 133.33 \text{ feet}$$

Station of high point:

- PVT - x = (16+00) - 133.33 = 14+66.67

$$y = \frac{-(G_2 - G_1)}{2L}(x^2) + Gx$$

Elevation of high point:

- Elev PT + y = 128.00 + 1.07 = 129.07

Maximum Grades for Vertical Alignments

Maximum Vertical Grades

The grades selected for vertical alignments should be as flat as practical, and should not exceed the values listed in the following, Table 7.1.

Type of Terrain	Maximum Grade (%) for Specified Design Speed (mph)													
	15	20	25	30	35	40	45	50	55	60	65	70	75	80
Industrial Roadways														
Level	-	-	4	4	4	4	3	3	3	3	-	-	-	-
Rolling	-	-	5	5	5	5	4	4	4	4	-	-	-	-
Mountainous	-	-	6	6	6	6	5	5	5	5	-	-	-	-
Local Rural Roads														
Level	9	8	7	7	7	7	7	6	6	5	-	-	-	-
Rolling	12	11	11	10	10	10	9	8	7	6	-	-	-	-
Mountainous	17	16	15	14	13	12	11	10	10	-	-	-	-	-
Local Urban Streets														
Level	12	11	11	10	10	9	9	8	8	-	-	-	-	-
Rolling	14	13	12	11	11	10	10	9	-	-	-	-	-	-
Mountainous	17	16	15	14	13	12	11	-	-	-	-	-	-	-
Rural Collectors														
Level	-	7	7	7	7	7	7	6	6	5	-	-	-	-
Rolling	-	10	10	9	9	8	8	7	7	6	-	-	-	-
Mountainous	-	12	11	10	10	10	10	9	9	8	-	-	-	-
Urban Collectors														
Level	-	9	9	9	9	9	8	7	7	6	-	-	-	-
Rolling	-	12	12	11	10	10	9	8	8	7	-	-	-	-
Mountainous	-	14	13	12	12	12	11	10	10	9	-	-	-	-
Rural Arterials														
Level	-	-	-	-	-	5	5	4	4	3	3	3	3	3
Rolling	-	-	-	-	-	6	6	5	5	4	4	4	4	4
Mountainous	-	-	-	-	-	8	7	7	6	6	5	5	5	5
Urban Arterials														
Level	-	-	-	8	7	7	6	6	5	5	-	-	-	-
Rolling	-	-	-	9	8	8	7	7	6	6	-	-	-	-
Mountainous	-	-	-	11	10	10	9	9	8	8	-	-	-	-
Rural and Urban Freeways (Limited Access Facilities)														
Level	-	-	-	-	-	-	-	4	4	3	3	3	3	3
Rolling	-	-	-	-	-	-	-	5	5	4	4	4	4	4
Mountainous	-	-	-	-	-	-	-	6	6	6	5	5	-	-

Table 7.1

Image Source: Georgia DOT Design Policy Manual

Maximum values vary based on types of terrain, facility classification, and design speed.

The maximum design grade should be used infrequently; in most cases, grades should be less than the maximum design grade in the following Table.

Maximum Vertical Grades, industrial roadways are defined as local and collector streets with significant (15% or more) truck traffic.

Exceptions to the maximum vertical grades listed in Table 7.1 are as follows:

- For short sections less than 500-ft. and for one-way downgrades, the maximum grade may be 1% steeper than the values listed in Table 7.1.
- The maximum vertical grade for local streets, collectors and arterials may be increased by as much as 2% under extreme conditions.

Maximum values in Table 7.1 may be reduced when:

- Upgrades cause a speed reduction greater than or equal to 10 mph

For streets and highways requiring long upgrades the maximum grade so that the speed reduction of slow-moving vehicles (i.e., trucks and buses) is not greater than or equal to 10 mph

Use of Climbing Lanes

Where reduction of grade is not practical, climbing lanes should be provided to meet these speed reduction limitations.

