HIGHWAY RESEARCH RECORD

Number 270

Photogrammetry and Aerial Surveys

Geometric Design

5 Reports

Subject Area

21 Photogrammetry
22 Highway Design

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

Washington, D. C., 1969

Publication 1647

Price: $2.20

Available from

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

Department of Design

W. B. Drake, Chairman
Kentucky Department of Highways, Lexington

HIGHWAY RESEARCH BOARD STAFF

L. F. Spaine

GENERAL DESIGN DIVISION

M. D. Shelby, Chairman
Texas Transportation Institute
Texas A & M University, College Station

COMMITTEE ON PHOTOGRAMMETRY AND AERIAL SURVEYS

(As of December 31, 1968)

Glenn Anschutz, Chairman
Kansas State Highway Commission, Topeka

William T. Pryor, Secretary
Bureau of Public Roads, Washington, D. C.

Robert L. Alston
Fred B. Bales
Forrest G. Bentley
H. L. Brantley
Richard H. Burke
James J. Byrne
Roger R. Chamard
J. E. Colcord, Jr.
Richard A. Coleman
John Oran Eichler
Hubert A. Henry
Lloyd O. Herd
David S. Johnson, Jr.
George P. Katibah
Gottfried Konecny
M. H. MacLeod
Charles E. McNoldy
Robert D. Miles
Olin W. Mintzer
Grover W. Parrott
Arthur C. Quinnell
Harold Rib
Vernon H. Schultz
Charles R. Shade
James I. Taylor
Robert D. Turpin
John Waller
Robert J. Warren
James I. Webster
Dwight E. Winsor
Marshall S. Wright, Jr.

COMMITTEE ON GEOMETRIC HIGHWAY DESIGN

(As of December 31, 1968)

W. A. Wilson, Jr., Chairman
North Carolina State Highway Commission, Raleigh

William P. Walker, Secretary
Bureau of Public Roads, Washington, D. C.

John E. Baerwald
P. B. Coldiron
Harley T. Davidson
W. A. Frick
Maynard Glass
William C. Gray
Peter J. Hunt
Nelson C. Jones
Jack E. Leisch
Robert L. Lewis
D. W. Loutzenheiser
Val G. Rinehart
B. H. Rottinghaus
Ronald D. Schmied
Bradford G. Sears
M. D. Shelby
Bob L. Smith
K. A. Stonex
John Walter

Foreword

Photogrammetry and Aerial Surveys

Most highway agencies are now using aerial surveys, ranging from elemental general uses to specific detailed and accurate applications. In recent years, effort has been made to reduce the cost of control surveying for obtaining the coordinates of position and elevation points essential for photogrammetrically making precise measurements and compiling large-scale topographic maps. Fortunately, progress has been made in the use of aerial analytical triangulation to reduce the cost of obtaining supplemental control, thereby relegating ground surveying to basic control and using precision photogrammetry to obtain the supplemental control. These procedures not only have reduced costs, but also have improved the ease with which maps can be compiled and measurements made photogrammetrically, and they have done so with reliability and confidence.

The paper by Habel details the developments, procedures, and successes achieved in the Virginia Department of Highways in determining all supplemental control by photogrammetric techniques. Virginia's is the first state highway department to use these methods on a staff basis. Habel lucidly explains the principles utilized, procedures developed, and results attained.

Jensen and Steele report the factual work accomplished in making supplemental control surveys by photogrammetric techniques for mapping an 83-mile project at the scale of 100 feet to 1 inch in a mountainous area where much of the ground is obscured by deciduous trees. The authors give details of the work undertaken, the problems encountered, solutions achieved, and the precision of work accomplished, all of which were satisfactory from an economical and functional point of view. The mapping was accomplished with greater ease using the photogrammetrically determined control than had been the case when all supplemental control had been surveyed on the ground.

—W. T. Pryor

Geometric Design

The last three papers of this RECORD present techniques for providing optimum geometric designs. They are concerned with methods that will aid in visualizing highways in the design stage.

Porter describes in detail an inexpensive technique using scale models and photographs for evaluating alternative designs of relatively small sections of a given highway. A scale model (1 in. = 40 ft) was constructed using a mixture of motor oil or glycerine and asbestos powder for the built-up terrain. Both mixtures stayed malleable and could be easily remolded as alternative designs were studied. The visual evaluation of the alternative designs, as modeled, was significantly aided by photographs that gave a realistic "driver's view" of the roadway. The details of both the photographic and modeling techniques are given.

Smith and Yotter describe the use of perspective drawings as an aid to the designer in his efforts to provide visual quality in highway design. Computer-drawn perspectives of the roadway from the driver's vantage point were made and provided a highly realistic picture of the roadway. As a result of the study of such perspective drawings, a graph was developed showing visually desirable relationships between the length of sag vertical curve and viewing distances for various grade changes. This graph should be of significant aid to highway designers. Computational techniques for perspective drawings as well as several examples of perspectives of highway alignments are included in the paper.

Geissler and Aziz describe techniques of highway model-building and photographic evaluation of a modeled design. The techniques are applied to a complex interchange design. A brief discussion of other techniques used in inexpensive model building is included. For the purpose of design analysis and evaluation, still and movie photographs of the interchange model were shown to a randomly formed group of drivers. A discussion of the analysis and evaluation of the design is included in the paper.

—Bob L. Smith

Contents

Analytical Aerial Triangulation Within the Virginia Department of Highways

GEORGE W. HABEL, JR., Assistant Photogrammetric Engineer,
Virginia Department of Highways

The Virginia Department of Highways was the first state highway department to use analytical triangulation as a method of control extension as a totally in-house operation. This paper deals mainly with the mechanical operation and the gathering of data rather than the processing of these data in an electronic computer.

The process described uses a Wild PUG-3 to transfer and mark points and a Mann monocomparator to read photo coordinates. The techniques employed in using the instruments and the results obtained are discussed. It is concluded that analytical aerial triangulation is a satisfactory method of control extension for highway photogrammetric surveys and that the new skills required can be mastered by the average highway photogrammetrist.

•THE Aerial Survey Section in Virginia began operating late in 1957 with three Kelsh stereoscopic plotters, which by now have been increased to a total of seven. Two of these are four-projector K-100 models that are used as two-projector plotters most of the time. The personnel of this section were all drawn from the drafting and survey branches of the Virginia Department of Highways. Four of these men received several weeks of training on the Kelsh plotter, initially at the Bureau of Public Roads photogrammetric center in Washington, and since that time all of our photogrammetric personnel have received in-house training.

In all of our early work, we attempted to control each stereoscopic model and used no control extension. In fact, this policy continued for about eight years, at which time we became interested in some method of control extension. We have never been convinced that the large, optical train, stereoscopic plotting instruments would be satisfactory for large-scale work. Further, these instruments are awkward for measuring cross sections, and we would be using a $45,000 instrument to do the work that a $7,000 Kelsh instrument would do quicker. Another reason we never became interested in a heavy plotter was that analytical aerial triangulation seemed to be just around the corner, and the initial investment for instrumentation would be considerably less than the $100,000 required for a heavy instrument with bridging capability. We had watched the development of analytical aerial triangulation within the U.S. Coast and Geodetic Survey with more than passive interest and when an electronic computer program written for the IBM 1620 computer became available in 1965, we started a program to sell this method of control extension within our own organization.

The method of analytical aerial triangulation we are using was recommended by G. C. Tewinkel of the U.S. Coast and Geodetic Survey, and is based on their two-photo computer program, and use of the Wild PUG-3 point transfer device and the Mann monocomparator with Data Logger. In this system, points are marked and transferred from one plate to the next with the Wild PUG-3. The plane coordinates of these points

---

Paper sponsored by Committee on Photogrammetry and Aerial Surveys and presented at the 48th Annual Meeting.

are then measured to an accuracy of ± 1 micron with the comparator, and the readings punched into IBM cards. This information, along with the ground position of certain select control points, serves as the input to a rather lengthy series of computer programs. This series consists of a coordinate refinement program, a relative orientation program, a cantilever extension program, and a strip adjustment program.

These programs are written for an IBM 1620 computer with 40K storage and, as written, are a nightmare of card-handling, duplicating, sorting, and adding control punches. We have written additional program routines so that all of the programs will run from the beginning to the output of the strip adjustment program with very little attention from the computer operator. Also, several combinations of ground control may be selected for the initial pass through the computer. Normally two adjustments are made during the initial pass through the computer using as varied a combination of control as possible. This allows us to detect and eliminate any point that probably contains an error. A detailed discussion of these computer programs is given elsewhere (1, 2, 3, 6).

The programs for the IBM 1620 with 40K storage allow only a second-degree adjustment in the vertical adjustment program, and this does not always give a good fit to the vertical control. It appears that a better fit would be obtained if the strip could be twisted more.

We like the analytical approach to control extension because of the relatively low investment for equipment and the fact that the operators do not have to be as skilled as those required on a heavy instrument. The cost of the PUG and comparator was $36,353. The smaller photogrammetric unit, which has an Auto-Trol scaler available that can be spared one day a week, can save at least $10,000 on this price.

I would recommend the Auto-Trol scaler over the Data Logger that comes with the Mann comparator because the Auto-Trol is a much more flexible unit and can be used to digitize other devices. The Data Logger, although very reliable electronically, is more or less a one-shot deal—good only for digitizing the Mann comparator or a coordinatograph.

The Wild PUG-3 is used to transfer and mark points on the glass plates on which the aerial photography has been printed. The accurate transferring of points from one glass plate to the next is the most critical job in analytical aerial triangulation when a monocomparator is to be used to measure the plate coordinates. The operation of the PUG-3 requires a skilled photogrammetrist. We find that there are only a few men in our organization who have the stereoscopic vision and the other qualities required to obtain the best results from this instrument.

The selection of pass points is also very critical. These should be in flat areas where the parallax can be easily cleared. We have found that natural image points in areas where there is considerable change in elevation, such as in paved gutters or at corners of buildings, usually have large y-parallax residuals in the output of the orientation program. These conditions usually pertain to horizontal control points. Vertical control points are usually selected where it is not necessary to be on a definite point to obtain the correct elevation, and they do not cause this problem.

In marking a point with the Wild PUG, the parallax is cleared only in the local area. The point is then marked by drilling a hole in the photographic emulsion on the glass plate. These drills come in 40, 60, 100, 180, and 250 micron sizes. We started out using the 100-micron drills, because these are not as fragile as the smaller drills. It was found that the 100-micron drill hole was causing operator bias when transferring the point from one plate to the next for all but our more experienced operators. Also the residual y-parallaxes were much smaller in the first stereoscopic model, where there is no point transfer of previously drilled holes, than in successive models. We then used 60-micron drills in the hope that the smaller hole would improve this condition. There was no apparent improvement in the transfer bias, however, and we will probably make the 100-micron drilled hole standard practice, since this is the smallest hole that can be seen when the photographic images are projected in the Kelsh plotter. A point transfer device that would allow the simultaneous drilling of all three glass plates would be desirable, but we cannot be sure that it would be worth the cost, because the more experienced operators are not obviously biased by one plate having been drilled when transferring points.

As far as we know, there is no practical method to adjust the travel of the drills on the PUG. We are working to micron tolerances, so by necessity there must be a very close fit between the drill and its holder. The drill is so constructed that it telescopes into the holder as the holder is lowered. The drill is spring-loaded to control the pressure on the drill bit. A problem was encountered when the bit would stick in the holder as the drill holder was withdrawn, then release suddenly before the holder was high enough for the bit to clear the plate. This caused the bit to hit the plate a hammer-like blow, which would often destroy the point being drilled as well as occasionally break the bit. This was corrected by placing a shim under the arm that raises and lowers the holder to limit its travel. It is suggested that the movement on this arm be made adjustable during manufacture.

The PUG has caused considerable eyestrain for all of our people who have used it. The optics on the PUG are excellent, and apparently it is just the nature of the instrument to cause eyestrain.

The PUG comes equipped with either of two types of optics. One type is designed to measure glass plates that are made to be used in direct projection plotters with the emulsion side down and the other with the emulsion side up. We did not know this when we bought our instrument. All of our plates are used emulsion side down, and our PUG was made to measure plates that are to be used emulsion side up in what Wild calls the "American design" system. The so-called American design gives a mirror image, makes misidentification of points much more likely, and causes the operator to take greater precaution than would normally be required in identifying a point. We have had the optics changed that caused this reversal of the image.

The Mann comparator can be operated successfully with very little training. The chief problem for the operator of this instrument is keeping the points numbered correctly. The Mann 422F comparator, which we have, is equipped with a Bausch and Lomb zoom binocular microscope and is very confortable to use. Most operators report no eyestrain. The microscope on our instrument gives a mirror image, which is objectionable, but not as much as it would be if we were measuring images instead of drilled points and fiducial marks.

We normally measure a point at least three times with the comparator. The error in pointing is so small that one time would be sufficient were it not for the backlash in the screw-type comparator, which makes it necessary to approach a point with the lead screws turning in the positive, or clockwise, direction. There is always a possibility that the operator will turn the lead screws in the counterclockwise direction when making a pointing, and measuring three times allows an error of this type to be detected. It is our experience that very few of these errors occur—possibly one apparent erroneous measurement for every 20 models—and the error is then usually in measuring fiducial marks, which are difficult to center correctly.

We have had the fiducial marks on our Wild RC8 camera changed from the open-cross type to the interrupted cross with a small dot in the center. At the same time, four more fiducial marks were added, one on each side, so that we now have a total of eight. After this change, there was a 10 to 15 percent reduction in the magnitude of the residual y-parallaxes in the relative orientation program. This was probably because the fiducial marks could be measured more accurately, and better correction for film deformation could be attained. The fiducial marks are still not as easy to measure as a drilled hole.

We are now measuring the glass plates with the emulsion side down, since our plates are printed to be placed in Kelsh plotters this way. The plates are measured in this manner because the drilled points on the plates are much easier to find when they appear in the same relative position on the plate as on a contact print. The images on the plate are difficult to see when the plate is placed on the comparator because the surfaces below the plate are black, unpolished cast iron. We have lined this black area with white paper, which reflects enough light to make the image on the plate visible. This area should be painted white and a light placed below the plate.

The original X and Y drive motor switches required both hands for operation. We have replaced the two-hand control with a "joy stick" arrangement, which we consider to be much better. This feature leaves the operator with one hand free to change the Data Logger while moving the measuring system from one point to the next, and he is in a much better position to view his paper print of the photograph. The X and Y axes can be reversed on the comparator by changing the position of the X and Y plugs in the Data Logger, and the apparent direction can be changed by rotating or reversing the photographic plate. This makes it possible to measure the plate emulsion side up or emulsion side down and still have the X and Y axes in the desired position on the plate.

Our Mann comparator is equipped with what is known as a pivot stage. This stage allows as much as 15 degrees of rotation, and the cost is some $1,200 less than the rotating stage. We have found this amount of rotation to be adequate in all cases. This rotation is used only while aligning fiducial marks of the open-cross type with the reticle in the comparator microscope. We would prefer to have a fixed stage when measuring plates that have our new fiducial marks. We have placed two bosses on the stage to aid in returning a plate to its original position on the comparator in case a point is missed or has to be checked. When the plate is placed on the stage, it is placed against these bosses, which hold the plate in a fixed position on the stage. We have had very good success with points that we have added after the initial measurement of the plate, or with points that were missed in the first measurement. This is more or less an emergency procedure with us, and it is up to the operator to deter-

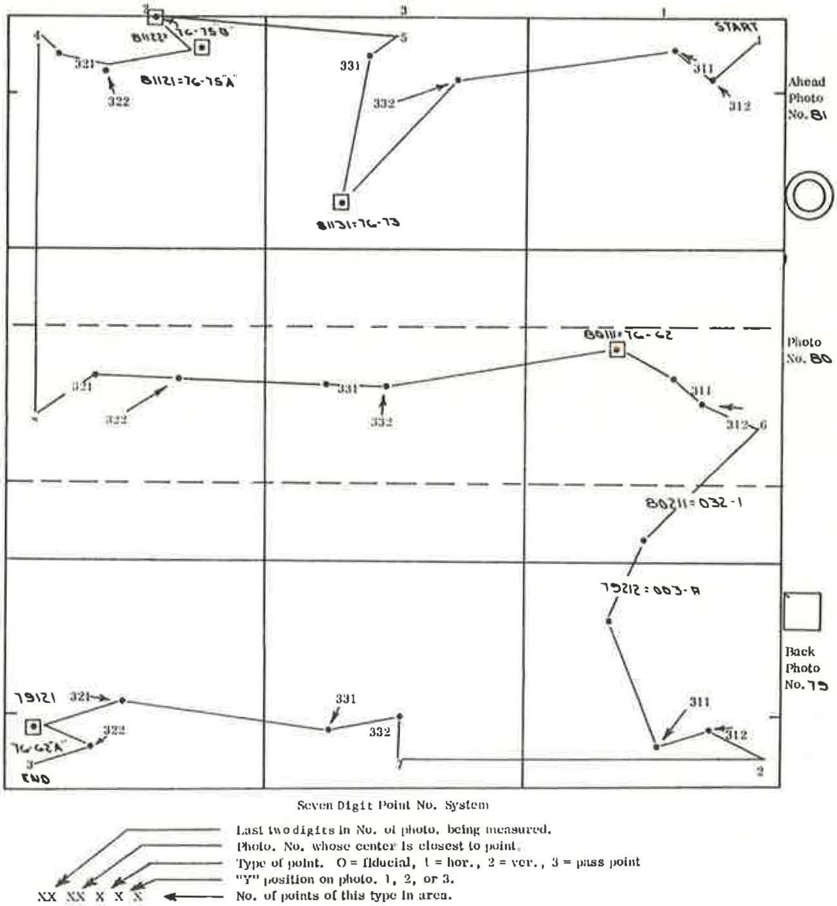
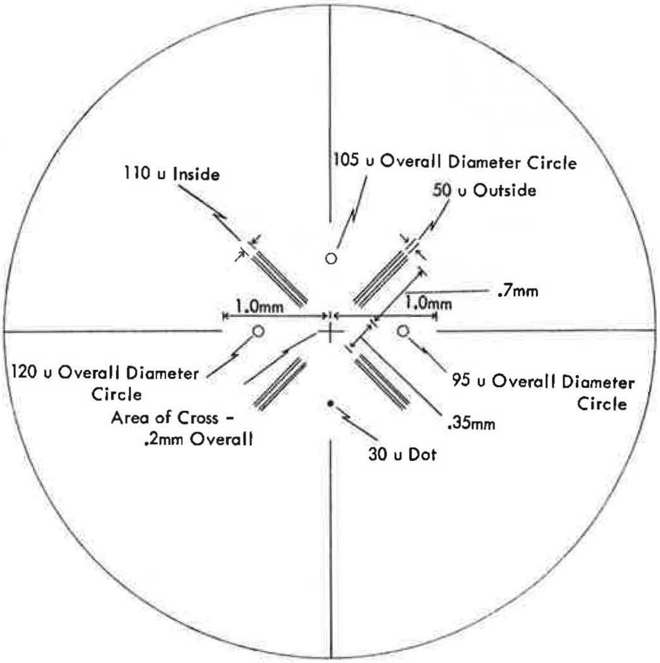


Figure 1. Aerial triangulation point record (Job No. 052 Photo. No. 180).



Dimensions given are apparent, as measured by comparison with a point on a plate on the stage of the comparator. Line weights are apparent 5 microns, except for the three circles which shall be apparent 20 microns. Diagonal lines to be centered on center cross. Placement of three circles and dot is not critical.

Figure 2. U. S. Coast and Geodetic Survey reticle.

mine whether to measure the plate over or whether to attempt to remeasure only the missing point. This usually depends on the availability of a card punch and the importance of the point.

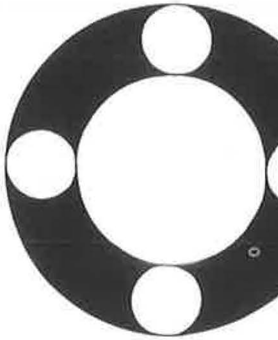
Our comparator is connected to a card punch in the Computer Section by about 200 feet of cable. IBM's engineering section advised us that this probably would not work, but to try it anyway. We have an intercom system set up so that the comparator operator can listen to the keypunch operate and communicate with the Computer Section. The operator can tell when the card punch is operating correctly, because the sound on the intercom is the same for every reading. This system has worked so well thus far that, if it were not for running out of cards, the intercom would be unnecessary. There have been very few instances where a point has been missed or where a card was punched incorrectly, once the machine was programmed correctly.

Figure 1 is a form we are using to record the location of the control and pass points and their number. All points are numbered on this form in their approximate position before the comparator operator starts making measurements. The comparator operator draws a line from point to point as he measures it. We do not have a typewriter with our comparator.

We do obtain an IBM listing of the cards and check the listing against our comparator record form to make sure that all points are measured and are numbered correctly. This form is probably not necessary except when measuring more than one pass point in each of the strategic areas of the model or on experimental or research projects, where the ground control is dense and misidentification likely. We also check to make sure that all points meet a certain tolerance.

Our comparator is equipped with motor drive on both the X and Y axes. It takes approximately one minute for the comparator measurement marker to travel from one side of the plate to the other. The fiducial marks are numbered according to the copy of our comparator record form (Fig. 1), and must enter the computer in numerical order. We originally read the plates in this order, which theoretically requires a minimum travel time of $9\frac{1}{2}$ minutes per plate. By adopting the path as shown on the form, which requires a minimum travel time of 4 minutes, we have actually saved from 5 to 10 minutes per plate. A plate can be measured in about 45 minutes, and an experienced operator can measure about 9 plates per day. Using this method, it is necessary to run the cards through a card-sorting program, which requires only a few minutes for the entire strip.

We are now measuring only six pass points per model, which speeds up the whole operation. This has naturally reduced the Y residuals in the orientation program from an average of 5 microns when using 12 points in the orientation to an average of about 2 microns. We expected some loss of accuracy, but so far there is no obvious deterioration.



95-micron outer circle. 55-micron inner circle. Recommended reticle for reading 100-micron drilled holes and fiducial dots. The four open circular areas allow accurate centering of fiducial dots of between 55 and 95 microns diameter.

Figure 3. 95-μ circle.

We are using a U.S. Coast and Geodetic Survey reticle design in our comparator (Fig. 2). This is a good reticle, but we would probably make some changes in it if we were designing a new reticle based on our experience. At present we are using the center cross and the 95-micron circle. The 95-micron circle gives excellent repeatability when reading 100-micron drilled holes. There is an area of doubt, however, when measuring the fiducial marks that have a center dot varying from 65 to 90 microns in diameter, depending to some extent on the density of the photographic plate. This area of uncertainty could be largely eliminated with a reticle design similar to that shown in Figure 3.

The flash plate, which is made by exposing the fiducial marks of the camera directly on a glass plate, should be mentioned. It is the calibration plate containing the fiducial mark positions and is used in the coordinate refinement program to determine corrections for film deformation by adjusting the X and Y coordinates of all points on the successive photographic transparencies to agree with the camera fiducial marks as imaged on the positioning calibration plate. Determination of the correct coordinates for the fiducial marks is very important. The flash plate should be measured in at least two positions, and possibly four positions, 90 degrees different in orientation on the comparator in order to remove any error due to the fact that the axes are not exactly 90 degrees to each other.

We have been very well pleased with the results obtained from analytical aerial triangulation. We have found that the azimuth tie between models that are bridged is much better than when we controlled every model by use of ground-surveyed supplemental control. This is due to the larger scale base, which results in a better edge check between models. We have done several jobs that could not have been done conventionally. One was a 14-model strip through a wooded, swampy area where we needed to extend cross sections. We had previously measured cross sections through this area photogrammetrically and had to secure 60 percent of the cross sections by conventional ground methods. The new photography had been secured when there was less than $\frac{1}{4}$ inch of snow on the ground, and it was obvious that we could see the ground, even where the ground cover was the densest. There were not enough natural images on this photography that could be identified on the ground to serve as horizontal control for the photography, and it would have been useless without bridging. We were able to identify enough natural images to control the bridge, and the results were excellent. We did not have to make any cross section extensions by ground survey methods, and the tie in to the cross sections measured previously was unusually good. We have also bridged control on location surveys where we were unable to enter property without a court order.

The determination of errors in production work is difficult. It is not easy to tell what the errors actually are—that is, what part of the error belongs to the ground survey and what part belongs to the photogrammetric work. This is especially true of horizontal control points, and even more so when images of natural objects are used for horizontal control points. With us, the horizontal control point that is a natural image is usually a corner of a barn, or a pole, and is very seldom checked. We can usually sort out the large blunders in this type of control, such as selecting the wrong corner of a building or measuring the azimuth angle to one corner and the distance to another.

There is no way of being sure that other factors causing relatively small errors are detected. We often do not determine the apparent horizontal error in our bridges for this reason and also because there are usually relatively few horizontal control points for sampling. However, we do determine that the errors are small enough so that the horizontal accuracy of the mapping will not be affected adversely.

We recently had a job eight models in length where the photography was taken at a scale of 1,000 feet to one inch and only four government stations were used to control the bridge. There were several other traverse stations on the survey route—some that we had set for a previous mapping job and some government traverse stations of undetermined accuracy. Our previous traverse had passed within 1,500 feet of one of the triangulation stations without tying into it. The party chief probably decided that he could run to the next triangulation station quicker than he could tie into this one. This meant that on this bridge we had three separate systems of horizontal control—that is, controls that had not been tied together and adjusted within the local area. The largest horizontal closure error on this bridge was 1.5 feet. There was some evidence, however, that we had been lucky, because this point was near a triangulation station that had been used in the adjustment and this station missed in the opposite direction.

Vertical control is a somewhat different story. Such control usually contains fewer errors, although in the selection of vertical control points for bridging, there is a tendency to begin and close a line of levels on the same bench mark. Also, if just a little skill is used in the selection of vertical control points, a natural image is about as good as a targeted vertical control point. It is for this reason and the fact that good vertical results are more difficult to obtain than satisfactory horizontal results that we have watched and calculated our vertical results more closely. Our vertical results to date indicate that we can expect a root mean square error of from 0.10 to 0.20 per 1,000 feet of flight height when a 6-inch focal length lens is used. We may possibly be able to reduce this error by 10 to 20 percent with a better vertical adjustment program.

The present vertical adjustment program adjusts to a second-degree curve and applies a certain amount of twist to the strip. It seems that we could secure a better fit of the control if a separate curve could be developed for each side of the strip. These should probably be third-degree curves with certain constraints. These constraints should be flexible and under the control of the photogrammetrist.

The temperature control in the comparator room is not as critical as many have been led to believe. We had a specially controlled air conditioner installed, but we seldon use it because the central air conditioner is stable enough for production work. Our plates stay in the comparator only about 45 minutes and, because both the comparator and the plate are at room temperature to begin with, the small changes in temperature that occur will not affect routine work.

