VISUAL ASPECTS OF HIGHWAY DESIGN

by

EDWARD E. YOTTER

BSCE, Kansas State University, 1964

A MASTER'S THESIS

submitted in partial fulfillment

of the requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1968

Approved by

Major Professor

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PAGE

PAGE

INTRODUCTION

The introduction to the AASHO "Blue Book" (1) states, "A complete highway incorporates not only safety, utility and economy, but beauty as well." But a visually pleasing highway does not just happen, it has to be designed that way from the beginning. Therefore, in the final analysis, design--and aesthetic-related design--is basically the responsibility of the design engineer, and his alone.

The question then is how does the highway designer judge his design for appearance or for visually disturbing elements.

PREVIOUS WORK

There are several references concerning this quest for an understanding of the problem. Tunnard and Pushkarev (2), Smith and Fogo (3), and F. W. Cron (4,5,6) each present indicators of possible trouble spots and suggest some techniques to avoid them. Appleyard, Lynch and Myer (7) outline some of the problems and a general approach to a solution. Leisch (8) presents several techniques for solving some of the vexing problems facing the designer. Snowden's list (9) of selected works, "First Readings in Visual Design for Engineers", references several excellent works for an understanding of some of the problem areas and possible approaches to solutions.

An awareness of a problem is the first step to a solution but by reading from these references the designer will probably continue to ask the question of how to test his design for aesthetic qualities. An answer to his question is the concern of the research described in this paper.

PURPOSE

The purpose of the research described in this paper was to investigate specific ways to aid the highway designer in his task of designing an "aesthetically pleasing" highway.

SCOPE

The research was limited to the following:

1. The sag vertical curve was studied to relate the algebraic difference in grades, the angle of sharp focus of the eye, and the sighting distance from which the curve is viewed, such that the "optimum" length of vertical curve can be determined.

2. A small change in direction of the horizontal alignment was investigated to establish a relationship between length of curve required to appear flowing rather than as a lateral "jerk".

3. Investigate some simple, easy means for the highway designer to determine if certain combinations of a horizontal and a sag vertical curve produce an unaesthetic, warped appearing roadway.

LOCATIONS STUDIED

Several locations were studied and rated on the premise that the ribbon of roadway should appear smooth and flowing, as opposed to appearing disjointed and erratic.

Kansas Interstate I-70, between Salina and Topeka, was the first stretch of highway rated. The curves were rated on how the ribbon of highway appeared: short, OK or good. There are few horizontal and sag vertical curve combinations for rating on this section of I-70.

Two locations of particular interest were found:

The first was approximately one mile east of the Maple Hill Exit between Manhattan and Topeka. The vertical curves seemed too short and the horizontal curve following the three sag vertical curves gave the location a warped appearance.

The other location on I-70 that was studied lies approximately one mile west of the Vesper Exit north of Ellsworth. The surprising appearance of a small change of direction (1°30') made this location particularly interesting.

The ease of access from Manhattan made these two locations ideal for study. Plans for I-70 were furnished by the Kansas State Highway Department.

In May of 1967 a trip was organized to rate Oklahoma I-40 east of Oklahoma City. This one hundred mile section is generally very well done and it was hoped some insight into the problem of design would be acquired. Most of the sag vertical curves appeared good and the horizontal alignment was flowing without appearing overdone. The median widening and curvilinear alignment was quite effective. Particular locations were not modeled or drawn on I-40.

On this trip, a location on Oklahoma I-35 north of Oklahoma City was photographed and the plans obtained. At this location there is an abrupt widening and subsequent narrowing of the median which was displayed to the driver. The median widening has an appearance of a "barbell" and yet offers an acceptable appearance on the plans. If the plans are viewed more from the driver's vantage point, i.e. with the eye to one end and close to the plans, the barbell effect could be seen.

Plan sheets for I-35 and I-40 were furnished by the Oklahoma State Highway Department.

The special locations and their geometry are discussed later in this paper.

Some of the general observations evolving from rating these highways are:

1. Curves looked progressively better as they were approached, i.e. as the viewing distance shortened, there was a point at which the curve could be judged "very good" visually.

2. Any curve, when viewed from its beginning point (PC or PVC), appeared smooth and flowing. Smith and Fogo (3) observed this earlier.

3. Sag vertical curves viewed from long distances appeared to dip rather than flow.

4. Horizontal curves viewed from long distances appeared to jerk laterally.

5. A sag vertical curve preceeding or following a horizontal curve usually presented a warped appearance.

6. Median widening was more effective if there appeared to be a reason for the widening.

7. Oklahoma did a good job of fitting the highway to the landscape on I-40 with most of the horizontal curves having a degree of curve of less than 0°30'. The smallest observed degree of curve was 0°04'.

8. A variety of views--over-looking a valley, restricted by trees or an underpass, wide and spacious--offered to a driver, helped to make a visually pleasing highway. This was done quite effectively on I-40.

Location Photography

Photographs of actual situations were taken with a 35mm, NIKON F, automatic single lens reflex camera with a focal plane shutter. Two special lenses were available:

1. NIKKOR Zoom, f3.5, 43mm to 86mm
2. TAMRON Zoom, f6.3, 95mm to 205mm

A GOSSEN Lunasix lightmeter was used for accurate light readings.

An 86mm lens setting was found to give the most realistic picture of the highway.

At the beginning of the project, the primary concern was to:

1. Develop a method of modeling which would be fast, inexpensive and realistic for judging the appearance of the ribbon of roadway.

2. Develop an analytical approach to the solution of the required length of horizontal and vertical curves.

Information on the use of an electronic computer and plotter to make perspective drawings was being accumulated and it appeared to be a technique that could be of great value in the project.

MODELS

Models have been used in the past with some degree of success but have generally been very laborious and expensive to construct. Many techniques have been developed recently that decrease the time required for construction and the cost of materials. Berry and McCabe (10) describe some techniques of particular interest. A model, to be of any use, must appear realistic with respect to the ribbon of roadway. Three methods of modeling were investigated.

1. T-Pegs, The California Method

The first method of modeling tried was a technique developed by the California Division of Highways (11). It consisted of using T-pegs of 1/8 inch diameter wooden dowels with a rectangle 1/2 inch by 1 inch of thin plastic attached to one end of the dowel by a metal eyelet. The rectangle of plastic was attached so that it could rotate to show the superelevation of the highway. The roadway was made of strips of acrylic plastic of cross section 1/8 inch by 1/16 inch, laid side by side and fastened to the T-pegs by rubberbands. The strips were free to slide as the roadway curvature was changed. A plan of the desired section of highway was attached to a 3 inch by 4 foot by 8 foot styrofoam base for positioning of the T-pegs. The T-pegs were then inserted into the styrofoam base at scaled heights. A scale of 1 inch equal to 20 feet vertically and 1 inch equal to 100 feet horizontally was found to give the best representation. The resulting model is reasonably accurate but the rubberbands holding the acrylic strips to the T-pegs distracted from a smooth and flowing appearance of the roadway. Realism was not as great as desired. Special equipment for modeling was obtained from the California Division of Highways.

2. 1/4 inch Urethane for Profile and Horizontal Alignment

The second technique utilized was a procedure described by Berry and McCabe (10). Profiles were cut from 1/4 inch by 4 feet by 8 feet foamed urethane sheets at scales of 1 inch equal to 20 feet vertically and 1 inch equal to 100 feet horizontally. Highway plan sheets were pinned to the 3 inch by 4 feet by 8 feet styrofoam base and the profiles were pinned to the base following the horizontal alignment on the plan sheets, Figure 1. The method was fast and inexpensive but horizontal control of the tops of the profiles was not considered precise enough for our use.

3. 1/4 inch Urethane Profiles and Pressboard Horizontal Alignment

The last method investigated was to cut three identical profiles from 1/4 inch urethane sheets at a scale of 1 inch equal to 20 feet vertically and 1 inch equal to 100 feet horizontally. The profiles were then pinned to the 3 inch styrofoam base with approximately 12 inches between profiles and braced with short pieces of urethane, Figure 2. Very little curvature existed in the situations modeled so that the profiles were pinned in straight lines. The horizontal alignment was drawn carefully on .015 inch red pressboard and emphasized by 1/4 inch yellow tape. The pressboard was placed on the profiles, Figure 3. This method required little time to construct and was inexpensive but has the limitation of requiring both roadways on a divided highway to have the same profiles.

Three models were made using this method. The first was of the Maple Hill location. Figure 4 is a photograph of the location, Figure 5 shows the model of this location.

The next model was of the "kink" location on I-70 north of Ellsworth. A photograph of the location is shown in Figure 6 and the modeled situation in Figure 7.

The last location modeled was the "barbell" on I-35 north of Oklahoma City, shown in Figure 8. The model of the "barbell" appears in Figure 9.

Model Viewing

The models were viewed from the ends of the naked eye but this did not contribute to the realism of viewing the

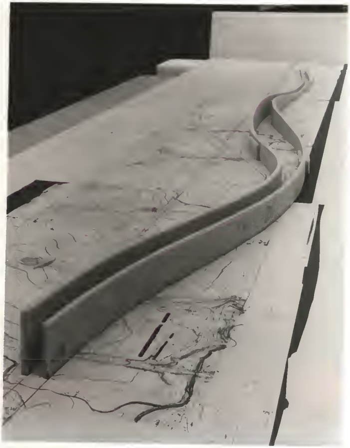


FIGURE 1. Urethane Profile and Horizontal Alignment

FIGURE 2. Urethane Profiles

FIGURE 3. Pressboard and Profiles

FIGURE 4. Maple Hill Location on I-70.

FIGURE 5. Urethane-Pressboard Model of Maple Hill Location.

FIGURE 6. Kink Location on I-70

FIGURE 7. Urethane-Pressboard Model of Kink Location

FIGURE 8. Barbell Location on I-35

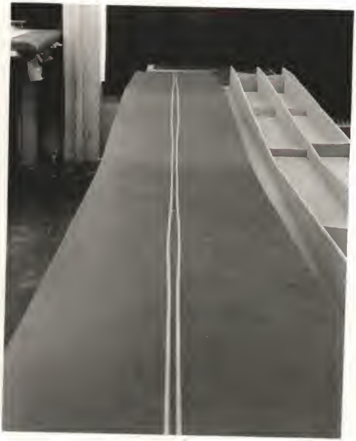


FIGURE 9. Urethane-Pressboard Model of Barbell Location

models. In an effort to place the eye at the driver's vantage point a modelscope was used. The modelscope is a small periscope-type device mainly used by architects to place themselves within scale on models. Figure 10 shows the use of the modelscope. Figures 11, 12 and 13 were taken through the modelscope of the three models, Maple Hill, the "kink" and the "barbell" respectively.

Model Photography

Photographs of the urethane models, Figures 1, 2, 3, 5 and 7, were taken by a professional photographer with a special box camera. The camera has an adjustable focal plane to increase the depth of field so as to enable the entire model to be in focus.

Photographs through the modelscope, Figures 11, 12 and 13, were taken using a 35mm EXA camera with a special modelscope fixed focus lens. Although our results through the modelscope are not very satisfactory, Butcher and Pearson (12) have had extremely good results from the modelscope. Their reference on the use of the modelscope is probably one of the best.

Observations

Models and model photography was not particularly helpful for the special problems associated with this research.

The urethane models might be a real aid in coordination studies.

Because of the promise of perspective drawings and time limiations, models and model photography were not extensively developed.

