Sight-Distance Design for Curved Roadways with Tangential Intersections

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The intersections created by the projection of a minor road from the tangent of a major road at a curve allow drivers to make an unusual form of left-turn movement and engender some operational patterns that may lead to difficulties in assigning right-of-way. These curved-tangential intersections appear to be more common on secondary or local rural roads, but they are not confined to those settings. Special design issues may arise at these skewed intersections at the beginning or end of the curve. Horizontal sight restrictions and middle ordinate values that would define an adequate line of sight through a curve are considered. At locations where curved roadways intersect with tangential roadways, using stopping sight distance alone to evaluate the adequacy of sight distance around the curve does not appear to be sufficient; a sight distance adequate for stopping may not satisfy intersection sight needs. Current intersection sight-distance design criteria may not fully address the operational behaviors found at these curved intersections. After relevant issues and special needs are considered, conceptual design criteria for intersections of curved roadways with projecting tangential roadways are developed. An example application of the method indicated that this intersection type needs a much larger roadside area clear of sight obstructions than that required solely by criteria for stopping sight distance. These intersections with projecting tangential roads at curves will require more attention when new projects are designed and when old roads are retrofitted.

This paper examines the peculiar design issues found at locations where the major roadway is curved and minor roads extend or project from the tangents, creating intersections with some unusual turning movements and right-of-way assignments. These intersections seem to be more common on secondary or local rural roads, but they are not confined to such settings.

The discussion begins with a listing of developments that have contributed to the existence of these peculiar intersections on curved highway sections. Second, the paper briefly reviews current design criteria that address certain aspects of intersections on curves. Then the text discusses how these intersection alignments create special sight-distance requirements that current practices may not address. Finally, the article explains a conceptual approach that would address design needs at intersections of curved roadways with tangential roadways.

BACKGROUND

Roadway alignments do not always follow a straight path or route from Point A to Point B. Obvious reasons for deviating from tangent alignments and incorporating horizontal curvature are to avoid rough terrain and to change the direction of the roadway. Political and social history have also influenced the layout of roads.

Political and Social Factors

The rural road alignments in many parts of the United States are a legacy of the Land Ordinance of 1785 (*1*, p.74). This law implemented the grid system of property boundaries and called for 1 mi^2 (640 acres) sections of land. Each section was further subdivided into square or rectangular fractional sections, which at 40 to 80 acres were of a more suitable size for a family farm of that era. As settlers occupied the new lands, the wagon roads often straddled the boundaries of the sections and the fractional sections. This was especially true in areas in which the terrain was relatively flat.

As the decades passed, some towns in the new lands thrived and others vanished. Farmers purchased the adjoining tracts of their neighbors, thus increasing the size of farms. The automobile replaced the wagon, and the county or state paved some rural roads. The major routes connecting the principal towns and the routes with the heavier volumes may not have followed the straight line of a continuous section-line boundary. Instead, the newly paved routes sometimes meandered along stairstep or "dogleg" alignments. For instance, a northward-running route might be superimposed on a north-south boundary for a distance, then turn 90 degrees to the east and follow an east-west boundary for a quarter-mile, then turn back 90 degrees to the north and follow another north-south boundary parallel to the initial one.

Resulting Roadway Pattern

The present roadway system, especially in the Midwest and Great Plains regions, sometimes reflects patterns from an earlier era. When roads follow the stairstep routes, a horizontal curve may connect the alignments of two intersecting legs. This creates a unique intersection. The major route alignment proceeds around the curve, but minor roads that project from one or both tangents to the curve intersect the curve near the point of curvature (PC) or the point of tangency (PT). The minor and major routes intersect at a very flat angle.

Oriented a certain way, the intersection layout takes on the appearance of the number 4. Figure 1 diagrams one of these "4-intersections."

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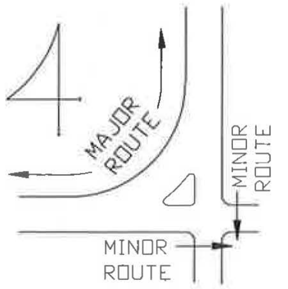

FIGURE 1 Diagram of intersection of curved with tangential roadway.