Bridging has the same advantages of all photogrammetric operations over field work. It brings operations in out of the weather to where conditions are much more predictable and where it is easier to keep experienced people working. Of course, it greatly reduces the man-hours required to control each stereoscopic model.

About 3 man-hours per model are required to drill and measure the photographic plates, to prepare the computer input forms, and to check the comparator measurement recordings when six points are used in the orientation. This increases to more than 4 hours when 12 points are used. More time is required if additional adjustments are needed, and of course the additional time depends on how much time is used in studying the results of the initial adjustment.

The organization using analytical aerial triangulation does not need a large staff of experienced photogrammetric programmers, but can adapt programs that have been derived by a larger organization. It should be able to train its existing personnel to handle all of the additional skills required. We feel that our experience proves that analytical aerial triangulation can be used by a relatively small photogrammetric unit whose personnel are primarily highway-oriented to greatly reduce the cost of ground control surveys. In most cases, that quality of the final photogrammetric product will be improved over what is attainable where every model is controlled conventionally by ground surveys.

REFERENCES

1. Harris, W. D., Tewinkel, G. C., and Whitten, C. A. Analytic Aerotriangulation. U.S. Coast and Geodetic Survey Technical Bull. No. 21, July 1962.
2. Keller, M., and Tewinkel, G. C. Aerotriangulation Strip Adjustment. U.S. Coast and Geodetic Survey Technical Bull. No. 23, Aug. 1964.
3. Keller, M., and Tewinkel, G. C. Aerotriangulation: Image Coordinate Refinement. U.S. Coast and Geodetic Survey Technical Bull. No. 25, March 1965.
4. Horsfall, C. T. Electronic Computer Programs for Analytical Aerial Triangulation. U.S. Coast and Geodetic Survey, June 1965.
5. Horsfall, C. T. Aerotriangulation Strip Adjustment Using FORTRAN and the IBM 1620 Computer. U.S. Coast and Geodetic Survey, March 1965.
6. Umbach, Melvin J. Supplement to: Electronic Computer Programs for Analytical Aerial Triangulation and Aerotriangulation Strip Adjustment Using FORTRAN and the IBM 1620 Computer. U.S. Coast and Geodetic Survey, Feb. 1966.

Production Mapping With Computational Photogrammetry

J. R. JENSEN and J. J. STEELE, Bureau of Public Roads,
Federal Highway Administration

The interdependence of precise ground surveying, aerial targeting, aerial photography, analytical aerial triangulation, and map compilation are depicted in reporting the results of an 83-mile, continuous, large-scale mapping project. This project would have been considered impossible without the implementation of aerial photogrammetry and specifically without the aid of aerial triangulation. The paper describes the operations performed from project inception to the completed map manuscript with discussion on surveying procedures, targeting, comparator operations, and map compilation. It should be emphasized that the work was performed on a production basis and not as a research project.

•ON October 3, 1966, the National Park Service asked Region 15, Bureau of Public Roads, to make an aerial survey and prepare large-scale topographic maps of an 83.5-mile section of the Blue Ridge Parkway. Detailed land-use maps encompassing the existing Parkway right-of-way at a scale of 100 ft = 1 in. with a 5-ft contour interval were specified. These maps were intended to serve as an aid in the administration of management programs, including:

1. Determining land-use patterns to expedite the year-to-year management of agricultural programs.
2. Simplifying the study of adjacent public roads for the purpose of minimizing nonconforming use of the Parkway and for eliminating private crossings and accesses where feasible.
3. Providing an invaluable aid to the landscape architects in location, planning, and design of roads, campgrounds, picnic grounds, and other facilities.
4. Providing an accurate reference for fire-fighting and other protection purposes, because these maps would show all roads, public and private, even little-used woods roads or trails, and other vital features.
5. Furnishing, in many instances, the only accurate location of electric and telephone lines, roads, and other features valuable in the day-to-day administration of the Blue Ridge Parkway.

This section of the Parkway extends from milepost 136 at Adney Gap to milepost 218 just beyond the Virginia-North Carolina State Line (Fig. 1). Throughout this area the Parkway meanders southwesterly along the crest of the Blue Ridge front. The terrain adjacent to the Parkway and to the west is in a series of rolling hills displaying the natural beauty of rural landscapes enlivened by the highland farms, campgrounds, trails, and wayside exhibits of the hill culture of the area. To the east lies the Blue Ridge escarpment, which affords numerous overlooks and vistas along the Parkway. Approximately 50 percent of the area has a cover of hardwood trees with intermittent

---

Paper sponsored by Committee on Photogrammetry and Aerial Surveys and presented at the 48th Annual Meeting.

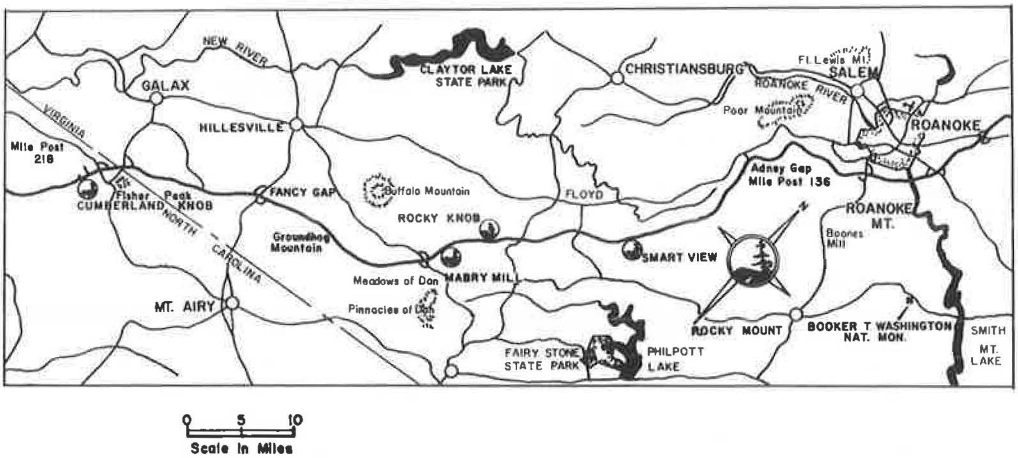


Figure 1. Location map.

stands of white pine and rhododendron, and the remaining 50 percent is cultivated farms and pasture land.

BASIC CONTROL REQUIREMENTS

To insure the development of an accurate and usable topographic map at a reasonable cost, the following basic control requirements were established:

1. The control survey should be connected to the Virginia South Zone State Plane Coordinate System.
2. The basic plane coordinate grid for the mapping should be established on an adjusted datum corresponding to the average elevation of the area.
3. The basic control traverse should be of second-order accuracy or better.
4. Semipermanent control monuments should be established along the Parkway in areas where future surveys and construction are contemplated.
5. Supplemental control should be obtained by photogrammetric aerial triangulation techniques to reduce the cost of field surveys.
6. Existing right-of-way monuments should be recovered and targeted to determine their coordinate positions by photogrammetric methods.

PRELIMINARY PREPARATIONS

To expedite the project the Park Service requested that late fall photography be obtained. Timing was critical due to the length of the project. A maximum of 8 weeks was available in which to prepare and negotiate a contract for aerial photography, obtain supplies, establish a control traverse throughout the project, and place photographic targets on all required horizontal and vertical control points.

All existing control for the area was obtained from the U.S. Coast and Geodetic Survey and the U.S. Geological Survey. Fifteen-minute quadrangle sheets were then assembled into a single map of the area. The geodetic control data received were reviewed and all second- and third-order geodetic control convenient to this section of the Blue Ridge Parkway was identified on the map.

A contract was negotiated with a local aerial photographer to obtain high-altitude photography (approximately 1:24000 scale). The area of coverage was specified by delineating five flight lines on the assembled quadrangle sheets. As soon as this photography was received, a base map (flight map) was constructed. The high-altitude vertical photographs were assembled into five strip mosaics using alternate photographs.

Each strip was fitted and sized by using identified image points and distances scaled from the 15-minute quadrangle sheets. By correlating the mosaics to the same area on the quadrangle sheets, their average scale was determined to be 2100 feet to 1 inch. The mosaics were then studied closely to determine a minimum number of flight lines required to obtain 1:6000 scale photographic coverage of the area to be mapped.

Due to the curvilinear alignment of the Parkway, the most efficient flight line arrangement proved to be a series of single flight strips overlapping at each change in direction. A line, indicating the path and direction that the aircraft should follow when obtaining the large-scale mapping photography, was plotted on the mosaics. The width of photographic coverage was also drawn on them, delineating the area each flight strip should cover. The exact number of stereoscopic models was determined for each flight strip and their photocenters marked along each flight line. The average elevation for the terrain in each flight strip was determined by studying the same area on the quadrangle sheets. Utilizing this information, the flying height for each flight line was written on the flight map. The positions of required horizontal and vertical control points were then selected and marked in the prescribed models of each flight line while making a stereoscopic examination of the photography. The final product was a detailed flight map containing 31 flight lines varying in length from 5 to 15 models comprising 260 photographs. Twenty-seven of the flight lines were controlled and four were uncontrolled. Figure 2 illustrates the first three flight lines for the project.

The density and spacing of the basic control delineated on the flight map were patterned after specifications for analog bridging of supplemental control on a universal type photogrammetric instrument. The first model in each flight strip was fully controlled with two horizontal and four vertical targeted points. Thereafter, one horizontal and two vertical control points were placed in every fourth model and the last model in each strip. Additional horizontal control points were placed in each flight strip to meet Region 15 requirements for spacing semipermanent control stations along the Parkway. The total number of targeted control points delineated on the flight map came to 170 traverse points and 170 elevation pass points.

A second contract was negotiated with the local aerial photographer for taking the 1:6000 scale photography. A copy of the flight map was furnished with instructions concerning its use. Emphasis was placed on the importance of exposing the first photograph in each flight strip precisely as shown by its marked center on the flight map. This precaution was necessary to insure that all targeted ground control would occur in the prescribed model as shown on the flight map. This requirement was not unreasonable since the aerial photographer would be able to identify actual ground objects for precisely orienting the aircraft while exposing the film. Another requirement concerning the photography was that it be taken between the hours of 10:30 a.m. and 1 p.m. to keep excessive ground shadows, which occur during the late fall months, to a minimum.

On October 17, 1966, a meeting was held with representatives of the National Park Service in Roanoke, Virginia, to discuss a timetable for accomplishing the field work. An agreement was made that while the Region 15 control survey party was laying out the basic control traverse and placing the required aerial targets, the Park Service would furnish additional personnel to locate and target as many right-of-way monuments as possible before the mapping photography was taken. Public Roads agreed to supply the necessary target material along with instructions for placing the targets.

FIELD SURVEYS

Actual field work began on October 18, 1966. The first activity was to fabricate the photographic targets. Three types of targets were used (Fig. 3): target 1 was used for right-of-way monuments; target 2 was used for traverse points (horizontal and vertical); and target 3 was used for vertical control points only. Target types 2 and 3 were symmetrical with black centers and white outer legs. The black centers were omitted for the type 1 target and its overall dimension increased to 16 feet. This was done in an effort to increase photographic identity, because many of the right-of-way monuments were in wooded areas.

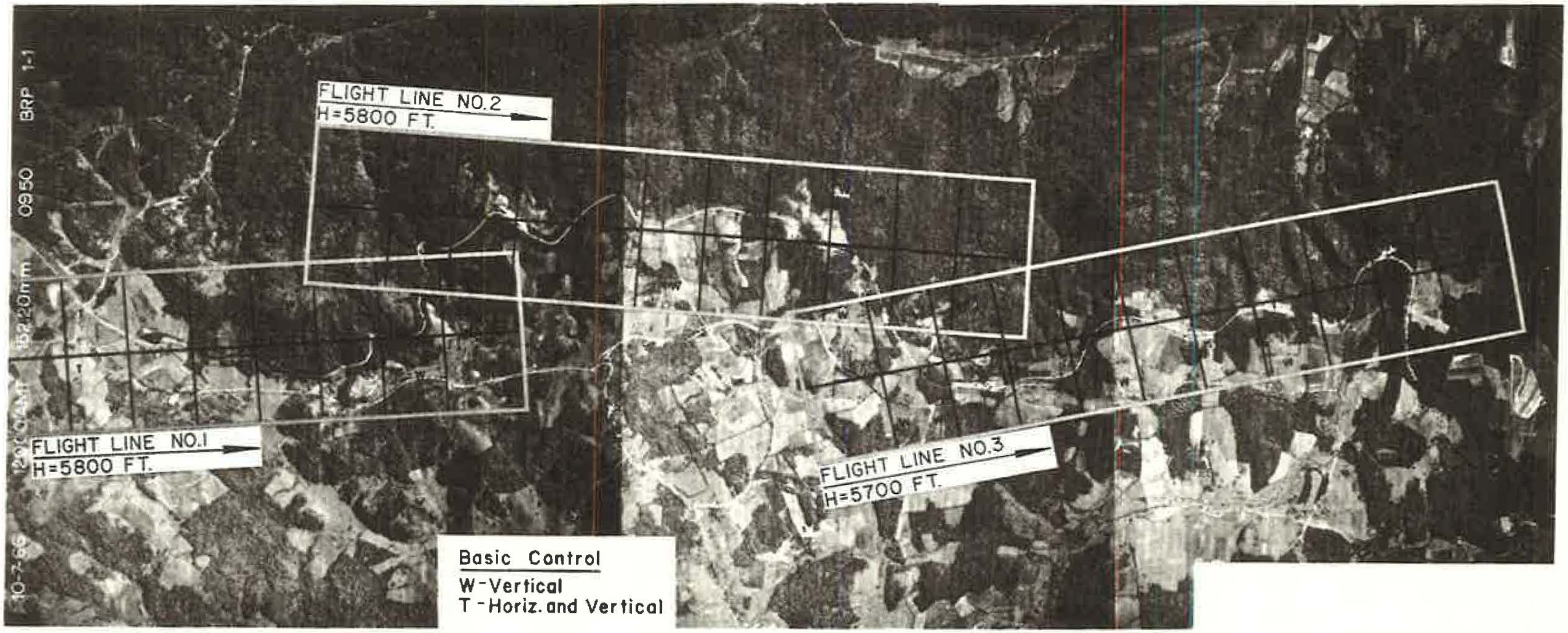


Figure 2. Flight map.

The targets were made of a vapor barrier material produced by the American Sisalkraft Corporation. It has a polyethelene facing laminated to a treated paper base with a tar-like binder and is available in black and white. The material came in rolls 8 feet wide containing 125 linear feet and had to be cut into rolls 9 inches wide with a bandsaw. The material has several characteristics which make it excellent target material:

1. The paper side of the material has a matte-type surface that is non-reflective.
2. It is inexpensive; the cost for each target was approximately 60 cents.
3. It is very durable; i.e., it is resistant to moisture and does not separate or ravel from exposure.
4. It has sufficient weight to adhere to the ground when fastened at 4-foot intervals along its edges.
5. Livestock and other animals will not eat this material. It is conjectured that the tar binder makes if offensive to animals.

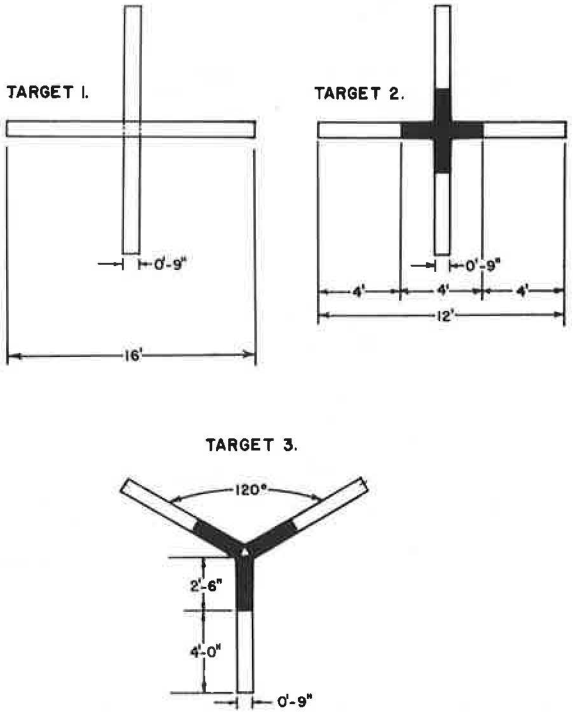


Figure 3. Design for photographic targets.

In certain areas where horizontal control was required, the Parkway was the only open area where aerial targets could be placed. In these instances a white cross with a gap in the center was formed with Scotch Lane Striping Tape on the asphalt surface.

A total of 170 type 2 targets and 170 type 3 targets were fabricated and placed within a 7-day period by six engineering technicians. This work was expedited by use of the flight map described previously. Target placement on right-of-way monuments required 4 weeks due to difficulty in locating these points. Many of the recorded right-of-way monuments could not be found and, as a result, were not targeted.

While the targets were being placed, the basic control traverse was established along the Parkway. The targeted horizontal control points were interconnected with a minimum number of auxiliary stations to form a continuous traverse. Considerable effort was made to keep the distances as long as possible, but many short distances resulted due to the curvalinear alignment of the Parkway. The decision to establish the basic control traverse along the Parkway was influenced by two factors: the cutting of trees was prohibited, and portable survey towers were not available.

The total length of the resulting traverse was 514,006 feet (97.35 miles) with 424 individual stations. The bulk of the basic control survey work was accomplished during the 6-week period from November 1 to December 17, 1966. Three 3-man level parties established elevations for traverse and wing points, while three 2-man Electrotape units measured distances. Following these operations, two 4-man instrument parties equipped with Wild T-2 Theodolites measured the angles.

Differential levels were first run through all traverse stations along the Parkway. USGS bench marks were recovered at frequent enough intervals to maintain third-order level closure throughout the traverse. Wing point elevations were then established by running closed level loops through each point from the nearest traverse station. In all, approximately 200 miles of differential levels were run on this project.

All distances were measured with Electrotapes operated in a leap-frog sequence. While two units were measuring the distance between adjacent stations, the third unit

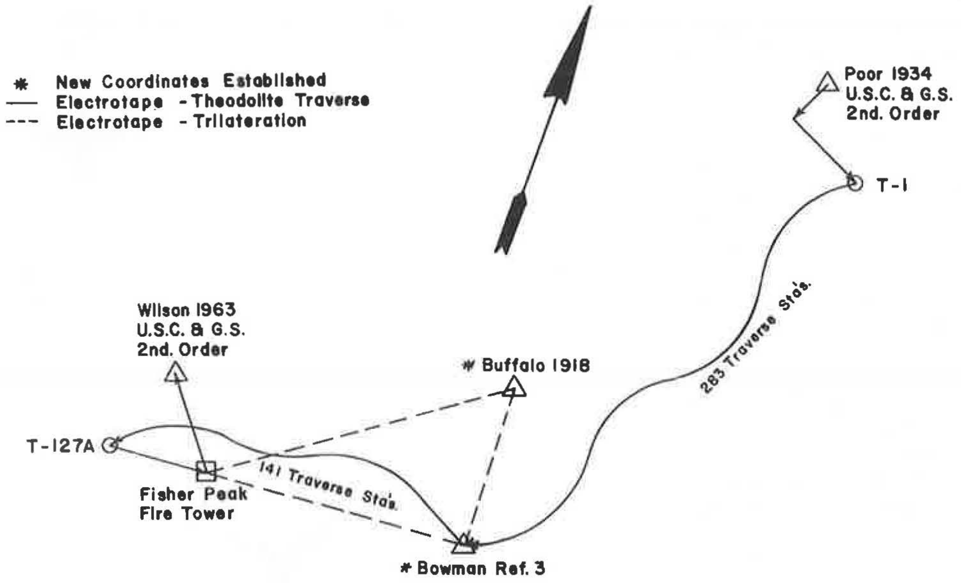


Figure 4. Basic control traverse diagram.

moved ahead to the next station. With this procedure, an average of 25 lines were measured each day. The Electrotapes were operated during all kinds of weather including rain, light snow, and fog, with temperatures ranging from 14 to 73 F. A special umbrella was used to shield the instrument and operator during inclement weather.

All angles were measured using Wild T-2 Theodolites and sighting tripod-mounted targets. Special targets used consisted of a section of range pole (point up) held by an adapter mounted on a Wild tribrack. The optical plumb in the tribrack insured accurate centering of the target over the station marker. Once the tripod was in place, a 16-oz plumb bob was extended from the tribrack. For short distances the instrument man sighted on the plumb bob string; on intermediate distances he sighted on the tip of the range pole; and on long distances he sighted on the shaft of the range pole.

The control traverse (Fig. 4) began at a second-order USC&GS triangulation station (Poor 1934), and was closed on another second-order station (Wilson 1963). At Groundhog Mountain (Milepost 189), a third-order control station (Bowman), plotted on the quadrangle sheets during the reconnaissance stage, was not recovered. However, reference mark No. 3 for this station was recovered and this point was incorporated into the basic control as a traverse station. New coordinates (second order) were determined for this point by electronic traverse and trilateration methods. This point was used as a closing station and the overall traverse was computed and adjusted for a closure in two segments. A least squares adjustment program developed by Kenngott (1) was used to compute traverse closures on the IBM 1401 computer. Before survey closure the plane coordinates were adjusted using a Datum Adjustment Factor (DAF = 1.000156).

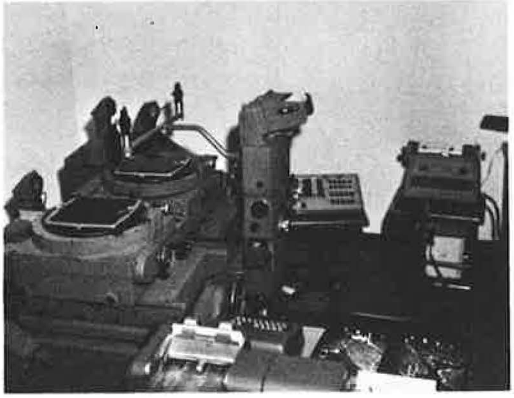
The first section from Poor to Bowman reference No. 3 contained 283 stations and the adjusted distance was 312,496 feet. Angle closure before adjustment was 170 seconds, approximately 0.6 second per station. The error of closure after azimuth adjustment was 2.82 feet (one part in 110,830). The second section from Bowman reference No. 3 to Wilson contained 141 stations and the adjusted length was 201,510 feet. Angle closure before adjustment was 128 seconds, approximately 0.9 second per station. The error of closure after azimuth adjustment was 11.05 feet (one part in 18,233). Polaris observations were made on the first leg of the traverse at station Poor and on the traverse leg terminating at Bowman reference No. 3 for azimuth control. An established azimuth mark was recovered and used for azimuth control at the end of the traverse at station Wilson.

An early snowstorm, preceded by 2 or 3 days of freezing temperatures, moved through the area the weekend of November 12 and 13. It was accompanied by high winds, and leaves on the deciduous trees were 95 percent removed over the 2-day period. The aerial photographer was given notice by telephone to proceed on the morning of November 15. Three days were required to photograph the entire 83.5 miles due to the flying time required to reach the project, the restricted hours for taking photography, and the length of the project. A Wild RC-8 aerial camera was used to obtain the 1:6000 scale mapping photography.

Considerable effort was expended in an attempt to complete all field work before the end of the year, but due to snow and freezing temperatures, work had to be suspended on December 17. The field work was about 85 percent complete. Emphasis was placed on completing the level work since it was realized that wing point targets would not remain in place through the winter.

Field work was resumed the first week in March and was completed by April 1, 1967. Approximately 200 traverse stations were referenced throughout the project. Semipermanent survey markers (metal T-bars with $1\frac{1}{16}$-inch diameter nickel-plated brass caps) were used at these locations. These points are intended to preserve coordinate position and azimuth control in all areas where future surveys and construction are contemplated. Also, approximately 60 test profiles were measured between control points at random throughout the project for future use when checking the contour plotting accuracy of the mapping contractor.

Wild PUG-3 point transfer device used for marking points on the diapositives.



Wild STK-1 stereocomparator used to measure image coordinates on diapositives.

Figure 5. Analytical bridging equipment.

PHOTOGRAMMETRY

The analog bridging of supplemental control was delayed due to unexpected complications. Because of the magnitude of the project, and the time element involved, other means were investigated for accomplishing the bridging work. Jesse R. Chaves, Engineering Systems Division, Office of Research and Development, Bureau of Public Roads, recommended that the analytical method be used. Through arrangements made by Mr. Chaves, the USC&GS offered the use of their bridging equipment located at the Washington Science Center, Rockville, Maryland, after regular working hours.

The analytical aerial triangulation work was performed with two Wild STK-1 stereocomparators and a Wild PUG-3 point transfer device (Fig. 5). The STK-1 comparators were equipped with digital readout.

Measurements were made by two operators. One operator, on loan from the Aerial Surveys Branch, Highway Standards and Design Division, Bureau of Public Roads, had 5 months' prior operating experience with the Wild STK-1 comparator. The other operator, a graduate civil engineer, was trained by the "experienced" operator for one week. At the end of this training period, the new operator began measuring a strip consisting of six models. Four days were required to measure the flight line. As experience and confidence in his measurements were developed, the new operator's speed increased from one model per 6-hr shift to a maximum of four models.

The drilling of the pass points was performed by the two comparator operators and a technician. The technician had been training on the Kelsh plotter for 8 months before he was trained to use the PUG-3. After several days of experience with the PUG-3, the technician was able to drill the glass plates satisfactorily.

