HIGHWAY RESEARCH RECORD

Number 232

Geometric Design: Photogrammetry and Aerial Surveys

8 Reports

Subject Area

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22 Highway Design

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Foreword

Geometric Design

In addition to functional characteristics, good geometric highway design must respond to psychological and emotional aspects of the total highway environment. New concepts and techniques are available to aid the designer in preserving natural features, enhancing aesthetic values and minimizing the effects of highway intrusion into the social values of the adjacent communities. The first five papers of this RECORD suggest methods and techniques for providing optimum geometric designs.

Beaton and Bourget give the results of a study to determine a desirable limit for vehicle noise near highways. Charts are provided which permit the designer to predict with reasonable accuracy future truck noise at various distances from a proposed highway location. They suggest some methods and adjustments in geometric design for reducing noise radiation and conclude that plantings possess none of the physical properties required for a good sound shield.

Pearson and McLaughlin suggest relating driver reaction to geometrical elements as a means for establishing objective geometric criteria for highway aesthetics. They view the driving process as a system in which the driver receives input from the highway environment, evaluates and assigns a level of risk to geometric aspects, and reacts or produces outputs which control driving tasks. When the level of risk perceived by the driver is coincident with actual risk the driver is free to enjoy the environment. Galvanic skin response and other apparatus are suggested to measure outputs.

The next three papers describe computer plotting techniques which make it possible to study highway location, alignment and design problems in perspective. Spatial movies produced from the driver's point of view are suggested as a means for group review of the total design concept. The new techniques are presented as an effective means for evaluating the functional and aesthetic values of highways prior to construction.

—HRB Staff

Photogrammetry and Aerial Surveys

The value of precision photogrammetry in making surveys for highway location and design purposes is no longer a topic of debate. Use is now widely accepted and developments are being continually made to improve techniques and procedures and to increase accuracy. The three papers pertaining to aerial surveys in this RECORD are representative of the research recently accomplished for such purposes.

Arneson gives a report on two separate approaches to the utilization of photogrammetry for determining the horizontal position and elevation of supplemental control points which can be used for photogrammetrically measuring position of finite points and for compiling topographic maps for highway location and design. Procedures employed and accuracies achieved are thoroughly explained.

Herd presents a lucid explanation of a unique technique for using aerial photographs in a precision photogrammetric instrument to acquire data regarding the movement, spacing, and behavior of vehicles on highways. The unique techniques developed are thoroughly explained and illustrated.

Ghosh and Ramey give a report concerning aerial triangulation investigations financed by HPR funds and made especially to determine the usability of super-wide-angle photography for determining the X, Y, and Z coordinates of identifiable points to control topographic and other mapping done by photogrammetric methods for highway surveying and design purposes. Analog and analytical methods of using such photography, taken from a flight height of 5,000 feet at a scale of 1:17, 000, are described in detail. Conclusions indicate further investigations would be beneficial, although results achieved were better than expected.

—William T. Pryor

Contents

Can Noise Radiation From Highways Be Reduced by Design?

JOHN L. BEATON and LOUIS BOURGET, California Division of Highways

This paper discusses a study to determine a desirable limit for external noise at residences nearest to a highway and the noise radiation characteristics of conventional highway designs. It presents some possible methods of reducing noise radiation by modifying these designs and some good and bad examples from practice.

The charts permit a reasonable prediction of future truck noise at various distances from a highway before the actual construction. All of the highway designs that are considered in this report are charted. The values are based on field measurements made adjacent to existing exemplary designs in normal operation at full highway vehicle speeds.

•THE problems arising from motor vehicle noise are a familiar topic in the press, and one does not have to be a noise expert to understand certain public reactions. Strong complaints are to be expected when the penetration of exterior noise to the interior of a home becomes severe enough to interfere with conversation, sleep, telephoning or the enjoyment of musical and TV programs. High exterior noise levels also prevent enjoyment of a patio or recreation yard.

Experience has shown that public reaction to the amount of exterior noise invading a backyard or impinging on a home can be anticipated (Fig. 1). The noise is ranked according to peak noise measured in decibels on the A scale of a sound level meter and is usually referred to, simply, as so many dBA. Evaluation of motor vehicle noise in terms of dBA has the approval of the International Standards Organization and the Acoustical Society of America. Recent findings by R. K. Hillquist confirm the merit of dBA over other single-number fast readout noise measurements (1).

The 70 dBA line (Fig. 1) is emphasized because it usually represents the maximum limit of exposure in a residential area before public complaint ensues. The complaints become stronger as the noise rises to higher numbers. A considerable variation in individual reaction is perfectly normal. Few complaints are received in industrial or commercial areas.

Perhaps the safest statement that can be made about the highway noise problem is that noise radiation from vehicles and, in turn, from the highway can be better controlled than it is now. Figure 2 shows

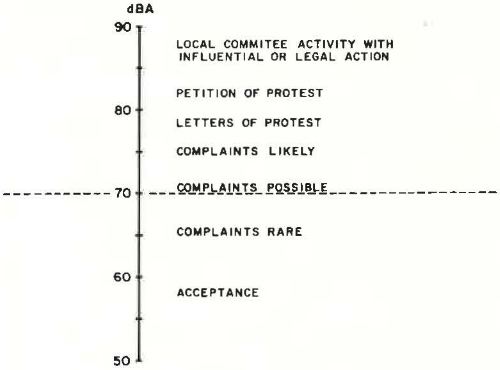

Figure 1. Trend of public reaction to peak noise near residences.

Paper sponsored by Committee on Geometric Highway Design and presented at the 47th Annual Meeting.

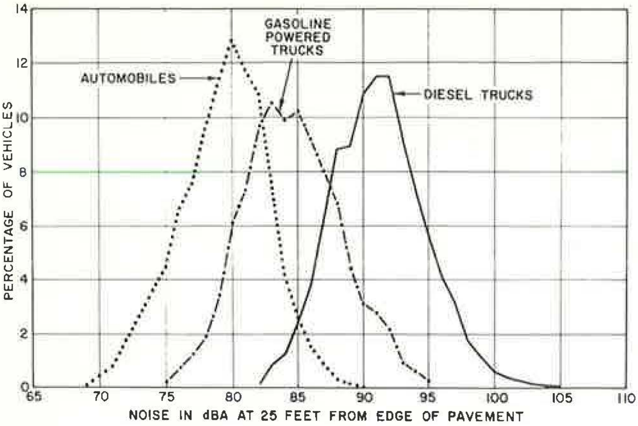

Figure 2. Measured noise distribution curves of highway vehicles.

that the major source of highway noise peaks is the diesel truck; therefore, the noise from diesel trucks will be used as the standard reference throughout this report.

In many well-planned residential areas the houses are often arranged with the bedrooms toward the rear to provide protection against the noise radiated from local vehicles. Local traffic often drops to nearly zero during the sleeping hours. The ambient noise may drop to levels of around 30 to 40 dBA when no vehicles are present.

If a highway penetrates this type of environment, a considerable change takes place. The highway traffic noise, more frequently than not, radiates toward the bedroom windows of the nearest exposed dwellings. The peak noise levels developed outside of these residences will vary with distance (Fig. 3). The figure of 70 dBA has a definite significance—it relates fairly well to the noise generated by local automobiles that may pass on the nearest city street during the night. Most people can adapt to this amount of external noise but would prefer a much lower figure if given a choice. Vern O. Knudsen (2) has suggested an acceptable maximum noise range of 35 to 45 dBA for the interior of apartments and houses. An exterior noise of 70 dBA can usually be reduced to 45 dBA, internally, by shutting the windows facing the source. Some people will object to this requirement, but experience shows that Dr. Knudsen's 45 dBA figure is well chosen as a maximum and that exterior noises in excess of 70 dBA will stimulate many complaints by raising the internal noise above 45 dBA. (If the nearest windows are partly open, an exterior noise maximum of less than 60 dBA is desirable.)

The most effective method for controlling airborne noise usually involves four steps:

1. Quieten the source (design-muffle-shield).
2. Spoil the path (interpose a dense, nonpermeable barrier).
3. Protect the receiver (obstruct or enclose).
4. Absorb the remainder (line the enclosure).

Unfortunately, the authority for exercising control over all of these steps does not rest with the highway engineer. Nevertheless, a beneficial range of control is available because each basic highway design has its own peculiar noise radiation characteristic. These inherent differences between various designs can affect the noise path (step 2) to a degree that may be slight or about 3 dBA; significant or about 6 dBA; or dramatic, say 10 dBA or more.