Table 1 shows a count of intersection types in two predominantly rural counties. The count was taken from 1980's county road maps, which show most roads except city and subdivision streets. Each intersection appearing on the maps was categorized. Because of the scale of the map and absence of on-site inspection, a small fraction of the intersections probably were incorrectly categorized. One of the counties is in a hilly region divided by a sizeable lake and has a land area of 720 mi^2. The other county is flat and has 1,019 mi^2 of land area. The table includes Y- and X-intersections because they can exhibit some of the same operational traits that curved-tangential intersections do.

REVIEW OF RELEVANT DESIGN CRITERIA

Many aspects of design affect curved-tangential roadway intersections. These aspects include stopping sight distance, intersection sight distance, and curved intersection design.

Existing Horizontal Sight-Distance Design

To be able to stop before striking an object in the road ahead, the motorist needs an unhindered line of sight around the curve for a certain distance ahead of the vehicle. In geometric terms, the middle ordinate, measured from an arc in the center of the inside traffic lane to the line of sight, must meet or exceed a minimum value, and the area up to this sight line must be free of objects that restrict vision around the curve.

A comparison of horizontal curve sight-distance design criteria shows that the 1990 AASHTO Green Book (*2*) has deleted some of the wording contained in the 1965 Blue Book (*3*) pertaining to sight obstructions that the engineer may need to address. The 1965 book reads, "Where there are sight obstructions—walls, cut slopes, wooded areas, hedgerows, high farm crops, guardrail under certain conditions, etc.—on the inside of curves, design to provide adequate sight distance. . . ."; the 1990 version reads, "Where there are sight obstructions (such as walls, cut slopes, buildings, and longitudinal barriers) on the inside of curves, a design to provide adequate sight distance. . . ." A comparison of the two shows that references to vegetation have been deleted, but the general intent appears to have changed little.

The 1965 Blue Book presents equations and one figure, Figure III-13, to determine the needed middle ordinate to the line of sight around a horizontal curve. The figure is based on the need to provide adequate stopping sight distance (SSD), not passing sight distance. The formulas apply only to circular curves longer than the needed sight distance. Chapter III of the 1990 Green Book discusses horizontal curve sight distance for stopping and for passing, but it emphasizes stopping sight distance. The 1990 version presents two figures, III-26A and III-26B. Figure III-26A is based on the "lower range" of stopping sight distances from Table III-1; these lower SSDs in turn assume a vehicle speed less than design speed. Figure III-26B is similar to Figure III-13 from 1965.

In a 1991 paper, Easa discussed horizontal curve sight issues (*4*). The paper included a method to evaluate sight distance when the circular curve length was less than the sight distance.

Existing Vertical Curve Sight-Distance Design

Likewise, the motorist needs a sufficient line of vision over the crest of a vertical curve, and the concept of sight-distance design criteria for vertical curves is well established. These criteria consider the resulting available line of sight, based on the height of driver's eye and the height of the object being viewed ahead in the roadway. Hall and Turner have discussed the evolution of design criteria for stopping sight distance (*5*).

Parameters for passing sight distance have also changed over time. The height of a vehicle ahead that the driver needs to see in order to judge passing distance has been lowered.

Existing Intersection Sight-Distance Design

The basic intersection sight-distance criteria were formulated in 1940. The parameters have been modified to reflect changes in the driver and the vehicle [NCHRP Research Project Statement, Project 15-14(1), FY 1992]. The fundamental concept is to provide the driver with a line of sight sufficient to see oncoming traffic and safely cross or pull into the traffic stream. Intersection design criteria have concentrated on the minor-road traffic attempting to cross or enter the major road; they have not been as concerned with the needs of those turning left from the major road. The standard value for the time needed by the driver at an intersection to perceive and evaluate options before acting is 2 sec (*2*).