If the maximum grade cannot be reduced and climbing lanes cannot be provided, a comprehensive study by an engineer and the prior approval of a design exception (high speed roadways) or design variance (low speed roadways) is required.

Minimum Grades for Vertical Alignments

Minimum Vertical Grades

Minimum vertical grades are typically used to facilitate roadway drainage. This is especially true of curbed roadway sections where drainage or gutter spread is a consideration.

Uncurbed Pavements

For projects involving uncurbed pavements, longitudinal grades may be flat (0%) in areas where appropriate cross slopes are provided.

In areas of superelevation transitions and/or flat cross slopes on those projects, minimum vertical grades should be consistent with those listed below in Table 7.2.

Curbed Pavements

For curbed pavements, minimum longitudinal grades are controlled by the values in Table 7.2.

This includes roadways with concrete median barriers or side barriers, V-gutter and those roadways adjacent to walls.

These values will generally ensure that roadway drainage "spread" is not excessive and can be contained within acceptable ranges by a minimum (reasonable) number of roadway drainage catch basins.

The minimum values in Table 7.2 should be used only under extreme conditions.

These situations include:

- a new location rural section
- roadways with high truck percentages that experience appreciable pavement rutting
- current rural roadways in urban, suburban or developing areas that have a realistic chance of being converted to a curb and gutter sometime in the foreseeable future
- areas containing superelevation transitions and/or flat cross slope areas
- interstate or other high speed facilities

Minimum Vertical Grades for Roadways where Drainage Spread is a Consideration

However, there are situations with uncurbed pavements where it is prudent that consideration be given to maintaining minimum vertical grades - similar to those for curbed roadway sections.

Type of Facility	Minimum Grade (%)	
	Desirable	Minimum
Industrial Roadways with Curb and Gutter	0.30	0.20
Local Urban Streets with Curb and Gutter	0.30	0.20
Urban Collectors with Curb and Gutter	0.50	0.30
Urban Arterials with Curb and Gutter	0.50	0.30
Urban Freeways or Limited Access Facilities	0.50	0.30

Table 7.2 - Minimum Vertical Grades for Roadways where Drainage Spread is a Consideration

Chapter 7: Other Roadway Alignment Design Criteria

Design Criteria for Road Alignments

Design Criteria

As a surveyor performing recon and preliminary road route surveys, it's beneficial to have a basic background of the various design criteria which a transportation engineer or designer uses when laying out a roadway corridor.

An overall familiarity with some basic design criteria and terminology helps when envisioning the ultimate route a road may follow, and when interacting with a roadway project's engineers and designers. Many factors come into play when deciding on a road's route.

These factors are based on the physical characteristics of the vehicles (vehicle types), the topography in which the road is routed, operational safety and speed of traffic on the road, and even driver behavior (such as speed, turns, following distances, and clear zones for emergencies).

Selecting the Best Route

Many factors are important and should be balanced when selecting the best route for a road or highway, such as:

- The classification of the road or highway
- what types of vehicles will be most frequent on the road segment
- design and check vehicles (explained on page 3 of this chapter)
- superelevation (degree of banking on the curves of the road)
- sight distances (especially important in mountainous terrain with steep grades)
- design speed (speed affects many of the other design factors)
- Intersections and interchanges (ensuring near 90 degree joining at intersections)
- Fencing (to delineate the road corridor to prevent encroachment; very important in highways)
- Right of Ways (providing excess width for other utilities to be run adjacent to the road)
- Frontage or access roads (the need for adjacent roads next to highways requires a great deal of extra width)

Classification of Roads and Highways

Classifications for Roads and Highways

Design considerations vary for different classes of roads in accordance with their intended use. Streets and highways are grouped into major classes based on the type or kind of service they provide to the travel infrastructure as a whole.

The three major classifications are:

- Freeways
- Arterials
- Collectors and local streets

Freeway Classification (uninterrupted flow facilities)

Freeways are distinguished from all other roadway systems in that they provide uninterrupted traffic flow with no fixed flow interrupters, (ie, cross traffic flow, etc.).