Almost equally important is the fact that certain design modifications offer an opportunity to reduce the noise even further. The degree of reduction that modifications can

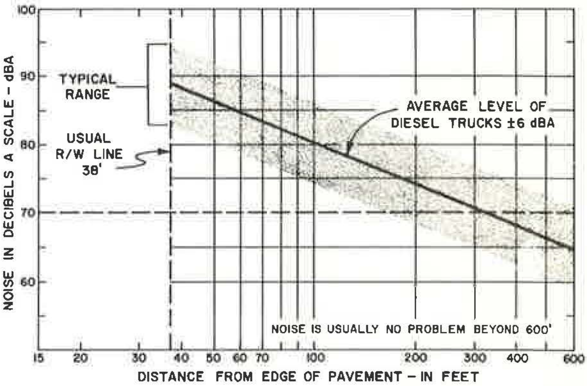

Figure 3. Flat section—diesel truck peak noise range over open terrain.

achieve may sometimes be just as great as already noted between different unmodified basic designs; namely, as much as 10 dBA or more. To avoid being overly optimistic, it should be said that not all modifications and variations are good ones. On the contrary, there are some variations that can destroy the noise shielding properties of an inherently quiet design in a given topography. There are others that make very little difference at all—except in the imagination.

UNMODIFIED HIGHWAY DESIGNS

The noise radiation characteristic of each type of highway presented is based on field measurements across open adjacent terrain. This represents the worst condition where no intervening buildings inhibit the soundpath and the highway profile becomes the dominating factor at a given distance from a vertical reference line at the edge of the pavement.

Flat Sections at Grade—Reference Condition

In Example A_1 (Fig. 4), the noise drop is 6 dBA for each doubling of distance as shown in Figure 3. The distances in Figure 4 are not quite double because the toe or top of most urban freeway fill slopes and cut slopes are at least 60 ft from the edge of the pavement. The next point shown is 100 ft from the edge of the pavement because it is an easily remembered number. All of the other designs are rated in terms of their relative noise advantage over A_1. In every case the microphone of the sound level meter is 5 to 6 ft above the ground. This is about ear height or about the same as window height in many single level residences.

Elevated Highways on Structure or Narrow Shouldered Fill

Example B_1 shows a slight advantage (3 dBA over A_1) for highways that are elevated on a structure or a narrow shouldered fill. The advantage is not very important for adjacent land areas but does become important underneath a structure with a solid deck. This should encourage the growing trend toward commercial exploitation of the space beneath a structure where the measured noise seldom exceeds 70 dBA from overhead traffic. The noise from adjacent city streets will usually exceed that from the highway.

Elevated Highways on Broad Shouldered Fill

Example C_1 shows a significant advantage (6 dBA over A_1) for highways that are elevated on a broad shouldered fill. This improves rapidly where the ramps widen the shoulder and begin to shield the traffic from view near the bottom of the slope. A 12 dBA advantage is possible where the tallest trucks are 90 percent hidden. A 15 dBA advantage is common where the tallest trucks are completely hidden.

Depressed Highways

Example D_1 shows a dramatic advantage (11 dBA over A_1) for highways that are depressed 20 ft below the adjacent land, but only at distances where the vehicles are screened from view. The advantage diminishes rapidly as you approach the highway and the more remote vehicles become visible. The advantage over A_1 becomes zero near the crest of the slope where all shielding is lost.

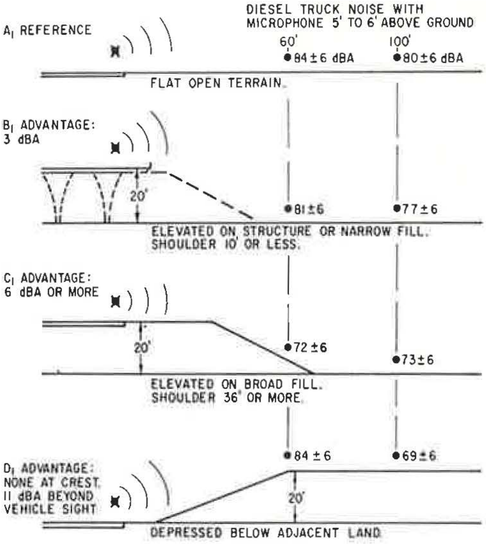

Figure 4. Unmodified highway designs—noise radiation measured from diesel trucks.

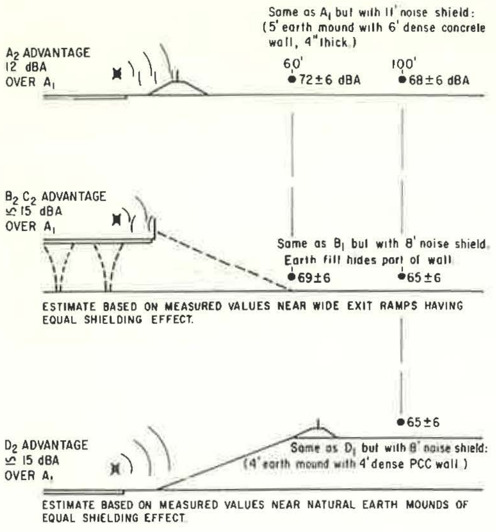

Figure 5. Modified highway designs for better noise reduction.

The preceding unmodified highway designs cover the most frequent conditions found near highways of conventional design. The major exceptions are those which might logically be anticipated. Tall buildings, with a direct view of the traffic, will have a direct range noise exposure about equal to that at the same distance from highway design A_1. The same will be true for direct line of sight positions on adjacent elevated lands or slopes. There is not much one can do to shield the highway where the adjacent land rises rapidly and permits a direct view of the vehicles over the top of any sound shield of reasonable height. This is simple geometry for either optics or acoustics. Favorable conditions exist where the adjacent land is fairly level or slopes downward away from the highway. The basic requirement for a sound shield or barrier is that it must block the view of the noise source (unless it is made of thick clear glass). A secondary requirement is that all of the remaining refractive or reflective soundpaths be rather poor ones, i.e., with high losses and low efficiency.

MODIFIED HIGHWAY DESIGNS FOR BETTER NOISE REDUCTION

Modifications can make a dramatic contribution to further noise reduction. The changes are great enough to be appreciated by either an untrained human observer or a sound level meter.

Shielding a Flat Section at Grade

The first modification involves adding a noise shield to highway design A_1 so that it becomes A_2 (Fig. 5). The advantage is 12 dBA quieter than A_1. A human observer would interpret this as a drop to about 40 percent of the original noise condition. This figure is based on actual measurements obtained in schoolyards where 11-ft high concrete walls served as the noise shield. The same amount of protection can also be found where natural earth mounds offer an equal amount of optical shielding. Although as effective acoustically, the use of an 11-ft high earth mound would require more footing width than is usually available along the right-of-way; and an 11-ft high wall might raise objections about appearances; but the combination of a 5-ft earth mound topped by a 6-ft wall can be visually pleasing as well as functional (Fig. 6).

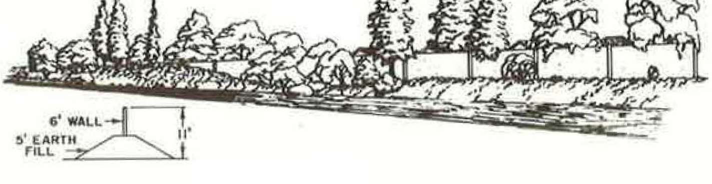

Figure 6. An aesthetic concept of a noise shield near residences in flat terrain.

Shielding an Elevated Highway

The center example, B_2C_2 (Fig. 5), illustrates a method of adding an 8-ft noise shield to a highway that is elevated on either an earth fill or a structure, B_1 or C_1. It is easier to screen the appearance of a noise shield at the crest of a fill, with some earth overlap and plantings, than it is to camouflage it at the side of a structure. Architectural ingenuity is needed. The noise protection may be worth the trouble where sensitive adjacent dwellings lie below horizontal incidence and the vehicles can be completely obscured. Under these conditions the noise advantage over A_1 is about 15 dBA. This is equal to reducing the noise to 25 percent of highway A_1 in terms of human hearing response. At more remote distances the advantage declines slightly but so does the need.

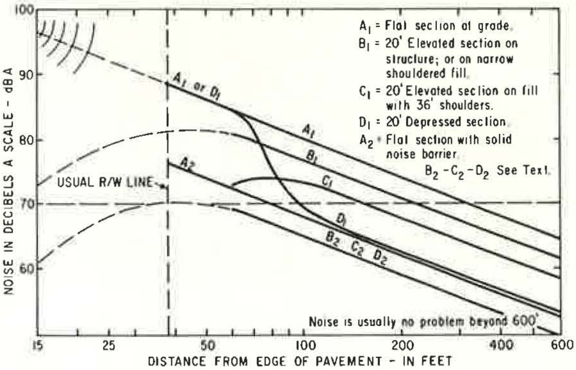

Figure 7. Noise comparison chart for different highway designs—based on average truck noise with ±6 dBA spread; adjacent land flat and unobstructed; microphone 5 ft above ground.

