ALIGNMENT COORDINATION IN HIGHWAY DESIGN

Bob L. Smith, E. E. Yotter, and J. S. Murphy,
Kansas State University

The purpose of this research was to study the coordination of horizontal and vertical elements of highway alignment in order to provide some definitive guidelines for the highway designer. The technique of plotter-drawn perspectives was used in this study. A battery of computer programs was developed that provided a means of rapidly and economically producing perspective drawings of a proposed or existing roadway. The programs provided for the computation of highway alignment and space coordinates, the perspective picture plane coordinates, and a "plot" program, all with the observer (eye location) at any arbitrarily selected location. The capabilities of the computer program are described in detail. A large number of perspective drawings were made for a detailed study of the coordination of vertical and horizontal curves as well as for the study of the visual appearance of spiral curves.

• THE PURPOSE of the research described in this report was to study the coordination of horizontal and vertical elements of highway alignment in order to provide some definitive guidelines for the highway designer.

Cron (1), Pushkarev (2), and Smith (3) speak of problems of fitting the highway to the landscape, of the visual quality of the highway, and of the visual discontinuities that have occurred in many of the existing highways. They all point to a common problem: How can the designer "see" his 2-dimensional (plan-profile) design as a 3-dimensional finished product? Recent research by Smith and Yotter (4, 5) has shown conclusively that electronic plotter-drawn perspectives of the roadway are a highly versatile and valuable tool in attacking the problem of actually accomplishing good visual design.

In view of the experience with plotter-drawn perspectives, the authors decided to use the technique to accomplish the objectives of this research. A battery of computer programs was developed that provided a means of rapidly and economically producing perspective drawings of a proposed or existing roadway. The programs provided for the computation of highway alignment and space coordinates, the perspective picture plane coordinates, and a "plot" program, all with the observer (eye location) at any arbitrarily selected location. The capabilities of the computer program are described in detail in another report (6).

COORDINATION OF HORIZONTAL AND VERTICAL ALIGNMENT

One of the well-recognized visual-design problems is that of combining horizontal and vertical curves so they present an alignment that is smoothly flowing visually. It is nearly impossible for the designer to visualize the real 3-dimensional curve by studying the horizontal and vertical alignments as they are shown on the plan-profile sheets. In order to aid the designer in his task, this study was made by using perspective drawings of various combinations of sag vertical curves and horizontal curves.

The geometry of the study alignment was as follows: Single roadway, 24 ft in width; and observer position, 4 ft left of roadway centerline and 3.5 ft above roadway surface.

Sponsored by Committee on Operational Effects of Geometrics.

The sighting distance, S, from the observer to the midpoint of the vertical curve varied. The total change in horizontal direction, Δ, was 3 deg 14 min right. For the vertical alignment the grade of the back tangent, g_1, was -0.77 percent, and the forward tangent grade, g_2, was +1.53 percent, giving a total change of grade, A, of 2.30 percent.

The effects of the displacement of PI's of horizontal and vertical curves, length of curve relationships, and observer position were studied by varying these elements as follows:

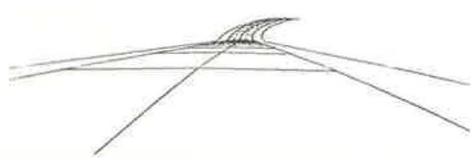
1. The PI's coincided, the vertical curve PI was located 250 ft ahead of (prior to) the midpoint of the horizontal curve, and the vertical curve PI was located 500 ft ahead of the midpoint of the horizontal curve;
2. Lengths of horizontal curve of 970, 2,000, and 3,000 ft were each combined with vertical curve lengths of 800, 1,000, 1,500, and 2,000 ft; and
3. For each combination of PI separation and curve length, the observer's location was set so that sighting distances of 2,400, 1,900, 1,400, and 900 ft were obtained (S was taken as the distance from observer to the PI of the vertical curve).

Figures 1 through 9 are perspectives selected from the 132 drawn for this particular study.