TABLE 1 Intersection Types Found in Two Counties

Intersection type	4	Y	X	all
Hilly county	39 (4.2%)	73 (7.8%)	7 (0.8%)	930 (100%)
Flat county	36 (3.4%)	10 (0.9%)	5 (0.5%)	1069 (100%)

Note: Intersection type "4" denotes curved-tangent roadway intersection

Existing Curved Intersection Design

Chapter IX of the 1990 Green Book briefly mentions curved intersection design issues. Beginning on page 687, the text states,

> Where the major highway is curving and a subordinate highway constitutes an extension of one tangent, realigning the subordinate highway is advantageous, as shown in Figure IX-9E, to guide traffic onto the main highway and improve the visibility at the point of intersection. This practice may have the disadvantage of adverse superelevation for turning vehicles and may require further study when curves have high superelevation slopes and when the approach road has adverse grades and a sight distance restriction due to the grade line. (*2*)

Need for Additional Criteria

Current Green Book design guidelines address stopping sight distance around horizontal curves and vertical curves. Some of the intersection sight-distance needs for vehicles on side streets attempting to cross or turn into the major street are addressed. The sight-distance requirements for a vehicle on the major road turning left are not fully addressed. The recent NCHRP research project statement for study of intersection sight-distance issues recognized the need for study of design criteria for left turns made from the major roadway [Project 15-14(1), FY 1992].

The evolution of land development patterns and the resulting stairstep road alignments have allowed curved and tangential roadways to intersect. These intersections combine aspects of two distinct roadway components: horizontal curvature and intersections. When an intersection is superimposed on a horizontal curve, operational problems can result that neither a curve nor a normal intersection alone would create.

Using only stopping sight distance to evaluate the adequacy of sight distance around curves does not appear to be sufficient when projecting roads intersect with the curved road, because intersection sight needs may not be addressed. Current intersection sight-distance design criteria may not fully address the factors found at these curved intersections. Before developing conceptual design criteria for projecting-road intersections, their peculiar issues and needs should be considered.

DESIGN ISSUES

Examining the geometry and operational patterns at curved-tangential roadway intersections will help explain the relevant design issues.

Geometry at Curved-Tangential Roadway Intersections

When the through or major route does not continue straight but instead curves, the tangential routes projecting or extending from major approaches become minor approaches. Traffic on the major route approaches the horizontal curve from two directions: from one perspective the alignment curves to the right; from the other, it curves to the left.

For the driver approaching the leftward curve, making what is technically or operationally a right turn is in reality a straight-ahead maneuver; there is little or no turning of the vehicle. For the driver approaching from the other direction (the rightward curve), making a technical left turn is also a straight-ahead maneuver.

Operations at Curved-Tangential Roadway Intersections

It would seem that a curved-tangential roadway intersection creates a number of movements and right-of-way priorities that are more of a challenge to the motorist than the normal 90-degree intersection is. Figure 2 shows four cases involving vehicles turning from the major route onto the minor route.

- *Case 1.* Approaching the leftward curve, the driver turns right—The driver turning right in fact proceeds nearly straight ahead, perhaps negotiating some abrupt change of roadway surface slope at the intersection, if the curve to the left is highly superelevated. This maneuver tends to be a high-speed exit from the major road onto the minor road.
- *Case 2.* Leaving the leftward curve, the driver turns right—The driver is turning in a direction over his or her right shoulder, making almost a U-turn. The driver is not required to yield to other major road movements.
- *Case 3.* Leaving the rightward curve, the driver turns left—The driver must make a near U-turn over the left shoulder. The nature of the maneuver and roadway alignment should clue the driver to yield the right-of-way to oncoming vehicles about to enter the major route curve.
- *Case 4.* Entering the rightward curve, the driver turns left—As in Case 1, the driver on the major road wishes to enter the minor road and is offered a tempting straight, high-speed exit. However, the Case 4 drivers do not have the right-of-way, because they are supposed to yield to the oncoming traffic following the major road curve. The driver wishing to go left encounters a somewhat unnatural situation. This driver is on the major route and wants to proceed straight ahead but is supposed to yield to oncoming traffic from around the curve.

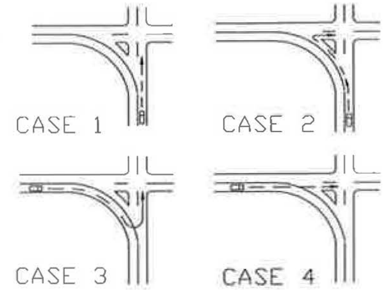

FIGURE 2 Four cases of vehicles turning from major route.