FIGURE 10. Use of Optic Modelscope

FIGURE 11. Maple Hill Model Through Modelscope

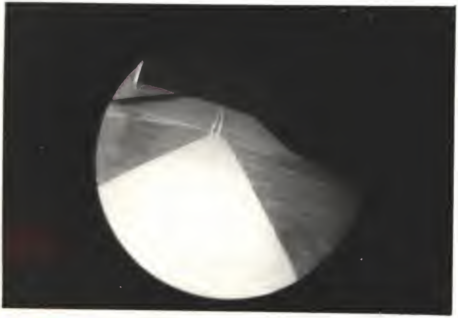


FIGURE 12. Kink Model Through Modelscope

FIGURE 13. Barbell Model Through Modelscope

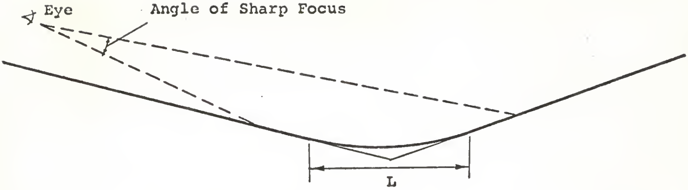
ANALYTICAL APPROACH

It was believed that the required length of a sag vertical curve could be related to an angle of sharp focus of the eye and the distance from which the curve was viewed. One purpose of this research was to investigate this hypothesis. Stated another way, the hypothesis was that for small changes of grade, a visual discontinuity of the alignment would appear if segments of each tangent enclosing the vertical curve were visible without refocusing the eye. In other words, if the angle of sharp focus of the eye included a section of both tangents of a sag vertical curve, the roadway edge would appear "jerky". Figure 14 illustrates this hypothesis.

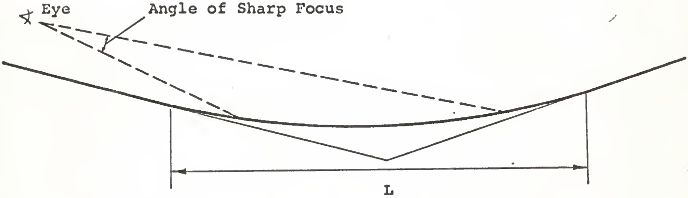
In Figure 14A, the curve would appear too short because sections of both tangents are seen in the angle of sharp focus. Figure 14B shows the situation in which the curve should appear good since the angle of sharp focus is within the vertical curve. The minimum length of curve that would give a good visual appearance is illustrated in Figure 14C.

Derivation

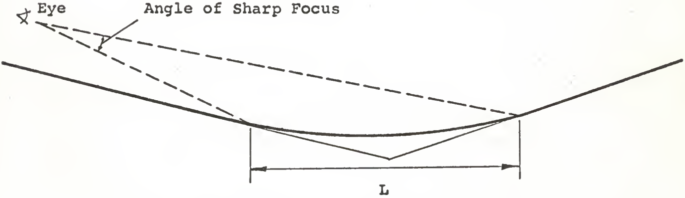
The formula developed related change of grade, length of sag vertical curve, eye height above roadway, angle of sharp focus of the eye and the distance from the observer to the PVI of the vertical curve (sight distance). Figure 15



A. A sag vertical curve which is too short.



B. A curve which should appear good visually.



C. The minimum length of curve which should give a good visual appearance.

FIGURE 14. Theoretical Relationships:
Angle of Sharp Focus vs Vertical Curve Length

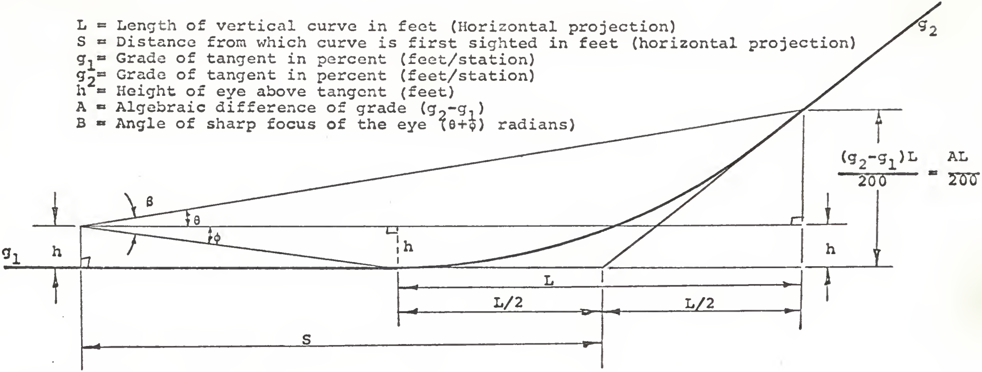
shows the development of the theoretical relationship. It should be pointed out that this derivation assumed the observer was in the same plane as the vertical curve. This assumption was not exactly true as the observer must be slightly to one side of the plane to see anything other than a straight line.

Many references on the eye and vision were studied, but little information applicable to the specific problem of an angle of sharp focus could be found.

From a crude experiment it was our belief that the angle of sharp focus was approximately 30' of arc.

DEFINITIONS:

- L = Length of vertical curve in feet (Horizontal projection)
- S = Distance from which curve is first sighted in feet (horizontal projection)
- g_1 = Grade of tangent in percent (feet/station)
- g_2 = Grade of tangent in percent (feet/station)
- h = Height of eye above tangent (feet)
- A = Algebraic difference of grade (g_2-g_1)
- B = Angle of sharp focus of the eye $(\theta+\phi)$ radians)



DERIVATION:

$$\tan\theta = \frac{(AL/200)-h}{S+(L/2)} = \frac{AL - 200h}{200S+100L} = \theta$$

$$\tan\phi = \frac{h}{S-(L/2)} = \frac{2h}{2S-L} = \phi$$

For small angles

$\tan\theta = \theta$ (radians)
$\tan\phi = \phi$ (radians)
$\tan\beta = \beta$ (radians)

$$\beta = \theta+\phi = \frac{AL-200h}{200S+100L} + \frac{2h}{2S-L} = \frac{2ALS-400hS-AL^2+200hL+400hS+200hL}{400S^2+200LS-200LS-100L^2}$$

$$400\beta S^2-100\beta L^2 = 2ALS-AL^2+400hL$$

$$400\beta S^2-100\beta L^2 - 2ALS+AL^2-400hL = 0$$

$$(A-100\beta)L^2 - (400h+2A5)L + 400\beta S^2 = 0$$

FIGURE 15. Theoretical Relationship - L,S,A

RESULTS

By using the formula developed and assuming the height of eye above the roadway as 3.5 feet and the angle of sharp focus as 0.1 radians or 34.4' of arc, computations using various sight distances (S) and changes of grade (A) were made and a graph was plotted, Figure 16. This graph was checked against the rated curves on I-70 in Kansas and I-40 in Oklahoma but the data proved too sparse for any concrete conclusions to be drawn. The data from I-70 and I-40 contained too few curves for any particular small range of change in grades. It was decided that to use vertical curves which were on horizontal curves would not be valid. Few of the rated curves were on tangent sections.

The correct length of vertical curve could not be satisfactorily judged from the use of models. Other methods were tried but perspectives drawings appeared to be the technique to enable a person to evaluate the sag vertical curve problem.

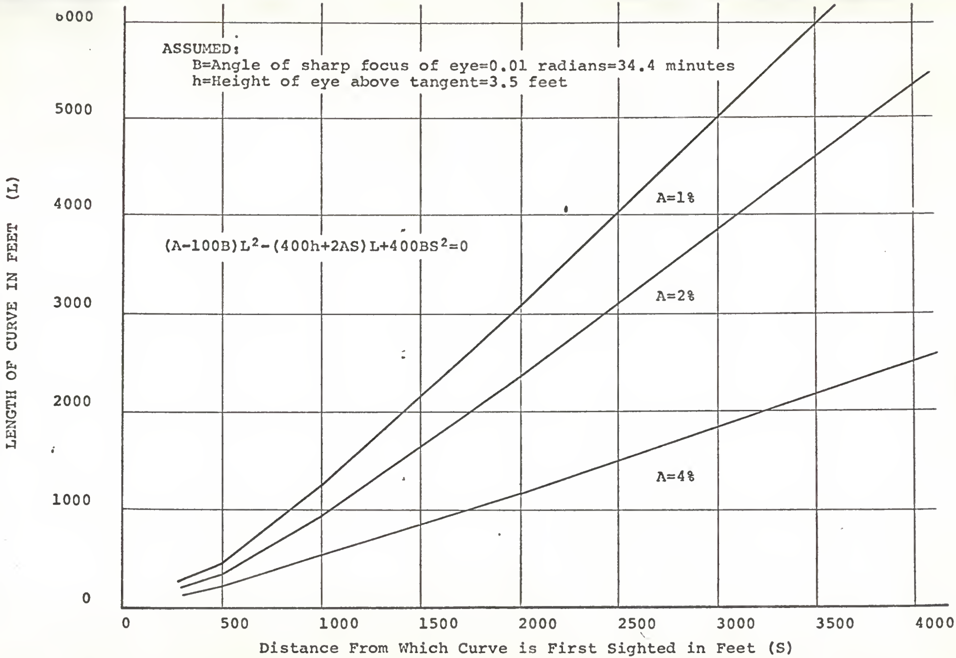


FIGURE 16. Graph of Theoretical Relationship - L,S,A

PERSPECTIVES BY COMPUTER

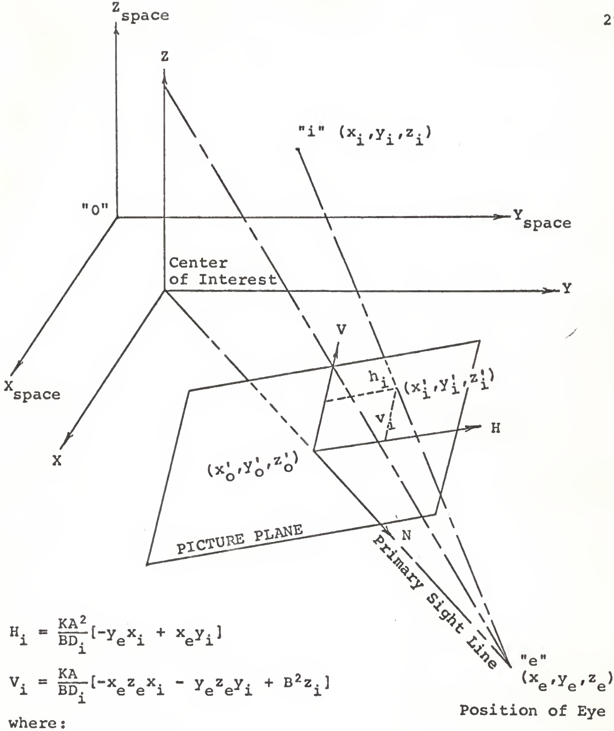
Many of the references mentioned in the first of this report made use of freehand sketches (a form of perspective drawing) in their works. Cron (5) and Pushkarev (2) used freehand sketches to illustrate awkward situations. The California Division of Highways had tried plotters but indicated only little success. A firm in Sweden had done considerable work in this area and were very enthusiastic about the possibilities of plotters. A French Highway Group (BCEOM) in a newsletter by Calcomp (13) demonstrated that perspectives were capable of being drawn by plotters. Correspondence with the French Highway Group set the price of their program at $200,000 and it was not yet available for the IBM 360-50 in September, 1967. The only alternative was to develop our own perspective plotting programs.