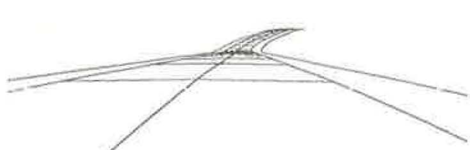
Figure 1 shows perspectives with a sight distance of 2,400 ft; the length of horizontal curve, L_H, is 970 ft, and the length of vertical curve, L_V, is 800 ft. Figure 1a shows a PI separation of 500 ft (PVI is 500 ft nearer the observer than is the PI of the horizontal curve). In this case the PC of the horizontal curve and the PVI nearly coincide. According to Pushkarev (2), "The vertical alignment is shifted half a phase with respect to the horizontal alignment." In this case the beginning of the vertical curve precedes or leads the horizontal curve by about 415 ft. There is a sharp break or discontinuity in the left edge of the roadway and in the trace of the centerline. Figure 1b shows a PI separation of 250 ft, and the alignment is shifted about ¼ phase. The vertical curve leads the horizontal curve about 165 ft. There is a sharp break in the left edge of the roadway although not so sharp as that shown in Figure 1a. Figure 1c shows the same 2 curves with the PI's coinciding. These curves are "in phase." In this case the horizontal curve leads the vertical curve by 85 ft or about 10 percent of the curve length. There is a marked improvement in the smoothness of the left edge of the roadway.

Figure 2 shows the same curve as that shown in Figure 1a, but the observer is located at different sight distances. As the observer approaches the curve there is a noticeable smoothing of the left edge of the roadway. Figure 2d shows that, where the observer is only 900 ft from the PVI, the roadway appears quite smooth and flowing.

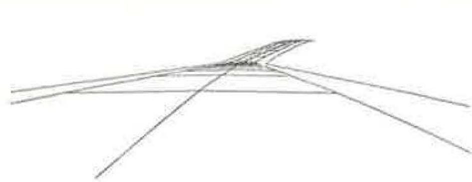
Figure 3 shows perspectives with S = 2,400 ft, L_H = 2,000 ft, and L_V = 800 ft and for PI separations of 500, 250, and 0 ft. All these perspectives show an apparent "hump" or slight inflection particularly in the left edge of the roadway. The centerlines show some discontinuity. The inflection shown in Figure 3a is somewhat less, and this is explained by the fact that the horizontal curve leads the vertical by 100 ft. The inflection shown in Figure 3c is due to the fact that the vertical curve is too short as compared to



A. No. 17101 PI-Sep. = 500'

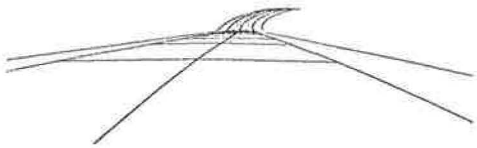


B. No. 17001 PI-Sep. = 250'

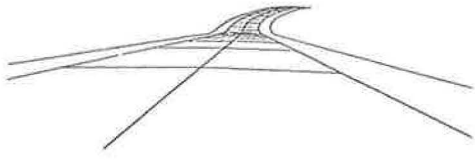


C. No. 17201 PI-Sep. = 0'

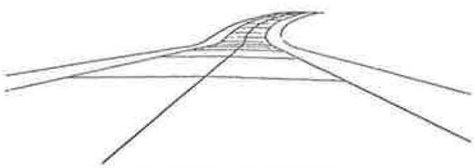
Figure 1. Perspectives for various PI separations, L_H = 970 ft, L_V = 800 ft, and S = 2,400 ft.