Contact prints for each flight line were examined to locate the targeted ground control points. Each identified point was circled on the photograph and its identification

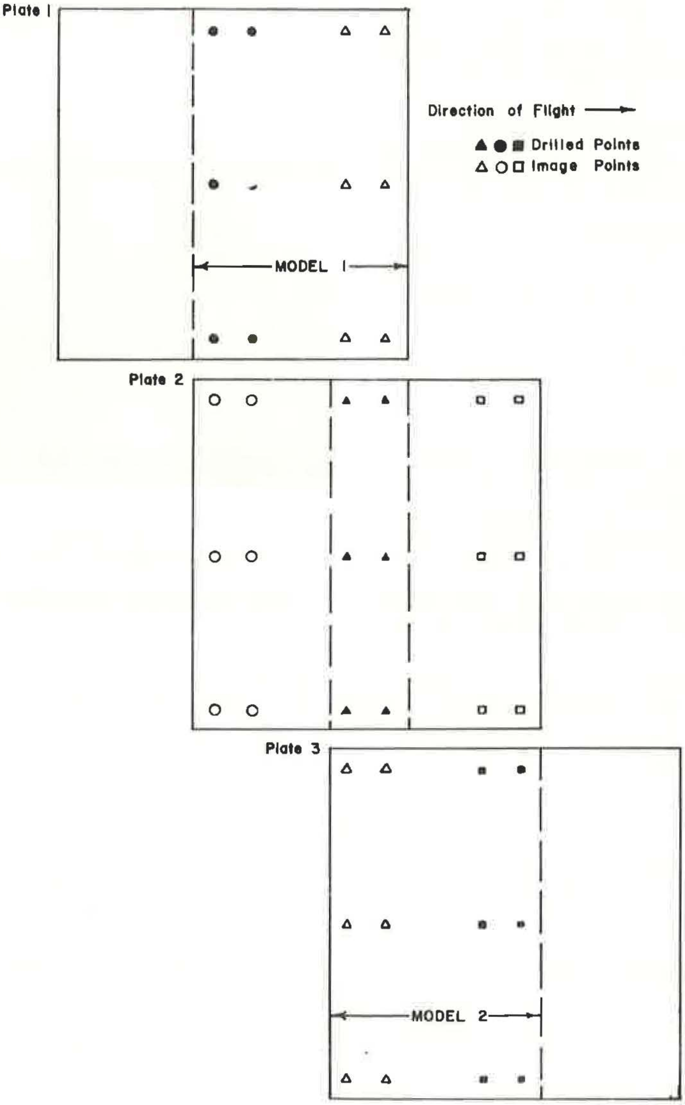
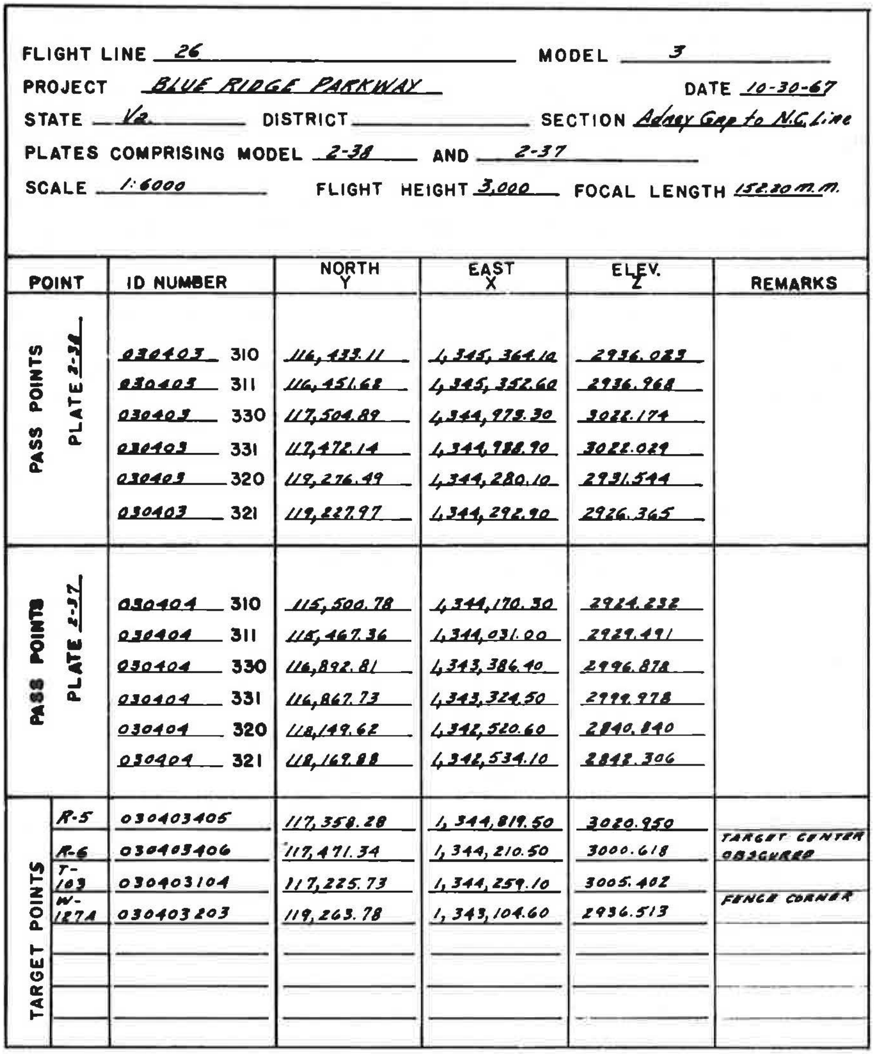


Figure 6. Pass point distribution.

number written beside it. Right-of-way points had to be located and marked on the photographs since their position was to be determined analytically.

Pass point distribution used on this project consisted of three sets of two points each, placed in the triple overlap area of each photographic plate. Each point was placed on the plate by drilling through the plate's emulsion with the Wild PUG-3. Since the measurements were to be made stereoscopically, it was necessary to drill only the triple overlap area of each plate (Fig. 6). Pass point areas were examined stereoscopically before the points were drilled. This procedure insured that the drilled points were in the triple overlap area and would appear in adjacent models.

Originally, effort was made to place one set of points near the photocenter with the other sets placed within 1½ inches of the plate edge (perpendicular to the flight axis). This placement gave the best theoretical geometry for the analytical computations and was followed on the first eight flight lines. Difficulty was encountered, however, in measuring the points placed in wooded areas because of bare limbs and shadows. After repeated attempts to measure points in wooded areas, it was decided to sacrifice



FLIGHT LINE 26 MODEL 3
PROJECT BLUE RIDGE PARKWAY DATE 10-30-67
STATE Va. DISTRICT SECTION Adney Gap to N.C. Line
PLATES COMPRISING MODEL 2-38 AND 2-37
SCALE 1:6000 FLIGHT HEIGHT 3,000 FOCAL LENGTH 152.80 m.m.

POINT		ID NUMBER	NORTH Y	EAST X	ELEV. Z	REMARKS
PASS POINTS	PLATE 2-38	030403 310	116,433.11	1,345,364.10	2936.023	
		030403 311	116,451.68	1,345,352.60	2936.968	
		030403 330	117,504.89	1,344,979.30	3022.174	
		030403 331	117,472.14	1,344,988.90	3022.029	
		030403 320	119,276.49	1,344,280.10	2931.544	
		030403 321	119,227.97	1,344,292.90	2926.365	
PASS POINTS	PLATE 2-37	030404 310	115,500.78	1,344,170.30	2924.232	
		030404 311	115,467.36	1,344,031.00	2929.491	
		030404 330	116,892.81	1,343,386.40	2996.878	
		030404 331	116,867.73	1,343,324.50	2999.978	
		030404 320	118,149.62	1,342,520.60	2840.840	
		030404 321	118,169.88	1,342,534.10	2848.306	
TARGET POINTS	R-5	030403405	117,358.28	1,344,819.50	3020.950	
	R-6	030403406	117,471.34	1,344,210.50	3000.618	TARGET CENTER OBSCURED
	T-103	030403104	117,225.73	1,344,259.10	3005.402	
	W-127A	030403203	119,263.78	1,343,104.60	2936.513	FENCE CORNER

Figure 7. Control data form.

geometry when necessary to insure measurable points. This was accomplished by selecting areas closer to the center of the photograph and outside the area to be mapped. This arrangement seemed to work satisfactorily insofar as analytical calculations were concerned.

One-hundred-and-fifty-micron diameter drills were used in drilling the pass points. After the pass points were drilled, their locations were marked and the identification numbers written on the emulsion with a felt-tip ink pen. When the entire flight line was drilled, control points were marked on every other plate with a grease pencil. The grease marks were made on the non-emulsion side so they could be erased if desired at a later date.

To help the comparator operator, data sheets were made up for each model listing all of the points to be measured (Fig. 7). In instances where the control points were photo-identified ground features, descriptions of the points were also included. The comparator operator noted any problems he encountered while measuring the points. These notes were reviewed when setting up the data for the final computer program. The Kelsh operator could also refer to them when setting up his model.

The general measuring procedure required three independent readings on each pass point and all targeted points. If the three measurements fell within a spread of 8 microns, they were considered good. (The least count of the Wild STK-1 stereocomparator is 1 micron.) The 8-micron limit was selected as desirable after each operator had measured several strips, determined his ability to repeat, and analyzed computed results of these measurements. In a few instances the targeted points were so badly washed out, hidden in shadows, or otherwise indistinguishable, that it was impossible to fall within the 8-micron limitation. In these cases, a determination was made by the operator, based on the target type (right-of-way, T-point, wing point), as to what spread could be allowed. When this was done, notations was made on the comparator sheets describing the difficulty and operator's judgment whether to use the point as control in the final adjustment.

After measuring all targeted points and pass points, the operator measured the fiducial marks. These plates had corner fiducials. The operator measured each fiducial leg three times with a total of 12 measurements recorded for each fiducial.

Contrast of the plates varied considerably throughout the project. Some flight lines had high contrast plates and some had very little contrast. Both operators experienced difficulty with the low contrast or "washed out" plates. The degree of operator difficulty was directly related to the degree of contrast and operator experience. It was generally agreed that the desirable comparator plate should have enough contrast to help distinguish targets in light areas.

COMPUTATION PROCEDURES

After each flight line was measured, a listing of the raw comparator punch data was made. The listings were checked to see that each model had 48 fiducial readings and 12 sets of pass point readings, and that all of the cards appeared to be punched correctly.

After review, the raw data were arranged for the first computer program (program 35) (2). This program took the three measurements for each fiducial leg and constructed a set of equations representing the fiducial legs.

These equations, when solved simultaneously, gave the center of each fiducial. The center of each plate was then determined from the fiducial equations. Once this calculation was performed, the program averaged the three readings for each measured point in the model and computed plate coordinates for each point with the plate center as the origin. The program also eliminates the inherent mechanical errors of the STK-1 comparator.

When review of program 35 output was completed, the data were arranged for the Three-Photo Aerotriangulation Program (3). This program computes strip coordinates for a strip of ". . . aerial photographs through an analysis of three photographs simultaneously, advancing one photograph at a time. Corrections are included for lens distortion, film distortion, atmospheric refraction, and earth curvature (if desired).

Blunders in the input data are detected and eliminated, and the rejection level is controlled by the user. The data is analyzed without reference to the ground control." (3)

Precisions for targeted points that were to be used for control in the next program were checked. When the precision for a control point exceeded 15 microns, its use as a control point was questioned. If another point could be used, the questionable point was used as a test point.

TABLE 1

REQUIRED CONTROL POINTS FOR AEROTRIANGULATION STRIP ADJUSTMENT

Degree of Adjustment	Minimum Points Required	
	Horizontal	Vertical
1	2	4
2	3	5
3	4	7

The final program, Aerotriangulation Strip Adjustment (4), transformed and adjusted the strip coordinates of the measured points to fit the ground control data. This program contains a variable degree provision that allows the selection of either third-, second-, or first-degree polynomial correction in the horizontal direction and also in the vertical direction independent of the horizontal choice. The minimum number of control points required for each degree adjustment is given in Table 1.

Control placement throughout each strip (as explained earlier) was placed for the analog bridging method. Therefore the control distribution, although more than adequate for analog bridging, was not the most desirable arrangement for analytical bridging. If the specifications had been followed stringently, flight lines containing six models would have had four horizontal control points, and flight lines containing three, four, or five models would have had three horizontal control points. Due to the flight line arrangement, control for the first model of each strip also appeared in the last model of the preceding strip. This, in all but two cases, resulted in at least five horizontal control points in each flight line.

In an effort to get the most stringent and best solution, all strips were run on a third-degree adjustment. Two strips contained only four horizontal points and, as a result, no horizontal control was available to use as test points. In these instances the amount of deviation from the control value used was examined. There was little deviation between the ground control value inserted and the computed control value; therefore, it was assumed that the analytic triangulation was adequate. Here, inexperience probably hindered judgment and a second-degree adjustment should have been made on these two strips.

The control distribution for each flight line was studied by examining the photographs and the three-photo output data. After some study, the ground control to be used in the strip adjustment was chosen. Targeted points not used for control were used as test points in the adjustment. Except for the instances referred to previously, at least one horizontal and two vertical test points were used in each strip.

MAPPING

The contract for the actual mapping work was negotiated with a local firm on September 1, 1967. The contract called for mapping a corridor averaging 1,000 feet in width along the 83.5-mile section, plotting referenced traverse points, and plotting all of the right-of-way points. The mapper was furnished the comparator sheets, a list of the right-of-way points and traverse points to be plotted, the glass plates, and a set of photographs with the area to be mapped outlined on them.

The completed maps were furnished on standard size 24- by 36-inch plan sheets. As the mapping progressed, blueline prints of each sheet were submitted for checking. When errors were found, they were noted and given to the mapper for correction. The completed project contained 131 sheets. Figure 8 illustrates one of the map sheets.

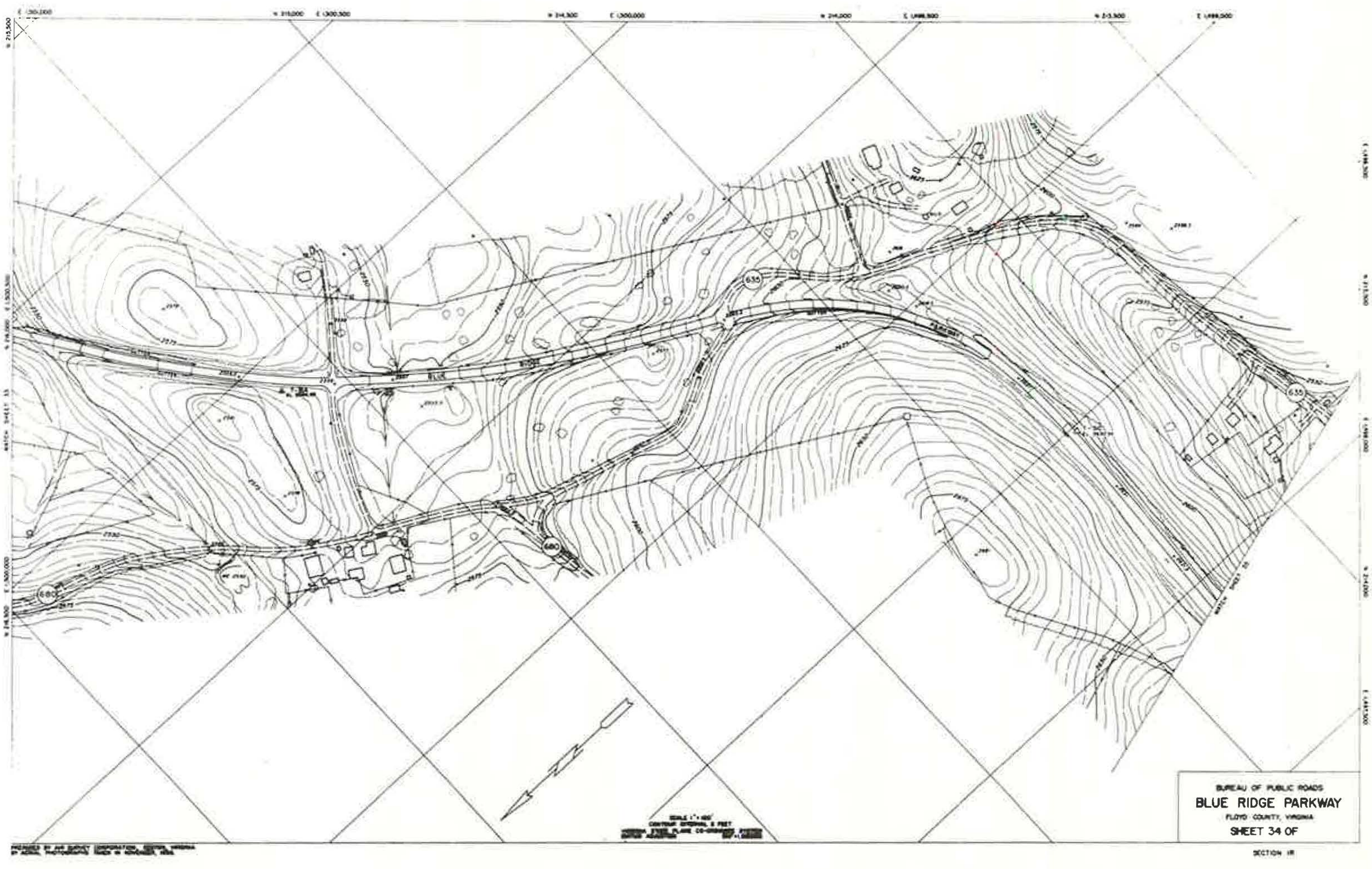


Figure 8. Typical map sheet—final manuscript.

DISCUSSION

Surveys

The length of the project created a tremendous amount of book work. In all, 22 field books were used on the project. All data for each traverse point were entered into a master book in order to facilitate the use of the data. Here, again, even with double checking, occasional copying errors were found.

Targeting

A 3-week time lapse occurred between the placement of basic control targets and obtaining the aerial photography. When the prints were available, they were checked to see if all targeted points appeared on them. Where the targets were missing, the photographs were studied for ground features that could be used in lieu of the missing targets. Road intersections, bases of telephone poles, ends of headwalls, and tips of islands were used when necessary as photo-identified points. Once the photo identification was made, these points were included in the control survey. The points used were circled and described on the back of the applicable photograph. The description of each point was very important as the comparator operator used the field description to identify and measure each point.

Analytical Aerial Triangulation

Three-legged targets (Type 3, Fig. 3) were used for wing points to eliminate any confusion as to the type of target. Finding the center of this target, however, did prove to be difficult when one of the legs was missing or the ground on which it was placed sloped sharply away from the camera exposure station. With one leg missing, it was extremely hard to repeat the comparator measurements for position within the 8-micron limit. In most instances the operator picked his center with the aid of land features and the two remaining legs.

Few problems were experienced in measuring the traverse control targets. Although in some low-contrast plates the white legs of the target distorted badly, it was still possible to find the center of the target within the measuring limit of 8 microns. Photo-identified points, in some instances, were difficult for the comparator operator to measure. Although they could be seen when using the comparator, many were not well enough defined for the operator to be certain that the point he was measuring was the same point the field party had measured.

Several blunders were found in the vertical ground control during the final strip adjustment program. In one case, an error of 100 feet was found through analyzing the output data. An examination of the level notes revealed a transcribing error of 100 feet. In another case, an error of 10 feet was found in a wing point used as a test point. A check of the field notes found a 10-foot error in the bench mark used to establish the wing elevation.

The horizontal control seemed to be good and very few problems were encountered. As indicated previously, the control traverse had been adjusted by the least squares method prior to using it for control in the strip adjustment.

Computation

Program 35 was processed on the IBM 360 computer. Average run time for a flight line of seven models was 3 minutes. The program was also revised to fit the IBM 1401 computer. Average run time for a flight line of seven models was 10 minutes.

The Three-Photo Aerotriangulation Program was processed on the IBM 7030 (STRETCH) computer of the Naval Weapons Laboratory at Dahlgren, Virginia. Average run time for a flight line of seven models (6 triplets) was 30 seconds.

The Aerotriangulation Strip Adjustment Program was performed on the IBM 1620 computer. Average run time for a flight line of seven models was 12 minutes.

TABLE 2

STANDARD DEVIATIONS FOR CONTROL DATA

Flight Line	No. Model	No. Control		3 Photo	Final Adjustment—Control Used			
		H	V	RMSE (fl. li. avg.)	STDX (micron)	STDY (micron)	STDX & STDY (micron)	STDZ (micron)
1*	6	5	9	1.7408	2.988	2.062	3.630	3.392
2	8	7	12	2.7109	5.836	8.369	10.203	8.313
3	9	5	10	3.4794	2.347	3.722	4.401	6.653
4	13	7	14	3.3879	5.378	8.920	10.416	23.077
5	6	5	11	3.3745	12.674	9.786	16.013	17.857
6	15	9	16	3.625	11.585	12.171	16.803	17.374
8	8	5	11	2.8027	4.102	4.958	6.435	12.573
9	15	6	15	3.5386	39.476	43.635	58.842	27.771
10	7	6	11	2.9973	10.515	10.456	14.829	17.688
11	6	5	9	2.5941	3.654	3.300	4.924	7.808
14	9	6	13	3.2901	13.913	21.338	25.473	12.291
15	7	4	8	5.0042	12.632	13.271	18.322	5.552
16	4	4	8	2.6254	10.338	3.436	10.894	2.517
17	8	7	12	2.3073	7.890	10.438	13.085	8.944
18	8	4	10	2.8230	4.084	4.737	6.255	12.162
19	8	5	13	2.4863	2.170	5.907	6.293	22.441
20	7	6	9	2.4395	40.994	46.074	61.671	6.754
21	4	4	7	5.1624	2.241	4.047	4.627	.0000
22	5	4	7	2.0432	10.405	29.441	31.226	.0000
23	7	4	9	2.5342	3.782	6.709	7.702	15.748
24	16	10	19	2.5110	20.711	9.546	22.805	19.728
25	8	7	10	3.9626	7.944	17.099	18.854	9.332
26	12	9	13	2.3234	19.013	27.824	33.699	21.895
27*	7	4	10	3.9623	0.097	3.075	3.076	9.742
28	8	5	10	2.5961	3.341	9.740	10.297	34.358
29	9	6	13	2.9733	9.051	6.097	10.914	7.795
30	5	5	9	3.3040	0.748	2.087	2.217	3.829
Project avg. (microns)				3.059	9.922	12.157	16.070	12.429
Project avg. (ft)					0.20	0.24	0.32	0.25

*No horizontal test points in this strip.

Mapping

Frequent liaison with the mapper was maintained to monitor progress of the work. The mapper experienced very few problems in setting up the models or in compilation. A few transcribing errors in the coordinate data for isolated points caused momentary problems, but these were easily corrected.

RESULTS

The overall results from the analytical triangulation were well within the accuracy required for this project. It should be emphasized that the work was performed on a production basis and not as a research project.

Table 2 gives the results of the three-photo aerotriangulation and final aerotriangulation strip adjustment. Definitions for abbreviations used in Table 2 follow:

1. RMSE—This is the strip average root-mean-square value of all residual parallaxes for all the pass points of the triplet expressed in microns at negative scale.
2. STDX & STDY—Standard deviation (root-mean-square-deviation) of all the horizontal control used in strip adjustment in microns at negative scale.
3. STDXY—Standard deviation vector (position) of horizontal control used in strip adjustment in microns at negative scale.
4. STDZ—Standard deviation (root-mean-square) of all vertical control used in strip adjustment in microns at negative scale.

The RMSE from the three-photo program gives an indication of how well the pass points in the strip were measured. In only one instance did the pass point measurements exceed the 25-micron rejection limit. This, in turn, did not affect the analysis of the strip because the other pass point of the set was substituted for the rejected point and used twice in the computations.

TABLE 3

PROJECT TEST POINT RESULTS

	Horizontal Control			Vertical Control	
	No. Points	X (ft)	Y (ft)	No. Points	Z (ft)
Project RMSE	49	0.41	0.88	77	0.49
Algebraic mean	49	-0.015	+0.059	77	-0.011

TABLE 4

QUESTIONABLE TEST POINT RESULTS

	T-67F	T-67
X	-0.46 ft	-0.60 ft
Y	-3.81 ft	+2.52 ft

The standard deviations are a confidence criteria relative to the validity of the strip adjustment. Since 1 micron at photo scale represents approximately 0.02 foot on the ground, the project average STDXY and STDZ for the control points were 0.32 foot and 0.25 foot, respectively.

Test points were regular targeted traverse and wing points with known field position. These points were measured with the other field control and selected as test points when setting up the data for the final strip adjustment. Many points that were noted on the comparator sheets as being difficult to measure, partially destroyed, or having poor precision were withheld from the control and were used as test points. The remaining targeted points not used for control were also used for test points.

In some cases test points were not uniformly distributed through the strips. The computed ground coordinates and elevations of the test points were compared with the field values and the RMSE for X, Y, and Z computed. Table 3 indicates the overall project accuracy obtained based on test point values. It should be noted that each flight line was drilled, measured, and computed independently from the other flight lines.

The RMSE for Y in Table 3 contains two test points from flight line 18 that are questionable. Their deviations from the traverse values are given in Table 4.

A recheck of the photographs did not indicate poor target visibility or a large amount of target distortion. With discrepancies this large, they should be classed as blunders. Two hypotheses can be suggested for these deviations: (a) operator difficulty in pointing during comparator measurement of these targets, and (b) error in original field survey data.

Additional computer work (a first- or second-degree adjustment) and varying the control points would probably give a better indication of the cause of these blunders. By withholding these blunders from the RMSE computation for Y, this value would have been 0.59 foot instead of 0.88 foot. This would make the RMSE for Y more compatible with the RMSE for X. Since X and Y are interrelated, it seems reasonable to assume their RMSE's should be near the same magnitude.

CONCLUSIONS

The USC&GS system of analytical aerial triangulation proved to be a satisfactory method for obtaining supplemental control for large-scale mapping. The cost to obtain these data by ground survey methods would have made this project economically unfeasible.

Based on the experience gained on this project the following conclusions are presented:

1. An 80-mile project is too long. Future projects will be limited to a maximum length of 50 miles with traverse closures every 25 miles. This will improve survey procedure and will reduce the tremendous amount of data handling.
2. Target design and placement is critical to precise comparator measurements. Major problems occur when sufficient contrast is not maintained between the target

and its photographic background. When using photo-identified control points, special care should be exercised to select finite points that can be readily identified by the comparator operator.

3. High-contrast glass plates are recommended for use in a stereocomparator to accentuate the targeted points.

4. Pass points should be of sufficient diameter to be easily recognized during map compilation. A 150-micron diameter hole is recommended when using a Kelsh instrument.

5. Results from the analytic aerial triangulation can be improved by more effective control placement during the basic control survey.

6. High-speed computers with large storage capacity must be used to perform analytic computations efficiently and economically. Small-capacity computers require considerable segmentation of the programs resulting in excessive card handling.

ACKNOWLEDGMENTS

The authors would like to express appreciation to the following individuals for their help on this project: Jesse R. Chaves, Engineering Systems Division, Bureau of Public Roads, for his technical assistance; Charles Theurer, Chief, Photogrammetry Branch, USC&GS, for the use of the Coast and Geodetic Survey equipment; Henry Eichert, Chief, Aerial Triangulation Section, USC&GS, and his staff for their technical assistance and cooperation; William T. Pryor, Chief, Aerial Surveys Branch, Bureau of Public Roads, for his cooperation; Donald N. Shaw, Aerial Surveys Branch, for his work as comparator operator; and Maury George, Location Branch, for his assistance.

REFERENCES

1. Kenngott, R. L. Traverse Adjustment by Weighted Least Squares. Charles H. Sells, Inc., Pleasantville, N.Y.
2. Lampton, B. Frank. STK-1 Coordinate Conversion Program. USC&GS.
3. Keller, M., and Tewinkel, G. C. Three-Photo Aerotriangulation. U.S. Coast and Geodetic Survey Tech. Bull. No. 29, Feb. 1966.
4. Keller, M., and Tewinkel, G. C. Aerotriangulation Strip Adjustment. U.S. Coast and Geodetic Survey Tech. Bull. No. 23, Aug. 1964.