Programs

In order to make a perspective drawing using the electronic plotter, it was first necessary to determine the space coordinates (X_{space}, Y_{space}, Z_{space}) of points on the object of which the drawing was to be made. A program developed by Massachusetts Institute of Technology some time ago called COGO (14) was used to do this very easily and accurately. Transforming space coordinates to picture plane coordinates was the next problem. Parks et al (16) and

Geissler (17) have published procedures for transformation of space coordinates to picture plane coordinates. Dr. Walter Bernhart, School of Engineering, Wichita State University, has done a considerable amount of work in this area of computer graphics. His approach is the most general and therefore of great value in all perspective drawing problems.

Figure 17 illustrates Dr. Bernhart's approach. To use his approach, the space coordinates of all points are first found by COGO. The center of interest (0) is next chosen. Simple subtraction of the space coordinates of the center of interest from all of the points in the space coordinate system translates the space coordinate axes to the center of interest. Next the position of the eye is chosen and transformed to the center of interest coordinate axes. When the center of interest (0) and the position of the eye (e) are selected, then a line between the center of interest and the eye position can be taken as the line of sight. The picture plane is then positioned perpendicular to the line of sight and between the eye position and the center of interest. The desired transformation is then accomplished by rotating the axes (X,Y,Z at the center of interest) so that X coincides with the line Oe. Another rotation of the (X,Y,Z) axes places the Y and Z axes parallel to the H and V axes in the picture plane. Then by analytic geometry a point in space



$$H_i = \frac{KA^2}{BD_i}[-y_e x_i + x_e y_i]$$

$$V_i = \frac{KA}{BD_i}[-x_e z_e x_i - y_e z_e y_i + B^2 z_i]$$

where:

$$B = \sqrt{x_e^2 + y_e^2}$$

$$A = \sqrt{x_e^2 + y_e^2 + z_e^2}$$

$$D_i = A^2 - (x_e x_i + y_e y_i + z_e z_i)$$

FIGURE 17. Transformation of Space Coordinates to Picture Plane Coordinates

X_i, Y_i and Z_i will be related to the H and V axes on the picture plane by the equations given in Figure 17. Bernhart's development of the equations is found in reference (15).

By applying the H and V equations to all points, each point's position is located on the picture plane. This transformation of space coordinates to picture plane coordinates is very general and makes no assumptions such as that the picture plane is vertical as assumed by Geissler (17).

During the early visits with Dr. Bernhart, it was learned that Wichita State University had ordered a Benson-Lehner electronic plotter, and they expected it to be in operation by early September, 1967. Arrangements were made, through the courtesy of Wichita State University and Dr. Bernhart, to use their plotter for making perspective drawings.

Calculation of Picture Plane Coordinates

Input for the Graphics Program is the number of points being considered (NPTS) and the number of different positions of the eye (NPEYE) which is also the number of perspective drawings to be calculated. Next the scale factor (SCALE) is read which determines where the picture plane will be located. In all of this work we used a scale factor of 1., which placed the picture plane at the center of interest, and then drew the perspectives to the desired size by scaling them down in the plotter programs. A scale factor of .5 would put the picture plane midway between the observer and the center of interest. Input to each program must also contain the maximum dimensions of the picture plane. Since our picture plane was at the center of interest, we found that HMAX = 10000. feet and VMAX = 1000. feet most satisfactory. The center of interest and each position of the eye must be defined by their space coordinates. The last part of the input is the space coordinates of the points themselves. The program also reads the stationing of the point but nothing is done with it.

After the reading of the input is complete the program begins calculations for each drawing. The first position of the eye is taken and used to calculate the constants for that perspective (XE, YE, ZE, B2, B, A2, A). These constants are then used in calculating the picture plane coordinates, H and V, (see Figure 17) of each point. If the point is in front of the observer (positive D) and within the picture plane ($|H| < HMAX$; $|V| < VMAX$), the point number, its station and the picture plane coordinates of the point are written and then punched for use in the plotter programs.

After all points have been calculated, the next position of the eye is retrieved and calculation of the next perspective is carried out. After all positions of the eye have been used, the program terminates.

Table 1 shows the graphics program flow chart and Table 2 is a listing of the computer graphics program.

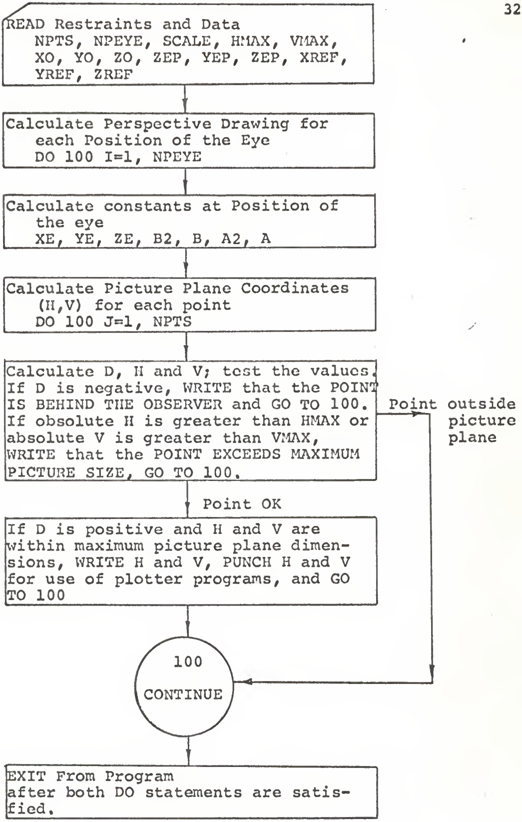


TABLE 1. Flow Chart

TABLE 2. Graphics Program

```
C HIGHWAY GRAPHICS PROGRAM FOR CALCULATION OF PERSPECTIVE DRAWINGS

C PROGRAM IS DIMENSIONED FOR MAXIMUM OF 500 POINTS
C AND A MAXIMUM OF 15 POSITIONS OF THE EYE
      DIMENSION STA(500),XREF(500),YREF(500),ZREF(500)
      DIMENSION XEP(15),YEP(15),ZEP(15)
C READ NUMBER OF POINTS (NPTS) AND NUMBER OF OBSERVER POSITIONS (NPEYE)
   10 READ (1,210) NPTS,NPEYE
  210 FORMAT(2I5)
C IF NPTS IS NEGATIVE OR ZERO, PROGRAM TERMINATES
      IF(NPTS)200,200,15
   15 CONTINUE
C READ SCALE FACTOR (SCALE)
      READ (1,220) SCALE
C READ MAXIMUM DIMENSIONS OF PICTURE PLANE (HMAX,VMAX)
      READ (1,220) HMAX,VMAX
  220 FORMAT(3F10.2)
C READ SPACE COORDINATES OF CENTER OF INTEREST (XO,YO,ZO)
      READ (1,220) XO,YO,ZO
C READ SPACE COORDINATES OF POSITIONS OF THE EYE (XEP,YEP,ZEP)
      DO 17 I=1,NPEYE
   17 READ (1,220) XEP(I),YEP(I),ZEP(I)
C READ SPACE COORDINATES OF ALL POINTS (XREF,YREF,ZREF)
      DO 20 I=1,NPTS
   20 READ (1,240) STA(I),K,YREF(K),XREF(K),ZREF(K)
  240 FORMAT(F14.2,I8,3F14.2)

C CALCULATE PERSPECTIVE FOR EACH POSITION OF THE EYE
      DO 100 I=1,NPEYE
C WRITE PAGE HEADINGS FOR EACH NEW POSITION OF THE EYE
      WRITE (3,410) I,SCALE,HMAX,VMAX,XEP(I),YEP(I),ZEP(I),XO,YO,ZO
  410 FORMAT(1H1,10HRUN NUMBER,I3/1H0,14H SCALE FACTOR=,F6.4/1H ,34H MAX
     1IMUM PICTURE DIMENSIONS  HMAX=,F6.0,3X,6H VMAX=,F6.0/1H ,24H OBSER
     2VER POSITION  XEP=,F9.2,6H  YEP=,F9.2,6H  ZEP=,F9.2/1H ,24H CENTER
     3 OF INTEREST  XO=,F9.2,6H   YO=,F9.2,6H   ZO=,F9.2/1H-,46H STATION
     4  POINT     HORIZONTAL        VERTICAL//)
C CALCULATE DISTANCE EYE IS FROM CENTER OF INTEREST
      XE=XEP(I)-XO
      YE=YEP(I)-YO
      ZE=ZEP(I)-ZO
C CALCULATE CONSTANTS
      B2=XE*XE+YE*YE
      B=SQRT(B2)
      A2=B2+ZE*ZE
      A=SQRT(A2)

C CALCULATE PICTURE PLANE COORDINATES (H,V) FOR EACH POINT
      DO 100 J=1,NPTS
C CALCULATE DISTANCE POINT IS FROM CENTER OF INTEREST
      X=XREF(J)-XO
      Y=YREF(J)-YO
      Z=ZREF(J)-ZO
```

TABLE 2. Graphics Program

```
C CALCULATE D
      D=A2-(XE*X+YE*Y+ZE*Z)
C IF D IS NEGATIVE THE POINT IS BEHIND THE OBSERVER
      IF(D)30,30,35
   30 WRITE (3,420) STA(J),J
  420 FORMAT(1H ,F8.2,I6,32H    POINT IS BEHIND THE OBSERVER)
      GO TO 100
C CALCULATE H OF POINT AND TEST IF LESS THAN PICTURE PLANE MAXIMUM
   35 H=SCALE*A2/(B*D)*(XE*Y-YE*X)
      IF(HMAX-ABS(H))40,45,45
   40 WRITE (3,430) STA(J),J
  430 FORMAT(1H ,F8.2,I6,38H    POINT EXCEEDS MAXIMUM PICTURE SIZE)
      GO TO 100
C CALCULATE V OF POINT AND TEST IF LESS THAN PICTURE PLANE MAXIMUM
   45 V=SCALE*A/(B*D)*(B2*Z-ZE*(XE*X+YE*Y))
      IF(VMAX-ABS(V))40,50,50
C WRITES H AND V WHEN BOTH POINTS ARE WITHIN LIMITS OF PICTURE PLANE
   50 WRITE (3,440) STA(J),J,H,V
  440 FORMAT(1H ,F8.2,I6,2F16.3)
C PUNCHES H AND V WHEN BOTH POINTS ARE WITHIN LIMITS OF PICTURE PLANE
      WRITE (2,450) J,STA(J),H,V
  450 FORMAT(I5,3F15.2)
  100 CONTINUE
      GO TO 10

C TERMINATION OF PROGRAM
  200 CONTINUE
C PUTS BLANK PAGE AT END OF RUN
  460 FORMAT (1H1)
      WRITE (3,460)
      STOP
      END
```

Realism of Perspectives

For perspectives drawn by an electronic computer to be of any use, it was first necessary to prove to ourselves that the drawings made were very similar to the actual observed situation. Photographs were taken and perspectives were made with the observer at the same location to check if the perspectives did, in fact, closely resemble the real situation.

Figure 18 shows the perspective drawing made of Maple Hill and the photograph taken from approximately the same observer position. Figure 19 is the geometry of the Maple Hill location.

The "kink" perspective and photograph is shown in Figure 20. The surprising lateral jerk for only 1°30' change of direction is quite apparent in both. Geometry for the "kink" is shown in Figure 21.