Shielding a Depressed Highway

The lower example, D_2 (Fig. 5), shows the addition of an 8-ft noise shield at the crest of the slope near a depressed highway. This is a most effective method for improving the noise protection to nearby dwellings that would otherwise have a direct optical and acoustical exposure to the vehicles. If the addition of the noise shield results in blocking the line of sight noise path, a 15 dBA advantage is possible over highway A_1. Of course, the more remote dwellings that were already optically shielded will not experience the same amount of change, but even these will obtain an improvement of about 4 dBA. In the latter instances, the advantage over A_1 will change from 11 dBA as shown on D_1 to 15 dBA as shown on D_2 at the more remote distances.

Figure 7 shows a noise comparison chart which summarizes all of the highway conditions covered.

SOME PROPERTIES OF MATERIALS FOR NOISE SHIELDS

Good sound shields must have reasonable mass and be impervious to air flow. In other words, they must neigher vibrate easily nor leak air through themselves. Dense concrete slabs or blocks with all cracks fully mortared are a good example. Earth mounds are even better because they can both block and absorb sound energy. Porous cinder blocks or expanded shale blocks offer a distinct advantage if given a final stucco coating on only one side after the installation. The side to be coated must face away from the highway. The side toward the vehicles should remain porous. With this technique the porous side acts as a sound absorber and the coated side improves the transmission loss or shielding effect (3).

Dense concrete materials are indicated in all sketches showing noise shields along highways, because of the superior durability of dense concrete in freezing and thawing environments. In other less demanding climates, the advantage of expanded shale materials may be exploited, especially when precast slabs are used. It may be desirable to face one side of the slabs with a thin layer of dense concrete or mortar.

SOME EXAMPLES

Figure 8 is an example of how the good shielding properties of a wide shoulder on a fill can be destroyed by the addition of an overhead structure that curves over the freeway and acts as a gigantic reflector as it turns and parallels the highway and the adjacent

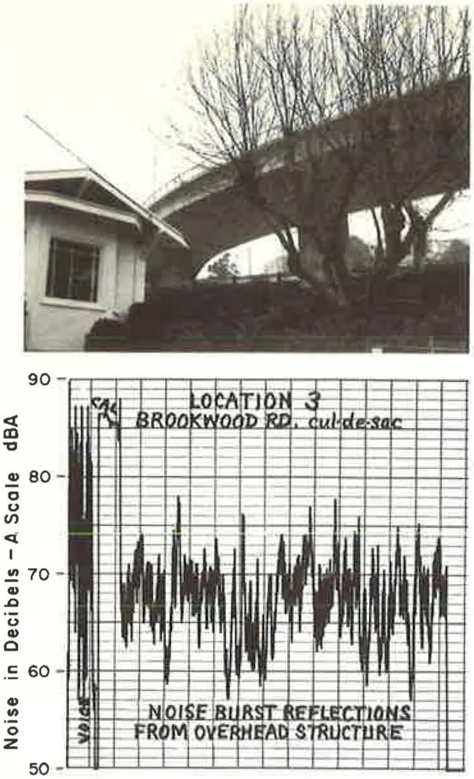

Figure 8. Short sample of noise recording; long-term measurements vary from 58 to 80 dBA.

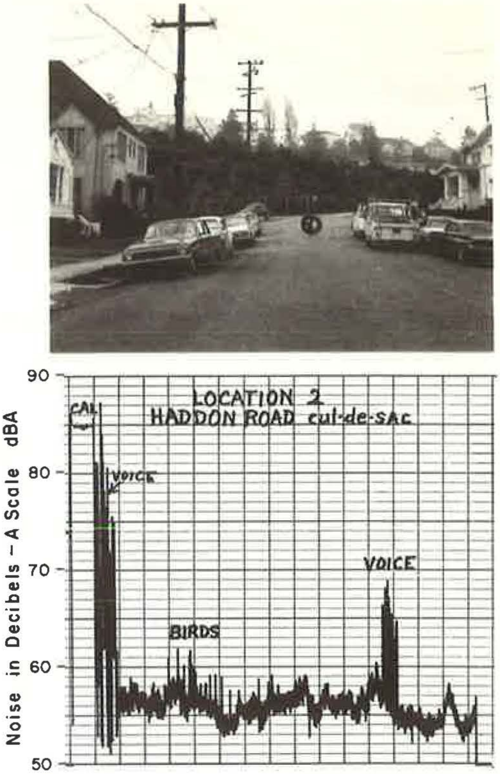

Figure 9. Short sample of noise recording; long-term measurements vary from 52 to 59 dBA.

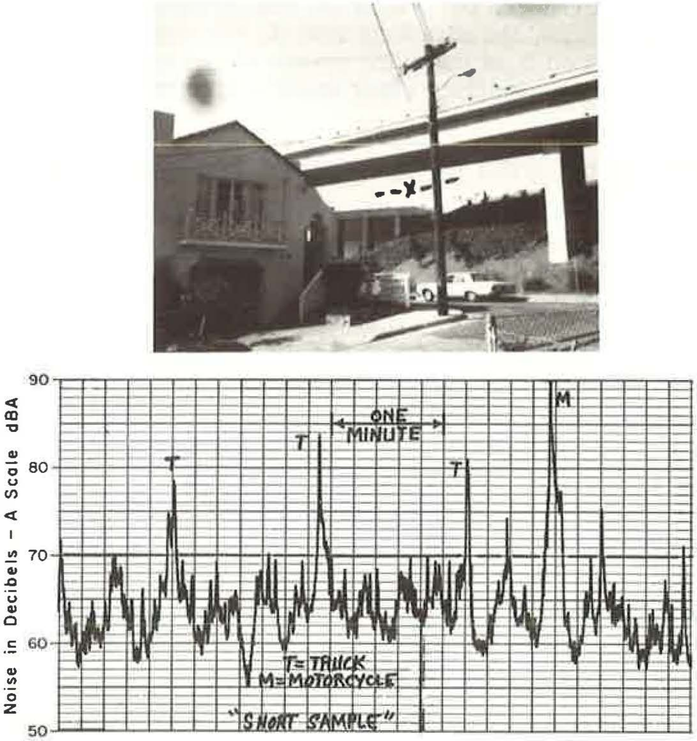

Figure 10. Noise peaks range from 70 to 90 dBA.

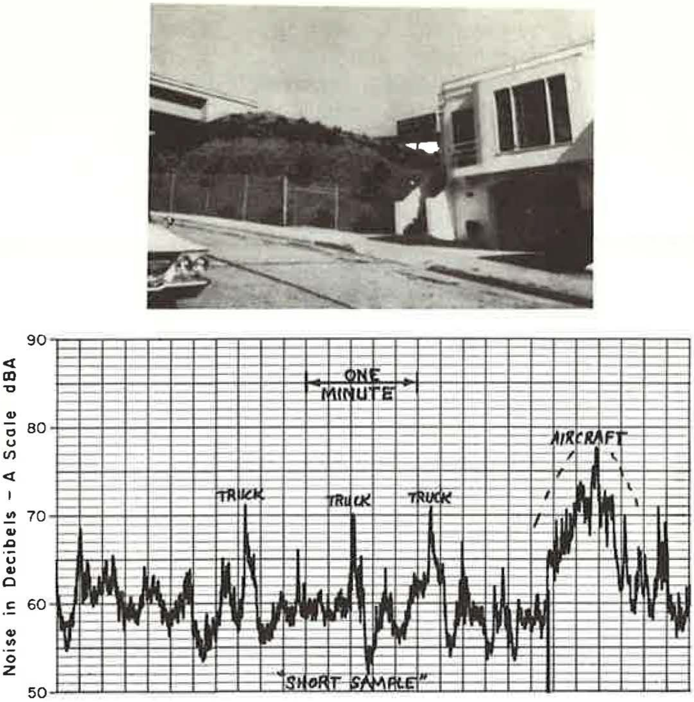

Figure 11. Noise peaks rarely go above 71 dBA except from aircraft; the earth fill acts as a noise barrier for traffic.

residences. The noise bursts come from vehicles out of sight, beyond and below the structure. The bottom side of the structure is in a perfect position to reflect the noise bursts down to the residences. The vehicles on top of the structure are well hidden and are virtually inaudible in comparison with the burst noise from invisible highway vehicles below the structure.