The traffic flow conditions along uninterrupted flow facilities result primarily from the interactions among vehicles in the traffic stream and between vehicles and the geometric and environmental components of the roadway.

Access to the freeway facility is controlled and limited to ramp locations, as opposed to access for an interrupted flow facility which uses at-grade intersections.

Categorization of uninterrupted and interrupted flow relates to the type of road as opposed to the conditions of the traffic flow at any given time.

Traffic Capacity

Freeway systems have several interacting components, including ramps, and weaving sections.

As such, the performance of a freeway may be affected when demand exceeds capacity on nearby road systems.

For example, if the connected street system cannot accommodate the demand exiting the freeway, over-saturation of the street system may result in queues backing onto the freeway, which adversely affects freeway performance and greatly affects safety.

Arterial Classification

Arterials are a classification of roadway that are intended to provide for through traffic "trips", that are generally further in distance, than the trips found on collector roads and local streets.

While the need to provide for ingress and egress onto properties abutting the road segment is not a primary function of an arterial, the design must take this need into account.

To accommodate the often competing demands of urban arterials, other modes of travel such as pedestrian traffic, bicycles, and public transit are also present and must be taken in consideration.

Arterial systems are often further sub-classified into Principal or Minor arterial road systems based on the trips served, the areas served, and the operational characteristics of the streets or highways.

The road systems for urban arterials and rural arterials differ due to factors such as intensity and type of development that occurs on these systems.

Rural Arterial Classification

Rural Principal Arterials – nearly all fully and partially controlled access facilities in rural areas are considered rural principal arterials.

Service characteristics of rural principal arterials include:

- traffic movements with trip length and density suitable for substantial statewide travel or interstate travel
- traffic movements between urban areas with populations greater than 25,000
- traffic movements at high speeds
- divided four-lane roads
- desired LOS B (LOS A is the highest service level, while LOS F is the lowest)

Service characteristics of rural minor arterials include:

- traffic movements with trip length and density suitable for integrated interstate or intercounty service
- traffic movements between urban areas or other traffic generators with populations less than 25,000
- traffic movements at high speeds
- undivided lane roads
- striped for one or two lanes in each direction with auxiliary lanes at intersections as required by traffic volumes
- desired LOS B

Collectors and Local Street Classification

Some characteristics of collector streets are:

- provide access and traffic circulation within residential neighborhoods, commercial, and industrial areas may penetrate residential neighborhoods, distributing trips from the arterials to destinations
- collect traffic from local streets in residential neighborhoods and channel traffic to the arterial system

Some characteristics of local streets are:

- local streets provide direct access to abutting land and access to higher systems
- local street systems offer the lowest level of mobility and usually contain no bus routes
- Service to through traffic movement in this system is usually deliberately discouraged

Design Vehicles

Design Vehicles

A design vehicle is a theoretical vehicle used to define critical features such as lane width, radii at intersections, median and commercial driveway openings, and the radius of turning roadways.

Design vehicles should be chosen during the conceptual design phase.

Fundamentally, a design should accommodate the largest vehicle that is likely to use that facility on a regular basis.

Multiple design vehicles may need to be defined for a single corridor or a design vehicle with special characteristics may apply to a single intersection or to a single movement.

In terms of providing adequate space for trucks, there are two categories of vehicles:
Design vehicle – This is an “everyday” vehicle which is often fully accommodated within prescribed travel lanes.

Full accommodation may not be possible in relatively tight urban street environments and some leeway may need to be given to encroaching on adjacent lanes approaching and/or departing an intersection.

Check Vehicle

This is an “infrequent” vehicle, normally larger that the design vehicle, which must be checked to see that it can get through an intersection.

A check vehicle will often use all available space on the road including opposing travel lanes and shoulder areas outside of the regular travel lanes designed to accommodate vehicle “off-tracking”.