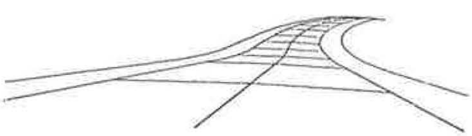
A. No. 17101 S = 2400'



B. No. 17102 S = 1900'

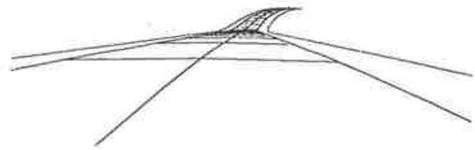


C. No. 17103 S = 1400'

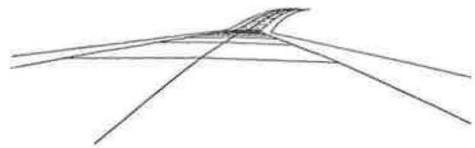


D. No. 17104 S = 900'

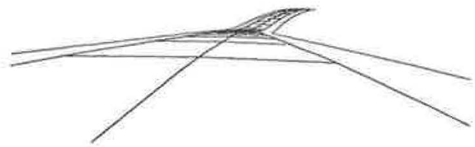
Figure 2. Perspectives for various sighting distances L_H = 970 ft, L_V = 800 ft, and PI separation = 500 ft.



A. No. 17105 PI-Sep. = 500'



B. No. 17005 PI-Sep. = 250'



C. No. 17205 PI-Sep. = 0'

Figure 3. Perspectives for various PI separations, L_H = 2,000 ft, L_V = 800 ft, and S = 2,400 ft.

the horizontal curve. If one were to approach the curve shown in Figure 3a from the right, an inflection similar to that shown in Figure 3c would be apparent.

Figure 4 shows a 3,000-ft (L_H = 3,000) horizontal curve and an 800-ft vertical curve with PI's coincident. The obvious inflection of the left edge of the roadway does not disappear until the observer is 900 ft from the PVI. The apparent inflection or reverse curvature is due to the fact that the vertical curve is much too short when compared to the horizontal curve. No amount of PI movement will solve this problem.

Figure 5 shows conditions quite similar to those shown in Figure 1. In this case the vertical curve, L_V = 1,000, is 30 ft longer than the horizontal curve. Figures 5a and 5b show curves shifted about $\frac{1}{2}$ and $\frac{1}{4}$ phases respectively and indicate very clearly that the vertical curve must not significantly precede the horizontal curve. Figure 5c shows that, where the vertical curve leads the horizontal curve by only 15 ft, no visual discontinuity is apparent.

Figure 6 shows perspectives with S = 2,400 ft, L_H = 970 ft, and L_V = 1,500 ft. The PI separations are 500, 250, and 0 ft. The inflection or discontinuity are shown in the left edges of the roadway in Figures 6a and 6b. The authors believe this is due to the fact that the vertical curve leads the horizontal curve in each case. A rather disconcerting discontinuity along the left edge of roadway is shown in Figure 6c, a case in which the PI's coincide. This can only be attributed to the fact that the vertical curve leads the horizontal or that, in this case, the vertical curve is significantly longer than the horizontal curve.

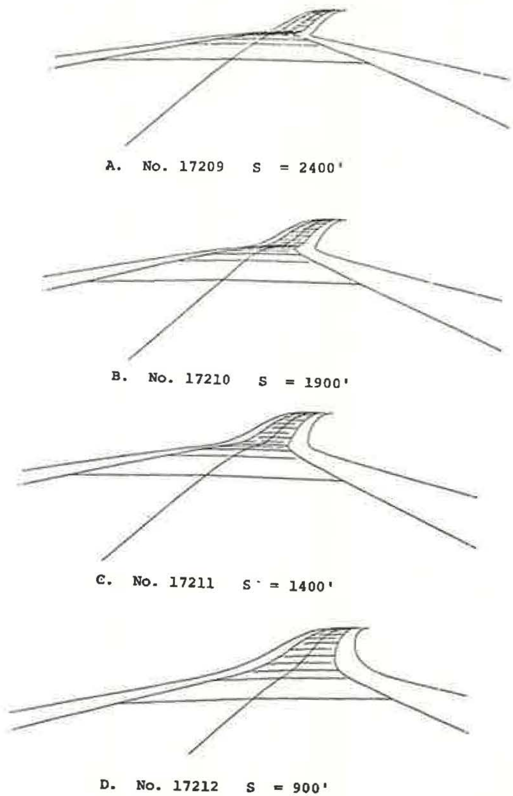


Figure 4. Perspectives for various sighting distances, L_H = 3,000 ft, L_V = 800 ft, and PI separation = 0 ft.