FIGURE 3 Vehicle making a Case 4 movement.

Case 4, which tends toward violating subtle driver expectation, needs further discussion. Drivers turning left at intersections usually make the maneuver from a stop or at low speed. Observations of Case 4 drivers reveal that many of them do not come to a near or full stop. Although the maneuver is operationally a left turn, many Case 4 drivers proceed at or near running speed. Figure 3 is a photograph of a Case 4 maneuver.

EXAMPLE FOR ILLUSTRATION

Design criteria for Case 4 can be developed by using an illustrative example and then analyzing operational requirements. Because of the many distances and terms employed, Table 2 has been included as an aid for the reader.

A two-lane road with 35-mph speed (V) will be used to calculate the middle ordinate to define an adequate line of sight on the basis of stopping sight distance. In this example, all lanes widths (w) will be 12 ft. Many of the curved-tangential roadway intersections found on secondary or local roads have narrower pavements. The example pavement is crowned in the center, sloping down toward both edges with a ¼-in./ft crossfall. The chosen design vehicle is a passenger car with boat trailer (PB), which is 42 ft long. The PB was chosen because rural traffic may consist of recreational traffic or pickups with short trailers. Using this design vehicle provides a small margin for the passenger car with no trailer.

The minimum centerline radius (R_{CL}), on the basis of rural side friction values from the 1990 Green Book, is

$$R_{CL} = V^2/[15 * (f + e)] = 35^2/[15 * (0.15 - 0.0208)]$$

$$= 632 \text{ ft}$$

TABLE 2 Selected Symbols and Abbreviations

SYMBOL	MEANING
Δ_{INT}	central angle of the arc from the P.C. to the clear point
$\Delta_{PC\text{-}ON}$	central angle of the arc from the P.C. to the initial position of the oncoming vehicle
$C_{CP\text{-}ON}$	distance along the centerline arc from the clear-point radial to the radial at the initial position of the oncoming vehicle
$C_{PC\text{-}CP}$	distance along the centerline arc from the P.C. to the clear point radial
$C_{PC\text{-}ON}$	distance along the centerline arc from the P.C. to the radial at the initial position of the oncoming vehicle
$D_{EP\text{-}PC}$	distance from the evaluation point to the P.C.
D_{MAR}	distance from the driver to the front bumper, plus a small margin
$D_{NON\text{-}Y}$	total distance traveled by a non-yielding vehicle, from beginning of perception-reaction time to clearing the oncoming traffic
$D_{PC\text{-}CP}$	distance from PC to clear point radial
D_{SEC}	secant length
L_{VEH}	length of vehicle
M_{ADJ}	adjusted middle ordinate for intersection sight distance
M_{SSD}	middle ordinate for stopping sight distance
R_{CL}	radius at centerline
R_{IN}	radius at center of inside lane
SD	stopping distance
t_{PR}	perception-reaction time
W	road width
w	lane width

Many of these rural curves have central angles (Δ) ranging from 45 to 90 degrees, so it is reasonable to assume that the horizontal curve length exceeds the needed stopping sight distance. The wet-pavement stopping distance (SD) on level pavement is

$$SD = 1.47\ V^2/[30 * (f \pm g)] = 248.4 \text{ ft}$$

The needed line of sight to provide stopping sight distance can be defined by the value of the middle ordinate (M_{SSD}) measured from the line of sight of the arc along the center of the inside lane. The radius of the arc in the center of the inside lane is R_{IN}.

$$R_{IN} = R_{CL} - w/2 = 632 - 6 = 626 \text{ ft}$$

$$M_{SSD} = R_{IN} * [1 - \cos(28.65\text{SD}/R_{IN})] = 12.3 \text{ ft}$$

This clear distance from the center of the inside lane, M_{SSD}, must be maintained on all parts of the curve that are a distance from the PC and PT equal to or greater than SD/2. For instance, if the length of curve (C) were exactly equal to SD, then M_{SSD} would need to be maintained only at the halfway point along the curve, because that would be the only point equal to or greater than SD/2 distance from both the PC and PT.