Figure 9 shows the dramatic change after the same structure descends and joins the exit ramp shoulder. The noise bursts disappear and the wide shoulder shields the traffic noise so well that the loudest noise on the chart is from chirping birds as shown on the recording. The peak marked "VOICE" was a comment by the recordist. Figures 8 and 9 show adjacent cul-de-sacs about 300 ft apart.

Figure 10 shows a residence exposed to very high noise peaks. The vehicles on top of the elevated bridge structure are not the cause. Highway trucks pass in the visible space (between the elevated bridge structure and the fill) at --X--. The direct noise bursts from the trucks are enhanced by reflections from the bottom face of the elevated bridge structure. Other noise peaks come from vehicles entering a tunnel colonnade under the highway fill, which can be seen slightly left of center. This tunnel approach is backed by a concrete retaining wall alongside of the highway. Thus, the entire combination is a multiple source of direct noise bursts, exalted by reflections and accompanied by reverberations from the tunnel.

Figure 11 shows a large earth fill just across the street from the residence in Figure 10. The house adjacent to this fill is very well shielded from traffic noise. This can be readily seen by a comparison of the two noise recordings.

The audible change is almost startling when a person walks from the north side of the shielded house in Figure 11 to the north side of the exposed house in Figure 10.

PLANTINGS

Sooner or later the question of planting is brought up during any discussion of noise radiation from highways. This topic should be laid to rest. The simple truth is that plantings possess none of the physical properties required of a good sound shield. They are porous to air flow, vibrate easily, and lack density. Their permeability to the flow of airborne sound is so great that virtually no acoustical benefit is obtained from planting within the right-of-way depth that is normally available. Their real merit is to improve appearances, and there is some "psychological shielding" that tends to favor public acceptance. Noise benefits are mostly folklore (4, 5, 6, 7, 8).

REDUCING NOISE AT THE SOURCE

Noise reduction at the source is an axiom in noise control. In the case of highways, the vehicles are beyond the control of the highway engineer. Many large diesel electric locomotives with two 2000-hp engines often radiate less noise than the 200 to 300-hp diesel trucks found on the highway. Diesel trucks can be made quieter (10). This would be a great step toward improvement, but it would not solve the entire problem, and it would not remove the need for quieter highway designs. Automobiles at full highway speeds radiate about 10 dBA less noise than the trucks, but some of the noisiest automobiles are more of a problem than the quietest of the trucks (Fig. 2). Noise control is usually needed along the highway wherever the external noise peaks exceed 70 dBA at the nearest dwellings in residential areas. Figure 7 compares various highway designs against the average of noise peaks ±6 dBA; therefore, only designs A_2, B_2, C_2, and D_2 are marginally acceptable to residences at less than 100 ft. D_1 is acceptable beyond 150 ft, C_1 at 250 ft, B_1 at 350 ft, and A_1 beyond 500 ft.

SUMMARY

The examples and conclusions in this report are based on several hundred noise measurement studies that were made at exemplary locations along highways in normal operation.

All of the measurements were obtained with General Radio sound level meters and graphic level recorders. Acoustical calibration was performed before every test run and repeated at intervals not exceeding one hour.

Highway design can include better noise control in the total engineering package. If this is ignored, the growing public awareness may bring increasing opposition to new highways in residential areas.

ACKNOWLEDGMENT

This paper is based in part on data collected during a research project financed jointly by the California Division of Highways and the U.S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads.

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Towards Design Criteria for Highway Aesthetics

P. M. PEARSON and W. A. McLAUGHLIN, University of Waterloo, Waterloo, Ontario

The objective of this paper is an attempt to establish a framework of investigations into design criteria which will not only include the traditional Newtonian criteria but measurable aesthetic considerations from the driver's point of view.

The driving task is developed as a system. The inputs are perceived by the driver, a value judgment is made and outputs are produced.

The experimental method suggested deals with the value judgment. It is suggested that the driver's outputs are a reflection of his state of mind. The galvanic skin response and other apparatus are suggested to measure these outputs.

By relating the state of mind or an acceptable level of risk to geometric elements, design criteria can be developed to allow the driver freedom to enjoy the beauty of the environment. Until this is accomplished, there is little logic in providing, at additional costs, so-called aesthetic qualities in design.

•WITHIN recent years, a great furor has arisen because of the highway designers apparent lack of concern for aesthetics. The major indication of the people's feelings is reflected in the United States by the enactment of Public Law 89-285. This law does not define beauty nor does it suggest the best means of incorporating beauty into highway design, but by its existence it does show that there is a dissatisfaction with what we, as engineers, have been giving the people. It should tell us that something is missing in our technical solutions. It would be naive to suggest that a highway designer who toils with traffic forecasts and highway location and geometrics under economic, time and political constraints is not concerned with how the final product looks. However, it might well be that these practical exigencies have used up our time leaving little thought towards incorporating beauty.

Aesthetics cannot be thought of as visual elements alone, but as Snowden suggests (1): "beauty is that which exalts or lifts up the mind or spirit. It may come to us through any one or more of the senses.... beautiful highways then, are those which uplift us in whatever way we experience them!" The definition indicates not only the presence of visual order is necessary but the viewpoint of the beholder must also be defined. Aesthetics is a function of age, sex, culture, occupation, etc. of the individual. For example, the same outer reality can cause different impressions to the same viewer at different times. In discussing highways, the viewpoint external to the road user is important in urban and other built up areas. In rural areas, the point of view of the driver and his passengers is more important. For the driver or the passenger the physical reality is also warped by other environmental factors such as weather, traffic density, and speed.

In the past, roads were "hacked" through the wilderness and did fit the topography. Although these roads may be visually pleasing, the driving task may be difficult because of poor geometrics. Todays highways, although incorporating satisfactory surface design and safety properties may not provide the basis for an enjoyable trip for many reasons. The driver may be confused by small design "errors," may be irritated by traffic congestion, may be upset by a previous experience (before or during the trip) or the highway itself may destroy rather than show-off the landscape. It is generally

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accepted that our modern rural highways incorporating long tangents and shallow curves, although safe in the Newtonian sense lead to driver boredom and hence to unsafe conditions.

The objective of this paper is an attempt to establish a framework of investigations into design criteria which will not only include the traditional Newtonian criteria but measurable aesthetic considerations from the driver's point of view. The investigation is restricted to the internal roadway effects on the driver on rural roads. It is the authors' belief that in defining the total problem this is the logical place to start.

HIGHWAY DESIGN

The objectives in highway design may be stated as follows: (a) maximize level of traffic service, (b) maximize safety, (c) maximize beauty, and (d) minimize costs. These objectives are not compatible and certain trade-offs must be made. Our problem is one of measurement; that is, there is no rational method or value function which relates all of these objectives so that an "equation" can be maximized or minimized.

Once a need for a facility has been established, a location is selected. Normally, this selection is the result of economic, service and political dictates. Geometric standards are then applied to carry the anticipated volumes safely. These standards have generally resulted from vehicular characteristics for horizontal alignment and some human characteristics as well as vehicular characteristics for vertical alignment.

Generally then, objectives (a) and (d) are considered directly and trade-offs made. The safety objective is usually considered as part of (a). Aesthetic considerations may be taken into account but these considerations normally do not involve road location or geometry but may involve structures and roadside development.

AESTHETICS IN DESIGN

Aesthetics or beauty in highways has been considered by designers and other interested people over the years. This is evident from the literature. Lately there has been a resurgence of interest in the total field of aesthetic design. This is probably due, in a large degree, to our more affluent society.

Generally, in highway aesthetics, the literature has dealt with how the road looks from the external and internal viewpoint. Subjective criteria or rules can be derived from this literature to aid the designer in making aesthetic judgments. Such criteria have been adopted and are being used by some authorities today (2).

These rules attempt to incorporate the third objective (maximize beauty) subject to the objective of minimized total cost. Other tools involve the use of models to create the environment before final designs are made. These may be the inverted periscope, motion pictures, photographs, perspective drawings, etc. Even though these aids exist and are valuable, the designer must keep in mind that he is not driving the road and thus cannot experience the impact of the total facility on the driver.

These techniques appear to be solutions to particular problems; however, they do not objectively establish any measurable criteria which reflect the driving experience.

It is normally accepted that curvilinear alignment is more pleasing than long tangent short curve alignment. However, it is not known objectively what range of degree of curvature would be optimal. A driver may find a curvilinear (or spiral) alignment more pleasing than a straight section at night, not because he can see the total curve set in the environment, but because of reduced headlight glare. This example has been cited to show the influence of environmental factors, other than those stated in the general rules on aesthetics.