The last example used to check for realism was the "barbell" on I-35 in Oklahoma. The perspective and the photograph shown in Figure 22 do not have the same observer position, but the awkwardness and similarity cannot be mistaken. An error in assigning the observer's position produced a drawing with the observer in the median and much closer to the "barbell" than in the photograph. Figure 23 shows the geometry of the "barbell".

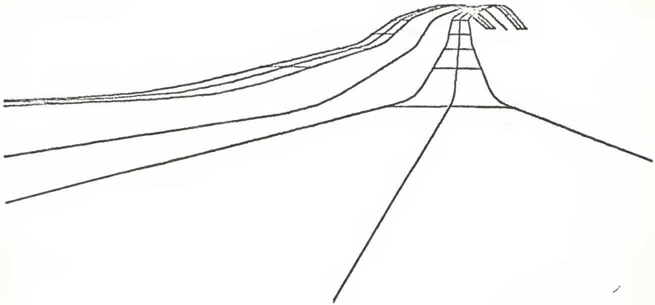


FIGURE 18. Photograph and Perspective of Maple Hill Location

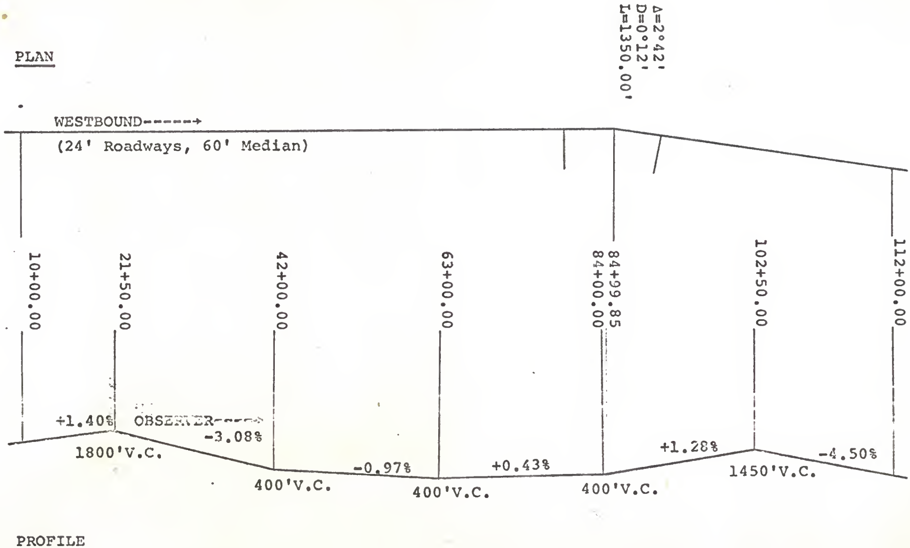


FIGURE 19. Geometry of Maple Hill on I-70 in Wabaunsee County

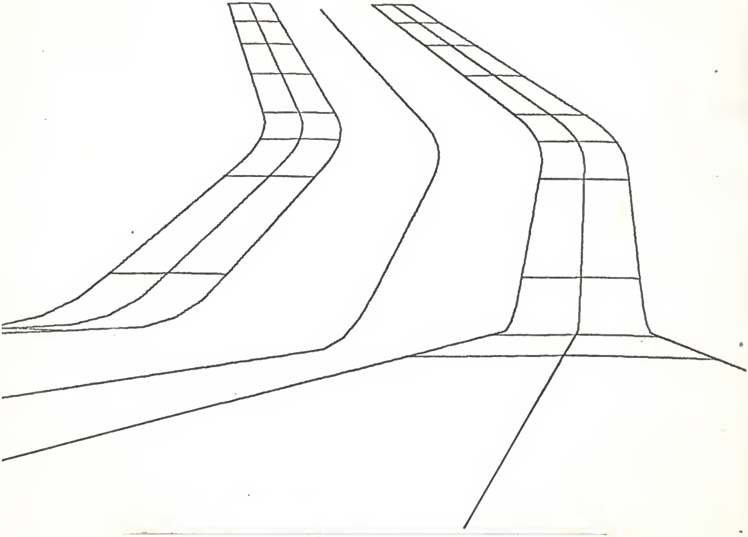


FIGURE 20. Photograph and Perspective of Kink Location

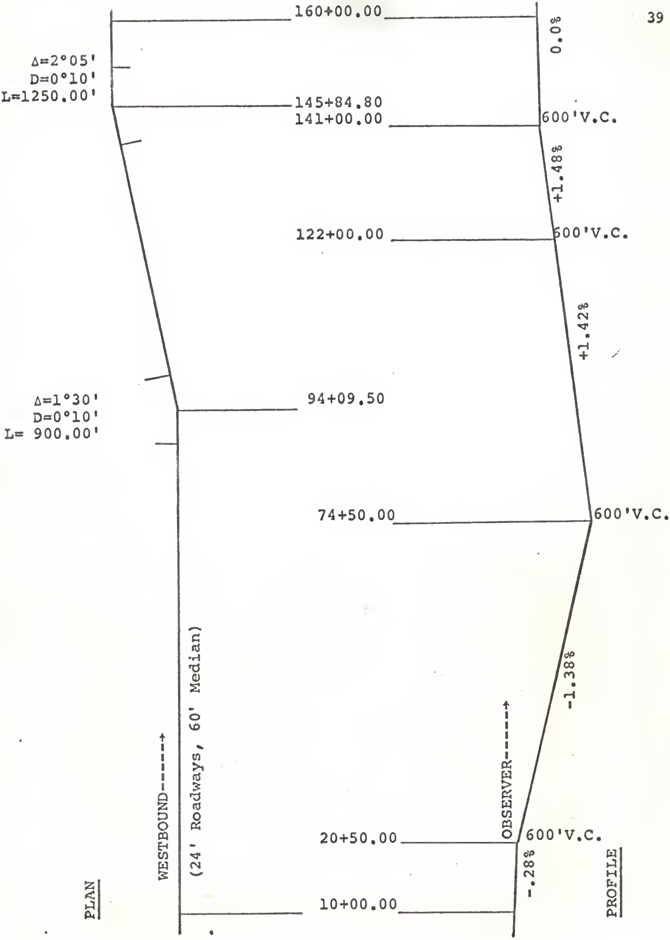


FIGURE 21. Geometry of Kink on I-70 in Ellsworth County

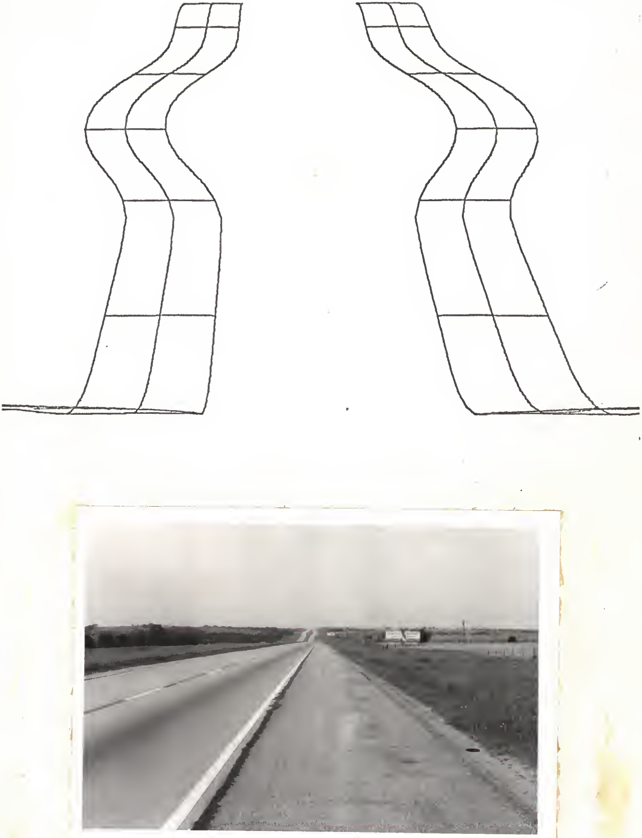


FIGURE 22. Photograph and Perspective of Barbell Location

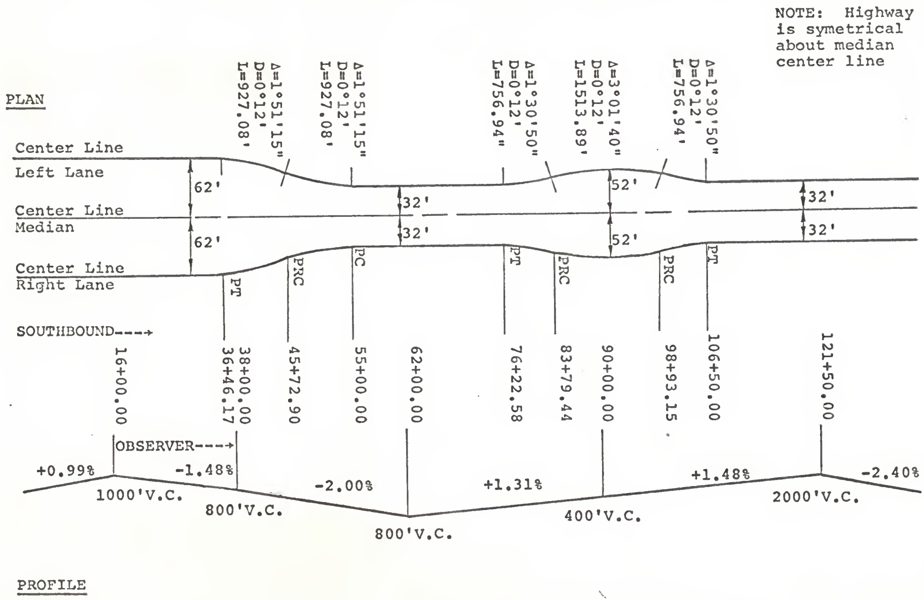


FIGURE 23. Geometry of Barbell on I-35 North of Oklahoma City

SAG VERTICAL CURVE PROBLEM

To test the theoretical relationship derived earlier relating the length of vertical curve (L), change of grade (A) and sighting distance (S), a series of perspective drawings were drawn and evaluated visually. Table 3 is a listing of the perspectives drawn.

The geometry of the road section drawn in all of the cases listed in Table 3 was of a typical two-lanes of a four-lane facility. Two 12 foot lanes were assumed with an inside (left) shoulder width of 6 feet and an outside (right) shoulder width of 10 feet. The road was considered to have a 0.25 foot crown with shoulder slopes of 0.05 foot per foot. Observer locations were two feet right of the roadway centerline and height of eye at 3.5 feet above the surface of the road. The change of grade (A) was taken as symmetrical. For example, A = 4%, the initial grade, g_1 = -2%, and the forward grade, g_2 = +2%. The center of interest (point at which the line of sight is directed) lay on the centerline of the roadway at the midpoint of the sag vertical curve. The sight distance was computed as the distance from the observer's eye to the center of interest.

The conditions for each perspective are listed in Table 3. The first series of perspectives were based on the angle of sharp focus graph, Figure 16. Selection of later perspectives to be drawn, were made in order that good to poor situations could be drawn in all regions.