Models for Highway Design: Some Construction and Photographic Techniques

REX G. PORTER, DeLeuw, Cather and Company of Canada Limited

The first primary purpose of this research was to find, by experiment, a mixture that was suitable for design modeling of highways. Many available materials were mixed, molded, observed, photographed and evaluated for this use. The ideal mixture was found to be motor oil and asbestos powder since it stayed malleable and could be easily remolded giving a realistic impression of grading in the photographs. Further research was done using glycerine instead of oil as a wetting agent and there was no appreciable difference in the two.

The second primary purpose was to apply this mixture to an actual design problem. Two design alternatives were constructed and the modeling techniques evolved. The method proved to be fast and effective as a preliminary design aid and it provided a reliable evaluation of the scheme finally constructed. Other alternatives could be examined at small additional cost.

A secondary result that evolved from this research was valuable experience in the photographic technique, instrumental in making a visual evaluation of preliminary design alternatives. The photographs taken through the modelscope gave a realistic roadway view that a driver would see.

Models and photography provide an inexpensive design evaluation tool and contribute to an efficient and aesthetic preliminary design.

•PRIOR to this study, polyurethane had been used to form the slopes on highway design models. This method required a great deal of time to shape the polyurethane by sanding and cutting, and later adjustment was not possible. If a design change was required after completing the model and studying it through a modelscope (for a description of the modelscope and its use, see the section on "Photographic Technique"), then a new model of the changed section had to be constructed. Dry sawdust had also been used but it did not give a realistic impression of the graded surface in the modelscope photographs.

A study of materials was made in order to recommend a material or a combination of materials that lent itself to modeling at the preliminary design stage; that is, the ideal material desired could be molded easily, then reworked quickly and yet retain its shape once remolded. At this stage, modelscope analysis of problem areas of vertical and horizontal alignment and grading irregularities could be used to advantage to show up problems and provide solutions not readily seen in two-dimensional plans and profiles.

A variety of materials and binders was described, mixed and formed into test slopes to narrow down the detailed analysis to only a few possibilities. Finally, an example problem was analyzed using the recommended material and several modelscope photographs emphasized the value of this inexpensive design aid.

Paper sponsored by Committee on Geometric Highway Design and presented at the 48th Annual Meeting.

GENERAL STUDY PROCEDURE

Initially, a wide range of fill materials and binders was tested in different combinations. Materials tested to be used as fill were sawdust; Ottawa sand; floorsweeping compound (sawdust); Hill & Dale modeling compound; Perma Scene modeling compound; asbestos insulating powder; Pollyfilla powder; and plastic wood. Materials used as binders were contact cement; Bulldog glue (fish base); liquid plastic varnish; rubber cement; water and Pollyfilla; lubricating oil (No. 10 grade); glycerine (liquid); and linseed oil.

The testing procedure consisted of mixing these different fill materials with various binders in varied proportions to produce a workable mixture. These mixtures were then molded into test slopes and small cubes to test shrinkage, and their appearance on drying was noted. The following observations were made:

1. proportions of components used;
2. description of mixing process;
3. wet workability in molding to shape;
4. binding power to itself and to the base;
5. dry workability in remolding by cutting, sanding, chipping, and reshaping;
6. shrinkage of mix on drying;
7. hardness of mix on drying;
8. strength when dry; and
9. relative weight of the mixes.

Color photographs were made to show the more promising mixes shaped in small sample slopes. An impression of the surface texture and coloring was noted in the photographs. After studying the relative advantages and disadvantages of each mixture tested, four promising mixes were picked for further study. They were the following:

1. Liquid plastic varnish and Hill & Dale compound.
2. A combination of $\frac{1}{3}$ by volume sawdust, $\frac{1}{2}$ by volume asbestos, and $\frac{1}{6}$ by volume Pollyfilla plus as little water as possible, to make a workable mixture.
3. Perpetually wet, malleable mix No. 1 of asbestos powder plus as little No. 10 grade lubricating oil as possible to make a workable mixture.
4. Perpetually wet, malleable mix No. 2 of asbestos powder plus as little liquid glycerine as possible to make a workable mixture.

A small scale model was made using these four mixes and a shrinkage disadvantage in using the Hill & Dale modeling compound was observed. A space developed between this mixture and the polyurethane road profiles.

Linseed oil was originally used as a binder for the asbestos to keep it malleable, but, after drying for several days, a thin skin developed on the surface and could not be remolded. This problem was not encountered using No. 10 grade lubricating oil or the liquid glycerine.

There was no appreciable difference in using liquid glycerine or lubricating oil in the malleable mixes and since the malleable type of model appeared to be the most promising material for design testing, a more complex modeling problem was attempted.

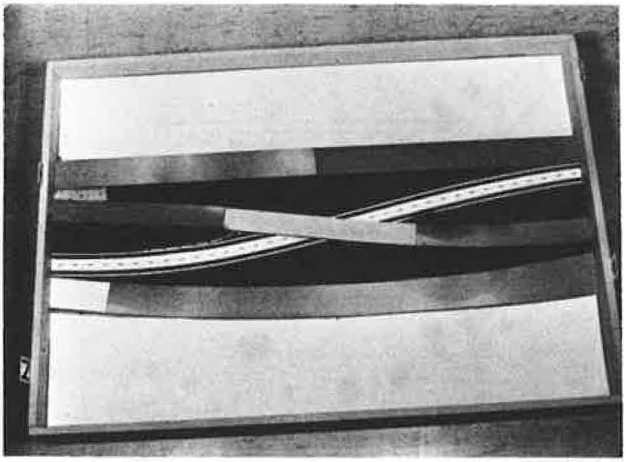
A model of a basketweave overpass on Highway 427 in Toronto, then in the final design stage, was constructed at a scale of 1 in. = 40 ft, and the malleable mix using lubricating oil was used to form the cut and fill slopes. Two retaining wall alternatives were modeled and photographed to show the advantage of this material as a design tool in pointing out visual differences in each alternative.

A detailed description of the construction technique with the recommended materials follows in the next section.

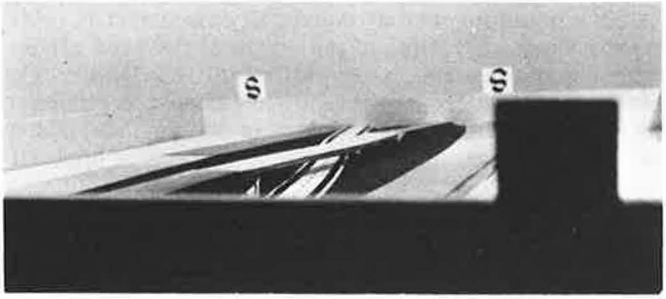
THE REMOLDABLE MODEL—A TECHNIQUE

General Setup of the Model

A 40-scale model of the southbound basketweave bridge area was constructed and two retaining wall alternatives were compared. Three oblique views of the model are shown in Figure 1.



PLAN VIEW



OBLIQUE VIEWS

Note: The letters "N" for north and "S" for south indicate in the photographs the actual sight direction.

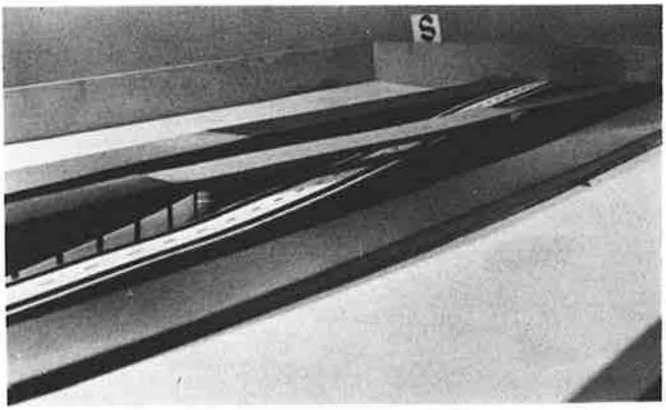


Figure 1. Overall photographs of remoldable model.

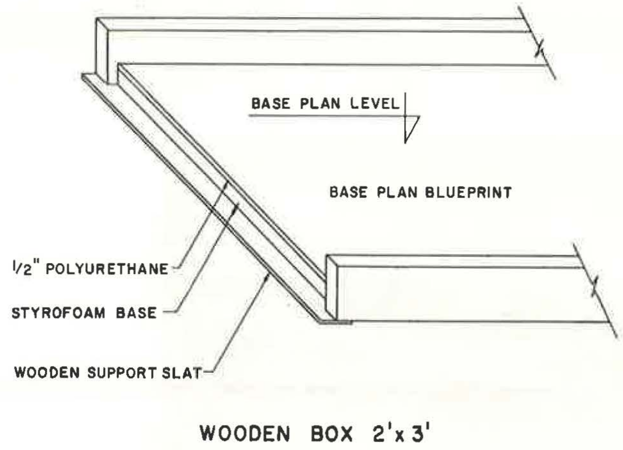


Figure 2. Cutaway view of container and base.

A wooden box 3 ft by 2 ft was constructed to fit the required area modeled at a scale of 1 in. = 40 ft. A styrofoam base was supported by wooden slats and a ½-in. piece of polyurethane was placed on this to provide a base plan elevation level at least 10 feet (to scale) below the lowest elevation in the area (see Fig. 2).

A base plan blueprint at the required scale (1 in. = 40 ft) was then set on the polyurethane sheet. Profiles of the edges of the road alignments were cut from ½-in. polyurethane and pinned along the required alignments on the base plan. The road subsurfaces were cut from ¼-in. polyurethane and pinned to the profiles. A 3.5-ft offset from the edge of shoulder was left as polyurethane subsurface since the usual minimum retaining wall offset is 3.5 feet. Areas of high fill were approximated with contours cut from ¼-in. polyurethane and then a top layer of asbestos and oil was used to make a smooth top surface (see Fig. 3 for detail drawings).

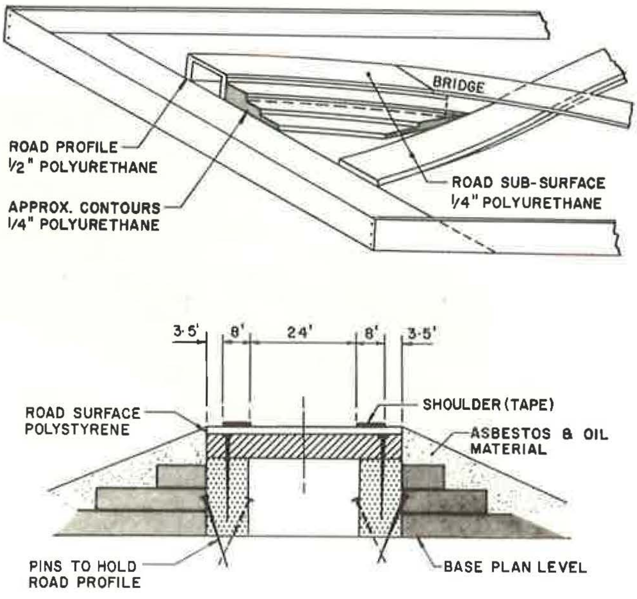


Figure 3. Contour material detail.

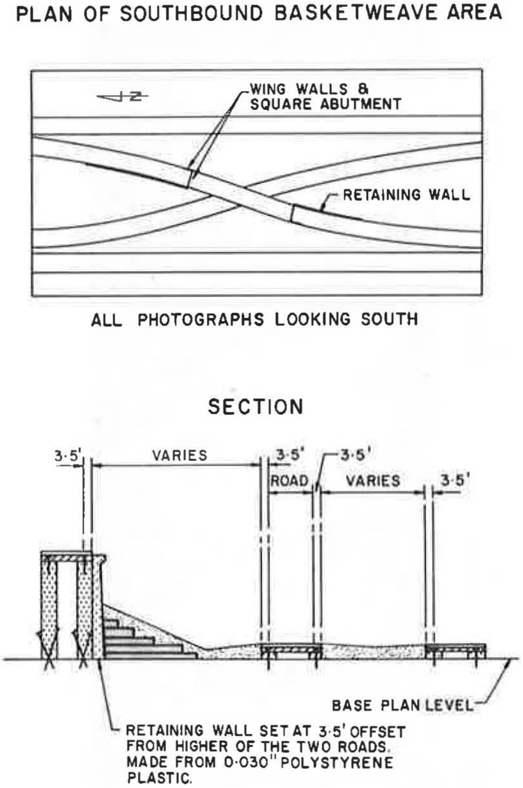


Figure 4. Retaining wall Alternative 1.

Road Surface Materials

The polyurethane road surfaces were found to be too rough when photographed by the modelscope; therefore, a smoother-textured material was required to give the effect of pavement in the photographs. Three materials were tried:

1. Cardboard (bristol board)—Since the asbestos material plus oil did come in contact with this road-surface material, the paper in the cardboard becomes saturated with the oil and, within three to four days, irregular dark patches appeared along the edges of the road. Changes in humidity also caused this material to warp.
2. 0.015-In. Polystyrene Plastic (rubber cement binder)—This material was too thin to hold a ribbon-like road shape without warping and forming undulations. Rubber cement was used as an adhesive to hold the plastic to the polyurethane and it did not dry completely. This could be due to saturation of the surface with oil, which destroys the binding effect of the rubber cement.
3. 0.030-In. Polystyrene (contact cement binder)—The contact cement formed a solvent bond with the polystyrene and dissolved the surface of the plastic; therefore, any excess contact cement on the top of the road surface could not be removed without scarring the surface. However, the bond with the polyurethane in contact with the oil-soaked asbestos was much stronger than when using rubber cement, as the contact cement is not affected by the oil. After photographing with lights, no warping was observed.

Slight undulations in profile were noticed but these did not distort the overall effect as in (2) above. In some test photographs a slight glare was observed on the surface of the road in front of the retaining walls. This was corrected by spraying the road and retaining wall surfaces with a dull lacquer (Letraset art fixative). On rephotographing this surface, the light was diffused enough so that glare was not a problem. The 0.030-in. polystyrene was recommended for future use.

Vertical lines spaced at 30-ft intervals to scale were put on the exposed face of the retaining walls to give an increased impression of depth in the photograph. A thin black tape was used.

Retaining Wall Alternative 1

A retaining wall cut from 0.030-in. polystyrene plastic was offset from the HIGHER edge of shoulder alignment by 3.5 feet (see Fig. 4). This retaining wall section was cut to the proper height and length when supported on the base plan level, and the material contoured to the proper 3:1 slopes (see Fig. 4). The asbestos and oil mixture was molded to shape very quickly and any changes in slope could be altered easily.

This alternative was photographed from different locations using a Pentax single reflex camera (see section on "Photographic Technique" for photographic details). A modelscope was attached to the camera to give an eye-level view of the road from the driver's vantage point and photographs were taken from five positions on the left-hand lane and five equivalent positions on the right-hand lane. A sequential set of photo-

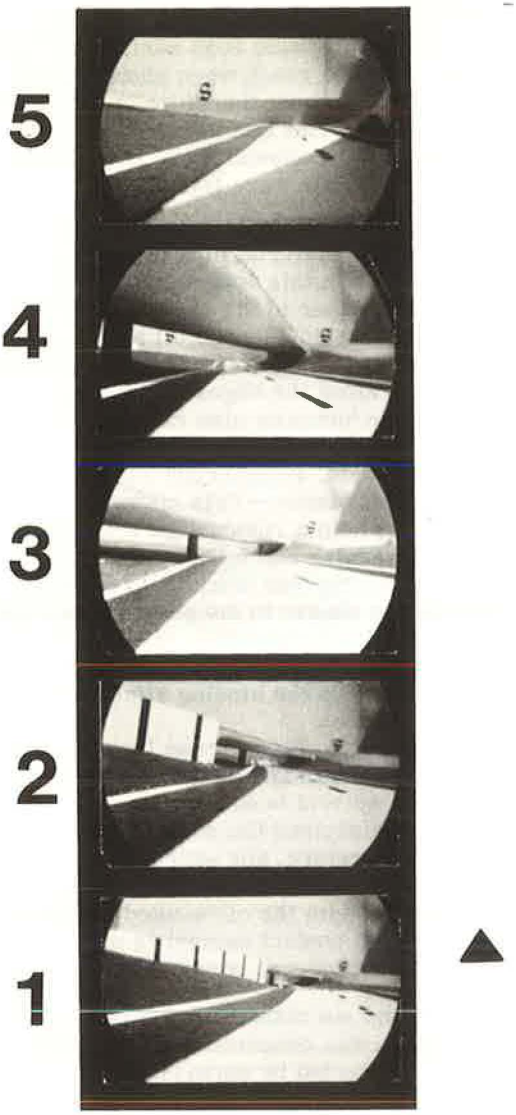


Figure 5. View driver sees from left-hand lane (Alternative 1).

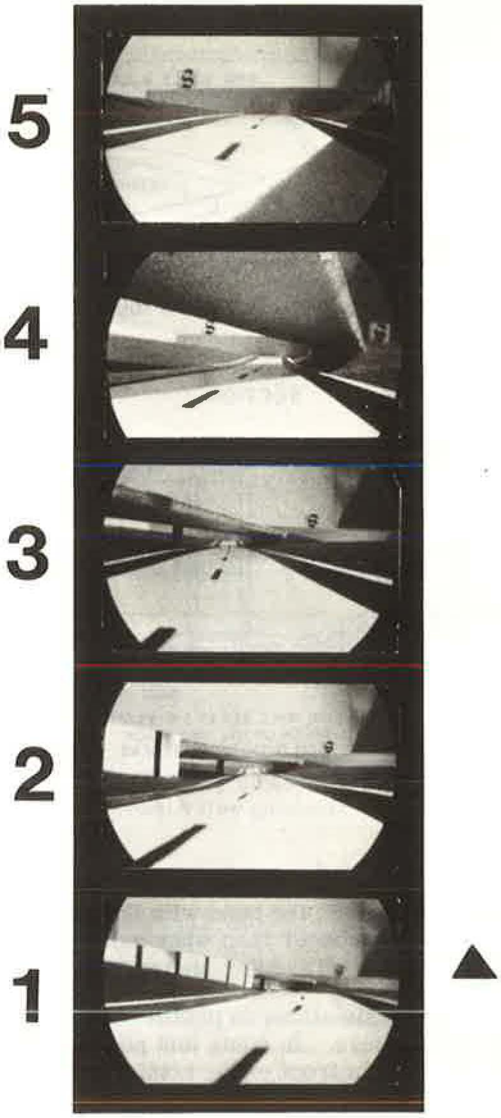


Figure 6. View driver sees from right-hand lane (Alternative 1).

graphs for the left-hand lane is shown in Figure 5 and a similar set of photographs for the right-hand lane is shown in Figure 6. The actual positions on the model from which these photographs were taken can be seen in Figure 7. The model was then changed to form the retaining wall alignment described in the next section.

Retaining Wall Alternative 2

The retaining wall used in Alternative 1 was removed and some of the malleable fill was remolded to suit the new grading. For Alternative 2 a retaining wall cut from polystyrene and resting on the base plan level was offset from the LOWER edge of shoulder alignment by 3.5 feet and curved under the bridge to fit the new grading contours (see Fig. 8). Alternative 2 was photographed from the same positions as Alternative 1 (see Fig. 7). The sequential photographs of the left-hand and right-hand lanes can be seen in Figures 9 and 10.

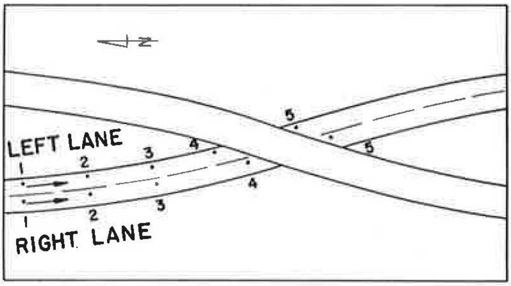


Figure 7. Position of modelscope (Alternatives 1 and 2). (Note: Numbers refer to photograph number shown in Figures 5, 6, 9, and 10).

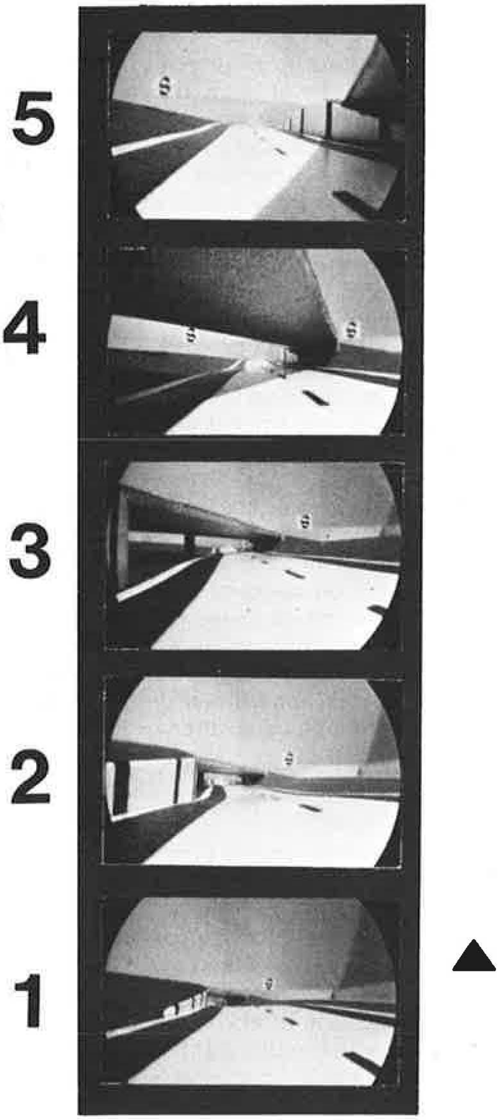


Figure 9. View driver sees from left-hand lane (Alternative 2).

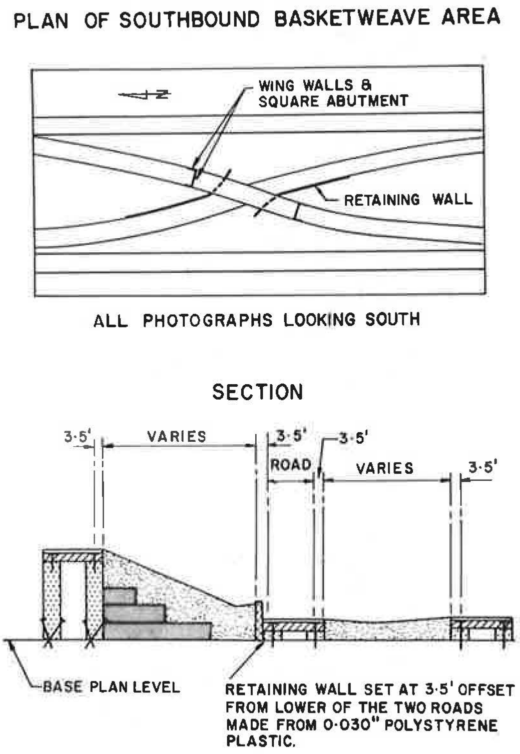


Figure 8. Retaining wall Alternative 2.

A Detailed Comparison of the Two Alternatives

A comparison of the two alternatives shown in this report with respect to design criteria such as sight distance, visual aesthetics and grading irregularities, will illustrate the usefulness of this technique. In order to decide which retaining wall design is better, the engineer can now compare similar views of each alternative taken from the driver's vantage point. For example:

1. Compare photograph 1a with photograph 2a in Figure 11. There is a much wider view through the bridge in Alternative 1 than Alternative 2.
2. Compare photograph 1b with photograph 2b in Figure 11. A feeling of enclosure and lack of room for maneuvering is felt in Alternative 2 due to the retaining wall being offset close to the lower road on the left. Alternative 1 leaves a slope on the left in case of emergency and is a better design.
3. Compare photograph 1c with photograph 2c in Figure 11. Alternative 2 gives the same feeling of enclosure on the right

as it did on the left in (2) above. Alternative 1 would be a better design.

Time and Cost Considerations

After gaining some experience in mixing and working with the recommended material, a technician can construct a small area model similar to the one tested here in two to three days. The change from Alternative 1 to Alternative 2 required one to two hours of work in cutting the new retaining walls and reforming the grading material.

Similarly, when experience has been attained in setting up the camera equipment, and after the optimum settings for the camera have been determined, one to two hours will be required to shoot 10 to 20 photographs of each alternative. Therefore, when processing time for photographs is taken into account, a comparison of preliminary schemes of a small area similar to the bridge described in the section on "Remoldable Model" at 40-scale can be completed in a matter of several days by one technician.

Material costs for this technique are inexpensive. Initially, the cost for photographic equipment (as described in the section on "Photographic Technique") is a large investment but it can be used for other purposes in any company, and most highway consulting and design firms require similar camera equipment. The modelscope is the only specialized instrument needed for this technique. Therefore, the total costs of a design model such as that described above are extremely low compared with its value as a tool in the design process. The realistic views given in the photographs indicate the confidence that can be placed on the decision of how a design will appear when constructed.

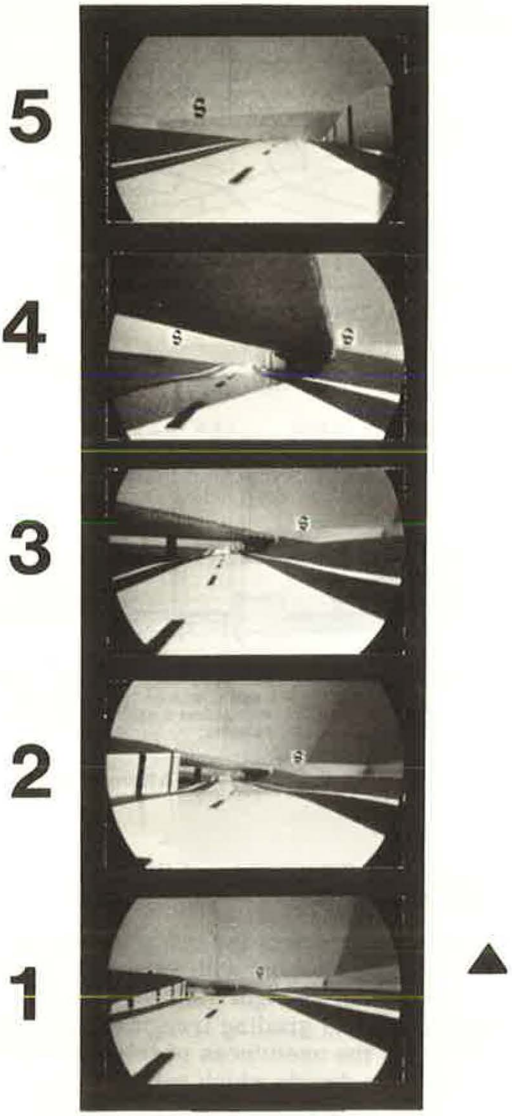


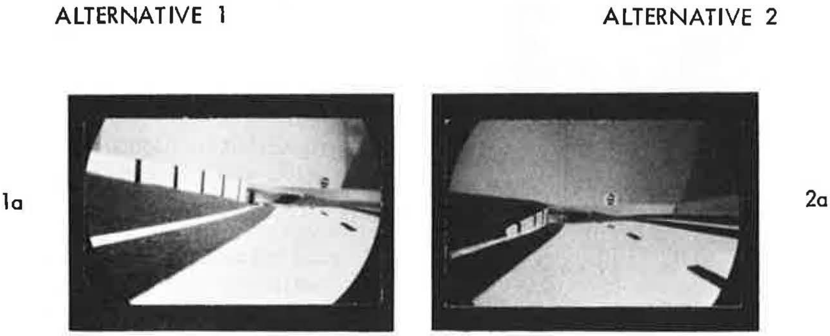
Figure 10. View drives sees from right-hand lane (Alternative 1).