Design Vehicle Types

The four general classes of design vehicles defined by AASHTO are:

- *Passenger Cars* - Passenger automobiles of all sizes, including cars, sport/utility vehicles, minivans, vans, and pick-up trucks;
- *Buses* - Intercity (motor coaches), city transit, school, and articulated buses;
- *Trucks* - Single-unit trucks, truck tractor-semi-trailer combinations, and truck tractors with semi-trailers in combination with full trailers.
- *Recreational Vehicles* - Motor homes (including those with boat trailers and/or pulling an automobile) and automobiles pulling a camper trailer or a boat trailer.
- *Oversize Overweight (OSOW)* - A vehicle may be classified as an OSOW if it is larger than a WB-67 design vehicle in height, width or length or if it is over the legal weight limit allowed on roadways, as defined in state statute.

Common examples of OSOWs include:

- long tractor trailers
- trucks which carry special loads or very large equipment
- mobile homes
- low boys
- farm equipment such as combines.

Where they apply, an OSOW will often be considered to be a “check vehicle”.

Superelevation

What is Superelevation?

Superelevation is the banking of the pavement surface on the approach to and through a horizontal curve. It is intended to assist the driver by counteracting the lateral acceleration produced by tracking the curve.

Superelevation is expressed as a decimal, representing the ratio of the pavement slope to width, ranging from 0 to 0.12 foot/feet.

Adopted design criterion allows for the use of maximum superelevation rates from 0.04 to 0.12. Maximum superelevation rates for design are established by policy established by each state’s DOT.

Maximum Superelevation rates

Maximum rates of superelevation are limited by the need to prevent slow-moving vehicles from sliding to the inside of the curve and, in urban areas, by the need to keep parking lanes relatively level and to keep the difference in slope between the roadway and any streets or driveways that intersect it within reasonable bounds.

AASHTO recommends that maximum superelevation rates be limited to 12 percent for rural roadways.

There are no single maximum superelevation rates which are universally applied. In order to promote consistency in design, a maximum rate is desirable for locations with similar characteristics.

Selection of a maximum superelevation rate is based on variables, such as climate, terrain, highway location (urban vs. rural), and frequency of very slow-moving vehicles.

For example, in northern states that experience extreme winter conditions, lower maximums may be established than for the milder weather states.

Safety and operational concerns

Inadequate superelevation can cause vehicles to skid as they travel through a curve, potentially resulting in a run-off-road crash.

Trucks and other large vehicles with high centers of mass are more likely to roll over at curves with inadequate superelevation.

Types of accidents and hazards associated with improper superelevation design are:

- Run-off-road crashes
- Cross-median crashes
- Cross-centerline crashes
- Skidding
- Large vehicle rollover crashes

Sharpest Curve without Superelevation

Although superelevation is advantageous for high-speed traffic operations, various factors combine to make its use impractical in many built-up areas.

Such factors include:

- wide pavement areas
- need to meet grade of adjacent property
- surface drainage considerations
- frequency of cross streets, alleys and driveways
- at major intersections or other locations where there is a tendency to drive slowly because of turning and crossing movements, warning devices, and traffic signals

The minimum curve radius is a limiting value of curvature for a given design speed and is determined from the maximum rate of superelevation and the maximum side friction factor selected for design.

Very flat curves need no superelevation. In many instances, it is desirable to maintain a normal crown typical section on the roadway.

In these cases, implementation of a curve with a radius flat enough as to not require superelevation should be considered.

Point of Superelevation Rotation

Roadway alignments are generally defined by a centerline (CL) and a profile grade line (PGL). The roadway may be rotated about various points on the typical section to achieve superelevation.

Typically, the point of superelevation rotation (axis of rotation) corresponds to the PGL located on the inside edges of the travel lanes.

On two-way roadways with a flush, raised or no median, the axis of rotation typically corresponds to the roadway centerline.

Generally, rotation will occur about the centerline on roadways with an urban typical section. In most instances, the axis of rotation, the PGL or centerline and the pavement crown line are the same, although it is not mandatory.