LENGTH OF VERTICAL CURVE, L(feet)

ALGEBRAIC CHANGE IN GRADE, A(%)	400	600	800	1000	1200	2000	3000	4000	5000	6000	7000
.5	250 500 750 1000	250 500 750 1000	500 750 1000	500 750 1000 2000		1000 1250 1500 2000 3000		2000 2250 2500 3000 4000			
1	250 500 750 1000	250 500 750 1000	500 750 1000	500 750 1000 2000		1000 1250 1500 2000 3000		1000 2250 2500 3000 4000			
2	500 750 1000 2000 3000	500 750 1000 2000 3000	500 750 1000 1250 2000 3000	500 1000 2000 3000	1000 2000 3000	1000 1500 2000 3000	2000 2500 3000 3500 4000	2000 2500 3000 3500 4000	3000 4000	3000 4000	4000
6	500 750 1000 1250 1500 2000 3000	2000 2500 3000	2500 3000	1000 1500 2000 2500 3000	3000 3500 4000			2500 3000 3500 4000			

TABLE 3. Sight Distances (S) for Which Perspectives Were Drawn For Each Given A and L

The perspectives were judged by laying the drawings on a table with no identification other than a number on them. The perspectives were then divided into three groupings: too short, acceptable and very good. The groupings were then sorted into their respective grade changes and marked.

A series of perspectives with A = 2%, L = 800 feet and S varying is given in Figures 24 through 29. The perspectives in Figures 24 and 25 were judged "very good". The drawing in Figure 26 was classified as "desirable" whereas the drawing in Figure 27 was classified as "almost acceptable". The perspectives in Figures 28 and 29 were judged definitely too short. On this series of perspectives, nothing changed except the sight distance from the vertical curve PI, but the decrease in desirability is quite evident.

A graph of the "desirable" relationships is given in Figure 30. These are the lines, above which all of the very good relationships lie and below which all of the barely acceptable and too short curves fall, for a particular grade change. Figure 31 is a graph of relationships which could be considered as minimum or barely acceptable curves.

Observations on Sag Vertical Curve Perspectives

As can be seen by comparing Figure 16 with Figure 31, the theoretical relationship was not substantiated. The relative positions of the change of grades (A) are reversed

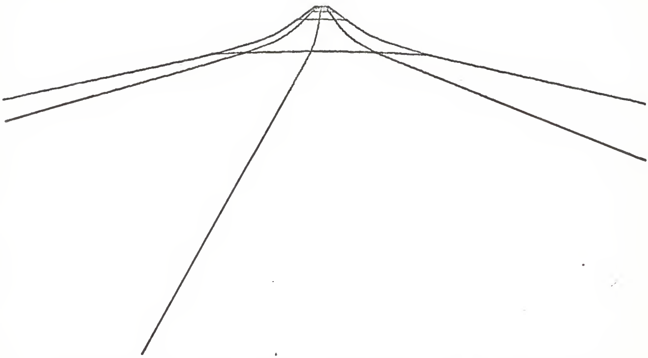


FIGURE 24. Vertical Curve Perspective A=2% L=800' S=500'

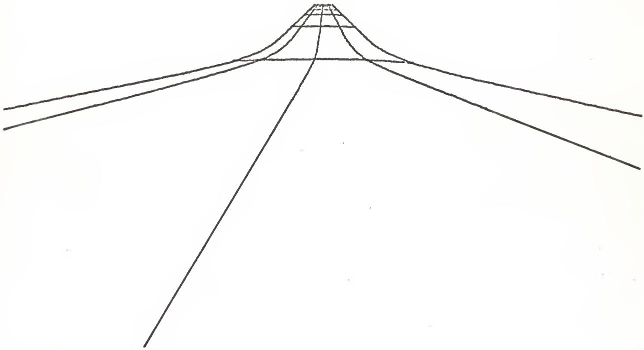


FIGURE 25. Vertical Curve Perspective A=2% L=800' S=750'

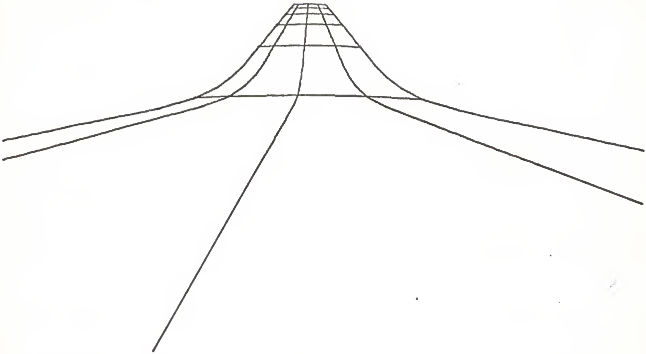


FIGURE 26. Vertical Curve Perspective A=2% L=800' S=1000'

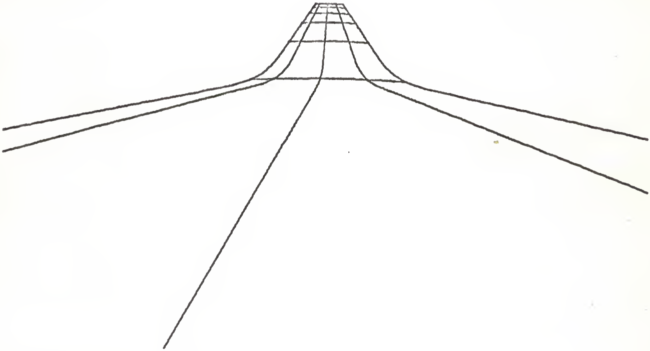


FIGURE 27. Vertical Curve Perspective A=2% L=800' S=1250'

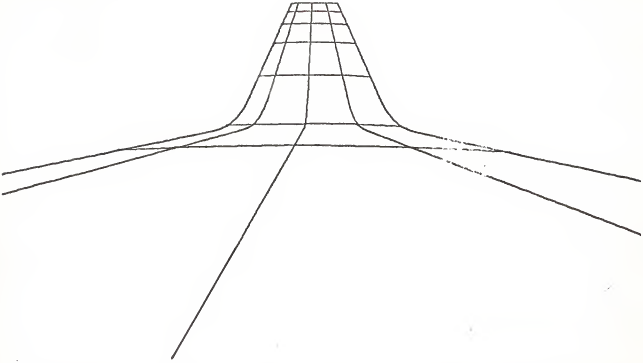


FIGURE 28. Vertical Curve Perspective A=2% L=800' S=2000'

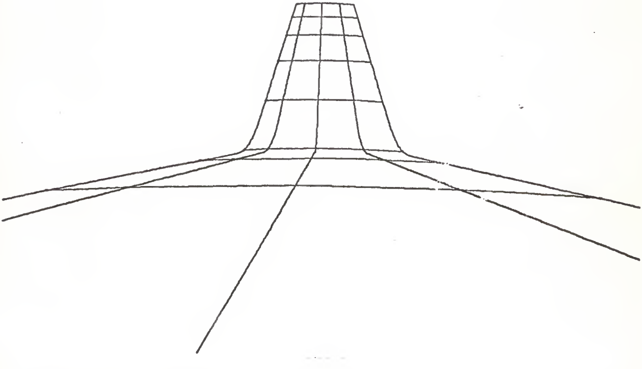


FIGURE 29. Vertical Curve Perspective A=2% L=800' S=3000'

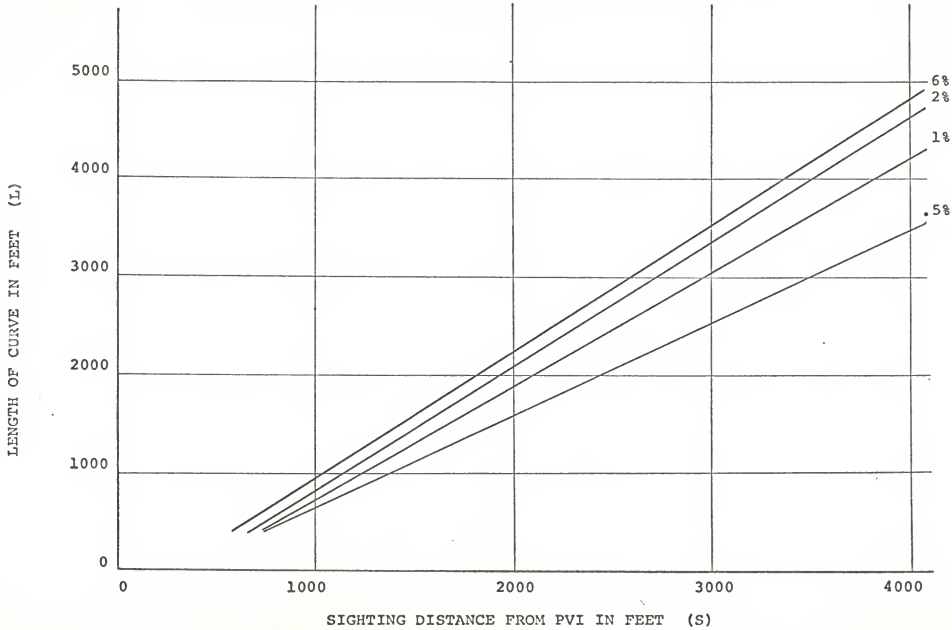


FIGURE 30. Desirable Relationship - L,S,A

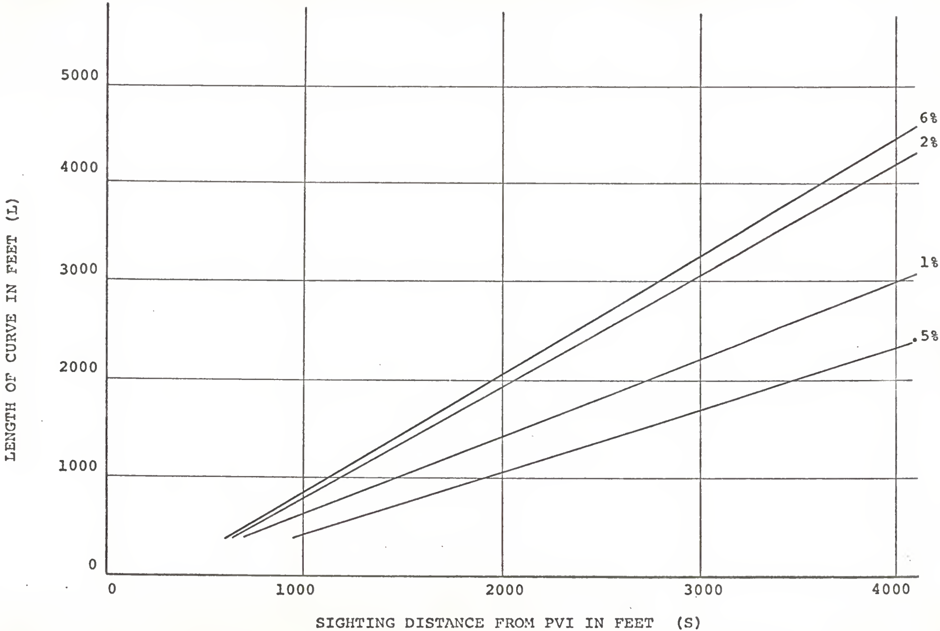


FIGURE 31. Acceptable Relationship - L,S,A

between the two figures. The relationships of up to 2% are believed most valid since small changes in grade are most critical. When a larger change of grade is encountered, it is believed the driver rationalizes that there is a good reason for the vertical curve. In other words, for the larger changes of grade there appears to be a good reason for the vertical curve.

The use of the graphs should be an aid to the designer to judge the length of vertical curve required for a specified change in grade and sighting distance. For a selected location, the designer could choose a minimum vertical curve length based upon Figure 31, "Acceptable". If the designer was dissatisfied with the required curve length, an alternative would be to relocate the highway to shorten the distance from which the curve would be seen. It should be kept in mind that these graphs are valid only for tangent alignments and are not necessarily valid for vertical curves on horizontal curves. A sag vertical curve on a horizontal curve is getting into the area of coordination which was beyond the scope of this research.