The problem of establishing measurable criteria has unintentionally been overlooked or skirted in the quest to develop solutions. It is not by any means an easy problem to understand and because of its complexity may never be completely quantitatively defined. It not only deals with how a facility or its environment looks, but how the driver (and his passengers) react to all inputs that highway designers have created. Except for a few isolated studies (3, 4) little work has been done to determine the inputs to which the driver reacts. An understanding of the driving process is essential if one hopes to define the problem.

THE DRIVING PROCESS AS A SYSTEM

The driver can be thought of as a system. This system receives inputs from the environment, places values on these inputs and reacts or produces outputs based on perceived values related to some objective function.

Inputs

The inputs themselves can be classed into two types: real time and lag time. The real time inputs are perceived in the environment when they are required. Road alignment, centerline markings and traffic signs would constitute some of the visual real time inputs. The lag time inputs are the result of previous experience which are held in the conscious mind. Particular knowledge about the vehicle's condition could constitute a lag time input. The real time inputs are sampled and in the light of lag time inputs a value judgment as to course of action is made. For this discussion, the lag time inputs will be assumed to have little or no effect on the driving behavior. Real time inputs will be referred to as inputs.

Signals from all elements in the environment exist simultaneously. Psychologists suggest that, although all the signals in the field of perception are received, there are only a few of these signals that one is aware of at any one time. The elements exhibiting the strongest signals are those to which one reacts. Reaction can result from inputs received by one sense to that received by another instantaneously. Consider a driver whose automobile suddenly develops engine trouble that he perceives through the sense of sound. The driver who had been performing his task with inputs of visual reception has now responded to an audio reception.

The major inputs can be classed under the four senses associated with driving (Table 1). Each input can be thought of as exhibiting qualities from pleasing to irritating. The inputs with the strongest signals will have the greatest weight.

Outputs

The outputs take the form of the driving task. The driver accelerates, decelerates, turns the steering wheel, changes lanes, etc. Methods have been devised to measure these outputs (5, 6).

Driver Evaluation

Each driver will evaluate the inputs differently; thus, different drivers will enjoy a trip for different reasons. To some users it may be enjoyable no matter what the road looks like as long as it is drivable. This class of users obtain their pleasure from the mere challenge of driving. Another class of users may find their exhilaration by placing themselves in a certain element of risk (7). Most, however, enjoy a trip if they feel secure on the road, and feeling secure, are able to divert their attention momentarily to other elements in the environment besides the roadway. It is this majority class of road users that enjoy aesthetics and must be considered if beauty is to be incorporated.

TABLE 1

INPUTS ASSOCIATED WITH THE DRIVING TASK

Input Perception	Directly Associated With Driving		Indirectly Associated With Driving
	Roadway Elements	Non-Roadway Elements	Non-Roadway Elements
Visual	Total roadway Centerline Shoulder markings Shoulders Opposing lane	Traffic signals Traffic signs Information signs Parked vehicles Abutments	Natural environment Man-made environment
Sound	Noise of tires on pavement	Engine noise Traffic noise	
Feel	Road roughness		
Smell		Engine of associated trouble	Natural gas Industrial odors

As the inputs are presented, the driver evaluates them. This evaluation develops a state of

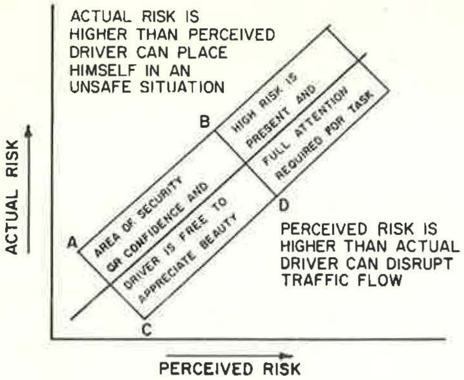

Figure 1. The concept of the value judgment.

mind under which the driving task is carried out. The driver perceives a level of risk which he compensates for in his task. If he perceives a great risk his attention will be occupied with the driving task, and even though certain elements in the environment might be considered aesthetic he will not be able to enjoy them. Partial attention to these elements may place the driver in an unsafe situation. (An actual situation and not a perceived one.) On the other hand, if a driver perceives a safe environment (and the design and prevailing conditions are such that it is safe) he will be free to enjoy the beauty of the trip.

Two other classes of roadways can be thought of in terms of a perceived risk function. On certain roads the driver will perceive a risk greater than there actually exists. The tourist driving a mountain road for the first time may feel a large risk and overcompensate for it. His perception and resultant action can cause interference with traffic flow and irritate other drivers. On the other hand, some of the prairie highways are examples, the driver can associate less risk with a certain road than does exist. He may then become bored, or uninterested in his task. As a result, the driver places himself in a true risk situation that he does not perceive and thus does not compensate.

By understanding the situations in which the driver is able to enjoy aesthetic values, when and why he feels safe on a highway and relating this to geometric elements, the basis of the complete highway can evolve. The basic element is the roadway and it should instill in the driver a perception of a level of risk that is consistent with the geometric design. The level of risk perceived by the driver should be reflected by his outputs. Once the limits of the level of risk have been established and related to geometric elements, then one can logically design those elements considered aesthetic. One does not ask the driver to isolate components of highway design as to their relative aesthetic merit. Presumably, the driver can appreciate beauty (or forms of it that appeal to him). However, one should be able to determine those elements that establish the acceptable limits of "level of risk" through measuring driver output.

FRAMEWORK OF EXPERIMENTAL ANALYSIS

The Value Judgment

The level of risk should be such that the driver perceives the actual risk and still feels free to appreciate aesthetic elements in the environment. Figure 1 is a schematic of the value judgment. The range that must be determined is shown by area ABCD.

Value Judgment's Relation to Geometrics

The concept of this value function is relatively simple. The human system perceives certain inputs. Each input will range in tolerance from pleasing to irritating. The inputs exhibiting the largest signals will have the greatest weight in determining the driver's perceived risk. If the geometric inputs are greatest and these are pleasing, the driver may associate little risk with his task. On the other hand, if the road roughness is irritating, this may exhibit a strong signal and the driver may decelerate or otherwise compensate. If one were to consider the basic roadway elements that could be quantitatively measured, the following components could be examined:

1. Horizontal alignment: (a) degree of curvature, (b) length of curve, (c) length of spiral, (d) degree of superelevation, (e) length of superelevation, (f) length of tangent, and (g) sight distance.
2. Vertical alignment: (a) radius of vertical curvature, (b) length of vertical curvature, and (c) sight distance.

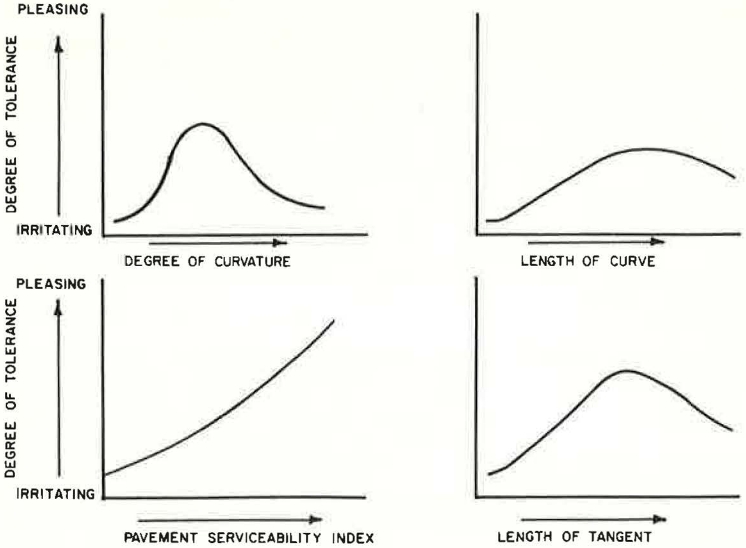

Figure 2. Schematic representation between levels of tolerance and geometric design standards.

3. Other roadway characteristics: (a) shoulder type, (b) shoulder condition, (c) shoulder width, (d) lane width, and (e) lateral clearance.
4. Interactions of all geometric elements.
5. Road surface characteristics, such as pavement roughness measures.

Relationships would be sought to establish levels of tolerance between the driver and the geometric standards. The relationships may be of the form suggested in Figure 2.

The Experimental Method

It must be determined which relationships or combination of relationships have the largest effect on the driver while he is performing his task. If the experiment were carried out in the field a large number of pavement sections would be required for examination. The degree of curvature, for example, could be varied in different sections showing similar properties.