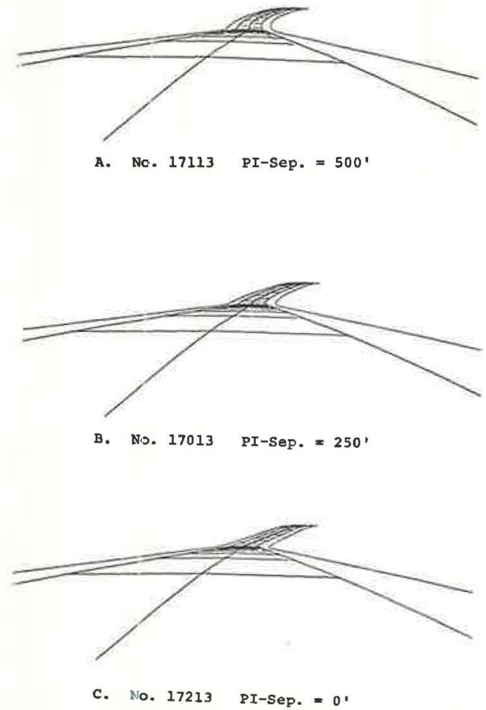


Figure 5. Perspectives for various PI separations, L_H = 970 ft, L_V = 1,000 ft, and S = 2,400 ft.

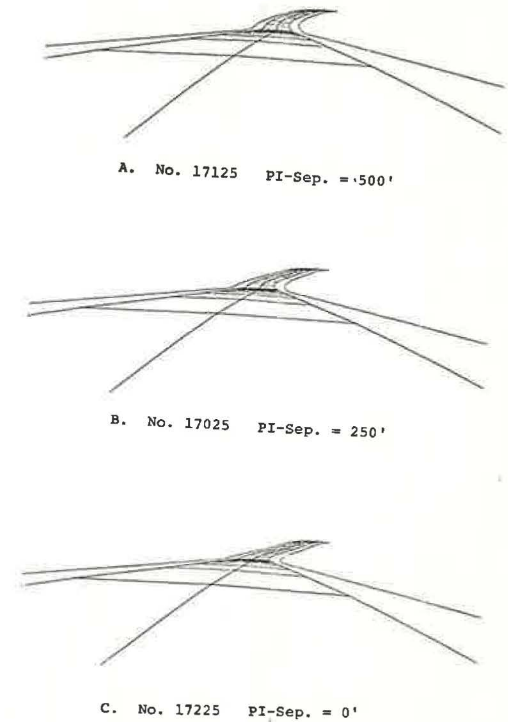
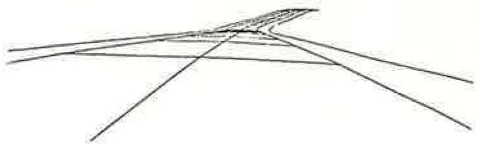
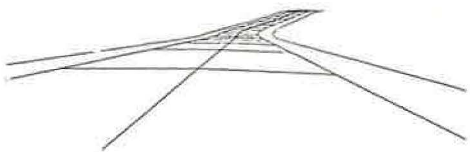


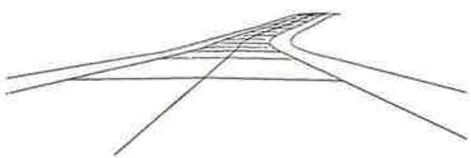
Figure 6. Perspectives for various PI separations, L_H = 970 ft, L_V = 1,500 ft, and S = 2,400 ft.