THE HORIZONTAL KINK PROBLEM

The problem of an awkward appearing small change of direction such as the "kink" on I-70 in Ellsworth County was recognized by the AASHO "Blue Book" (1). On page 191, the following statement appears:

> "4. For small deflection angles, curves should be sufficiently long to avoid the appearance of a kink. Curves should be at least 500 feet long for a central angle of 5 degrees, and the minimum length should be increased 100 feet for each 1-degree decrease in the central angle."

The "kink" on I-70 has a central angle of 1°30' and a length of 900 feet. The recommendation of the "Blue Book" is satisfied and yet the kinked appearance of the direction change is quite apparent. It seems logical that the kink problem might be closely related to the sag vertical curve hypothesis. That is, if parts of both tangents are seen without refocusing the eye, the horizontal curve will appear too short. In other words, if the angle of sharp focus completely encompasses the horizontal curve plus a portion of the back tangent and the forward tangent, the curve will give the appearance of a kink.

Another factor which probably has some significance is the extent to which the curve is being displayed. If the observer is nearly in the same plane as the curve, Figure 32, the curve is barely discernable. On the other hand, when the observer is quite a distance above the plane of the

FIGURE 32. Observer in Plane of Kink

FIGURE 33. Observer Above Plane of Kink

horizontal curve, as in Figure 33, the change of direction is displayed to the observer and becomes objectionable. When the curve is viewed from directly over it, it is again barely discernible.

Applying the technique of perspectives, two solutions were drawn for the I-70 "kink". The same tangent geometry was used and both solutions involved changing only the length of the horizontal curve.

The first approach eliminated the visible portion of the forward tangent by lengthening the horizontal curve. Figure 34 is the resulting perspective. A curve length of 9000 feet was required which yields a degree of curve of one minute. The horizontal curve is flowing but the problem has been moved to the vertical curve. The appearance of the vertical curve in combination with the horizontal curve might possibly be improved by using a longer vertical curve.

The second approach tried involved selecting a length of horizontal curve so that the vertical curve was not on any part of the horizontal curve. A curve length of 3000 feet was selected which gives a three minute degree of curvature. Figure 35 shows this solution. The kinked appearance has been removed and there is not as serious a coordination problem as with the curve of 9000 feet since the vertical curve and the horizontal curve do not interfere with each other.

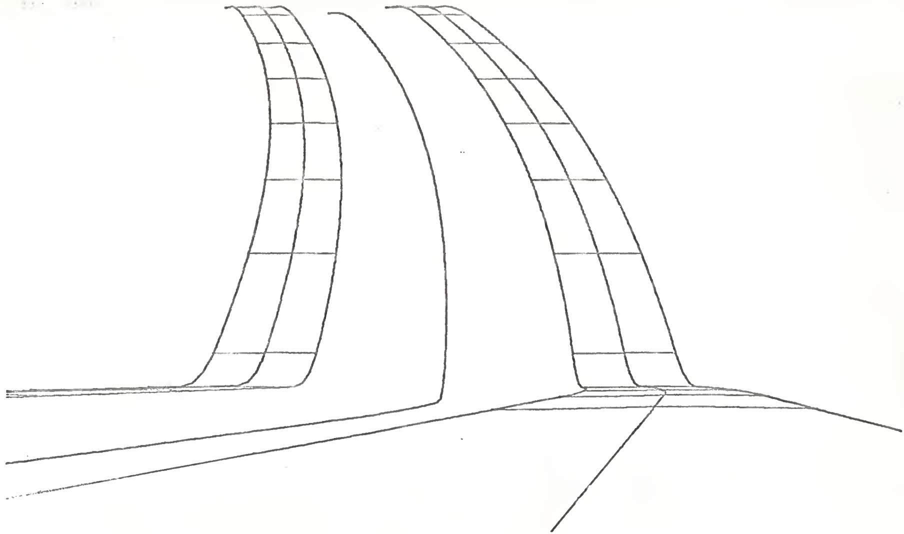


FIGURE 34. Kink Location with 9000' Horizontal Curve, Viewing Distance 7410' to P.I.

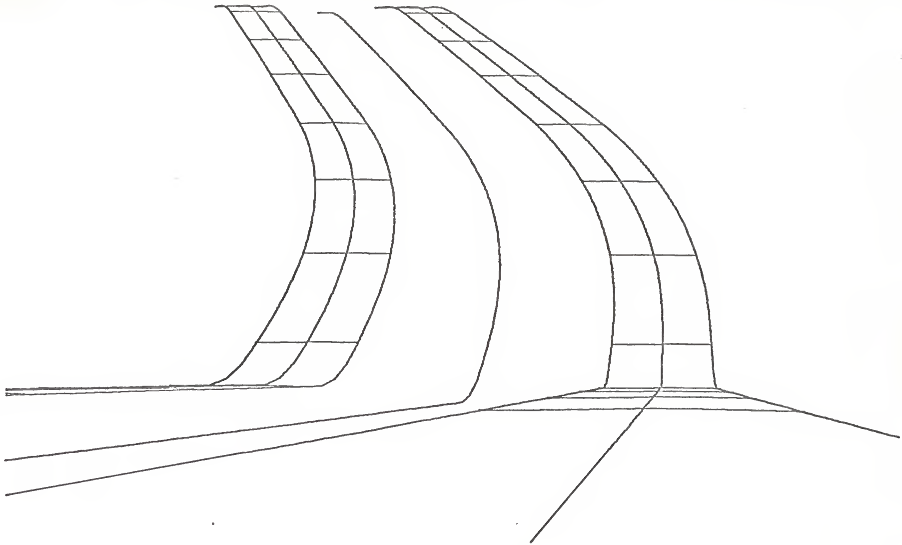


FIGURE 35. Kink Location with 3000' Horizontal Curve, Viewing Distance 7410' to P.I.

A series of perspective drawings were then made to see if the observer's position above the plane of the curve, as well as his distance from the curve, affected the appearance of the horizontal curve. A central angle of 1°30' was used on a +1.42% grade, corresponding to the geometry of the "kink". Two lengths of horizontal curve were utilized, the first was the same as that of the "kink" or 900 feet. The second series were from the identical observer positions used in the first series but with a curve length of 3000 feet. Figures 36 and 37 shows the observer positions and sight distances from which the two series were drawn.

Figures 38 and 39 are of the 900 feet curve and are from a sight distance of 4910 feet. The curve is barely recognizable in Figure 38A, becomes a severe kink in Figure 38B and begins smoothing as the observer becomes elevated above the plane of the curve. Figure 39 is more flowing but would still be judged abrupt.

From a sight distance of 7410 feet, the 900 foot curve is again only barely discernible in Figure 40A, when the observer is only 3.5 feet above the curve plane. The curve becomes a kink as soon as it is visible, Figure 40B, and shows signs of smoothing out in Figures 40C, 41A and 41B. Until in Figure 42 the curve is beginning to appear 'acceptable' visually. Point numbers 9-3 and 9-8 lie in about the same inclined plane and thus the display of the

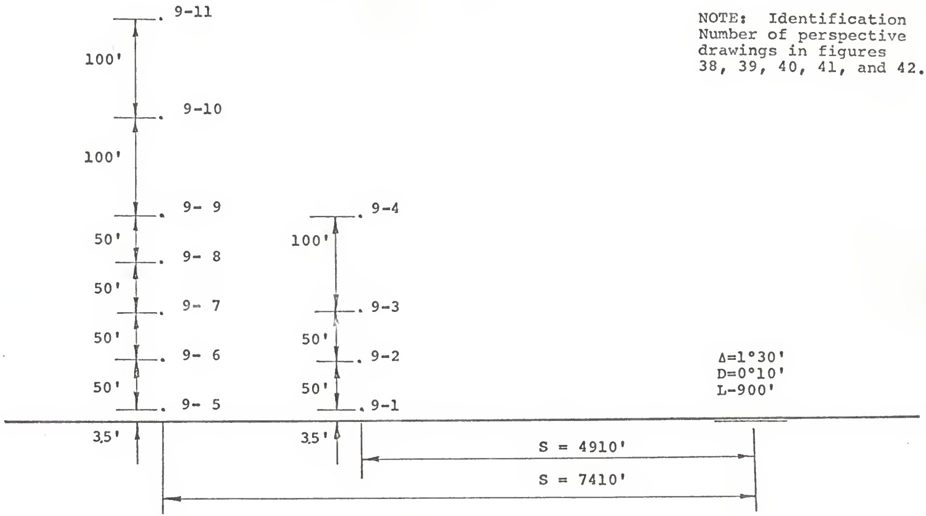
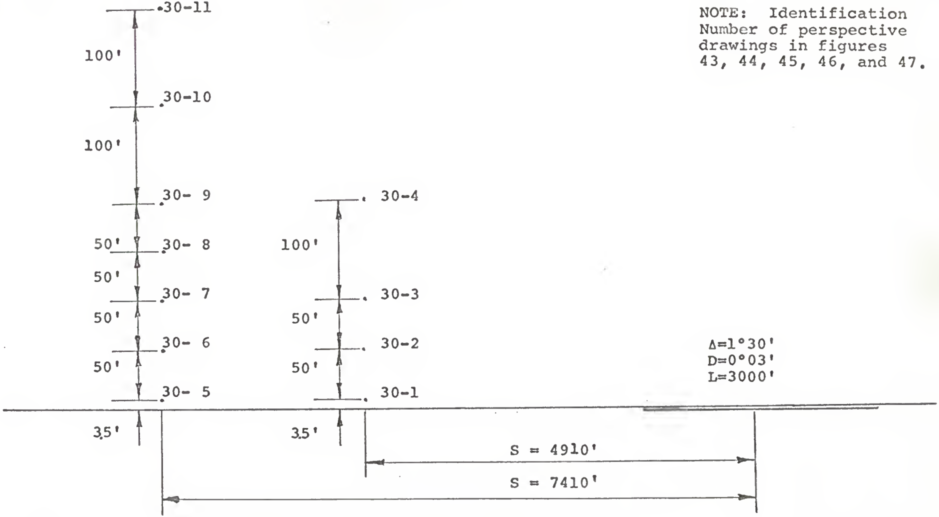


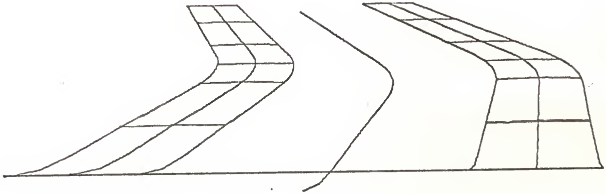
FIGURE 36. Positions of Observer Above Plane of 900' Horizontal Curve



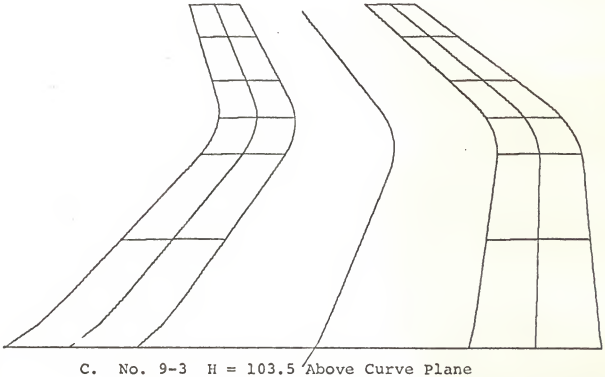
NOTE: Identification Number of perspective drawings in figures 43, 44, 45, 46, and 47.