An eye camera recording the inputs and simultaneous measurements of acceleration noise and steering wheel movements could be made. A galvanic skin response apparatus (8) could measure the level of risk perceived by the driver. By varying each of the selected elements, the data produced could be subjected to analysis and the significant ranges of each design element deduced. Most importantly, the eye camera would indicate under what geometric conditions the driver was able to perceive other elements in the environment.

Within recent months, the use of computer graphics (9) has become an inherent part of some design processes. It appears possible to coordinate this method with the use of driving simulators. The simulator environment is easily controlled and has been found to have an acceptable relationship with the actual driving task.

Application of Results

It is hoped that the results of such an experiment would allow the calculation of geometric design standards related to an acceptable level of risk.

Consider the present state of knowledge. The visual field changes with speed. As speed increases objects alongside or in front of the car become blurred and the driver extends his field of vision to a static zone further down the road. This point of concentration increases from 600 ft at 25 mph to 1800 ft at 60 mph. Simultaneously, the cone of vision decreases from 180 to 40 deg. To allow the road to be within the driver's

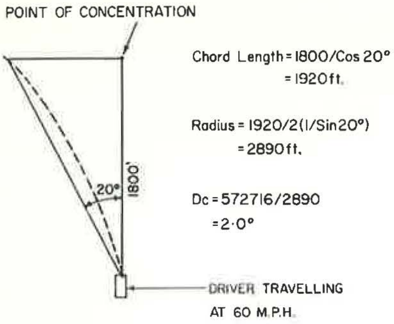

Figure 3. Calculation of Dc and R from driver limitations.

TABLE 2

COMPARISON OF MAXIMUM Dc AND MINIMUM R AT VARIOUS DESIGN SPEEDS

	Driver Limitation Standards		Vehicle Limitation Standards	
Design Speed	Dc	R	Dc	R
40	4.9	1170	11.3	508
50	3.3	1700	6.9	833
60	2.0	2890	4.5	1263

field of vision at all times, maximum degrees of curvature and minimum radii can be calculated for various design speeds. The method of calculation is summarized in Figure 3. Similar calculations were made for other design speeds and these were compared with the AASHO (10) minimum standards. The comparisons are given in Table 2. The AASHO standards are based on vehicular performance with maximum superelevation of 0.06 and a coefficient of friction from 0.11 to 0.15.

FOR THE PRESENT

Until such research is performed, considerations in design can be given. By assuring that the driver is always aware of the road alignment the first step in assuring driver confidence has been established. Geissler (11) has summarized the principles and tools that can be used in providing optical guidance. If optical guidance is properly provided, the driver can be free to enjoy the beauty present in the environment.

SUMMARY

1. The driving process has been presented as a system exhibiting inputs, outputs and a value judgment.
2. These value judgments may be related to the geometric design standards of rural highways.
3. The inputs perceived by the driver were hypothesized to exhibit levels of tolerance from pleasing to irritating and the form of possible relationships was established.
4. An experimental method was suggested to measure geometric standards and driver reaction. With the performance of such work acceptable limits of level of risk related to geometric elements can be deduced.
5. It is our belief that until the geometric standards and level of service are provided so that the driver is free to enjoy the aesthetic qualities of the environment there is little point in providing, at additional cost, so-called aesthetic qualities in design. When the road itself will allow the user to enjoy the environment there is logic in cleaning up the billboards. Perhaps then we will understand what the furor is all about.

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Discussion

E. H. GEISSLER and A. AZIZ, Department of Highways, Ontario, Canada—The authors suggest an experimental method to establish design criteria for highway aesthetics by measuring geometric elements and drivers' reaction. This is to be accomplished by setting acceptable limits of risk related to the geometric elements. This approach provides a welcome step toward the solution of a rather complex problem, but there are several other considerations which may be taken into account, some of which are mentioned in the following.

Two-Fold Viewpoint

The concept of providing determinate criteria for highway aesthetics may well include the understated points: (a) the view the highway offers to the onlookers across the environment the highway passes through, and (b) the view of the driver across the environment as he travels along the roadway.

Aesthetics as a Totality

The authors have done well to deal with the internal aesthetics of a highway, but we feel that to consider the external or the environmental elements at the same time will perhaps produce favorable results. It will from the very start give us an easier path for the integration of the internal and the external variables, namely geometrics and environment, under various topographic conditions.

Enhancement of Responsibility

As related to the considerations described above, "enhancement of responsibility" sounds a rather strange idea. We, as highway engineers and designers, have now come to realize that pure design and function by themselves very often jar our emotional and psychological sensibilities, and that there is something more required to make it satisfying for us to live with the things and environment around us, and this something we call aesthetics.

Traditionally, we have felt somewhat strange to the idea of aesthetics and form as it can be incorporated in finished highway work, and that architectural treatment is beyond us.

We feel that if we break out of this restraint, we would have a clearer perception and recognition of what beauty of function, design and form we wish to obtain.

P. M. PEARSON and W. A. McLAUGHLIN, Closure—The paper was confined to the relationships between the driver and the structural and geometric elements of the roadway. We felt that until there is a feeling of security on the part of the driver, there was no point in beautifying the roadway for his benefit. This was a stated constraint in that we did not consider the nondriving population.

A Three-Dimensional Approach to Highway Alignment Design

E. H. GEISSLER, Department of Highways, Ontario, Canada

The growing concern with the natural appearance of our roads makes it desirable, if not necessary, to adopt a design method in which both function and form are equally considered.

Although the determination of the location corridor and the alignment itself depends on many variables in the engineering and the economic field, equal emphasis should be placed on psychological and emotional values such as scenery and aesthetics. The optimum solution of the location and alignment problem in regard to psychological and emotional values can be obtained by means of a central perspective of three-dimensional design technique.

The author describes some methods whereby the electronic computer is used to produce various types of spatial motion pictures for the evaluation of scenic routes within the location corridor and roadway movies for the final test of the internal and external alignment. Additional improvement is obtained by the stereoscopic approach which provides an ideal condition for depth perception.

It is concluded that the central perspective method, in connection with the electronic computer, can be successfully used to assist the highway engineer in evaluating routes within the location corridor and testing and revising the three-dimensional alignment design before construction commences.

•ALIGNMENT design is still done by treating the horizontal and vertical layout separately. Even with the application of advanced engineering standards, the constructed road is not satisfactory because of the disharmony in the internal alignment itself and its relation with what is external to it. The common defects of such an alignment are well known and can be summarized into two main groups: (a) distorted vista such as roller coaster, broken back and break in the natural skyline, and (b) sudden change of direction.

Figures 1 and 2 illustrate a few of these undesirable conditions.

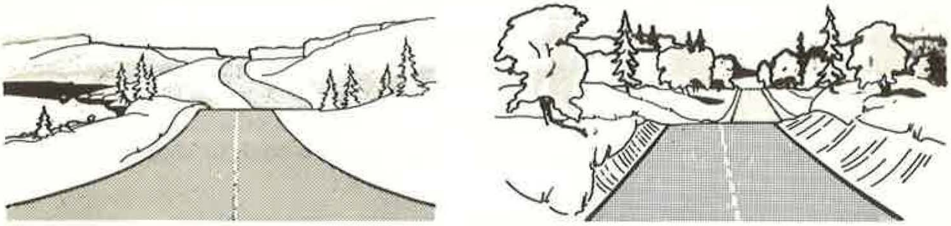


Figure 1. Distorted vista.

Paper sponsored by Committee on Geometric Highway Design and presented at the 47th Annual Meeting.

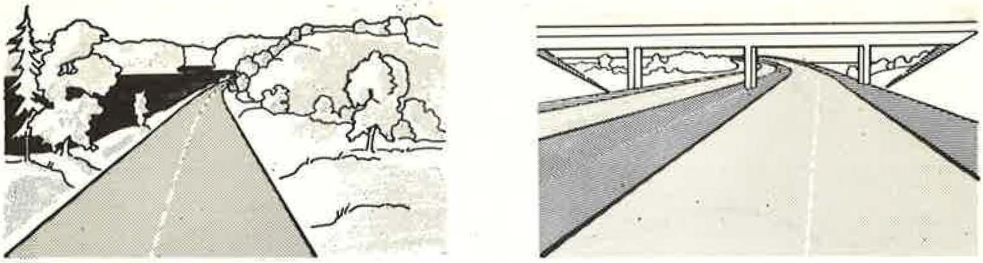


Figure 2. Sudden change of direction.