ANALYSIS

The analysis of Case 4–maneuver design needs must consider parameters for the stop-and-yield and for the proceed (no yield) situations. After developing a conceptual model of the sight-distance needs at a curved-tangential roadway intersection, the distance needed can be compared with distance actually provided when "regular" stopping sight distance criteria are used to define the limits of allowable horizontal sight restrictions along curves.

Several component concepts enter into this analysis. To identify the needed sight distance where the major road curves to the right and at the same place intersects with a projecting minor leg, the situation being analyzed will be first presented. Then the individual elements will be more fully described, one at a time.

Situation Analyzed

There are two roadways and two vehicles to consider. The major roadway consists of a tangent section entering into a curve to the right. The minor roadway projects from the major roadway tangent.

The actions of the drivers and the vehicles can be viewed as a three-step process. First, the driver who is about to enter the curve and make a technical left turn (i.e., follow the tangent instead of the curve) evaluates the advisability of proceeding. Second, the driver either stops or proceeds. Third, the oncoming driver, who has the right-of-way, approaches the intersection. Figure 4 shows a Case 4 vehicle in the left foreground yielding to an oncoming vehicle coming around the curve on the major road.

FIGURE 4 Case 4 vehicle yielding to oncoming vehicle.

- *Step 1.* The driver who is about to enter the curve and wishes to make what is technically a left turn must evaluate the adequacy of the gap (or lag) in traffic coming around the curve. This problem has elements of "intersection sight distance," one major difference being that the gap evaluation may be made while traveling at or near running speed, not while stopped. The point at which the driver begins to evaluate the options (or where t_{PR} begins) defines one end of the needed line of sight.
- *Step 2.* The driver of first vehicle decides either to yield to oncoming traffic or to proceed. Because the first vehicle may be traveling at running speed, the situation has elements of the signalized intersection "dilemma zone" problem, in that past a certain point, the vehicle is so close to the PC that it cannot stop without crossing the centerline and occupying the path of the oncoming vehicle. Once past the dilemma point, the left-turning vehicle needs to be able to continue in motion, cross the centerline, and clear the path of the vehicle coming around the curve. Step 2 is really two options: either 2*a*, the driver stops after rejecting the available gap, or 2*b*, the driver accepts the initial gap and proceeds without stopping. If the first vehicle chooses to proceed and crosses the centerline, then that vehicle must be able to continue and cross the entire oncoming lane. The point that this vehicle must reach may be referred to as the "clear point." For the geometric analysis, the clear point will be placed at the intersection of the right side of the right lane with the arc at the outside of the major roadway.
- *Step 3.* The oncoming vehicle, traveling around the major road curve, is approaching the point at which its path intersects the path of the first vehicle. The second or oncoming driver has the right-of-way. The distance traveled by the second vehicle during the total elapsed time of Steps 1 and 2*b* defines the other end of the needed line of sight.

Element 1: Detailed Geometry at Intersection

An analysis of the intersection geometry shown in Figure 5 will lead to the determination of the distances and travel times across the intersection. The angle between the PC radial line and the radial passing through the clear point is Δ_{INT}.

$$\Delta_{INT} = \arccos\ (1 - W/R_{OUT})$$

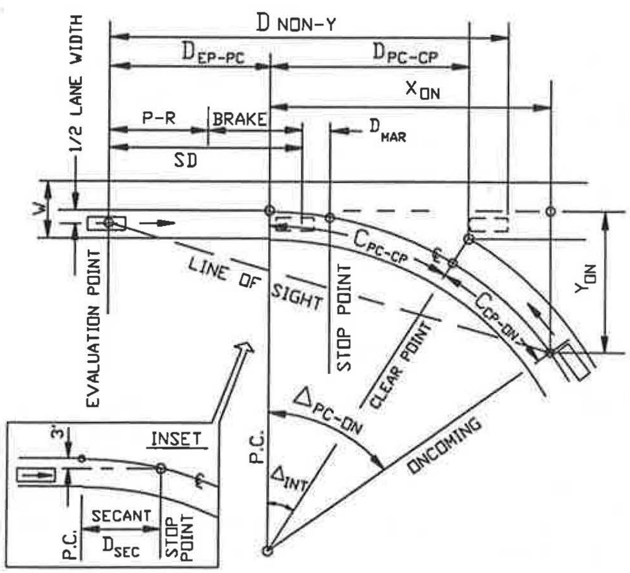

FIGURE 5 Detailed geometry and stopping dimensions.

where W is the pavement width and R_{OUT} is the radius of the outside of the curve. Using the 35-mph example, W = 24 ft, R_{OUT} = 644.25 ft, and Δ_{INT} = 15.6882 degrees.