Overall Comments, Summation and Conclusion

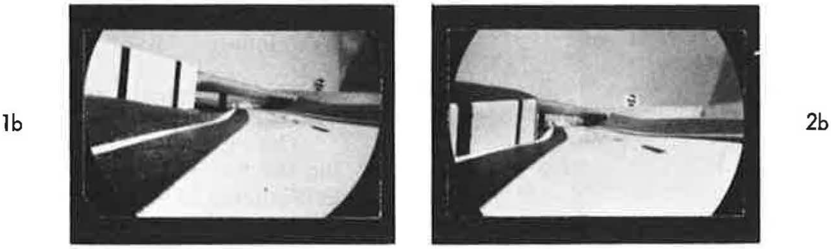
For a working model where design changes arise during preliminary stages, a remoldable mixture of asbestos powder mixed with lubricating oil was the most satisfactory material. Road surfaces cut from 0.030 polystyrene sprayed with a dulling lacquer to prevent a glare conveyed a smooth surface in the modelscope photographs.

Black-and-white photographs convey a tonal contrast more effectively than do color photographs; therefore, for a comparison of alternative designs, they are recommended. However, for presentation purposes where a more realistic effect is desired, more effort could be spent on coloring the asbestos mixture and using color photographs for visual comparison. Contrast between retaining walls and road surfaces can be attained by color tinting and placing lights for shadowing effects.

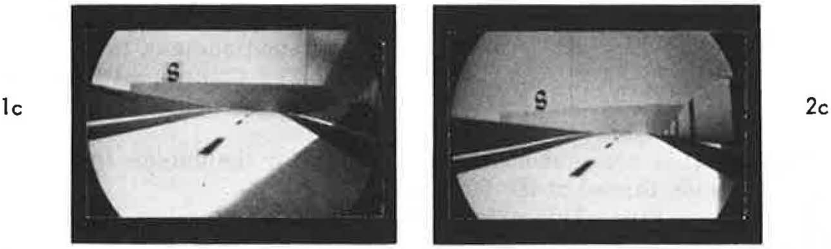
Different design alternatives can be easily constructed, photographed and analyzed in three-dimensional models. In the past, two-dimensional plans and profiles or illus-



Position No. 1 Left-Hand Lane.



Position No. 2 Left-Hand Lane.



Position No. 5 Right-Hand Lane.

Figure 11. Comparison of photographs.

trations have not been enough to visualize the driver's view and sight distance difficulties in complex design proposals. Grading problems adjacent to structures such as bridges, bridge wingwalls and retaining walls can be pointed out by using this type of modeling technique. By careful analysis of the model and photographs a suitable design to overcome these problems can result in good aesthetics from the driver's viewpoint.

This type of modeling can be done at the preliminary design stage and eventually used to show the final design for presentation purposes. In this way, time spent on modeling is being utilized in the design phase towards presenting the final solution.

This particular design example points out the specific usefulness of this technique of photographic model evaluation applied to retaining wall location and grading design.

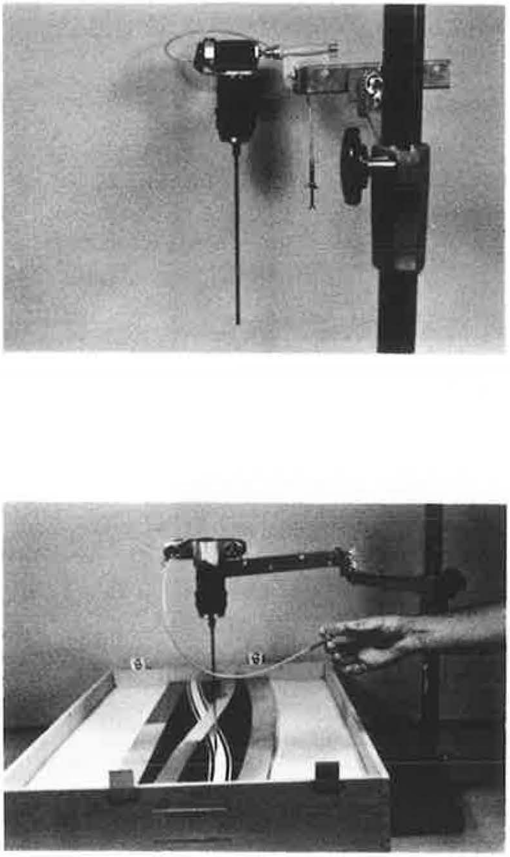


Figure 12. Photographic equipment setup.

In addition, other design evaluations that have been made using the modelscope are (a) correlation of vertical and horizontal alignment; (b) abrupt changes in horizontal and vertical alignment pointed out; (c) bridge evaluation with regard to openness, fit in the overall design and column and abutment placement; (d) sign locations to maximize driver perception and route continuity; and (e) guiderail location evaluation to minimize sight obstruction. All these uses will contribute to a better visual design by improving the driver's view of the highway.

In conclusion, the advantages of this method of design evaluation justify the relatively small costs of these modeling techniques.

THE PHOTOGRAPHIC TECHNIQUE

The equipment used in photographing the model is given below and shown in Figures 12 and 13.

The Modelscope (by OPTEC, Washington D. C., U. S. A., and London, England)—This device views the road from a small lens at eye level above the road surface. It gives an image that a driver would see sitting in a car if the height of the lens is adjusted properly to the vertical scale of the model.

The Camera—A Pentax Spotmatic 35-mm single lens reflex with a cable release.

Lens Adaptor—This was manufactured specially for the outside thread of the modelscope to fit the inside thread of the 50-mm lens.

A No. 1 Extension Ring—This extends the focal length to allow the image to fill the frame on the film.

Tele-Converter 2X—This converts the 50-mm lens on the Pentax camera to a 100-mm lens.

Vice Clamp With a Universal Socket—This is attached to the camera body and allows the camera to be leveled and also aligned so that the modelscope will be vertical. It can be purchased as an accessory to the camera.

Extension Bracket—This extends the camera over the model and can be adjusted to suit the size of the model. It was a piece of iron with a 90° bend and drilled holes to allow for additional extension pieces.

Pentax Photographic Copy Stand—This stand allows the camera to be placed over the model in any position desired to give the required view through the modelscope. It provides a rigid support to hold the apparatus and prevent movement of the scope.

The problems involved with this photographic technique are as follows:

1. Lighting is one of the most crucial factors in producing a true image of the model since the lighting intensity is greatly reduced due to the optics of the modelscope. The lighting cannot be read indirectly by a hand-held light meter nor directly by a light meter inside the automatic camera. The hand-held light meter does not record the actual amount of light coming through the scope. The automatic light meter in the

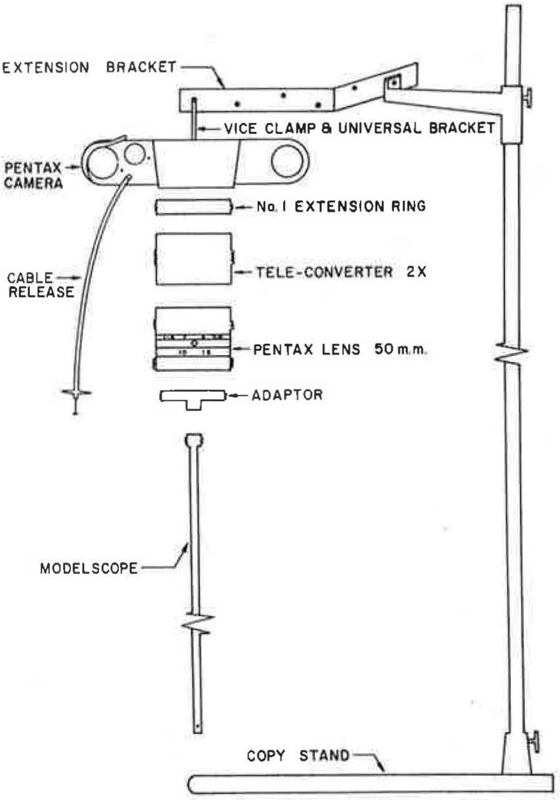


Figure 13. Equipment diagram.

camera is not sensitive enough to calibrate the available light through the scope nor is it illuminated by the light hitting the meter dial. Tests were made at different apertures and exposure times to determine the best setting for the lighting conditions. Because of the modelscope optics in combination with the camera lens arrangement a suitable depth of field chart was not available. Therefore, further investigation found that a focus adjustment on the camera ring of 12 to 15 feet was the best setting to use in this situation.

2. A possible way of avoiding these trial exposures under different lighting conditions would be to use a canon FT—QL camera. It has a booster meter attachment that is extremely sensitive to low lighting levels passing through the lens. As a visual aid, the meter is mounted on the outside of the camera.

3. Movement of the modelscope is another factor that will blur the image since long exposure times are required. Care must be taken to stop any pendulum motion of the scope. To anchor the end of the scope of the road surface before each shot, apply masking tape, with adhesive on both sides, to the position on the road where the scope is to be set, and firmly press the scope down for lateral stability.

4. In order to have the modelscope image located in the center of the negative, the modelscope must be positioned so that it is vertical. This was done by adjusting the camera position by means of the clamp and universal socket. The lens on the bottom of the scope should be square to the camera and not at a skew angle.

Black-and-white photographs were taken with Kodak Tri-X film with an A. S. A. rating of 400 using natural light. The model was set up outside on a clear sunny day and the settings used were aperture = f 2.0; exposure time = $^1/_{16}$th second (for all positions); and focus adjustment = 12 feet.

Color transparencies were also taken using Kodak 35-mm Ektachrome for artificial light with an A. S. A. rating of 125. The lighting was provided by three 500-watt, 3200°K lamps approximately 3 feet away from the surface of the model. The settings used were aperture = f 1.4; exposure time = 1 second (for all positions clear of a structure); exposure time = $1^1/_2$ seconds (under a structure); and focus distance = 15 feet.

ACKNOWLEDGMENTS

Valuable assistance in the development of this design technique was given by J. E. Leisch, Vice-President and F. R. Berry, Staff Engineer of DeLeuw, Cather & Company of Canada Ltd. W. E. Carroll, Drafting Supervisor, contributed many helpful comments on the photographic technique.

Evaluation of Complex Interchange Designs By Three-Dimensional Models

E. H. GEISSLER and A. AZIZ, Department of Highways, Ontario, Canada

This paper discusses some of the methods of constructing three-dimensional models used in the evaluation of the highway and interchange design, particularly as a means of determining the aethestics of the highway alignment and the surrounding terrain.

A case study is described of a three-dimensional model for a complex interchange in the City of Toronto, Ontario.

A step-by-step fabricating procedure is described and the role that motion and still photography plays in the evaluation of design is discussed. A photographic program is also described, which takes into account both the motorist's view and that of a pedestrian viewing the complex interchange from the surrounding area.

•HIGHWAY designers have known for some time that designing and building highways is not only a matter of producing good roads that are adequate for the safety of highway users, but also that they must be attractive and pleasing to the eye. This intrinsic requirement has become known as "highway aesthetics," and although it has not yet been precisely defined, it is becoming one of the prerequisites of highway alignment design.

Some successful work has already been done and this has enabled a more critical evaluation of the aesthetics in alignment design. Wider investigation is now being accomplished by means of computer programming techniques and, in addition to this, the three-dimensional model method is providing a further means of examining designs, particularly of interchanges, so that adjustments can be made during the functional design stages. This paper discusses some notable achievements in the construction of three-dimensional models and advances other ideas and methods, which it is hoped will assist in the comprehensive evaluation of future highway design.

KNOWN TECHNIQUES FOR THREE-D MODELS

Perhaps the simplest way of constructing a three-dimensional model is the method used in Germany (1) in which a model is constructed by cutting profiles from plain or corrugated cardboard, and mounting them on boards according to the horizontal alignment. The model roadway itself is constructed of paper strips of the required width. For more impressive representations, the profiles are overstated in the ratio of 1:10 or 1:5. For perspective or photographic control, a single scale is used for both plans and profiles. However, more comprehensive models, representing the terrain adjacent to the alignment corridor, incorporate cross sections of the immediate surroundings (Figs. 1 and 2).

For models representing larger terrains, contours are cut from a single styrofoam sheet. After placing the sheet on a wooden base, the corresponding contours are then lifted up vertically into the proper elevation and supported by blocks of plastic or other material as shown in Figure 3. The various contour sheets are then glued together and the sharp corners of the sheets are either cut off or filled in with a suitable filler. The

---

Paper sponsored by Committee on Geometric Highway Design and presented at the 48th Annual Meeting.

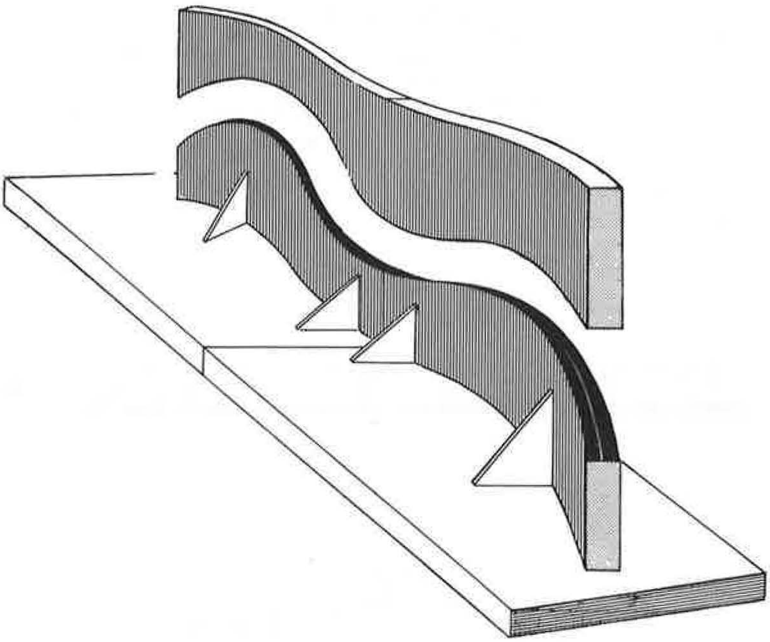


Figure 1. Simple alignment model.

roadway is then cut out along the proposed alignment by means of an electrically heated wire.

In the Netherlands a different type of model (2), known as the "Latten model," ranging in scale from 1:40 to 1:5, has been used. This model is constructed on a special layout table, which usually requires a fair-sized workshop. The roadway profiles are built up by means of wooden or metal supports, spaced about one foot apart, on top of

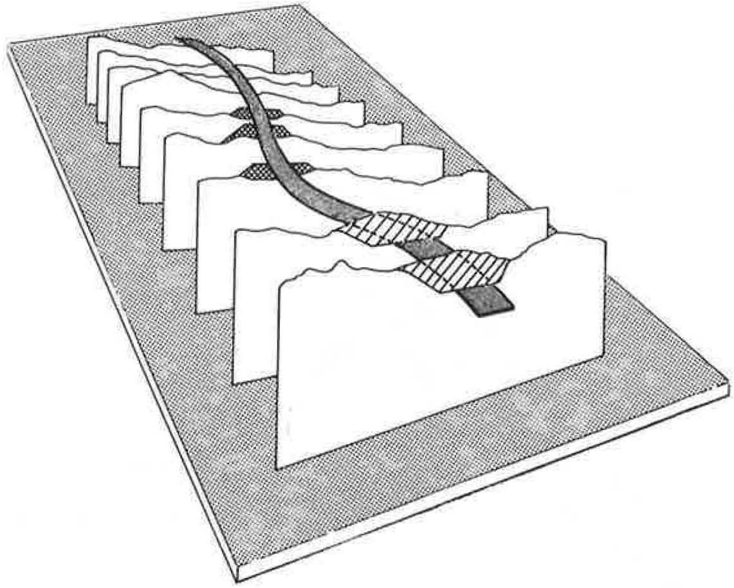


Figure 2. Alignment with adjacent terrain.

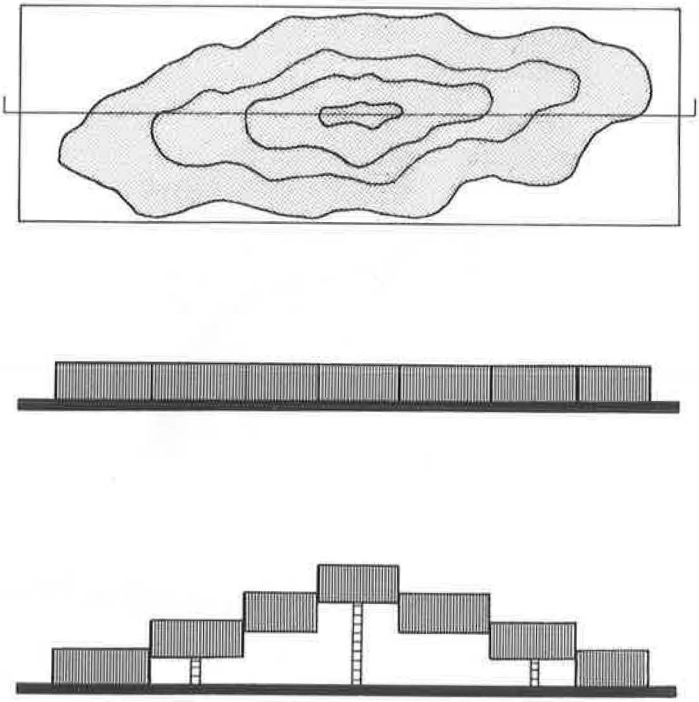


Figure 3. Terrain model.

which are fixed thin black wooden strips to represent pavements. The completed model shows terrain and landscaping of the immediate area (Fig. 4).

A somewhat different technique has been developed in Great Britain (3) in which the basic unit consists of a three-legged table with a rigid foam plastic sandwich fixed to the top into which steel pins can be pressed by hand. Depending on the lengths and the design, additional tables are set up as required. Plans are then laid out and steel pins

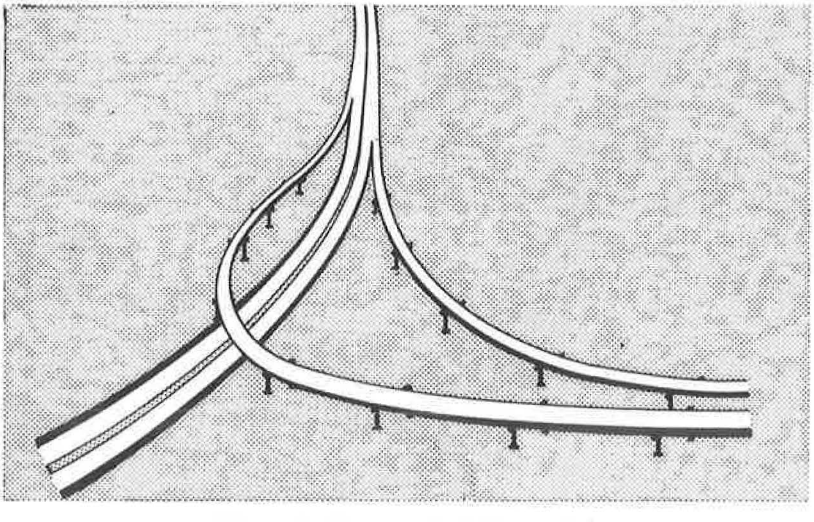


Figure 4. Large-scale Latten model.

inserted to proper elevations along the centerline. A rubber extension with curvature in both planes is then fitted across the top of the pins, usually to a scale of 1 in. = 15 ft (Fig. 5).

Model building for more complex designs (such as interchanges) has been adopted in some American states (4). In this method the model is built on a base plan of the interchange and pasted onto a rigid plywood sheet. The datum to accommodate the lowest sag is determined and profiles of all roadways are cut from prints and glued onto flexible cardboard. These in turn are placed on corresponding baselines of the plan base by means of balsawood blocks nailed to the plywood sheet. To facilitate better visual evaluation and different profile elements they are color coded according to type; i.e., roadways, ramps, and structures (Fig. 6).

Another method, used in California (5), is to build up the terrain with sections of styrofoam that are arranged to conform with the contour map of the area. This is sanded and covered with putty and painted; finally it is spread with glue and covered with ground wool to show the landscape. Trees made of sponge rubber and buildings copied from aerial photographs or ground photos are added. Grades of roadways are represented by means of wooden blocks; roadways and bridges are cut from pressboard and wooden blocks are used to duplicate prestressed concrete supports (Fig. 7).

Another simple method, which is not too different from those described, has been developed by the Department of Highways, Ontario. It consists of cutting pairs of terrain and slope strips of styrofoam on both sides of the roadway alignment. In this method, styrofoam is cut along the horizontal alignment by means of a thin electrically heated wire. This is followed by a second cutting to represent the profile of the line; side slopes are formed by adjusting the electrical wire to the slope gradients. All are glued together and attached to the layout plan. A thin layer of Pollyfilla is then applied

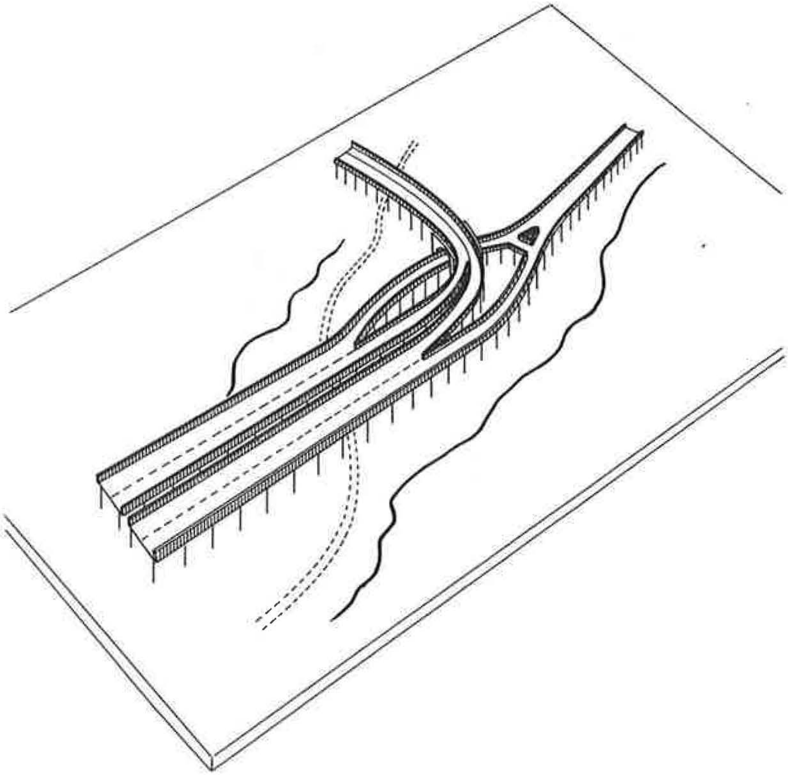


Figure 5. Three-dimensional road design.

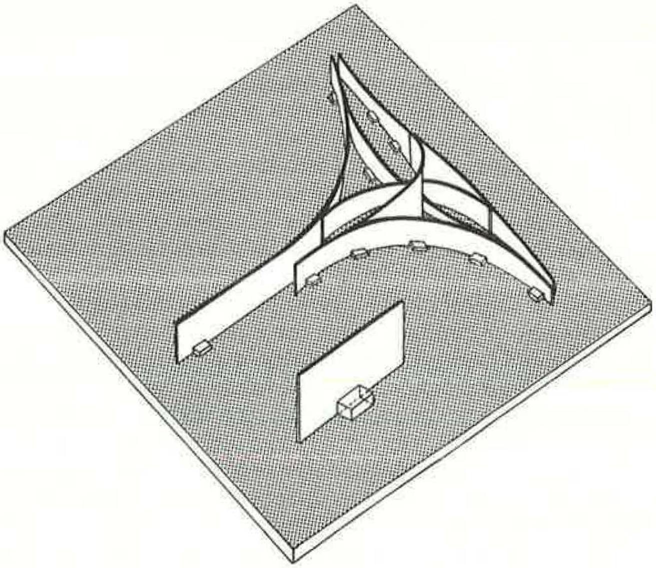


Figure 6. Interchange model.

and the pavement ribbon, made of thin cardboard, is pasted onto the roadway alignment. The model is then equipped with colored strips of a mosaic plan showing the terrain and land-use pattern. Figures 8 and 9 illustrate the cutting and assembling process.

CASE STUDY

The case study discussed is a new design of an existing interchange at the intersection of Highway 401 (MacDonald-Cartier Freeway) and Highway 27, located in the north-

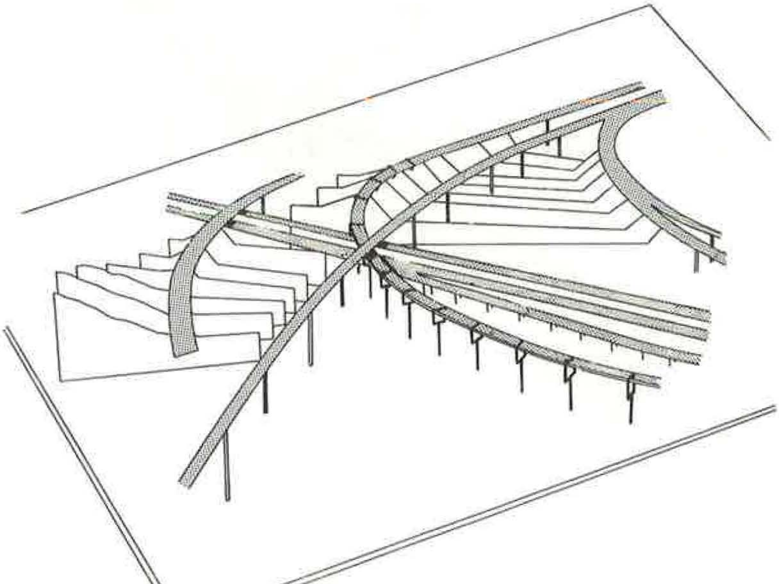


Figure 7. California terrain model.