Only recently have we begun to realize that the highway needs much more than the consideration of functional requirements. A well-designed road should contribute not only to the safety of road users but it should also present an aesthetically satisfying and pleasing picture. Whether the road is seen from the internal view or from the outside, it should fit the landscape harmoniously. Thus, we need to incorporate the human factor in design work by visualizing road location and alignment design in three dimensions.

OBJECTIVE AND SCOPE

The prime objective, therefore, is to describe briefly some methods of a three-dimensional approach in the dual problem of selecting a route, within the location corridor, and designing the alignment. The scope covers the rural highways.

LOCATION CORRIDOR AND ALIGNMENT

The determination of the location corridor depends on many factors while the location of the alignment itself, within the corridor, is influenced by road and rail networks, right-of-way, stream crossings, drainage, utilities, etc.

The essential factors in determining the location corridor can be grouped into: (a) psychological values, (b) public interest values, and (c) functional values. Figure 3 shows these main values with their correlated subvalues.

Because of the many variables, there is no infallible answer to the location problem. Conflicting points often force compromises.

The alignment itself consists of a series of straight lines connected by curves and spirals. It commences with long tangents and short curves, applied especially in the early years of railroad construction. Unfortunately, this technique is still in use.

Improvements can be made by shortening the tangents and increasing the length of the curves. It has been found that the minimum length of a circular curve should not be less than 1500 to 2000 ft. Finally, when longer spirals are applied, we arrive at a continuous curvilinear horizontal alignment.

The vertical alignment is just as important as the horizontal one (Fig. 4). Long grades have the same monotonous effect as straight horizontal lines. The gradual

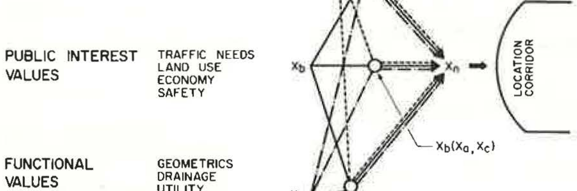


Figure 3. Relation between location corridor determinants.

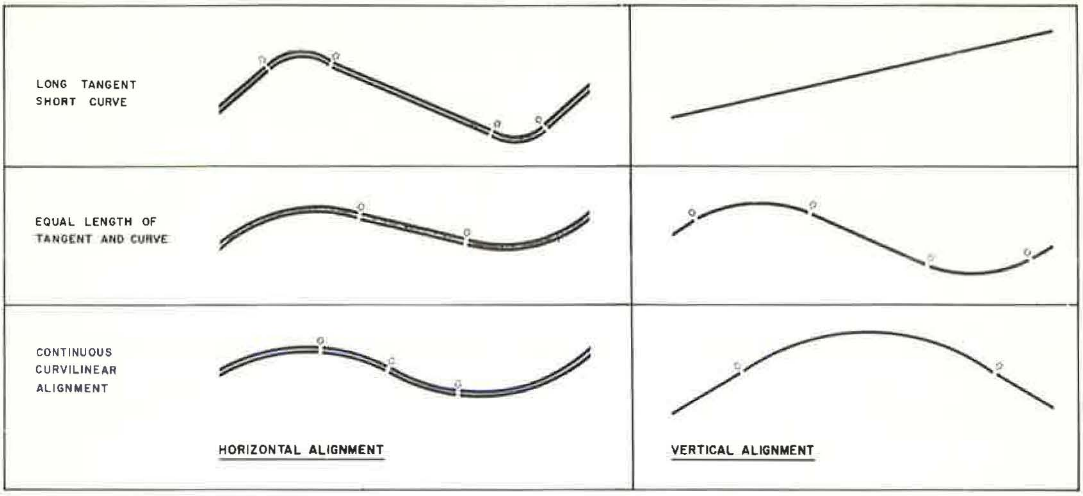


Figure 4. Development of horizontal and vertical alignment.

change between tangent grades is effected by a vertical curve which can be either circular, simple parabolic or cubic parabolic. The simple parabola generally is preferable because this curve has a constant rate of change and the vertical offsets from the tangent vary with the square of the horizontal distance from the curve end. The most used mathematical relation is

$$\frac{\text{Length of curve (ft)}}{\text{Algebraic difference between tangent grades}} = K$$

as a measure of curvature; it expresses the horizontal distance, L, in feet required to effect 1 percent change in grade.

The ideal form of alignment should have approximately the same scale for horizontal and vertical curves and coincide roughly with the beginning and end of both layouts. For comparative investigations between both types of curves, the parabolic curve can be transformed into circular curves; whereby for small angles R = K 100. Figure 5 shows various superimposing positions. In the ideal form, the tangent

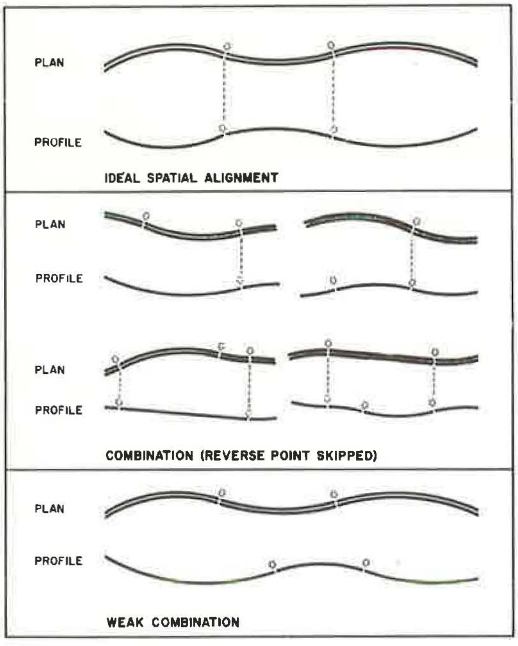


Figure 5. Superimposing of horizontal and vertical layout.

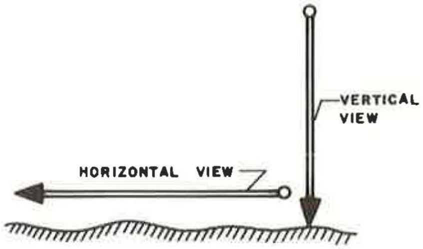


Figure 6. Direction of view.