Element 2: Distances When Vehicle Yields

The driver intent on making the "technical" left turn may determine that it is not safe to proceed and then yield and stop. This driver will be allowed 2.0 sec of intersection perception-reaction time (t_{PR}) to evaluate the adequacy of gaps in the oncoming traffic stream.

Assume that the vehicle is positioned so that its left edge is 3 ft to the right of the centerline. The decelerating vehicle can pass the PC and does not have to stop until the left front corner of the vehicle is about to cross the centerline. This stop point is defined as the intersection of the centerline curve with a straight line offset 3 ft to the right of the centerline. The straight distance from the PC radial to the stop point will be called the secant distance; it is

$$D_{SEC} = 6 * R_{CL} - 9$$

The distance from the "begin evaluation" point to the PC is

$$D_{EP-PC} = SD + D_{MAR} - D_{SEC}$$

The D_{MAR} term is added to allow a small margin and to account for the distance from the front bumper to the driver. The distance from the evaluation point to the stop point (D_{EP-SP}) is the stopping distance plus the 10-ft margin, or

$$D_{EP-SP} = D_{EP-PC} + D_{SEC}$$

In the 35-mph example, the distance needed to stop on wet pavement is

$$SD = 1.47\ V\ t_{PR} + V^2/(30 * f) = 102.7 + 120.1$$

$$= 222.8 \text{ ft}$$

where V is the initial velocity. Other distances are D_{SEC} = 61.5 ft, D_{EP-PC} = 171.2 ft, and D_{EP-SP} = 232.8 ft.

Element 3: Distance and Time If Vehicle Does Not Yield

The total distance that a nonyielding vehicle must travel in the face of oncoming traffic is the distance from the evaluation point to the clear point.

$$D_{NON-Y} = SD - D_{SEC} + D_{MAR} + D_{PC-CP} + L_{VEH}$$

The distance traveled and elapsed time during perception-reaction remains the same for the yield and the nonyield cases. For the nonyielding driver, the assumed distance traveled after t_{PR} is the sum of the braking distance and the 10-ft margin (D_{MAR}) less the secant distance (D_{SEC}), the distance from the PC to the clear point (D_{PC-CP}), and the vehicle length (L) (this is not entirely correct if the distance covered during t_{PR} places the vehicle past the PC).

The total elapsed travel time will be the perception-reaction time plus the time to traverse the distance from the end of perception-reaction to the clear point. The total travel time is affected by any rate of acceleration of the vehicle. The intersecting pavement surfaces at some of these intersections on curves have abrupt changes in crossfall; this warping may discourage higher acceleration rates at some locations.

In the 35-mph example, the distance traveled during the 2-sec t_{PR} is 102.7 ft, and the remaining distance traveled to clear the intersection is 284.8 ft. Allowing a 3-ft/sec^2 acceleration rate, the time to traverse the remaining distance is 4.9 sec. The total elapsed time from the moment the driver is at the evaluation point until the vehicle is clear of the oncoming lane is 6.9 sec.

Element 4: Distance and Time of Oncoming Vehicle

As measured around the curve, the total distance from the evaluation point to the oncoming vehicle's initial position (when the left-turning vehicle is at the evaluation point) is the sum of the distance from the evaluation point to the PC (D_{EP-PC}), the distance along the centerline arc from the PC to the intersection of the radial to the clear point (C_{PC-CP}), and the distance along the centerline arc from the clear-point radial to the initial position of the oncoming vehicle (C_{CP-ON}). During the total elapsed time of 6.9 sec in the example, the oncoming vehicle travels 352 ft at 35 mph.