Sight Distances

Sight Distances

Sight distance, as it applies to road design, is the length of roadway ahead which is visible to the driver.

Sight distance is how far a vehicle's driver can see before the line of sight is blocked by a crest curve, or obstacles on the inside of a horizontal curve or intersection, such as a structure, landscaping, etc. Sight distance has a considerable effect on the safety and function of a roadway or intersection.

Special consideration should be given to the sight distance requirements at queue backups over a hill, signals, and horizontal curves, turning movements, barriers, guardrails, structures, trees, landscaping, vegetation and other special circumstances.

Sight Distance on Curves

Stopping sight distance across the inside of curves plays a critical role in determining roadway horizontal curvature and applicable shoulder widths.

Enough right of way should be allowed to ensure that adequate stopping sight distance is maintained.

There should be no obstruction of sight lines on the inside of curves (such as median barriers, walls, cut slopes, buildings, landscaping materials, and longitudinal barriers).

If removal of the obstruction is impractical to provide adequate sight distance, a design may require adjustment in the normal highway cross section or a change in the alignment.

Because of the many variables in alignment, cross section, and in the number, type, and location of potential obstructions, the actual conditions on each curve should be checked and appropriate adjustments made to provide adequate sight distance.

Sight distance is the combined distance travelled during these two phases of a driving maneuver:

- *Perception-reaction time (PRT)* - is the time it takes for a road user to realize that a reaction is needed to a road condition, decided what maneuver is appropriate, and begins the maneuver.
- *Maneuver time (MT)* - is the time it takes to complete the maneuver. The distance driven during perception-reaction time and maneuver time is the sight distance needed.

During an investigation into the safety or proper design of a road segment, the sight distance which is available is compared to sight distance required for a particular situation.

Types of Sight Distances

Stopping Sight Distance

This is the distance traveled during PRT and MT:

- *(PRT) perception-reaction time* - the time period while the driver perceives a situation requiring a complete stop, realizes that stopping is required, and then reacts by applies the brakes.
- *(MT) maneuver time* - The maneuver being the act of stopping; the time period while the driver decelerates and comes to a stop.

Actual stopping distances are also affected by:

- road conditions
- mass of the car
- incline of the road
- numerous other factors

For design, a conservative distance is needed to allow a vehicle traveling at design speed to stop before reaching a stationary object in its path.

Typically the design sight distance allows a below-average driver to stop in time to avoid a collision.

Decision Sight Distance

is used when a driver must make more complex decisions than rather to stop or not. This time period is longer than stopping sight distance, to allow for the added distance traveled while processing a more complex decision.

Examples of locations where Decision Sight Distance should be considered are:

- multiphase at-grade intersections
- interchanges
- ramp terminals on through roadways
- lane drops (where the lane terminates and merges into adjacent lane)
- areas of concentrated traffic demand (where more visual demands and heavier weaving maneuvers occur)

The decision sight distance is the distance traveled while a driver:

- detects an unexpected or otherwise difficult-to-perceive situation or hazard in a roadway
- recognizes the hazard or its threat potential
- selects an appropriate speed and path
- initiates and completes the required maneuver safely and efficiently

Ideally, a road is designed for the decision sight distance, using:

- 6 to 10 seconds for perception-reaction time
- 4 to 5 seconds to perform the correct maneuver

In cases where it is not practical to provide decision sight distance, then stopping sight distance should be provided.

Passing Sight Distance

Passing sight distance is the sight distance needed for passing other vehicles (applicable only on two-way, two-lane highways at locations where passing lanes are not present).

Intersection Sight Distance

Intersection sight distance is critical for urban sections with narrow shoulders and limited right-of way where obstructions on private property may encroach into the sight triangles.

Special consideration should be given to obstructions within the right of way such as:

- Bridges
- retaining walls
- signs
- landscaping which is above the driver's line of sight such as trees and shrubbery
- signal control boxes
- utility features which may inhibit the driver's line of sight
- guardrails

Additional points of interest:

Graphical Studies

Where a sight line passes through a potential obstruction, a detailed graphical study using profile sheets and cross sections may be required.