FIGURE 37. Positions of Observer Above Plane of 3000' Horizontal Curve

A. No. 9-1 H = 3.5' Above Curve Plane

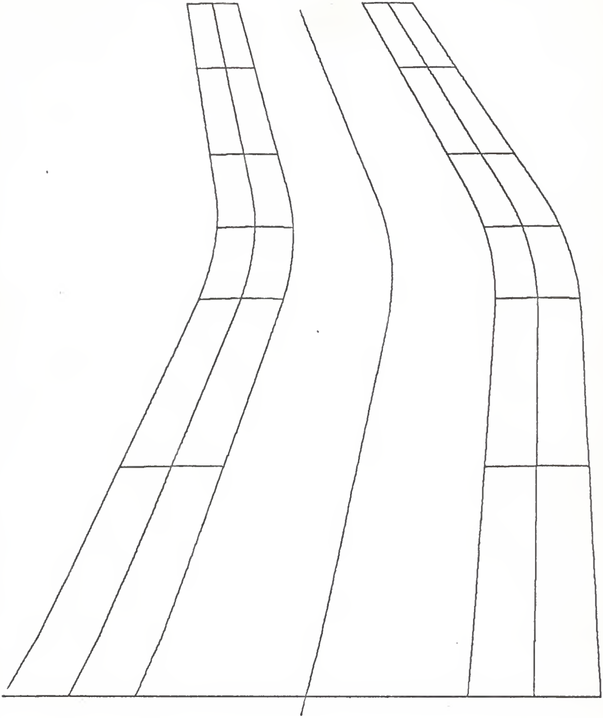


B. No. 9-2 H = 53.5' Above Curve Plane



C. No. 9-3 H = 103.5 Above Curve Plane

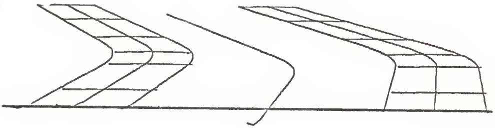
FIGURE 38. Perspectives of 900' Curve, S = 4910' Plate 1



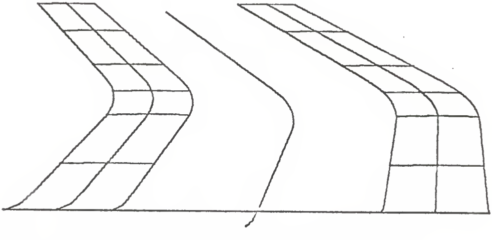
No. 9-4 H = 203.5 Above Curve Plane

FIGURE 39. Perspective of 900' Curve, S = 4910' Plate 2

A. No. 9-5 H = 3.5' Above Curve Plane

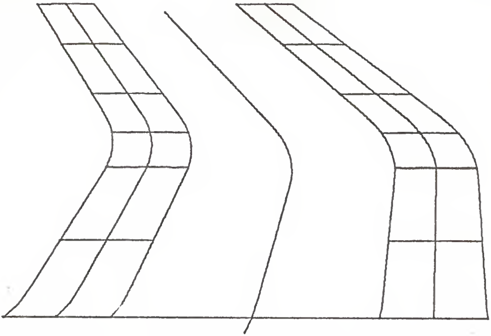


B. No. 9-6 H = 53.5' Above Curve Plane

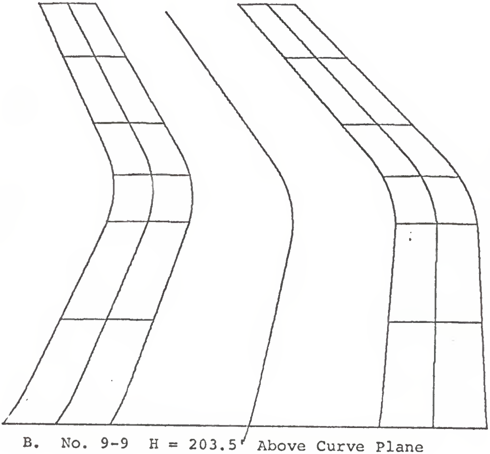


C. No. 9-7 H = 103.5' Above Curve Plane

FIGURE 40. Perspectives of 900' Curve, S = 7410' Plate 1

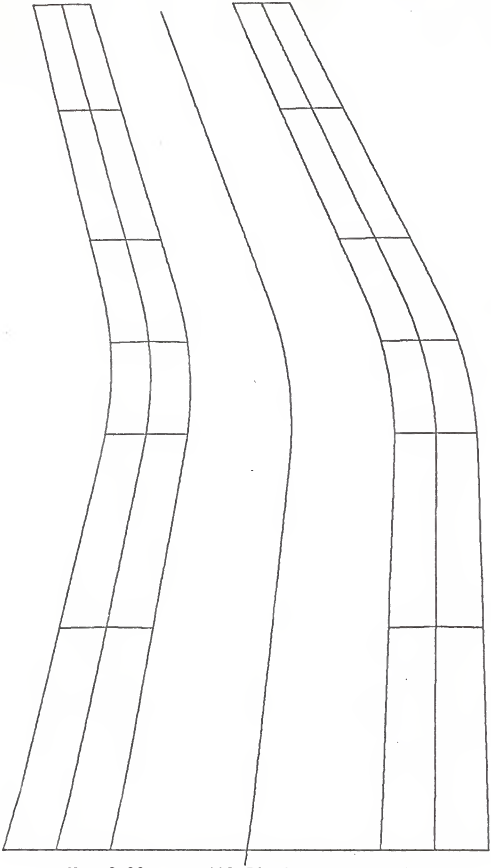


A. No. 9-8 H = 153.5' Above Curve Plane



B. No. 9-9 H = 203.5' Above Curve Plane

FIGURE 41. Perspectives of 900' Curve S = 7410' Plate 2



No. 9-11 H = 403.5' Above Curve Plane

FIGURE 42. Perspective of 900' Curve, S = 7410' Plate 3

curve is about the same. It is felt that 41A shows more lateral jerk than 38C, which is probably caused by the observer being further from the curve.

Two perspectives were drawn with the observer directly over the curve and as expected the curve could not be seen.

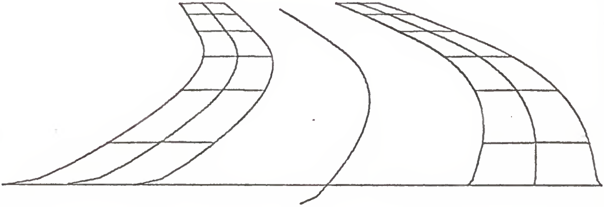
A series of curves were drawn from the same observer positions as the 900 foot curve for a curve length of 3000 feet. From a sight distance of 4910 feet, when the observer is in approximately the same plane as the curve, the curve is barely discernible, Figure 43A. Figure 43B perhaps displays too much lateral jerk and Figures 43C and 44 shows the 3000 foot curve to be smooth. When the observer is moved back to 7410 feet, again when only 3.5 feet above the plane the curve cannot be seen, but the lateral jerk becomes objectionable in Figures 45B and 45C. As the observer moves vertically above the curve plane the horizontal curve becomes more smooth and flowing until at 203.5 feet above the curve plane, Figure 47, the horizontal curve is quite pleasing.

Observations

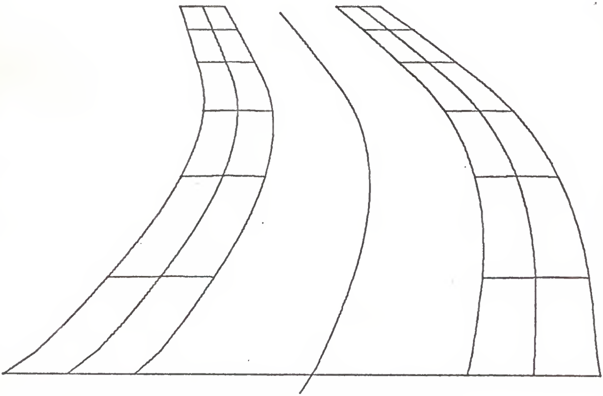
From the preceding perspectives, the best solution is not to have any small changes of direction in the horizontal alignment. But when a small direction change becomes necessary, put it on a crest vertical curve. This places the curve so that the forward tangent will not be seen until the driver is on the horizontal curve, making it impossible for him to see both tangents of the curve at the same time.

When small changes are necessary and cannot be hidden, the proposed design would best be studied by the use of perspectives to determine if the change of direction is going to be objectionable.

A. No. 30-1 H = 3.5' Above Curve Plane

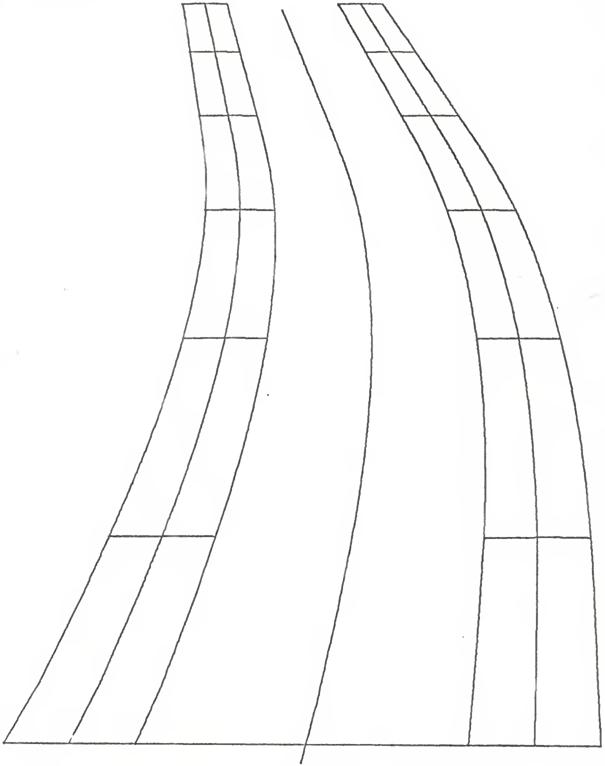


B. No. 30-2 H = 53.5' Above Curve Plane



C. No. 30-3 H = 103.5' Above Curve Plane

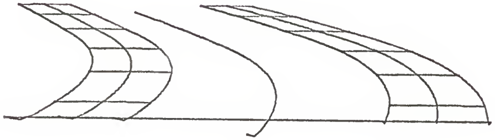
FIGURE 43. Perspectives of 3000' Curve, S = 4910' Plate 1