Element 5: Resulting Line of Sight and Middle Ordinate

If the first driver accepts the gap and proceeds instead of yielding, the driver must be able to see far enough around the curve to detect those oncoming vehicles close enough to cause a collision at the intersection. The distance around the curve that the driver should be able to see is a function of the time that it takes the driver to proceed and completely cross the oncoming lane, which in turn is a function of the distance that the vehicle must traverse.

The straight line, or chord, from the evaluation point to the point of the oncoming vehicle's initial position defines the needed line of sight for operation of curved-tangential roadway intersections. When evaluating stopping sight distance around a curve, the line of sight is normally measured from the center of the inside lane, not from the center of the roadway. This analysis of curved intersection sight distance kept the driver's position at the center of the inside lane, but it placed the other end of the line of sight at the roadway centerline adjacent to the oncoming vehicle.

If the arcs of the curved roadway are part of a circle with center at coordinates (0, 0), and the radial defined as the PC is also the y-axis, then the x, y coordinates of the centerline PC will be $(0, R_{CL})$. The coordinates of the evaluation point will be the pair $(-D_{EP-PC}, R_{IN})$.

Adding the lengths of two arcs along the centerline (from the PC to the radial passing through the clear point, C_{PC-CP}, and from the clear-point radial to the initial position of the oncoming vehicle, C_{CP-ON}) will lead to a central angle calculation.

$$\sum \text{arc lengths} = C_{PC-ON} = C_{PC-CP} + C_{PC-ON}$$

$$\Delta_{PC-ON} = C_{PC-ON} * 5729.58/(R_{CL} * 100)$$

These calculations supply values needed to find the x- and y-axis components of distance from the PC to the oncoming vehicle initial position. This leads to identification of the coordinates of the oncoming vehicle initial position (as projected to the centerline). The component distances along the axes are

$$X_{ON} = R_{CL} * \sin \Delta_{PC-ON}$$

and

$$y_{ON} = R_{CL} - R_{CL} * \cos \Delta_{PC-ON}$$

The x, y coordinates of the initial position of the oncoming vehicle are $(x_{ON}, R_{CL} - y_{ON})$.

After defining the two ends of the needed line of sight, the point on the arc along the center of the inside lane (x_{MADJ}, y_{MADJ}) that is at the maximum distance from the sight line can be found, because defining the two ends of the sight line permits calculation of the line's slope. Taking the derivative of the equation of the circle and setting it equal to the slope permits one to solve for the x-coordinate of the point on the arc farthest from the line of sight.

$$dy/dx = -x/\sqrt{r^2 - x^2}$$

Substituting the known radius and x-coordinate values into the equation of a circle will produce the y-coordinate value.

Once the point's coordinates (x_{MADJ}, y_{MADJ}) are determined, the distance from the point to the line of sight can be found.

$$M_{ADJ} = |\, m x_{MADJ} - y_{MADJ} + b \,|\sqrt{m^2 + 1}$$

where m is the slope and b is the y-axis intercept of the line of sight. The needed line of sight can be compared with the line of sight available when stopping sight distance around the curve is the controlling design factor.

In the 35-mph example, $\Delta_{PC-ON} = 47.59$ degrees and the slope of the sight line was -0.3132. The middle-ordinate distance from the center of the inside lane to the line of sight for intersection sight distance was almost 80 ft, compared with the normal stopping sight distance of $M_{SSD} = 12.3$ ft.

Other Design Considerations

Other related issues should be considered in the evaluation of design needs at curved-tangential roadway intersections. For instance, if a vehicle approaching a rightward curve encounters a downhill grade, the stopping distance will be longer, which in turn requires a more generous line of sight. A thorough analysis would also have to consider intersection sight-distance requirements for the driver who yielded to oncoming traffic and stopped and then needed enough time for perception-reaction and for acceleration from stop to cross the lane of oncoming traffic.

Choice of design vehicle can affect the results of the analysis. This analysis used a passenger car with a boat trailer. The braking distance and sluggish acceleration capabilities of trucks and other larger vehicles may impose even more stringent requirements.