Right of Way Flares

The preferred method to ensure adequate intersection sight distance is to acquire the area(s) within the sight triangles as right of way so the area can be properly managed and kept free of obstructions. These areas are referred to as right-of-way flares.

Corner sight distance (CSD)

is a specification which requires a thoroughly clear line of sight, in order to allow a driver waiting at a crossroad, the time to safely anticipate oncoming traffic.

Corner sight provides an adequate time period for the waiting driver to either cross all lanes of through traffic, cross the near lanes and turn left, or turn right, without requiring through traffic to radically alter their speed.

Intersection Skew Angle

Ideally, intersecting roadways should meet at or near right angles (90-degrees). This will ensure that the lines of sight are optimized for intersection sight distance.

Frontage and Access Roads, and Right of Ways

Frontage, Access Roads, ROWs

AASHTO defines a frontage road as "a road that segregates local traffic from higher speed through traffic and intercepts driveways of residences, commercial establishments, and other individual properties along the highway" (from the AASHTO Green Book).

The manner and use of frontage and access roads differs from state to state.

Frontage Roads

Frontage roads can serve many functions depending on the type of arterial they serve and the character of the surrounding area.

They are commonly used to control access to the arterial, to provide access to adjoining properties, and to maintain traffic circulation on each side of the arterial.

Most existing frontage roads were built along interstate or major arterial routes to control access to these routes and provide access to property that would otherwise be land-locked.

Access Roads

Access roads may also be used to provide access to landlocked parcels. Frontage roads typically run parallel to the mainline route while access roads provide access to individual properties and may not run parallel to the mainline.

Access roads and frontage roads should be offset from the mainline route to allow for a required clear zone and future roadway widening, if these are anticipated.

Right of Ways

Establishing right-of-way widths that adequately accommodate construction, utilities, drainage, and proper roadway maintenance is an important consideration of the overall design.

The bordering area between the roadway and the right-of-way line should be wide enough to serve several purposes, including provision of a buffer space between pedestrians and vehicular traffic (when applicable), encroachment prevention fencing, roadway drainage facilities, sidewalk space, lateral offset, clear zone, and an area for both underground and above ground utilities such as water, sewer, and electric.

A wide right-of-way width allows construction of gentle slopes and also allows for utility poles to be offset further from the road, which in turn results in greater safety for motorists as well as easier and more economical maintenance of the right-of-way.

Proper spacing and accommodation for guard rails should also be part of the ROW design.

Terrain Considerations

Right of way design considerations based on terrain and setting:

- *In hilly rural terrain* - construction limits vary considerably as the roadway passes through cut and fill sections. In these situations, the required right-of-way will likely vary, so it may be impractical to use a constant right-of-way width.
- *In flat rural terrain* - it is usually both practical and desirable to establish a minimum right-of-way width that can be used throughout most of the project length. Required right-of-way widths should be set at even offsets from the centerline, typically multiples of 5-ft., unless some physical feature requires otherwise.
- *In urban areas* - right-of-way widths are governed primarily by economic considerations, physical obstructions, utility conflicts or environmental considerations. Along any route, development and terrain conditions may vary affecting the availability of right-of-way. Property or environmental impacts may limit the amount of right-of-way that can realistically be acquired. In urban areas, it may be appropriate to set the required right-of-way

at the shoulder break point to minimize impacts. However, required lateral offset, should be considered when setting the required right-of-way. Also, permanent roadway features such as roadway ditches, drainage structures; steep fill slopes and back slopes, sight triangles at intersections, horizontal sight distance, etc. should be within the required right-of-way.

Design Speeds Considerations

What is the Design Speed?

This is the speed of operation, or AASHTO defines it, design speed is "the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern".