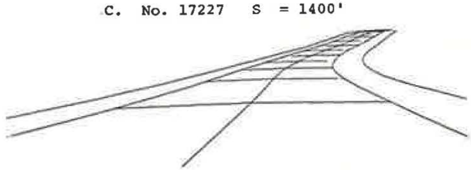
A. No. 17225 S = 2400'



B. No. 17226 S = 1900'

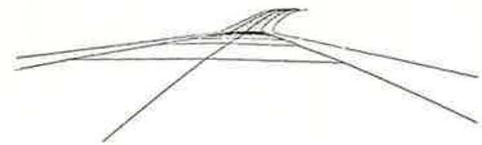


C. No. 17227 S = 1400'

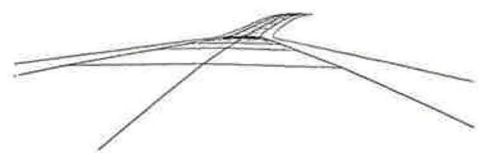


D. No. 17228 S = 900'

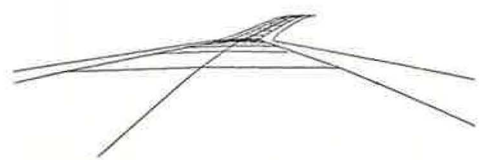
Figure 7. Perspectives for various sighting distances, L_H = 970 ft, and L_V = 1,500 ft, and PI separation = 0 ft.



A. No. 17129 PI-Sep. = 500'

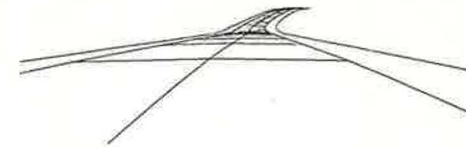


B. No. 17029 PI-Sep. = 250'

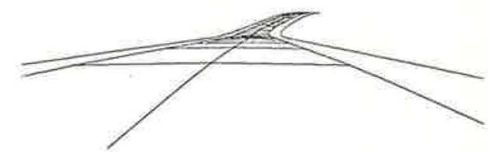


C. No. 17229 PI-Sep. = 0'

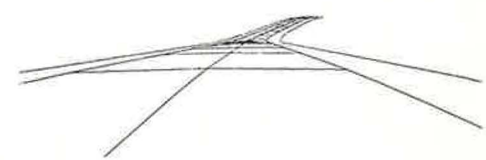
Figure 8. Perspectives for various PI separations, L_H = 2,000 ft, L_V = 1,500 ft, and S = 2,400 ft.



A. No. 17141 PI-Sep. = 500'



B. No. 17041 PI-Sep. = 250'



C. No. 17241 PI-Sep. = 0'

Figure 9. Perspectives for various PI separations, L_H = 2,000 ft, L_V = 2,000 ft, and S = 2,400 ft.

Figure 7 shows the same curve with the different sight distances. Figure 7d shows that, even when the observer is only 150 ft from the beginning of the vertical curve, the centerline looks a bit awkward.

Figure 8 shows perspectives with S = 2,400 ft, L_H = 2,000 ft, and L_V = 1,500 ft. There is very little apparent difference among the various PI separations shown. There is, however, a subtle inflection or break in the left edge of the roadway. The authors conclude, therefore, that the 1,500-ft vertical curve is a bit too short relative to the length of horizontal curve.

Figure 9 shows perspectives with S = 2,400 ft, L_H = 2,000 ft, and L_V = 2,000 ft. There is little apparent difference among the PI separations shown. The authors would not be surprised if, for longer sight distances, inflections became seriously apparent for those shown in Figures 9a and 9b. It is apparent that, if one uses very long horizontal and vertical curves, the visual problems caused by poor coordination are less serious.

The following conclusions were drawn from this study and are listed as rules for the coordination of vertical and horizontal alignment. In order for a roadway to have a smooth flowing appearance (which is also described as an absence of inflections or visual discontinuities), (a) the PI's must nearly coincide (within about 10 percent of horizontal curve lengths); (b) the length of vertical and horizontal curves must be nearly equal (within about 10 percent); and (c) if the curves are not of the same length, the horizontal curve should "lead" or slightly precede the vertical curve, i.e., the vertical curve should never be significantly longer than the horizontal curve.

The following observations were also made: (a) As the curves become longer (more generous alignment), slight violations of rules 1 and 2 are less serious; (b) the farther the observer is from the curves (longer sighting distances), the more accentuated are the visual discontinuities; and (c) if the rules are violated, it is strongly recommended that a series of roadway perspectives be drawn so that any visual discontinuities can be detected. These rules agree very closely with those suggested by Pushkarev (2, pp. 197-199).