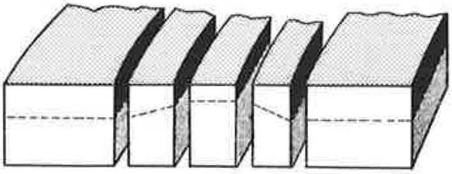


Figure 8. Cutting of small terrain model.

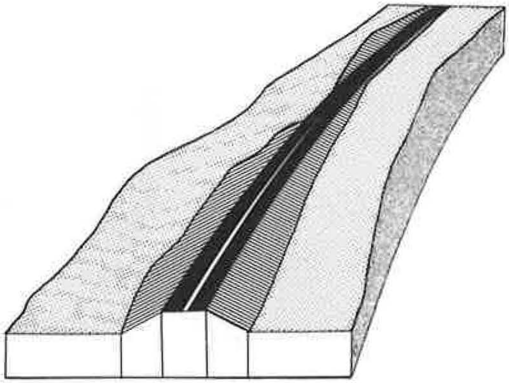


Figure 9. Assembly of small terrain model.

west section of Metropolitan Toronto in Ontario. The existing layout of the interchange is illustrated in Figure 10, with Highway 401 as the major east-west route, Highway 27 as the north-south route, and the Airport Expressway, to the International Airport at Malton, some two miles to the northwest.

Development and land use in the region is mainly residential along Highway 27. From Highway 401 north, the land is first zoned for industrial purposes and further out it is zoned for residential use. Because of industrial growth and other developments, large traffic volumes are anticipated in the area with heavy morning and evening peak-hour loads.

Traffic planning studies in this region have shown the future traffic desires and patterns to be as indicated in Figure 11. Based on these projected traffic volumes and patterns, the design finally selected is shown in Figure 12.

Comparing the existing interchange with the selected redesign, the following additions and changes were involved: (a) realignment of Highway 27 to join with the Airport Expressway; (b) a new freeway, Highway 403, leading southwesterly to link up with the Richview Expressway; and (c) a collector-distributor system for Highway 27.

The proposed design of the interchange at this location involves 27 structures with a total deck length of approximately 2½ miles, several retaining walls, and about 32 miles of roadways of all types; it extends over an area of about 1,200 acres (Fig. 13).

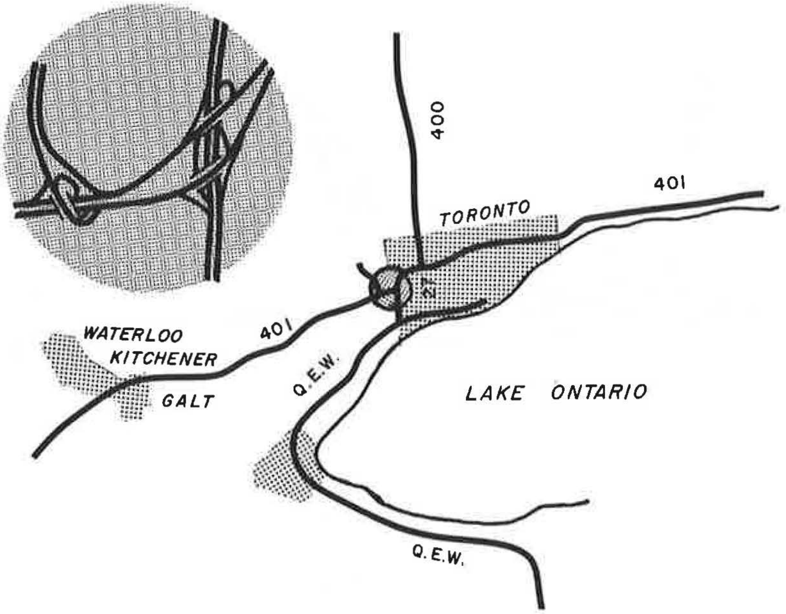


Figure 10. Existing interchange—Highways 401 and 27.

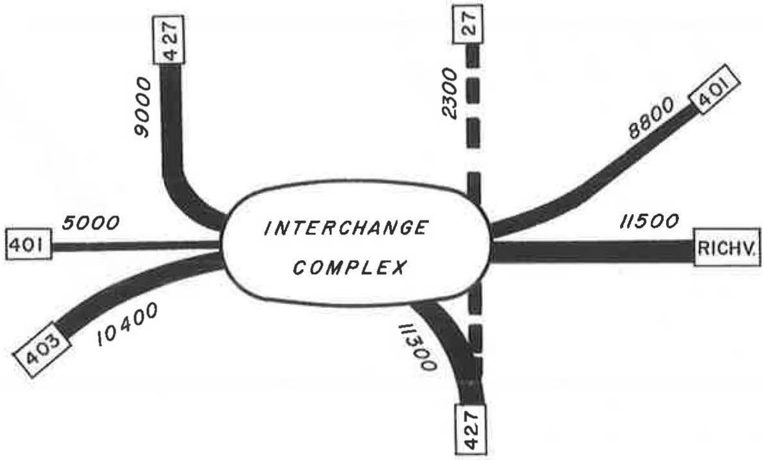


Figure 11. Future traffic volumes.

METHOD OF CONSTRUCTION OF MODEL FOR THE CASE STUDY

The basic building materials for this model were urethane sheets, wooden blocks and thin but firm cardboard sheets, etc. A two-step approach for its construction was necessary to: (a) build up the terrain model of the interchange area and its surroundings, and (b) construct the design in both planes, and to adjust it to the terrain.

The working scales selected for use on this model were 1 in. = 100 ft for horizontal alignment and 1 in. = 40 ft for vertical alignment; two sets of contour plans including the design layout were utilized.

Construction Steps

The following steps were used in the construction of the model:

1. A print of the contour plan of the area was pasted to a ½-in.-thick urethane sheet, which was attached to a ¾-in.-thick plywood base. Two consective contour lines were

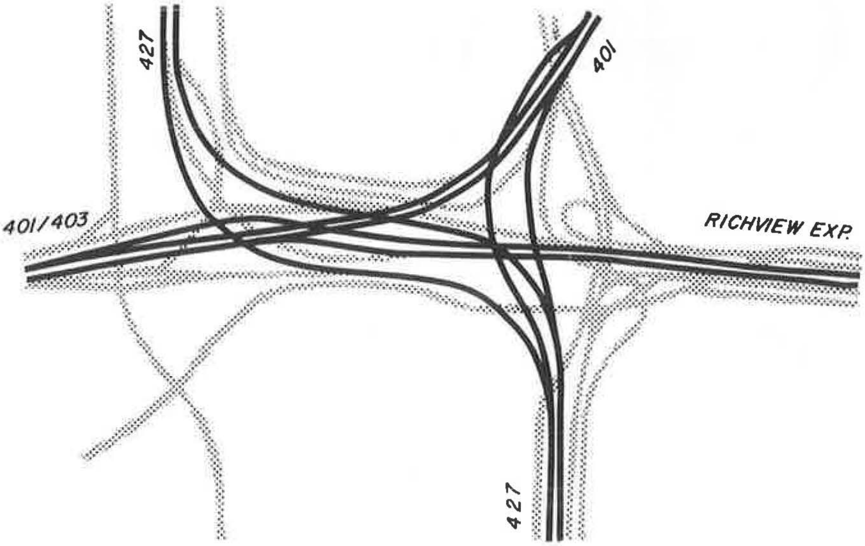


Figure 12. Selected interchange design.

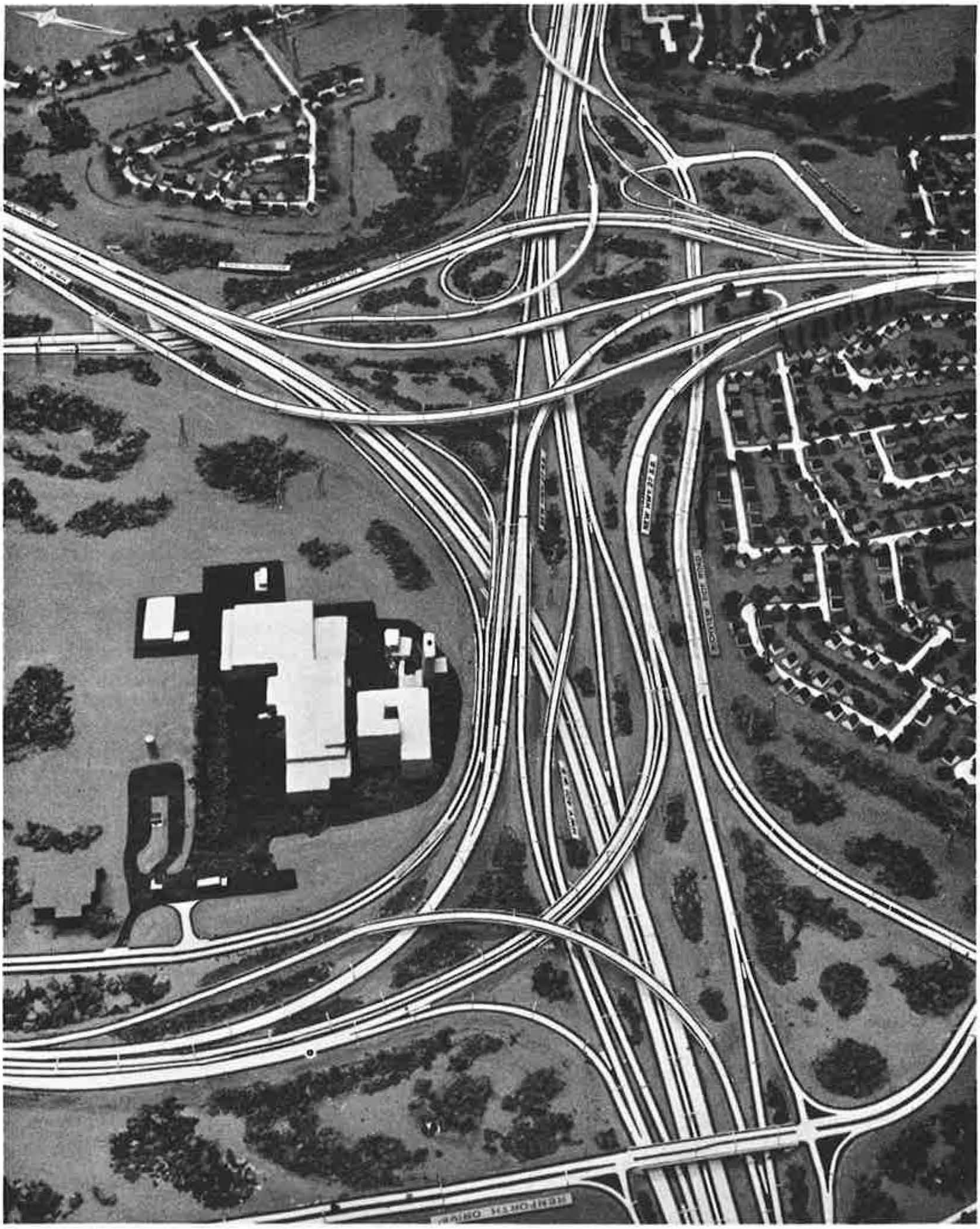


Figure 13. Overall view of new interchange.

traced on each subsequent urethane sheet—one line for the corresponding elevation, and the other to position the next urethane contour sheet. Each sheet was then cut along the contour line starting with the lowest contour so that when stacked up the sheets reproduced the terrain model of the whole area.

2. The interchange design layout was pasted onto a thin sheet of cardboard and the layout design cut out so that it could be used as a template. As each contoured sheet

of urethane was stacked and fixed, the horizontal design was correspondingly cut into the model.

3. The profile grades and vertical curves were traced on the side of the urethane sheets representing the roadways, and each roadway, already cut out, was arranged and fixed into position.

4. Cuts and fills were formed and attached and the surface of the model sanded; this was followed by coloring and landscaping. Further pavement and shoulders were traced on cardboard strips, color coded and glued to the roadways.

5. Bridge decks and piers, etc., were made of basswood and placed in position.

MODEL STUDY BY MEANS OF MOVING AND STILL PICTURES

Unaided visual inspection is inadequate for a total evaluation of a design represented on a three-dimensional model. The viewer's eyes are too far above the level normally experienced when driving and the resulting view of the model is only from above, or an oblique view as if in a stationary position. This dual disadvantage restricts detection of possible faults or desirable improvements in the design. Therefore, to fully appraise the proposed design, a three-phase study of the model by means of motion and still pictures was undertaken.

Appearance of the Constructed Interchange From the Onlooker's View

In order to consider the constructed interchange from the viewpoint of a pedestrian viewing the area surrounding the interchange, a photographic program was set up along the four roads enclosing the interchange complex.

To obtain a comprehensive overall view, a number of locations were selected on local streets and other points around the interchange from where scanning views could be obtained and still pictures taken. Figure 14 illustrates these selected positions.

Motorist's View From the Interchange Roadways

For this purpose a periscope was attached to the movie camera so that the pictures taken were those seen in the horizontal direction a few feet above the road surface.

It is well known that a motorist looks far ahead when driving as well as maintaining an awareness of his immediate surroundings. He controls his vehicle according to immediate and later needs and his judgment of the circumstances. Driving within an interchange, however, is quite different from open stretches of highway; because of confined space greater dexterity is required to cope with merging and diverging traffic. Any design or environmental features of the interchange that might cause unpleasant

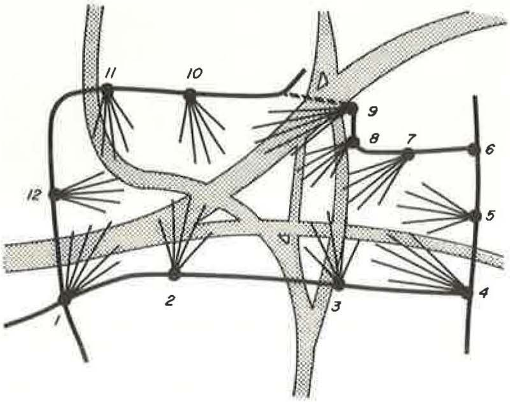


Figure 14. Photographic program for still pictures (onlooker's view).

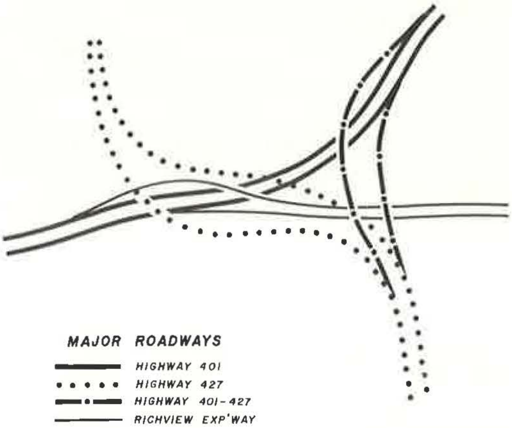


Figure 15. Photographic program for motion (motorist's view).

reaction on the part of the driver must be avoided. Because of this, unusual design elements and other highway features, such as bridges, structures and retaining walls, and their interrelation with the design and environment, must be carefully examined to avoid any condition that might cause drivers to feel ill at ease or unsafe while negotiating the interchange.

The photographic program for a motorist's view is illustrated in Figure 15. It contains all the major roadways of the proposed interchanges as represented by the model.

View of Construction and Total Environment

The third photographic program in the design investigation was to determine if the interchange, as a whole, would form an integrally aesthetic part of the total environment. This was accomplished by means of oblique motion pictures taken 8 in. above the model surface (Fig. 16). Some examples of views obtained from the photographic program are shown in Figures 17, 18, and 19.

ANALYSIS AND EVALUATION

For the purpose of design analysis and evaluation, the model photographs (still and movie) were shown to a randomly formed group of drivers consisting of six men and four women ranging in age from 20 to 60 years. Their occupations and individual travel patterns were as follows:

Men Drivers		Women Drivers	
Occupation	Traveling Pattern	Occupation	Traveling Pattern
Clerk	Occasionally	Housewife	Occasionally
Engineer	Daily	Clerk	Daily
Executive	Daily	Clerk	Daily
Mechanic	Occasionally	Librarian	Occasionally
Truck driver	Daily		
Salesman	Daily		

Single slides and 200-frame sections of motion pictures were shown to the group and guidance was given on how to rate their impressions. Each member of the group was then requested to answer the following question as the slides and movies were presented: What is your impression of the general appearance of the roadway including environment, etc.? The choice of answers was very good, good or poor.

The three photographic programs (Figs. 17, 18, and 19) were those that incorporated the criteria for appearance from the onlooker's view, the motorist's reaction as he drives on various roadways, and finally, how the constructed interchange would form an integral and aesthetically pleasing part of the total environment.

The answers to the questions were then analyzed. Figures 20, 21, and 22 show the results of this investigation; they are regarded as indicators of the quality of the proposed design. From these graphs, the following was apparent:

1. A pedestrian's or onlooker's view is generally satisfactory and rated good, except for the locations 8, 9 and 10. This is understandable because in an otherwise aesthetically pleasing location, the presence of a large brewery, seen from the rear of the buildings, spoils the view.
2. A motorist driving on Highway 401 east- or westbound is generally satisfied with the various design features. There is, however, one location (going towards a sharp curve beyond the structure) over which the driver would be somewhat disconcerted and

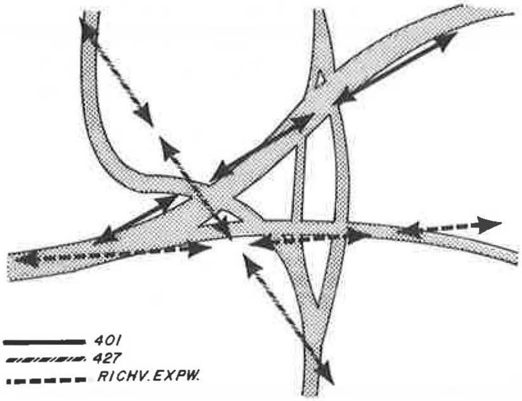


Figure 16. Photographic program for motion pictures (view of construction and total environment).

Figure 18. Motorist's view.

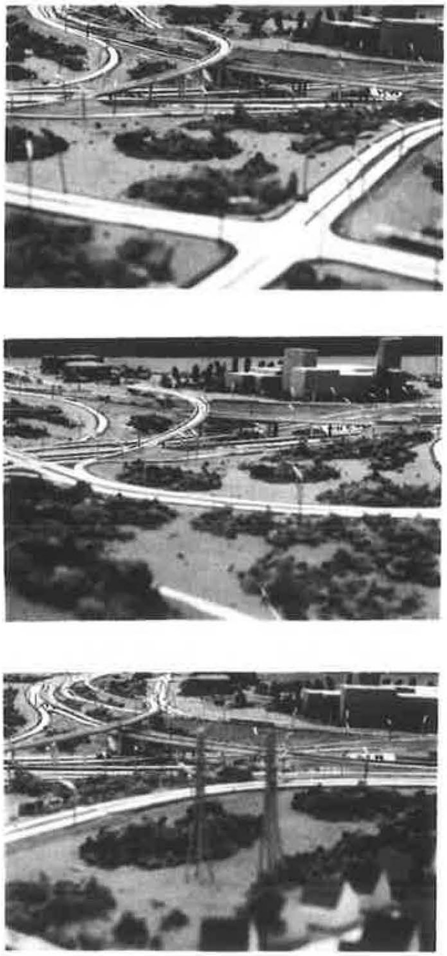


Figure 17. Onlooker's view.

Figure 19. Environmental check.

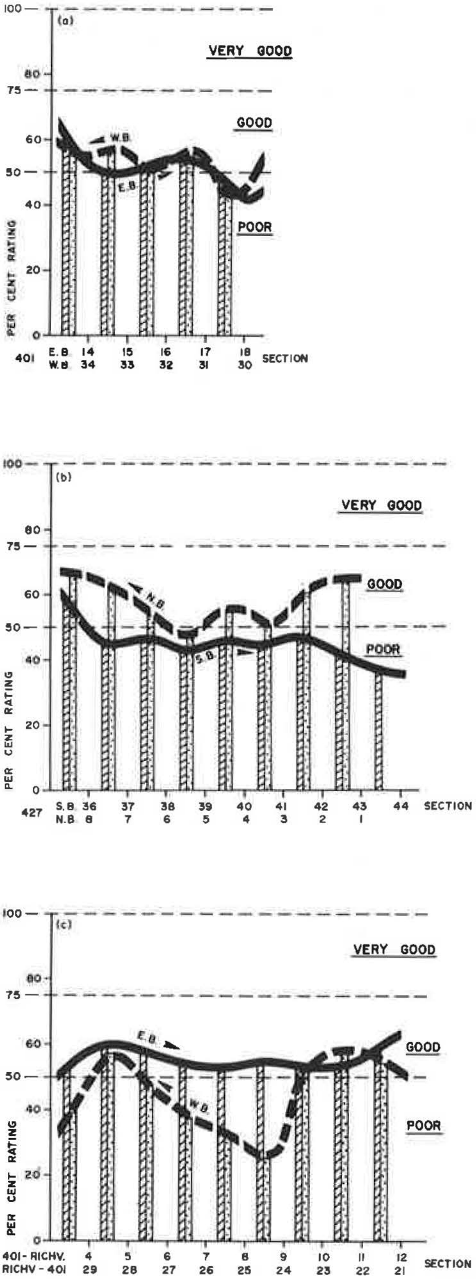


Figure 21. Investigation results, driver's reaction: (a) Highway 401, eastbound and westbound; (b) Highway 427, southbound and northbound; and (c) Highway 401, Richview Expressway.

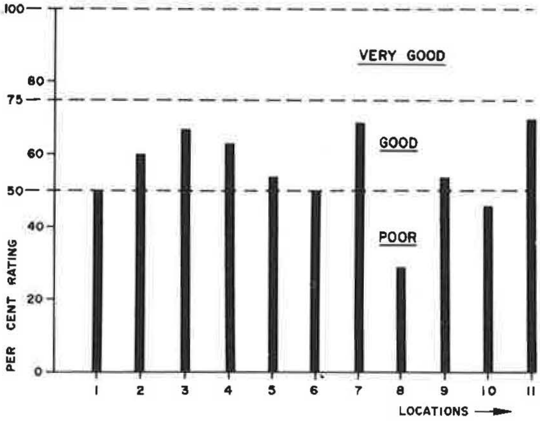


Figure 20. Investigation results, onlooker's view.

which would require a quick decision as to the route to take. In the case of Highway 401 and Richview Expressway westbound, the design is rated "poor" at some sections. This is due to the bullnose being situated beyond the structure and therefore not sufficiently visible until the driver is very close to it. Further, there appears to be a complex of structures and some sharp curves which cause discomfort to the driver. In the case of Highway 427 southbound, the motorists rated it extremely poor. This is mainly due to overhead structures, relatively sharp curves, and merging and diverging of lanes and restricted sight distances. In the case of Highway 427 northbound, the motorists rated it "good." The northbound lanes are in an open area with fewer overhead structures and therefore better driving.

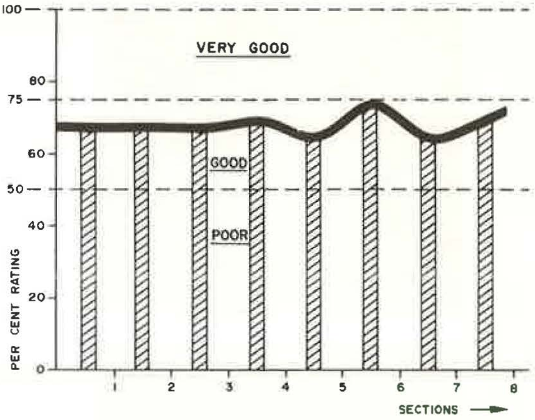


Figure 22. Investigation results, total environment.

3. The oblique pictures taken (1 in. = 40 ft scale) 8 in. above the model surface are rated "good" toward the higher limit.

CONCLUSIONS

Three-dimensional models are a serviceable tool for the investigation of designs of interchanges with regard to their internal and external appearance.

Photographic, still and motion pictures of the highway model can serve in the detection of possible faults in design and as a means of evaluating the aesthetic appeal of highways and interchanges.

A good deal of work still needs to be done to improve the technique. Doubtless, with time, improvements will be forthcoming that will enable highway engineers to design highways of the future with a built-in aesthetic appeal that would be unattainable without the help of three-dimensional models and photographic programs.

ACKNOWLEDGMENTS

Grateful acknowledgment is made for the assistance of I. C. Campbell and P. J. Harvey, of Planning Branch, Department of Highways, Ontario, for building the model and providing the encouragement to prepare this paper; and to B. Dunstall of the Department's Photographic Section for filming the photographic programs.

REFERENCES

1. Lorenz, H. Moderne Trassierung. Deutsche Strassen und Brückenbau-Zeitschrift, Heft 9, Sept. 1953, Germany.
2. Bakker, H. B. De belijning van de weg. Wegen, 36e Jaargang, No. 7, July 1962, The Netherlands.
3. Abbott, R. A. Facilitating Three-Dimensional Road Design. Traffic Engineering and Control, Vol. 4, Nov. 1962, Great Britain.
4. Ring, S. L. Highway Interchange Profile Models. Iowa State Highway Commission.
5. Collins, R. M. Design Models—New Techniques Result in Greater Versatility. California Highways and Public Works, Vol. 44, No's. 5-6, May/June 1965, U. S. A.

Computer Graphics and Visual Highway Design

BOB L. SMITH and E. E. YOTTER, Department of Civil Engineering, Kansas State University

The purpose of the research was to study some particular ways in which the highway designer can be assisted in his task of designing a visually stimulating highway. The research was limited to the following: (a) 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 will result; (b) a small change in direction of horizontal alignment was studied to determine the length of curve required for the alignment to appear smooth and flowing rather than a "kink."

Computer-drawn perspectives of the roadway from the driver's vantage point were made and provided a highly realistic picture. A large number of perspective drawings provided the basis for a graph showing visually desirable and acceptable relationships between the length of sag vertical curve and viewing distances for various grade changes. This graph should be of significant aid to the highway designer. In a similar manner perspective drawings of the kink alignment provided the basis for a number of conclusions regarding the appearance of the alignment with respect to various locations of the observer and various lengths of horizontal curve.

A previously unpublished technique, developed by others, transforming space coordinates to "picture plane" coordinates (perspective drawing coordinates) is included. Perspective drawings, produced by the electronic plotter, provided a highly versatile and valuable tool and show great promise as an aid to the highway designer in his complex task.

•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. The study was jointly financed by the highway commission and the U. S. Bureau of Public Roads.