Design speed selection is a critical decision that should be performed at the preliminary stages of the planning and design process. It is an overall design control for horizontal alignments in roadway design that may equal or exceed the legal statutory speed limit.

(Meaning, a 55 mph highway corridor would typically be designed to meet or exceed 70 mph specifications.)

LOS

The level of service (LOS) of a roadway segment is directly related to the design speed. It should meet driver expectations, predictability, and comply with the road's functional classification and location.

If design speed does not compliment these other design needs, then the LOS of a road may be affected.

A design speed should balance these critical characteristics:

- Safety
- Mobility
- Efficiency

With the following considerations:

- Potential environmental quality
- Economics
- Aesthetics
- Social and political impacts
- Impact on other roadway features

Roadway Design Features

(Curve radii, superelevation, sight distance, etc.)
Design features are impacted by the design speed, as well as other characteristics not directly related to speed. Therefore, changes to design speed may affect a variety of roadway design elements.

Higher design speeds

For rural roads, these should be as high as may be practical, to supply an optimal degree of safety and operational efficiency.

Data has shown that drivers operate quite comfortably at speeds that are higher than typical design speeds.

Lower Design Speeds and Traffic Calming

These may be appropriate for certain urban settings (residential and school zones, etc.).

Traffic calming techniques have proven to be a viable option for residential traffic operations.

Designers should evaluate high speed compatibility with safety (pedestrians, driveways, parking, etc.) for urban arterials.

Course Summary

The geometric design of roadways involves the specifying of cross sections, vertical alignments, horizontal alignments, and various other design details.

The following are some design highlights to consider when laying out a roadway alignment:

- A standardized cross sectional arrangement for tangent horizontal alignments, are specified by most design organizations.
- Vertical alignment consists of vertical tangents and parabolic vertical curves.
- Maximum grades for vertical tangents are determined based on the effects of vehicle

power/weight ratios on speeds on various grades. Both the length and steepness of the grade are important.

- Minimum grades for highways should be determined based on drainage requirements.
- Minimum lengths of vertical curves are determined based on sight distance, comfort, or appearance criteria.
- Horizontal alignment consists of horizontal tangents; circular horizontal curves; and, in some cases, spiral transition curves.
- Superelevation (or banking of curves) is used to counteract centrifugal forces developed when a vehicle is driven on a curve.
- Maximum and minimum superelevation rates are limited by the need to prevent slow moving vehicles from sliding to the inside of the curve, maintaining the predictability of the driving experience, and also the need to prevent various vehicular crash scenarios due to the effects of centrifugal forces.
- Minimum horizontal curve radii are limited by maximum superelevation rates, and by relationships between various roadway features such as: design speed, superelevation rate, curve radius, sight distances and also by aesthetical considerations.
- Spiral transition curves, when used, will coincide with the superelevation transition. In the case of railways they are required for reasons of vehicular dynamics, while in highway design they are used primarily for aesthetical reasons.
- Coordinating the horizontal and vertical alignment design is important for reasons of aesthetics, economics, and safety.
- (CAD) software packages are now almost exclusively used when designing a roadway, with Geopak from Bentley being the most commonly used by state DOT's.
- These 3-D modeling programs, though very expensive, allow for the rapid design of all three components simultaneously, with the ability to visualize the road corridor within a 3-D model view or perspective, while continually upgrading the necessary production drawings as the model is revised.

Bibliography

Sources for this course:
Much of this course is based on the principles which are illustrated in Chapter 2 (Road Surveying), and Chapter 3 (Curves) of the US Army Corp of Engineers (USACE), **Field Manual (FM-5-233), titled "Construction Surveying"**. This is a field manual that covers the standards, methodologies and key elements of construction surveying, used by the US Army to teach surveying skills to military surveyor personnel.

Various **Wikipedia** pages: including "Geometric Design of Roads"

AASHTO's "A Policy on Geometric Design of Highways and Streets", 6th Edition, 2011: Which is more commonly referred to as the "Green Book"

GDOT Design Policy Manual: Released 1/20/2017