SPIRAL PROBLEM

The problem of the foreshortened appearance of horizontal curves was studied. In particular, an attempt was made to determine criteria for the selection of a spiral length that would ensure a smooth and flowing appearance in the ribbon of roadway. Additional detailed information on this portion of the study is given in another report (6).

From personal observations and the information gained from the literature search, it was hypothesized that the factors affecting the visual appearance of a horizontal curve were observer distance, OD, display angle, DA, and the geometry of the curve. Observer distance in this case is defined as the distance from the observer to the beginning of the curve, PC or TS, whichever is appropriate; display angle is defined as the angle between the observer's line of sight and the plane containing the curve; and the geometry of the curve is defined as the spiral length, if any, and the limiting radius of the curve.

Approximately 500 perspective pictures were plotted with varying sight distances, limiting degree of curve, spiral length, and display angle. For any given set of geometric conditions, the sight distance and display angle were varied by moving the observer position. Moving the observer up into space above the roadway created artificial display angles and simulated the case where a sag vertical curve is located between the observer and the horizontal curve without the disruptive element caused by the vertical curve.

A wide range of geometric conditions was investigated. The degree of curve was varied from 30 min to 5 deg. Some of the curves were constructed without a spiral transition so that the visual effect of adding a spiral curve could be tested. The spiral lengths varied from 100 to 2,000 ft. The lengths of spirals examined at each limiting degree of curve are as follows:

0.5 Deg	1 Deg	2 Deg	3 Deg	4 Deg	5 Deg
0	0	0	0	0	0
500	250	300	200	200	100
2,000	500	500	600	500	400
	1,000				
	2,000				

All curves were rated according to their smoothness of appearance and the rate at which they seemed to diverge from the tangent. The rating scale was acceptable, questionable, or unacceptable. Although this may seem a crude rating scale, it was felt that any refinement beyond this level was not justified because at some point the decision had to be made whether a curve was acceptable or unacceptable.

The following was concluded from the spiral curve study:

1. Spiral curves do improve the appearance of most circular curves;
2. When the observer is near the plane of the curve, there is no significant difference in the appearance of a spiraled and an unspiraled curve;
3. As the distance from the curve to the observer increases, the length of spiral needed increases for good visual quality;
4. As the height of the observer raises above the plane of the curve, increasing display angle, the length of spiral needed decreases for good visual quality;
5. Curves that consist entirely of spiral curves give the best visual appearance, all other conditions being equal; and
6. The rate at which a curve visually appears to diverge from the tangent affects the visual quality of the curve.

ACKNOWLEDGMENTS

The research reported in this paper was conducted under an agreement between the State Highway Commission of Kansas, the Civil Engineering Department, and the Engineering Experiment Station of Kansas State University, Manhattan, Kansas. The study was jointly financed by the Commission and the U. S. Bureau of Public Roads.

REFERENCES

1. Cron, F. W. Fitting the Highway to the Landscape. In The Highway and the Landscape, (Snow, W. B., ed.), Rutgers Univ. Press, New Brunswick, N.J., 1959.
2. Tunnard, C., and Pushkarev, B. Manmade America. Yale Univ. Press, New Haven, Conn., 1963.
3. Smith, B. L., and Fogo, R. D. Some Visual Aspects of Highway Design. Highway Research Record 172, 1967, pp. 1-20.
4. Smith, B. L., and Yotter, E. E. Visual Aspects of Highway Design. Eng. Exp. Station, Kansas State Univ., Manhattan, Spec. Rept. 80, 1968.
5. Smith, B. L., and Yotter, E. E. Computer Graphics and Visual Highway Design. Highway Research Record 270, 1969, pp. 49-64.
6. Smith, B. L., Yotter, E. E., and Murphy, J. S. Alignment Coordination in Highway Design. Eng. Exp. Station, Kansas State Univ., Manhattan, Spec. Rept. 90, 1970.