The highway designer is faced with an extremely complex task if he is to design a complete highway; i. e. one which is functional, safe, economical, and aesthetically (visually) pleasing.

A number of people believe that the highway designer has not been concerned enough or aware of the importance of the "visual aspect" of highway design. Pushkarev (1) presents his opinion perhaps best of all. Appleyard et al (2) present a convincing picture of some of the problems and suggest a general solution. Smith and Fogo (3) made a further attempt to bring an awareness of the problem to the highway designer. F. W. Cron (4, 5) offers some solutions to problems of fitting the highway to the landscape. Leisch (6) suggests some techniques for solving some of the vexing problems facing the designer. Snowden (7) has prepared an annotated bibliography of 10 references.

PURPOSE AND SCOPE

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

Paper sponsored by Committee on Geometric Highway Design and presented at the 48th Annual Meeting.

The research was limited to the following:

1. The sag vertical curve was studied to place limits on the length of vertical curve so that an aesthetically pleasing ribbon of roadway will result.
2. A small change in direction of the horizontal alignment was studied to determine the length of curve required for the alignment to appear smooth and flowing rather than a kink.
3. An investigation was made of some ways in which the highway designer could test his design for visually disturbing elements.

BACKGROUND

In May 1967, just prior to the initial work on this research, the authors, accompanied by a senior in Civil Engineering at Kansas State University and a member of the Landscape Architecture faculty, visually rated sections of Interstate Highways, I-35 and I-40, in Oklahoma. An attempt was made to rate the visual adequacy or flowing quality of the roadways. Of particular concern was the appearance of sag vertical curves. Good agreement among raters was obtained as to when the curves appeared too short, acceptable, or quite good. This judgment was based on the premise that the roadway (centerline or pavement edge) should appear to flow smoothly from tangent-vertical curve-tangent rather than to give an abrupt or jerky appearance. In attempting to analyze why certain curve lengths appeared acceptable and others appeared too short, it was noted that as one viewed the curves from shorter and shorter distances, they looked progressively better. As a matter of fact, any vertical curve viewed from its PVC or beginning point always looked smooth and flowing. This observation was the same as that made by Smith (3) earlier. An attempt was made to graphically portray the observations showing length of vertical curve, change of grade, viewing distance, and curve rating. The resulting graphs showed some promise.

RESEARCH PROCEDURE

Early efforts in the research were aimed at: (a) the development of an analytical approach that would be of help in solving the sag vertical curve problem, and (b) the the development of scale models which would look like the real roadway and which could be used to visually test solutions to highway alignment problems. The scale models and photographs of them were not very helpful for the particular problem studied.

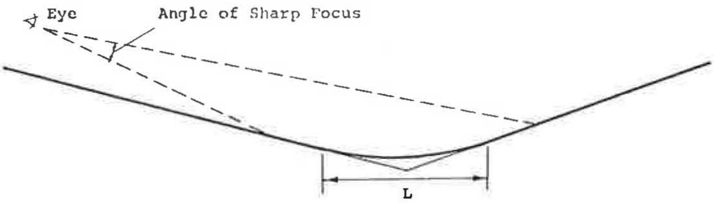
Early in the research it was learned that a French highway group (9) was able to draw perspectives of the roadway using an electronic plotter. The lack of success with models coupled with the apparent advantages of perspective plotting led to the investigation of the use of perspective drawings for the research. This technique provided a laboratory in which many roadway alignment situations could be studied visually due to the rapidity with which the highly realistic drawings could be made using the electronic plotter.

Smith and Yotter (8) give the results of the model studies and a more detailed discussion of the perspective plotting technique and other aspects of the research.

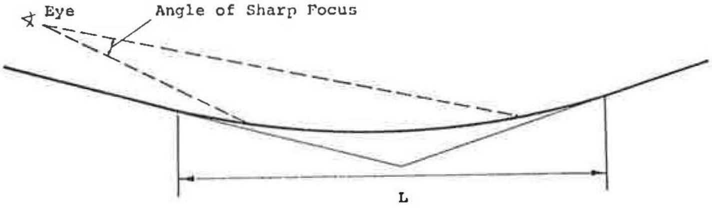
ANALYTICAL APPROACH

It was assumed throughout the research that a visually pleasing alignment is one which produces a ribbon of roadway that appears to be smooth and flowing. Of particular concern are the small changes in grade joined by relatively short vertical curves (see Figs. 22, 23, and 24 (3)). The authors have studied this problem for some time and believe that the visual discontinuity or visual "jerk" of such alignment occurs when one sees, without refocusing the eye, portions of each tangent enclosing the vertical curve.

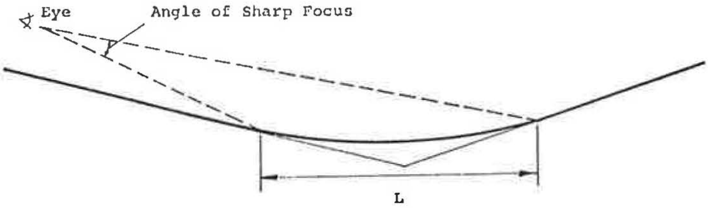
Figure 1 illustrates the above hypothesis. Figure 1A shows a sag vertical curve which is too short because the tangent sections are seen in the outer edges of the sharp focus angle. Figure 1B shows a curve which should give good visual appearance since



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 1. Theoretical relationships: angle of sharp focus vs vertical curve length.

the outer edges of the sharp focus angle are within the curved section. Figure 1C illustrates the minimum length of curve which should give a good visual appearance.

Figure 2 contains the derivation of a formula relating change of grade, length of vertical curve, eye height above roadway, angle of sharp focus, and distance from observer to the P. I. of the vertical curve (sight distance).

The formula as developed assumes the observer to be located in the same plane as the vertical curve. Obviously the observer must be a bit to one side of this plane to see anything other than a straight line on a tangent alignment. However, the formula developed is believed to be a good first approximation.

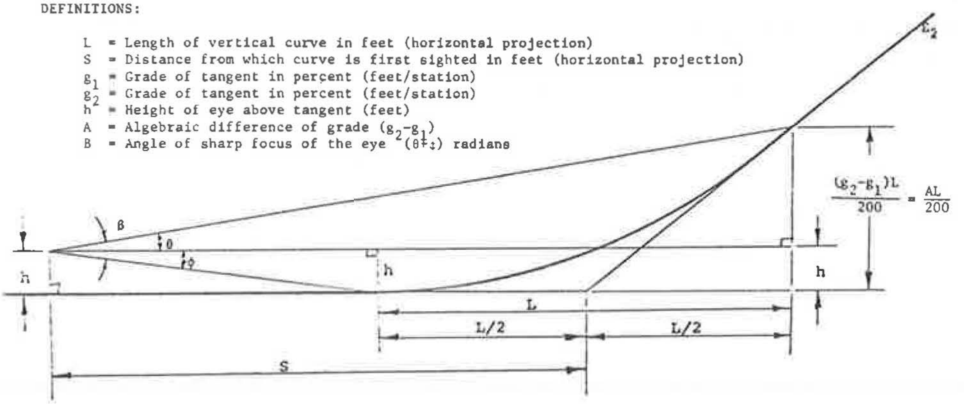
Several references on seeing and the eye were studied in an effort to gain some usable insight into this problem. Very little information applicable to this problem was found. A crude experiment led us to believe that the angle of sharp focus, B, was about 30' of arc.

Using the formula as derived in Figure 2, a plot was made of length of vertical curve vs sight distance for grade changes of 1, 2 and 4 percent (Fig. 3). An attempt was made to verify the curves using the vertical curve ratings from the visual analysis of I-40 in Oklahoma. The data were much too sparse to permit conclusions.

Scale models did not provide the desired realism for testing the analytical results. Perspective drawings, on the other hand, did provide a laboratory for a detailed study of the sag vertical curve problem. The use of perspectives is discussed in a following section.

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)

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

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

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

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

Figure 2. Theoretical relationships—L,S,A.

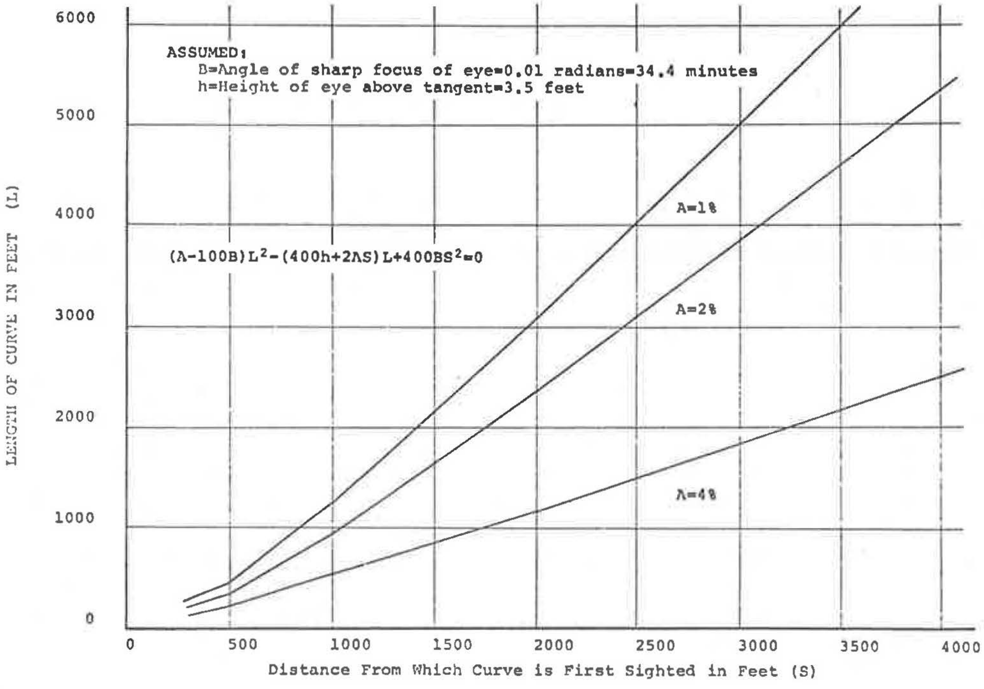


Figure 3. Graph of theoretical relationships—L,S,A.

PERSPECTIVE PLOTTING BY COMPUTER

As mentioned earlier, it became apparent that perspective drawings should be of significant aid provided they could be made quickly. Cron (4) illustrated many awkward highway design situations by using freehand sketches which are certainly a form of perspective.

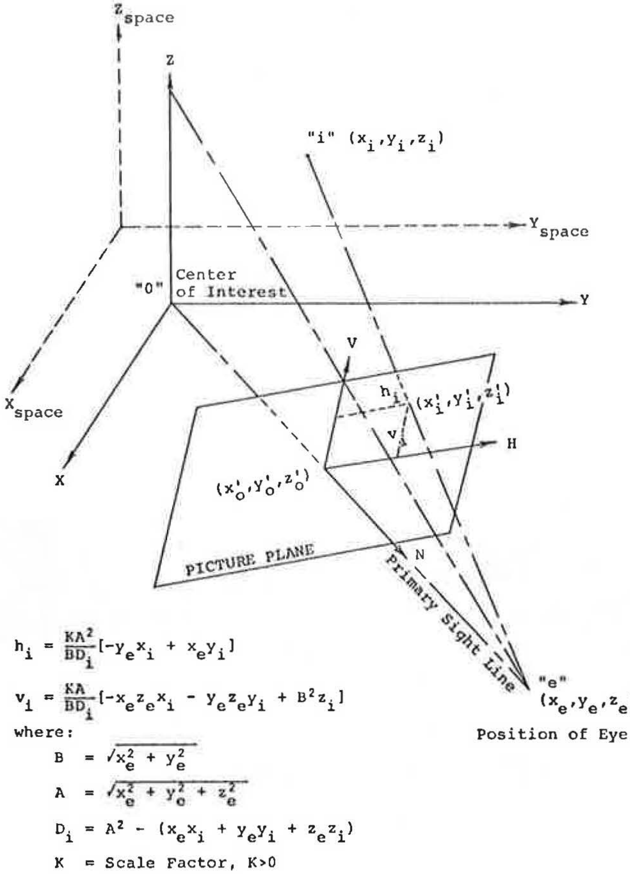
To make a perspective drawing, using the electronic plotter, it is first necessary to determine the space coordinates of points on the object of which the drawing is to be made. The space coordinates must then be transformed into "picture plane" coordinates which, with an appropriate set of commands, enables the electronic plotter to draw the desired perspective.

The space coordinates of points along the ribbon of roadway were quickly and accurately calculated using a computer program, COGO (10). The transformation of the space coordinates into picture plane coordinates was accomplished using a procedure obtained from Walter Bernhart, Wichita State University. Bernhart's paper, "The Development of a Perspective Coordinate Transformation" (11), is very general in its application and is included by Smith and Yotter (8) as Appendix A.

Parks et al (12) and Geissler (13) have published computational procedures for the transformation of space coordinates to picture plane coordinates.

CALCULATION OF PICTURE PLANE COORDINATES

Figure 4, based on Bernhart's work (11), was the basis for the computational procedure described in the following.



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

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

where:

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

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

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

K = Scale Factor, $K>0$

Figure 4. Transformation of space coordinates to picture plane coordinates.

The space coordinates (X_{space}, Y_{space}, Z_{space}) of all points were first determined. Next, the center of interest, O, was selected. A simple subtraction of the space coordinates of the center of interest from the space coordinates of all points effectively translated the space coordinate axes to the center of interest coordinate axes. Next the position of the eye, e, was chosen and also translated to the center of interest coordinate system. After the center of interest, O, and the position of the eye, e, were selected, a line between O and e was taken as the primary line of sight. The picture plane was then positioned perpendicular to the primary line of sight and located between O and e (Fig. 4).

A scale factor, K, determined the location of the picture plane. A value of K = 1 located the picture plane at the center of interest O. A value of K = ½ placed the picture plane midway between O and e. A scale factor of K = 1 was used in this study.

The transformation of the coordinates of any point "i" (x_i, y_i, z_i) from the center of interest coordinate system to the picture plane (H and V axes) coordinate system with coordinates h_i and v_i was accomplished using the equations given in Figure 4 and developed by Bernhart (11).

As noted earlier, the picture plane coordinates of points on the object, with an appropriate set of commands, enabled the plotter to draw the desired perspective; however, all points on the object did not necessarily appear in the perspective drawing

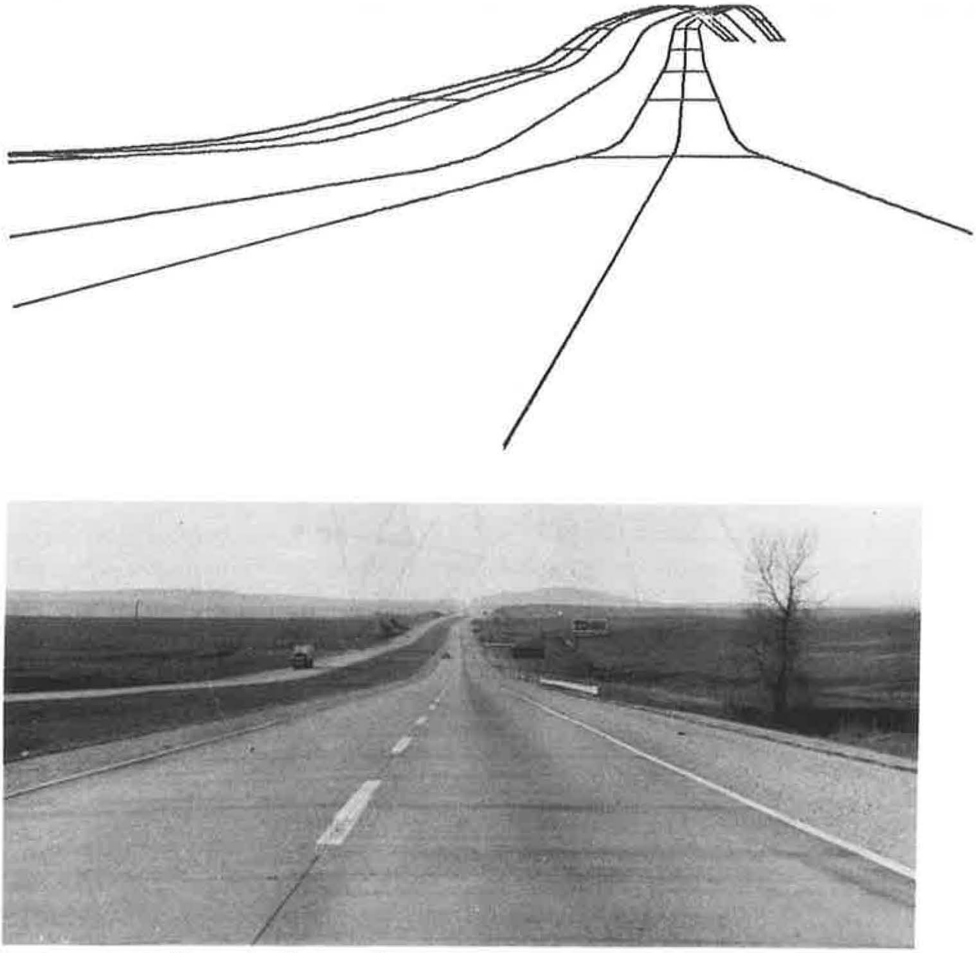


Figure 5. Photograph and perspective of Maple Hill location.

(e. g., those points "behind" the eye or observer's position and those points "outside" a selected picture plane size). Negative values of D_i indicated points behind the observer while absolute values of h_i and v_i, which exceeded selected maximum values of h and v, indicated those points falling "outside" the picture plane. In this research maximum values of h and v were limited to 1000 feet.

REALISM OF PERSPECTIVES

Although examples of computer-plotted perspective drawings of roadways, airplanes, runways, etc., had been observed, there was some question concerning how closely they resembled the real situation. Perspective drawings of two existing roadway alignments were made placing the observer at the same location from which a photograph was made. The Maple Hill location on I-70 was photographed and drawn (Fig. 5). The

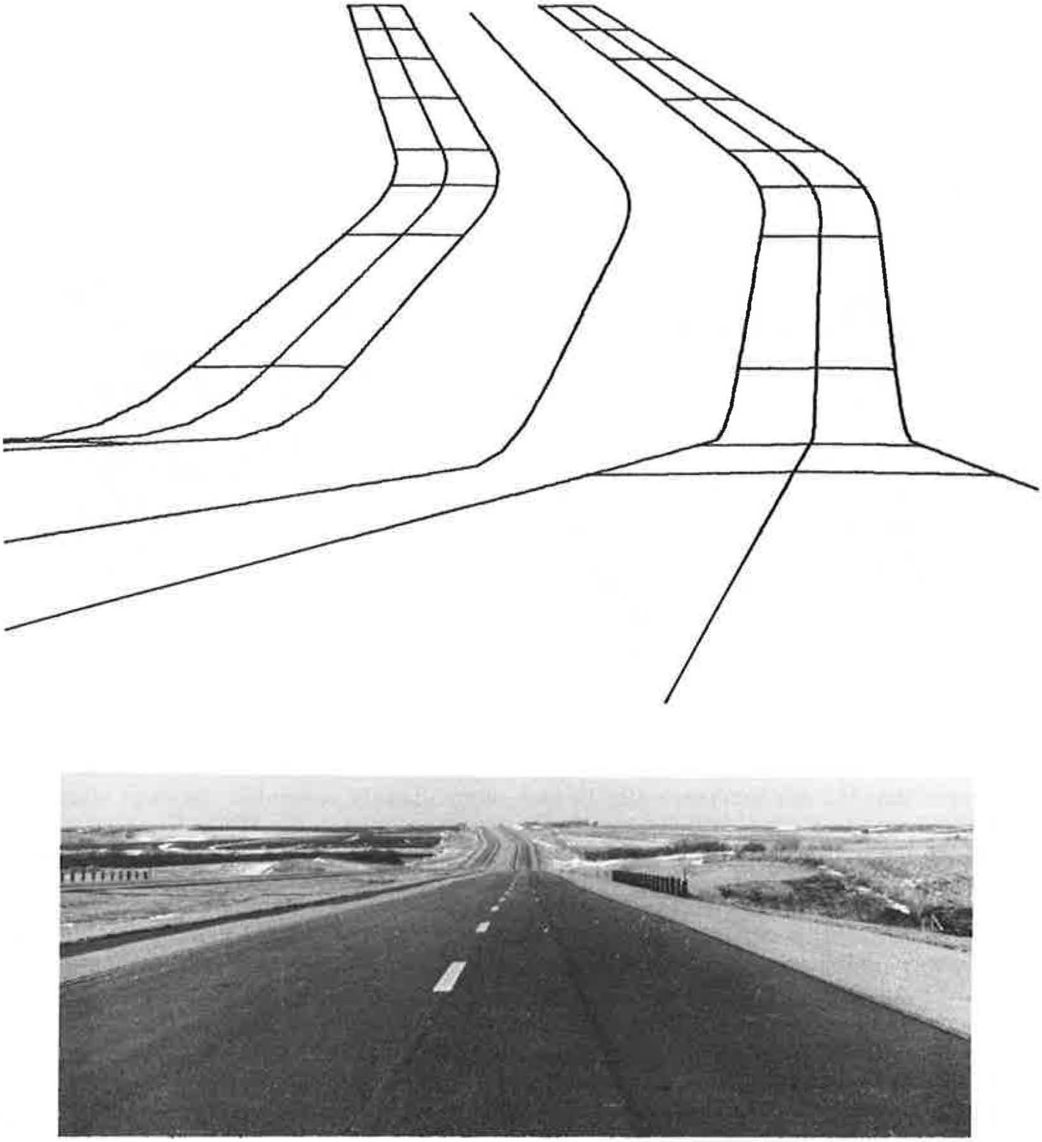


Figure 6. Photograph and perspective of kink location.

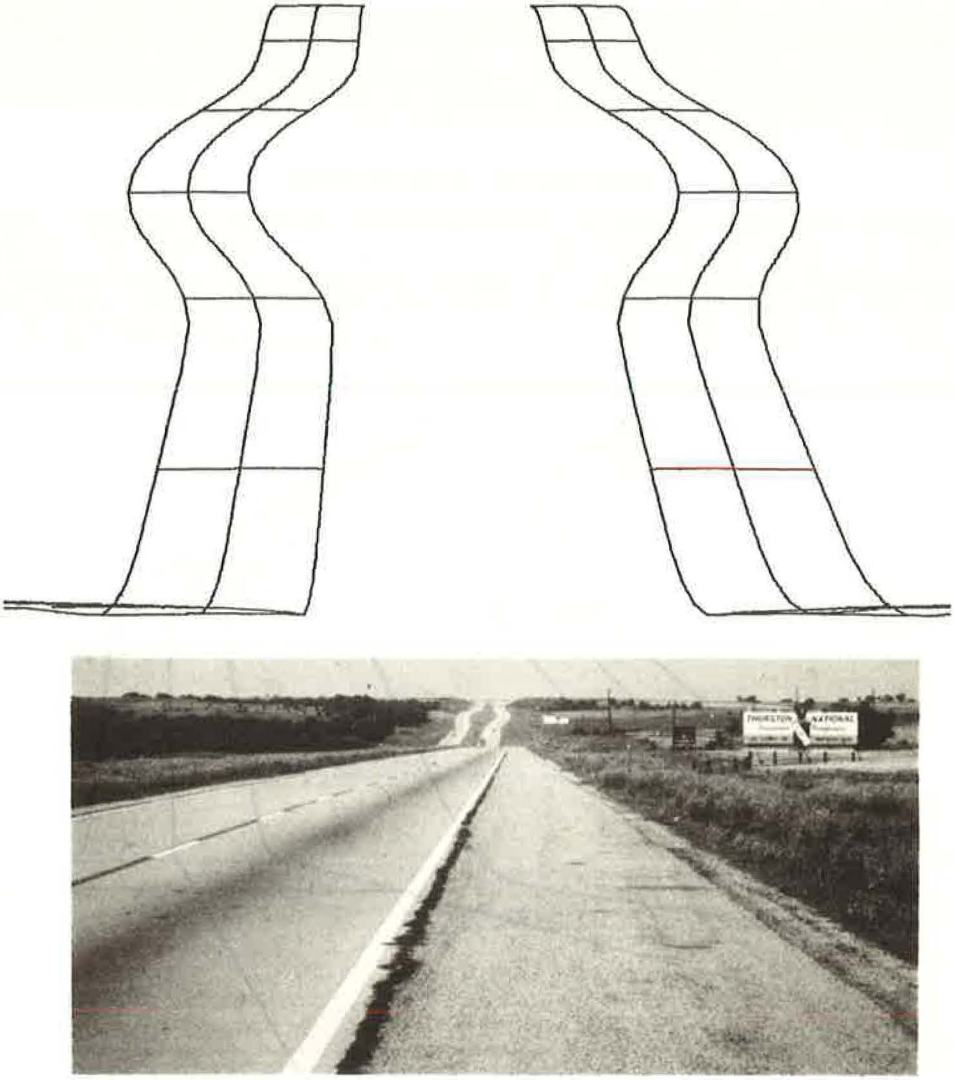


Figure 7. Photograph and perspective of barbell location.

kink location in Ellsworth County was also photographed and drawn (Fig. 6). It was concluded that the perspectives did, in fact, very closely resemble the real situation.

A third site was photographed and later drawn perspectively (Fig. 7). This was called the barbell location because of its appearance. In this case the perspective drawing was made with the observer's eye in the median rather than on the outside shoulder. The perspective drawing points up the awkwardness of the alignment quite vividly. When the plan view of this particular section was examined from usual vantage points above the highway plans, no particular problem was apparent. However, if the eye was placed near the plans (the driver's vantage point), the barbell effect was very pronounced.