In addition to needed horizontal curve sight distance, the designer must examine crest vertical curve limitations. A vertical curve based on passing-sight-distance object heights would be appropriate and would allow shorter vertical curves than those called for by stopping-sight-distance object heights. But the use of the curved-tangential sight distances developed herein, instead of stopping sight distances, would act to lengthen the required crest vertical curve.

Variations of the layouts described may place the actual intersection well within the limits of the curve. A vector analysis of braking behavior suggests that less friction is available for stopping within the limits of a curve (*6*). The reduced braking abilities would effect greater middle-ordinate values.

This analysis assumes that the driver who must yield can correctly estimate the point at which braking must begin in order to stop the vehicle in time, or else the vehicle must proceed to cross the oncoming traffic stream. An overestimation of the needed braking distance may cause the driver to proceed even though there was still distance to bring the vehicle to a stop before the vehicle crossed the centerline into the path of oncoming traffic. This behavior could increase the needed minimum horizontal sight distance.

Those studying intersections of curved-tangential roadways may note that drivers who determine the last-moment need to yield can steer so that the vehicle comes to a stop as it travels around the curve. However, some drivers may resist the obvious solution of staying on the main curved roadway once they have committed to proceeding onto the projecting tangential roadway. One reason is that staying on the curved road causes the driver to overshoot the desired turnoff point.

This conceptual approach is tentative. It may need modification when more is known about the actual operating traits, such as approach speeds and perception-reaction times, at these locations. The following factors may mitigate the potentially undesirable impacts of these sight deficiencies:

1. Lower volumes on many of these roads may decrease the chances of vehicles' being in critical positions with respect to each other at the same time. Although one might assume random arrival patterns to simulate conflict probabilities, a study of actual accident frequencies as a function of volume would provide a better means of determining when volumes are sufficiently low to make the potential problem insignificant.
2. Drivers may sense the potential problems and be more alert, and thus exhibit decreased perception-reaction times.
3. Drivers may slow down upon approaching these intersections and thus need less sight distance.
4. Upon seeing each other, one or both drivers may greatly increase or decrease their approach speeds, providing a greater margin to avoid collision.

On the other hand, as compared with a normal 90-degree intersection, drivers at these curved intersections may have more difficulty judging whether there is an acceptable gap in oncoming traffic through which to proceed. Contributing to this difficulty would be the relative position of oncoming cars (approaching each other from around a curve instead of from straight ahead), and the left-turning driver evaluating the gap while moving, not stopped. Field studies are needed to identify correctly the input design values, such as approach speed, to use in developing design criteria.

COMMENTS AND CONCLUSION

The "normal" criteria may provide a line of sight necessary to maintain stopping sight distance at curved-tangential roadway intersections but not enough sight distance for the turning maneuvers that occur at these intersections. Drivers approaching curves to the right, where the minor road projects straight ahead, may want to make what is operationally a left turn at running speed. The drivers at such intersections need sufficient sight distance to perceive oncoming cars and either stop or safely cross the left lane before the oncoming car arrives.

Considerations for Implementation

It would require a major land acquisition, demolition, and vegetation removal effort to provide greater sight distance at the many locations at which curved roadways intersect with tangential roadways. Unless a location has an accident history, the costs of remedial actions may be difficult to justify. When remedial actions are needed, possible actions to address the situation include

1. Removing obstructions to improve the line of sight for the driver;
2. Providing a separate, sheltered left-turn bay for traffic on the approach where the major road curves to the right and the projecting tangential road veers to the left;
3. Realigning the intersection so that the minor road will not project along a tangent from the major; and
4. Requiring motorists making the left turn onto projecting roads to come to a stop before turning left.

At some locations the first remedy may be impractical because a very large visually unobstructed zone would be needed. Fences, fields, parking lots, and buildings occupy needed space in many situations. However, at other locations the highway agency may have to purchase additional right-of-way in order to provide greater sight distances. The second and third remedies might give left-turning drivers a greater sense of performing a minor movement and reinforce the need to yield. They could also encourage them to slow as they maneuver into the turn bay. The fourth opinion may require unrealistically high levels of enforcement and driver education.

Closing

The evolution of land development patterns and traffic operations chacteristics have created a demanding intersection design problem. These curved roadways with tangential intersections will require more attention when new roads are designed and existing roads are retrofitted.

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