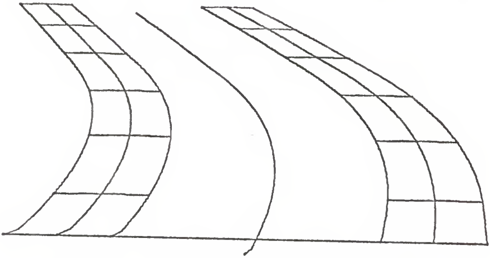
No. 30-4 H = 203.5' Above Curve Plane

FIGURE 44. Perspective of 3000' Curve, s = 4910' Plate 2

A. No. 30-5 H = 3.5' Above Curve Plane

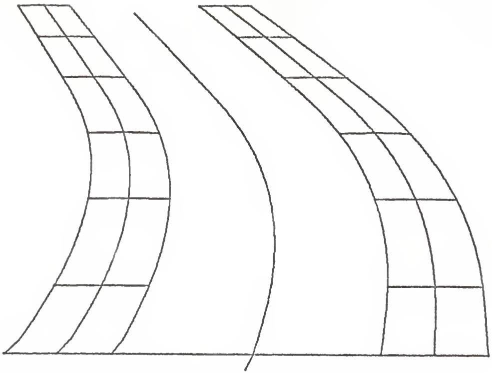


B. No. 30-6 H = 53.5' Above Curve Plane

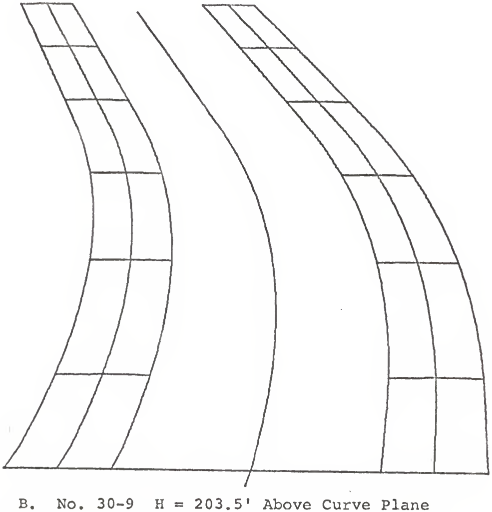


C. No. 30-7 H = 103.5' Above Curve Plane

FIGURE 45. Perspectives of 3000' Curve, S = 7410· Plate 1

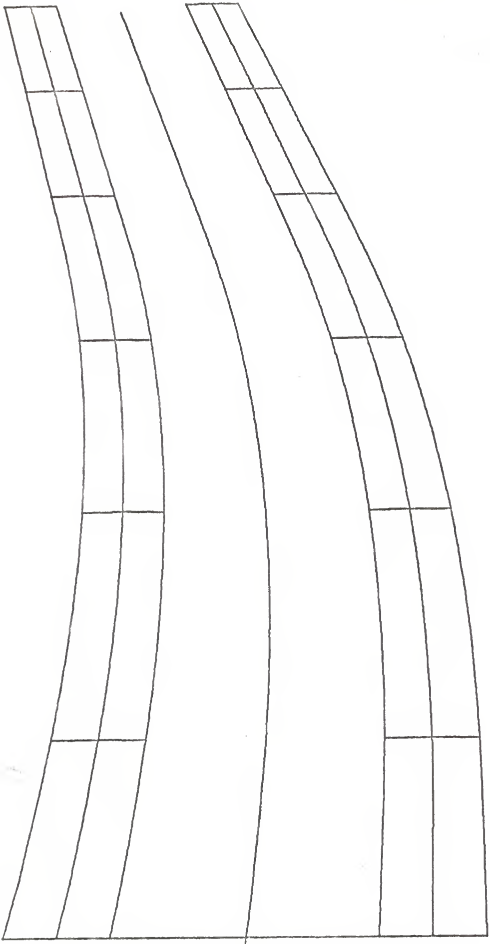


A. No. 30-8 H = 153.5' Above Curve Plane



B. No. 30-9 H = 203.5' Above Curve Plane

FIGURE 46. Perspectives of 3000' Curve, S = 7410' Plate 2



No. 30-11 H = 403.5' Above Curve Plane

FIGURE 47. Perspective of 3000' Curve, S = 7410' Plate 3

CONCLUSIONS

Within the limitations imposed by the scope of this study and from the data collected, the following was concluded:

1. The models which were built were not very helpful for the particular problems studied.

2. The models were of greater aid than the highway plan and profile sheets alone.

3. The highway plan and profile sheets, when viewed from the driver's vantage point, will show many of the visual irregularities.

4. Perspective drawings provided a very realistic picture of the roadway.

5. Perspective drawings provided a very versatile and valuable tool in this study and show great promise as an aid to the highway designer in his task of better highway design.

6. The two graphs developed, Figures 30 and 31, showing desirable and acceptable relationships between the length of sag vertical curve and viewing distance for various grade changes, can be of significant aid to the highway designer.

7. For sag vertical curves, as the algebraic change in grade increases, the length of vertical curve should increase for good visual quality of the roadway.

8. For sag vertical curves, as the distance from the viewer to the curve increases, the length of curve needed increases for good visual quality.

9. The results of the analytical approach to the sag vertical curve problem were not supported by the study of the perspective drawings.

10. As the observer increases his height above the plane of the "kink" type alignment (small change in horizontal direction), the "kink" effect becomes less noticeable.

11. As the observer gets nearer to the "kink" alignment, the "kink" appears somewhat less noticeable.

12. The "kink" appearance is more sensitive to the viewers height above the plane of the "kink" than to the distance from which the "kink" is viewed.

13. When small changes of direction in horizontal alignment are placed on the crest of a vertical curve (so that the observer cannot see the tangent beyond the curve), no "kink" should be apparent.

RECOMMENDATIONS FOR FURTHER RESEARCH

The designer's primary obstacle to good visual highway design is the proper coordination of horizontal and vertical alignments. Many roadways are thought to be aesthetically satisfying because both the horizontal and vertical alignments, considered separately, are correctly designed and integrated with the terrain. The constructed road is often disappointing. This is because the alignment is a three-dimensional curve whose perspective appearance depends not only on the vertical and horizontal projections but also on the combination of the two. The electronic plotter can now serve as a laboratory for the designer. He will be able to vary the various elements of his design to see the results from the driver's view.

The models described in this report may be a real aid in a study of this sort.

The research described in this report made no attempt to incorporate the surrounding terrain. This capability should be pursued further. Bernede, et al (19) have been quite successful in this area.

Dynamic studies (cartoon-like perspectives) appear to be feasible (17,18,19) and their application to design problems should be extensively investigated. A commercial plotter is now available which plots the perspectives on a cathode ray tube. Photographs of a series of perspectives can produce an effect similar to driving the road.

The problem of "jerk" in the horizontal alignment should be studied. Computer plotted perspectives should make it possible to determine the lengths of simple horizontal and spiral curves necessary to achieve the desired smoothness of alignment. A new version of the COGO computer program (Civil Engineering Coordinate Geometry) for the IBM 360-50 is now available. This program will allow very rapid computation of the space coordinates of spirals and vertical alignment as well as simple curve horizontal alignment.

REFERENCES

1. A Policy on Geometric Design of Rural Highways. American Association of State Highway Officials, Association General Offices, 1965.

2. Tunnard, Christopher and Pushkarev, Boris. Manmade America. Yale University Press, New Haven, Connecticut, 1963.

3. Smith, B. L., and Fogo, R. D. Some Visual Aspects of Highway Design. Highway Research Record 172, Highway Research Board, 1967.

4. Cron, F. W. Geometric Design as Related to Landscape Features. Talk for Highway Beautification Conference at Kansas City, Missouri, April 1966.

5. Cron, F. W. Fitting the Highway to the Landscape. In The Highway and the Landscape, Ed., W. B. Snow, Rutgers University Press, New Brunswick, New Jersey, 1959.

6. Cron, F. W. Modern Curvilinear Highway Location and Design. Proceedings ASCE, No. 2278, December 1959.

7. Appleyard, Donald, Lynch, K., and Myer, John R. The View From the Road. M.I.T. Press, 1963.

8. Leisch, J. E. New Techniques in Alignment Design and Stakeout. Proc., ASCE, Jour. of the Highway Division, Vol. 92, No. HW1, March 1966.

9. Snowden, Wayne H. First Readings in Visual Design for Highway Engineers. An information circular of the Institute of Transportation and Traffic Engineering, University of California, Berkeley, July 1966. (10 references are annotated).

10. Berry, F. R., McCabe, E. J. Development and Use of Models in the Design of Highways. Highway Research Record 172. Highway Research Board, 1967.

11. Collins, R. M. Design Models, California Highways and Public Works. May-June 1965.

12. Butcher, C., Pearson, J. The Photography of Architectural Models. Paper resulting from a senior project in the Department of Architecture, California State Polytechnic College, San Luis Obispo, California, 1964.

13. Driver's Eye Plotter Aids French Highway Engineers, Digital Plotting Newsletter, California Computer Products, November-December, 1966.

14. COGO (Civil Engineering Coordinate Geometry Computer Program), Department of Civil Engineering, M.I.T., Cambridge, Mass., 1965.

15. Smith, Bob L. and Yotter, Edward E. Visual Aspects of Highway Design. Preliminary Research Report Submitted to the Kansas State Highway Commission, February 1, 1968.

16. Parks, R. A., Rowan, N. J., Walton, N. E. A Computer Technique for Perspective Plotting of Roadways. Research Report 19-3, Texas Transportation Institute, July 1967. Presented at the 47th Annual Meeting of the Highway Research Board, January 1968.

17. Geissler, E. H. A Three-Dimensional Approach to Highway Alignment Design. Department of Highways, Ontario. Report Number RR138. Presented at the 47th Annual Meeting of the Highway Research Board, January 1968.

18. Fetter, W. A. Computer Graphics in Communication. Engineer Graphics Monograph Series, McGraw-Hill, 1965.

19. Bernede, J. F., Godin, P., Deligny, J. L., Antoniotti, P., Day, J. A. Visual Quality Studies in Highway Design. French Power Bureau, Washington, D.C. Presented at the 47th Annual Meeting of the Highway Research Board, January 1968.

VISUAL ASPECTS OF HIGHWAY DESIGN

by

EDWARD E. YOTTER

BSCE, Kansas State University, 1964

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment

of the requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1968

ABSTRACT

The purpose of the research, described in this report, was to study some particular ways in which the highway designer could be assisted in his task of designing a visually stimulating highway.

The research was limited to the following:

1) The sag vertical curve was studied in order to place limits on the length of vertical curve, so that an aesthetically pleasing ribbon of roadway would result.

2) The determination of the minimum length of simple horizontal and/or spiral curves which would yield a smooth-appearing alignment rather than a kink in the road ahead.

3) An exploratory study of problems concerned with the coordination of horizontal and vertical alignment.

The early research efforts in the project were aimed at:

1) The development of models which would look like the real roadway and which, hopefully, could be changed readily to reflect refinements in design.

2) The development of an analytical approach that would be of help in solving the sag vertical curve problem.

3) The carrying out of an extensive literature search. The literature concerning how one views a road or what is seen and how this is actually accomplished was not very helpful. On the other hand, a significant body of literature

concerning models, model photography, and perspective drawing of the roadway was found and much of it was extremely helpful in the research. The list of references contains the more significant papers which were studied.

Three types of models were constructed, studied, and photographed. A large number of photographs were taken of some specific highway locations which exhibited some readily apparent awkwardness.

As the research progressed it became increasingly apparent that perspective drawings of the roadway ought to be of significant aid. We became convinced that it was feasible to prepare perspective drawings of the roadway, from the driver's vantage point, using an electronic plotter.

Quite fortunately, an electronic plotter located at Wichita State University was made available for the research. Dr. Walter Bernhart, WSU, was very helpful and encouraging throughout the study.

A series of perspective drawings were made of specific existing highway geometry in order that the "realism" of the perspectives could be assessed. The drawings were extremely realistic.

Next a series of perspectives were made to study the sag vertical curve problem and the horizontal kink problem Nearly 200 perspective drawings were made and studied. We are now fully convinced that perspective drawings, produced by the electronic plotter, will prove to be a highly effective tool to be used in the design of a modern highway system.

The two graphs developed, Figures 30 and 31, showing desirable and acceptable relationships between the length of sag vertical curve and viewing distance for various grade changes, can be of significant aid to the highway designer.