THE SAG VERTICAL CURVE PROBLEM

The visual problem concerning sag vertical curves has been discussed in a previous section. To develop relationships among length of vertical curve, L, algebraic change of grade, A, and viewing sight distance, S, for curves which appeared too short, acceptable, or quite good, a series of perspectives were drawn and then judged visually. The

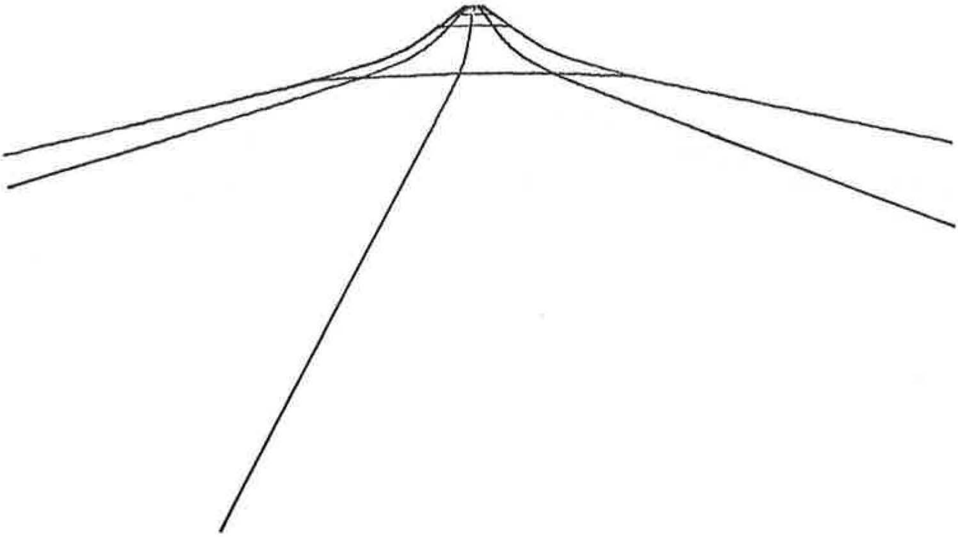


Figure 8. Vertical curve perspective, A=2 percent, L=800 ft, S=500 ft.

roadway section was a 24-ft roadway with a 6-ft shoulder on the left and a 10-ft shoulder on the right. The roadway had a 0.25 crown with left and right shoulders lying 0.54 feet and 0.74 feet, respectively, below centerline elevation. The observer was placed 2 feet right of centerline and 3.5 feet above the roadway surface. The center of interest of the observer was taken to be the midpoint of the vertical curve on the centerline. The sight distance, S, was the horizontal distance from observer to center of interest.

The vertical curves were on tangent alignment and the grades were assumed to be symmetrical; e. g., for A = 2 percent, the initial grade, g_1, was -1 percent and the forward grade, g_2, was +1 percent.

For various changes in grade and sight distances 116 perspective drawings were made. The selection of perspectives to be drawn were made in two stages: first, elements

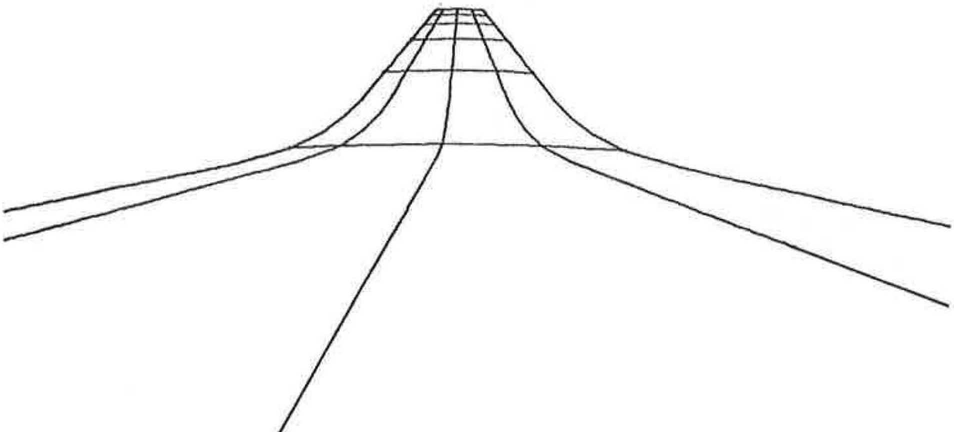


Figure 9. Vertical curve perspective, A=2 percent, L=800 ft, S=1000 ft.

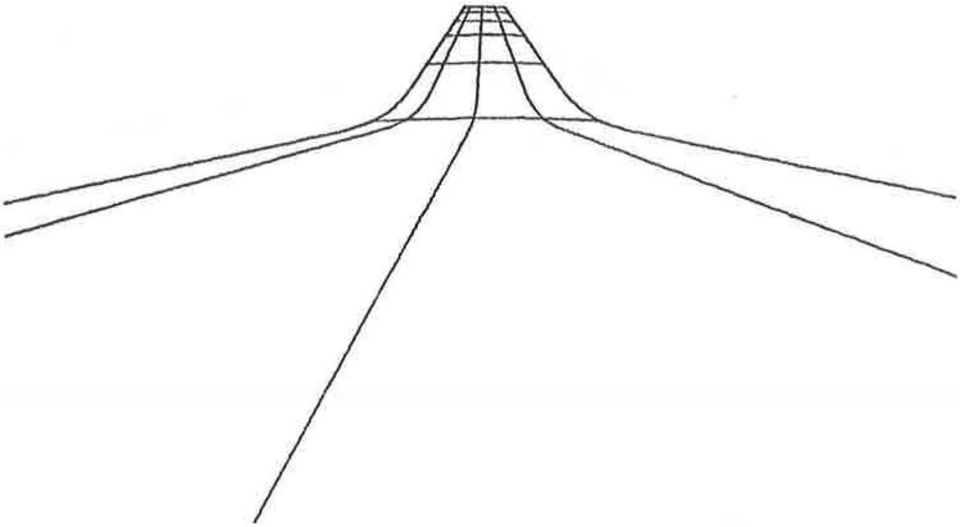


Figure 10. Vertical curve perspective, A=2 percent, L=800 ft, S=1250 ft.

were selected based on Figure 3; and later, additional selections were made in order that good to poor situations could be drawn in regions not previously covered.

The perspectives were examined in each grade change-curve length group, and a subjective decision was made as to whether the particular drawings exhibited smooth-flowing lines. The drawings within each group were laid on the table with no identification on the face of the drawings. The drawings were then ranked from excellent, to good, to barely acceptable, to unacceptable.

Figures 8 through 11 show a series of perspectives for A = 2 percent and L = 800 feet, and various viewing distances. Figure 8 was judged to look very good. Figure 9

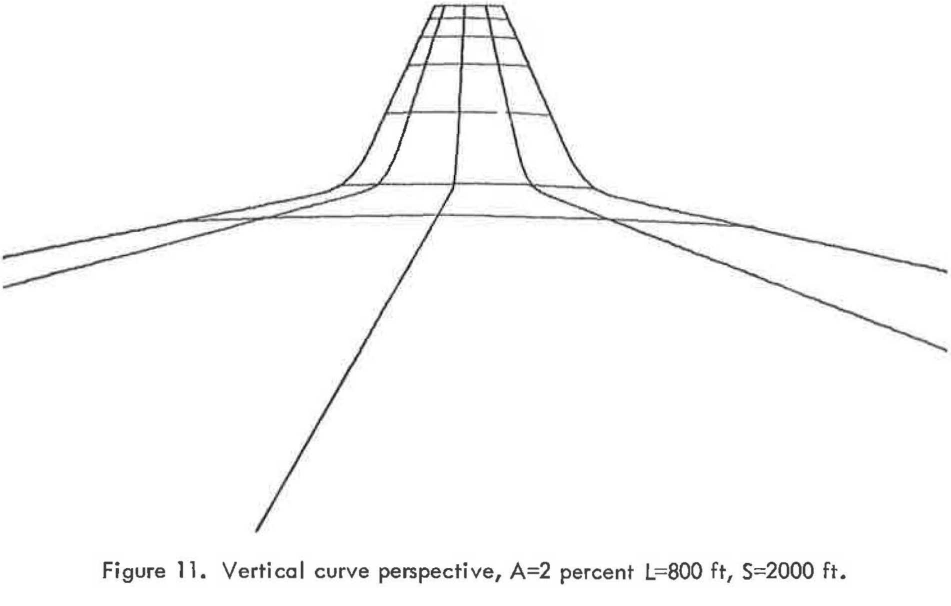


Figure 11. Vertical curve perspective, A=2 percent L=800 ft, S=2000 ft.

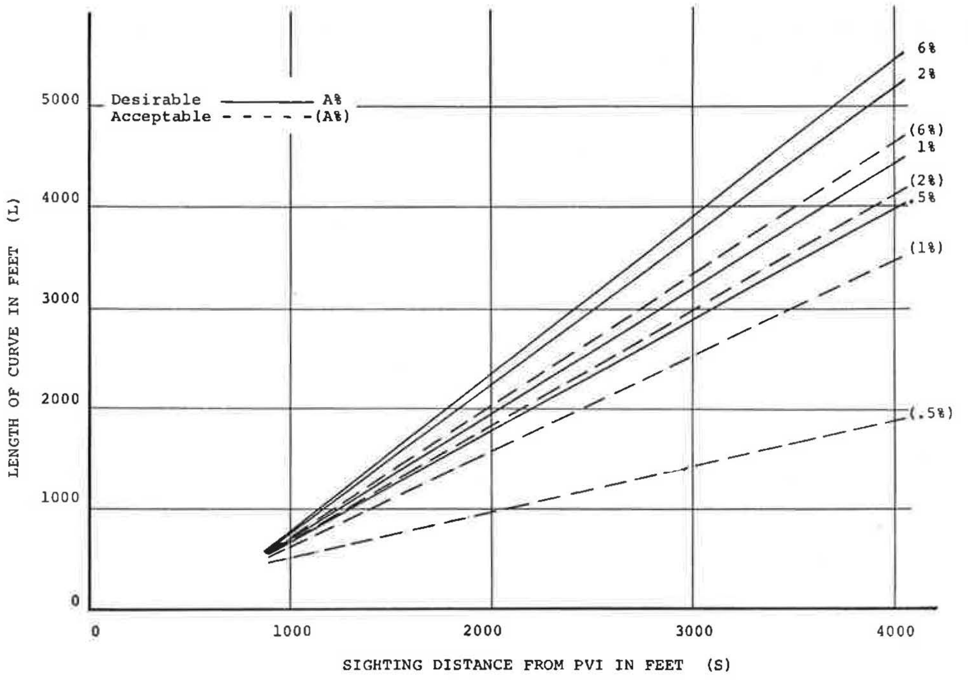


Figure 12. Desirable and acceptable relationships—L,S,A.

was judged to be desirable, whereas Figure 10 was judged to be almost acceptable or just below the acceptable line. Figure 11 was judged to be unacceptable.

Those perspectives rated as good were the basis of the solid line curves' desirable relationship in Figure 12. Those rated barely acceptable were the basis for the dashed line curves' acceptable relationship in Figure 12.

Observations

It was hoped that Figure 12 would substantiate Figure 3, the graph of theoretical relationships among L, S, and A. An examination of the graphs shows extensive differences. The shape of the curves for individual values of A are similar, but the relative position of the curves for various A values is reversed. The theoretical approach apparently did not take into account enough of the factors involved. Although the theoretical curves could not be substantiated, it is felt that the basic hypothesis has not been disproved.

The authors feel that the curves for A values up to 2 percent (Fig. 12) are the most valid. The vertical jerk for small grade changes is perhaps more offensive because there is likely to be no apparent reason for such situations. On the other hand, the reasons for large grade changes are usually obvious and sharper-appearing curves are more acceptable.

It is believed that the curves in Figure 12 can be of significant aid to the designer. For example, the designer can examine for selected locations the sight distance, S, and change of grade, A, and select a minimum curve length based on a dashed curve (acceptable relationship) in Figure 12.

Another alternative open to the designer is to decrease the distance, S, from which one sees the curve. This can be accomplished by searching for appropriate locations in which horizontal curvature can be inserted into the alignment. It should be kept in mind that proper coordination of the alignment becomes extremely critical to the visual quality of the resulting roadway.

Note that the graph is based on tangent alignment and has not been shown to be applicable to curvilinear alignment.

THE KINK PROBLEM

On page 191 of the AASHO Blue Book (13) appears the following statement:

> 4. For small deflections 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 central angle.

The kink location (see Fig. 6) conforms to the above recommendations and yet the kinked appearance is very noticeable. The curve is 900 feet in length with a change in direction of 1° 30'. It is believed that this problem is similar to that of the short vertical curve; i.e., the horizontal kink becomes noticeable when one sees, without refocusing the eye, portions of each tangent enclosing the horizontal curve. After studying the problem further, it became apparent that the problem is compounded when the curve is displayed or laid out before the driver. For example, if the driver is in the plane of the curve, such as on a long grade, the kink may be barely discernible. If, however, the driver is traveling in a plane different than that of the curve, the kink is likely to be readily apparent.

In view of the time available for the research only two lengths of curve, both longer than the 900-ft existing curve, were tested for their usual effect. First a length of curve was selected such that no tangent alignment existed between the vertical curve and the point at which the highway disappeared over the hill. In this instance a 0° 01' curve was selected giving a curve length of 9000 feet. Figure 13 shows the perspective drawing with the observer 7410 feet from the P. I. This design gives a smooth and flowing appearance to the change of direction. However, the shortness of the vertical curve is more pronounced and it appears that this design may merely have moved the kink to the vertical curve location. The real problem, in this instance, is one of coordination of the vertical and horizontal alignment. The length of horizontal curve was increased so much that the vertical curve was actually located at the beginning of the horizontal curve—a situation that is always potentially awkward.

It was also reasoned that perhaps a short length of tangent on either end of the curve might not be objectionable. In view of this, a 0° 03' curve was selected giving a length

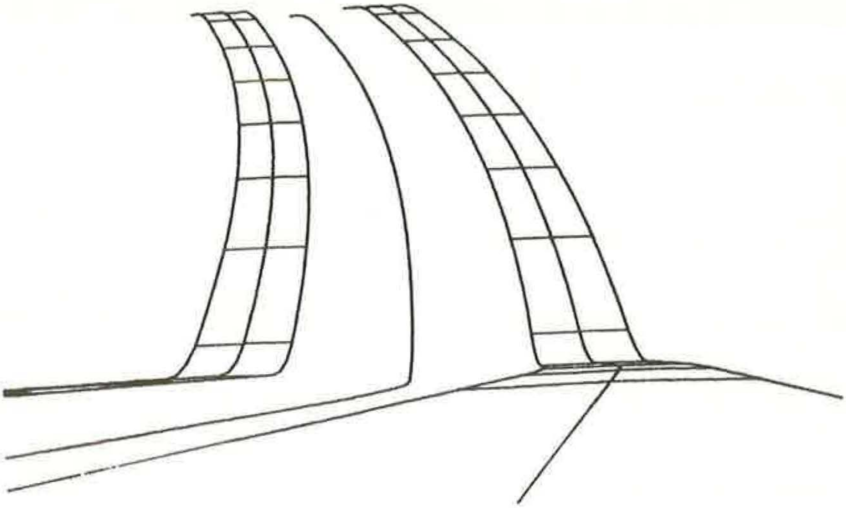


Figure 13. Kink location with 9000-ft horizontal curve viewing distance 7410 feet to P.I.

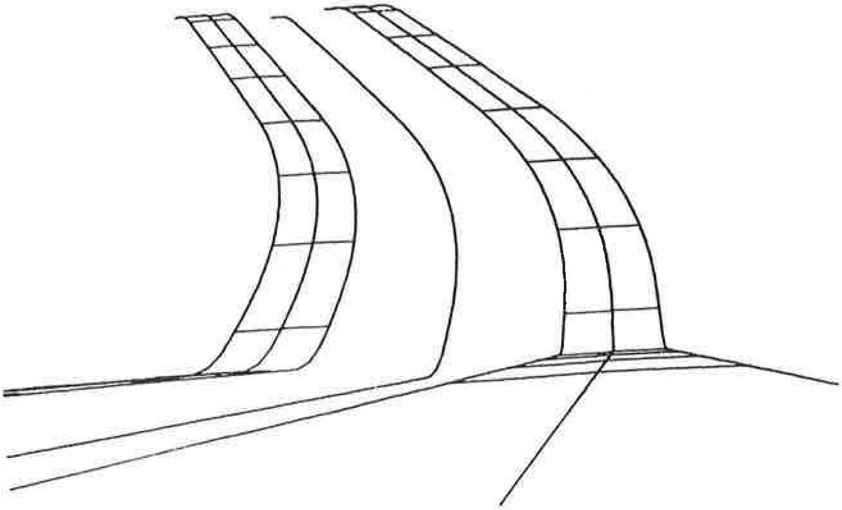


Figure 14. Kink location with 3000-ft horizontal curve viewing distance 7410 feet to P.I.

of curve of 3000 feet. Figure 14 shows the perspective drawing with the observer 7410 feet from the P. I. This design eliminated the kink appearance and yet did not present as serious a coordination problem as the 9000-ft curve.

A series of perspectives were drawn of the kink alignment to determine if the observer's position above the alignment as well as his distance from the alignment did, in fact, significantly affect the appearance of the alignment.

The horizontal alignment ($\Delta = 1^\circ 30'$) was on a +1.42 percent grade. For the 900- and 3000-ft horizontal curves, perspectives were drawn with the observer at two locations from the P. I. and at various elevations above the +1.42 percent grade, extended.

Figures 15 and 16 show the 900-ft curve viewed at a distance of S = 4910 feet from the P. I. and at the indicated heights above the plane of the horizontal curve. The curve is noticeably smoother (Fig. 16) when viewed from a height of 203.5 feet.

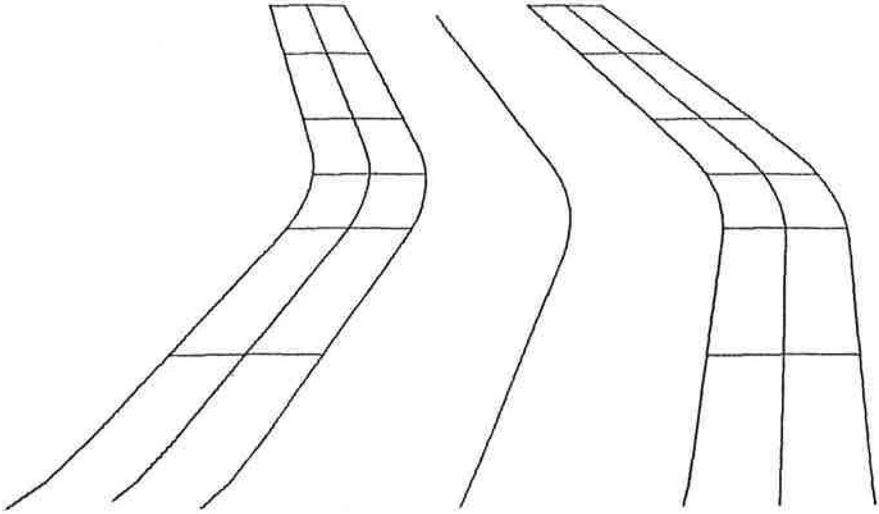


Figure 15. Perspective of 900-ft curve, S=4910 feet, H=103.5 feet above curve plane.

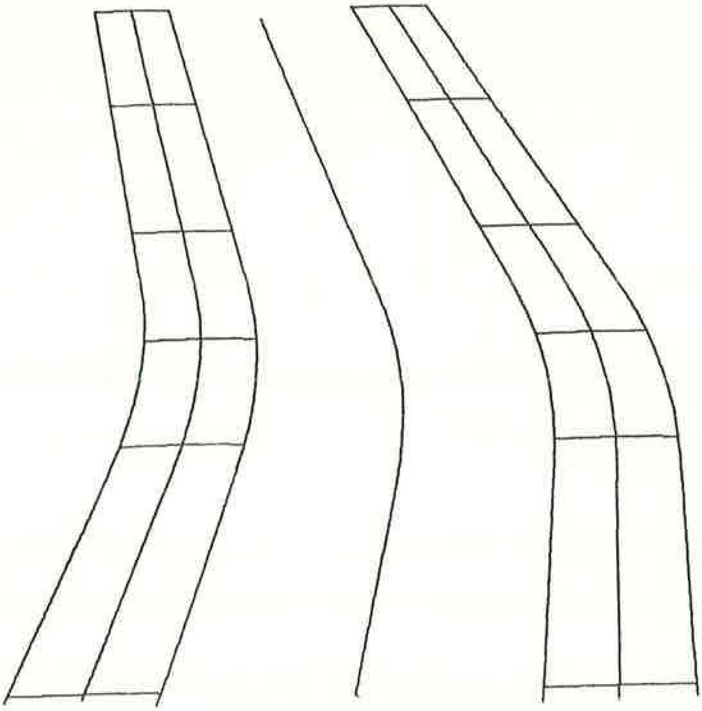


Figure 16. Perspective of 900-ft curve, S=4910 feet, H=203.5 feet above curve plane.

Figures 17 and 18 show the same curve viewed from 7410 feet and at the indicated heights of observer. The curves in these figures appear noticeably sharper than those in Figures 15 and 16.

Figures 15 and 18 lie in about the same inclined plane, thus the display of the curve should be about the same. It is felt that Figure 18 shows somewhat more lateral jerk than Figure 15 where the observer is nearer the curve.

Two perspectives were drawn of the 900-ft curve from a position directly over the P. I. As one would expect, they gave the same effect as the highway plans. The kink was not discernible.

Similar perspectives of the 3000-ft curve were studied and the same conclusions were reached (8).

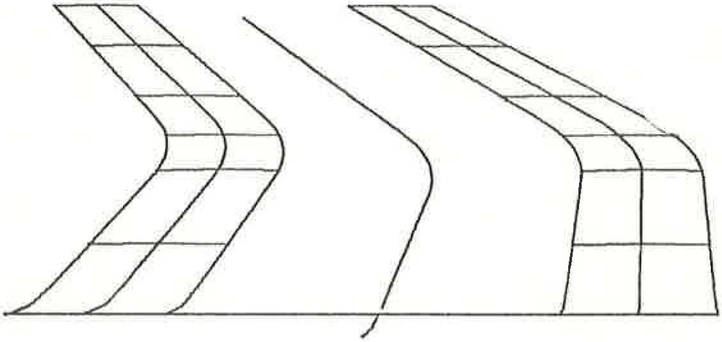


Figure 17. Perspective of 900-ft curve, S=7410 feet, H=103.5 feet above curve plane.

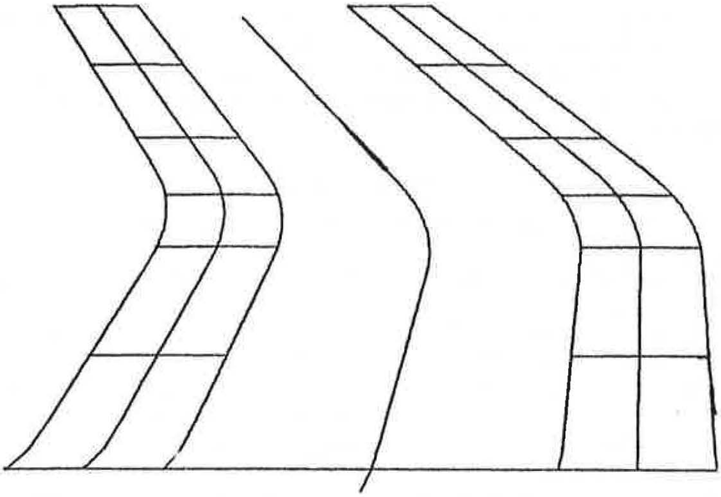


Figure 18. Perspective of 900-ft curve, S=7410 feet, H=153.5 feet above curve plane.

Observations

In studying the kink problem it is readily apparent that the best solution is not to have such small changes in direction in the design. If a small change in horizontal direction is necessary, hide it on the top of a hill. This can be done quite easily without surprising the driver and need not violate the Blue Book's (16) admonition, "Sharp curvature should not be introduced near the top of a pronounced crest vertical curve." For example, there is another small change in direction ($\Delta = 2° 05'$) about a mile beyond the kink and in driving this curve, no kink effect was evident. The curve lies on a crest vertical curve and thus is not totally displayed. As a matter of fact, when the kink location was approached, driving the opposite direction of that shown in Figures 14 through 18, no kink effect was visable. If the small change in direction is really necessary and cannot be hidden, it is believed that the evaluation of the design can best be made, at this time, by studying a series of perspective drawings.

CONCLUSIONS

The following conclusions resulted from this study:

1. Perspective drawings provide a very realistic picture of the roadway.
2. Perspective drawings, produced by the electronic plotter, provided an extremely versatile and valuable tool and show great promise as an aid to the highway designer in his complex task.
3. The graph (Fig. 12) showing visually desirable and acceptable relationships between the length of sag vertical curve and viewing distances for various grade changes should be of significant aid to the highway designer.
4. 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.
5. For sag vertical curves, as the distance from viewer to curve increases, the length of curve should increase for good visual quality.
6. Although the results of the analytical approach to the sag vertical curve problem were not fully supported by the study of the perspective drawings, the theory was not shown to be invalid.
7. As the viewer significantly increases his height above the plane of a kink-type alignment (small change in horizontal direction), the kink effect becomes less noticeable.
8. As the viewer gets nearer to the kink alignment the kink appears somewhat less noticeable.

9. The kink appearance is more sensitive to the viewer's height above the plane of the kink than to the distance from which the kink is observed.

10. If a small change of direction in horizontal aignment is placed on the crest of a vertical curve (so that the viewer cannot see the tangent beyond the curve) no kink should be apparent.

REFERENCES

1. Tunnard, Christopher, and Pushkarev, Boris. Manmade America. Yale Univ. Press, New Haven, Conn., 1963.
2. Appleyard, Donald, Lynch, K., and Myer, John R. The View From the Road. M. I. T. Press, 1963.
3. Smith, Bob L., and Fogo, R. D. Some Visual Aspects of Highway Design. Highway Research Record 172, p. 1-20, 1967.
4. Cron, F. W. Fitting the Highway to Landscape. In The Highway and the Landscape, (W. B. Snow, ed.). Rutgers Univ. Press, New Brunswick, N. J., 1959.
5. Cron, F. W. Modern Curvilinear Highway Location and Design. Proc. ASCE, No. 2278, Dec. 1959.
6. Leisch, J. E. New Techniques in Alinement Design and Stakeout. Proc. ASCE, Jour. Highway Div., Vol. 92, No. HW1, March 1966.
7. Snowden, Wayne H. First Readings in Usual Design for Highway Engineers. An information curcular of Institute of Transportation and Traffic Engineering, Univ. of California, Berkeley, July 1966. (10 references are annotated.)
8. Smith, Bob L., and Yotter, E. E. Visual Aspects of Highway Design. Special Report No. 80, Eng. Expt. Sta., Kansas State Univ., Manhattan, 1968. (A Research Report prepared for the State Highway Commission of Kansas.)
9. Godin, P., et al. Visual Quality Studies in Highway Design. Highway Research Record 232, p. 46-57, 1968.
10. COGO (Civil Engineering Coordinate Geometry Computer Program). Department of Civil Engineering, M. I. T., Cambridge, 1965.
11. Bernhart, W. D. The Development of a Perspective Coordinate Transformation. Unpublished (see Appendix A of Ref. 8)
12. Park, R. A., Rowan, N. J., and Walton, N. E. A Computer Technique for Perspective Plotting of Roadways. Highway Research Record 232, p. 29-45, 1968.
13. Geissler, E. H. A Three-Dimensional Approach to Highway Alignment Design. Highway Research Record 232, p. 16-28, 1968.
14. A Policy on Geometric Design of Rural Highways. American Association of State Highway Officials, Washington, D. C., 1965.