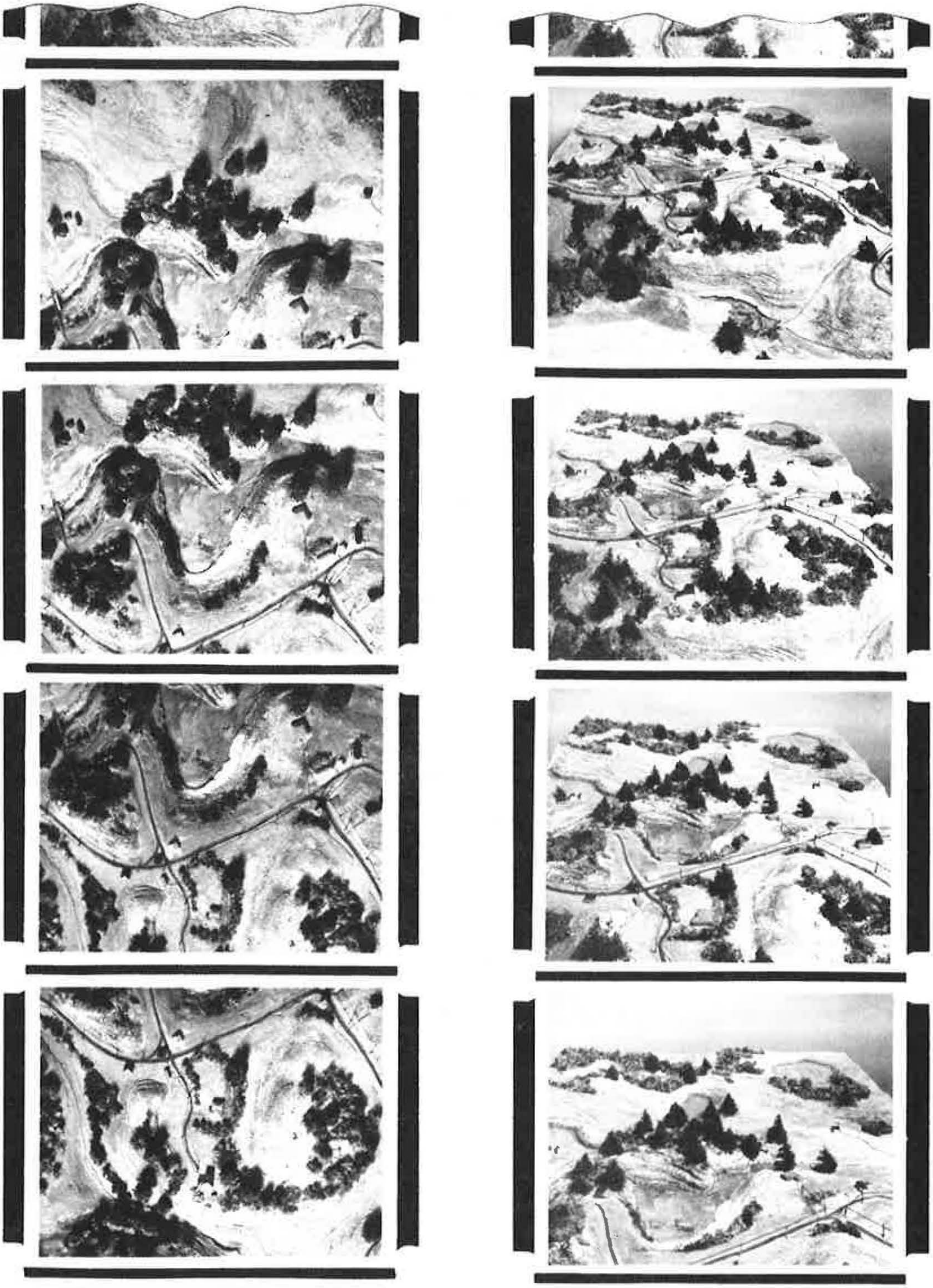


Figure 7. Difference between vertical and horizontal view.

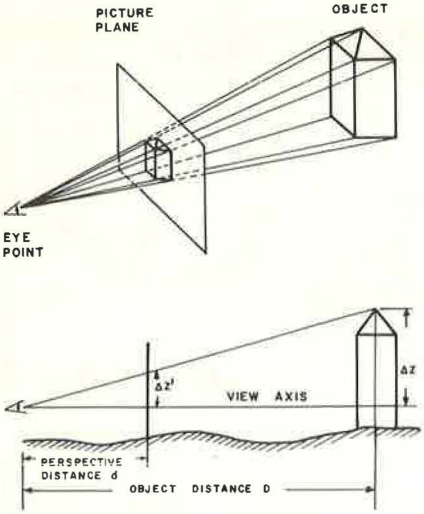


Figure 8. Sketch of central perspective.

points on crest and sag curves are always located at the superelevated section while the reverse points of the horizontal alignment lie within the descending and ascending grades.

TOOLS FOR OPTIMIZING THE CORRIDOR AND THE ALIGNMENT PROBLEM

The success of optimizing the corridor and alignment problem depends on applying engineering and economic principles, and also consideration of landscape. Since, in the final analysis, we will be judged by the appearance of our highways, special emphasis must be laid on psychological values which include scenery and aesthetics.

In order to arrive at an acceptable solution in regard to psychological considerations, a device is necessary to perceive a three-dimensional view. Although aerial photogrammetry provides a three-dimensional perception, it is seen only in the vertical direction and not in the horizontal view as the driver observes the roadway. A more realistic view perhaps can be obtained through the central perspective which satisfies this desired view in the horizontal direction (Fig. 6).

To exhibit the difference between vertical and horizontal view sight, a short movie of a route corridor model has been produced. From the same selected line, we see first the landscape from the vertical view of an airplane, followed by the same site but in the horizontal direction (Fig. 7).

MATHEMATICAL BASIS OF PERSPECTIVE

The perspective deals with the projection of a spatial object on a projection plane seen from a central point or eye point. The picture itself is projected on the plane by all the view rays between the central point and the object. Figure 8 shows the relation of main rays and points whereby the main axis or view axis is the prime reference line for the geometric build-up. The following mathematical relation can be obtained from the principle of similarity:

$$\frac{\Delta Z'}{\Delta Z} = \frac{d}{D} \tag{1}$$

and with d = 1, we derive the fundamental formula for the central perspective

$$\Delta Z' = \frac{1}{D} \Delta Z \tag{2}$$

If we project spatial object points perpendicular to the vertical view axis and notate the effects with ΔX_i, Eq. 2 can then be transformed into two-dimensional perspective coordinates

$$\Delta Z'_i = \frac{1}{D} \Delta Z_i$$

$$\Delta X'_i = \frac{1}{D} \Delta X_i \tag{3}$$

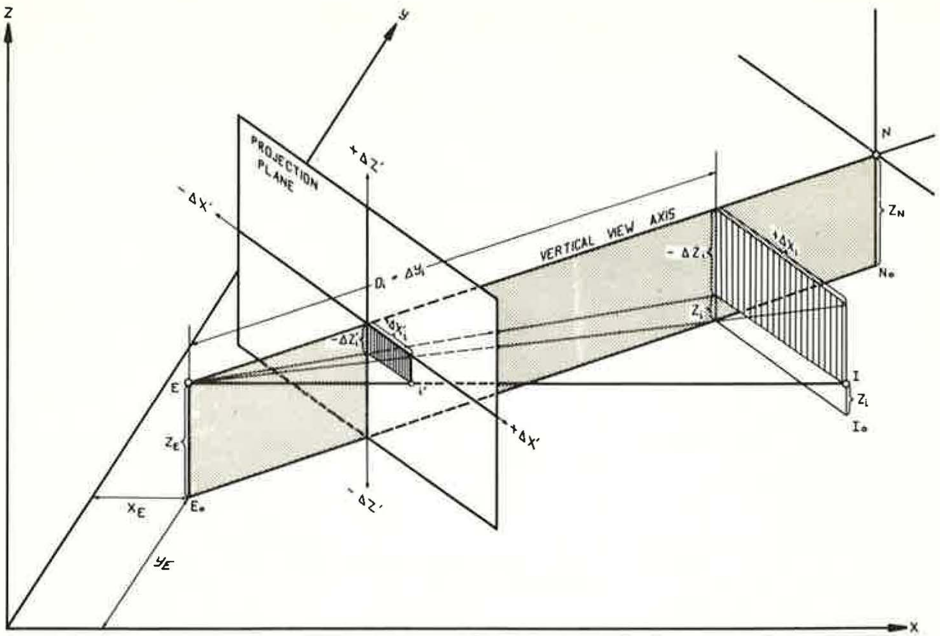


Figure 9. Perspective projection of spatial objects.

Each object point is determined by the coordinates ΔZ_i, ΔX_i and the distance D_i (Fig. 9). The perspective illustration of any object can then be plotted by coordinates of a number of connected points.

A further development of Eq. 3 leads then to the ordinate ΔX_i and the abscissa ΔY_i. With $D_i = \Delta Y_i$ we derive first

$$\Delta Z_i' = \frac{1}{\Delta Y_i} \Delta Z_i$$

$$\Delta X_i' = \frac{1}{\Delta Y_i} \Delta X_i \qquad (4)$$

and by the simple mathematical relation

$$\overline{E_O - I_O} = \sqrt{(Y_I - Y_E)^2 + (X_I - X_E)^2}$$

$$\operatorname{cotan} \alpha_I = \frac{Y_I - Y_E}{X_I - X_E}$$

$$\operatorname{cotan} \alpha_N = \frac{Y_N - Y_E}{X_N - X_E}$$

$$\alpha = \alpha_I - \alpha_N$$

Finally, with α and the distance $\overline{E_O - I_O}$ we derive

$$\Delta X_i = \sin\alpha\,\overline{(E_O - I_O)}$$

$$\Delta Y_i = \cos\alpha\,\overline{(E_O - I_O)}$$

$$\Delta Z_i = Z_E - Z_I \qquad (5)$$

Eq. 4 for perspective coordinates can then be completed by substituting ΔX_i, ΔY_i and ΔZ_i from Eq. 5:

$$\Delta Z_i' = \frac{1}{\cos\alpha\,\overline{(E_O - I_O)}}\,(Z_E - Z_I)$$

$$\Delta X_i' = \frac{1}{\cos\alpha\,\overline{(E_O - I_O)}}\,\sin\alpha\,\overline{(E_O - I_O)} \qquad (6)$$

PROGRESSIVE STAGING OF THE DUAL PROBLEM

The central perspective can be applied in a progressive staging process in the dual problem of the location corridor and alignment design. Three phases are proposed from the very early stage during the process of planning:

1. Preliminary spatial motion pictures with the eye point approximately 100 ft above the ground, to make the first rough selections of lines with the best scenic qualities.
2. Refined spatial motion picture with the eye point approximately 25 ft above the landscape to evaluate the selected lines.
3. Roadway movie to make the final test with incorporated horizontal and vertical alignment.

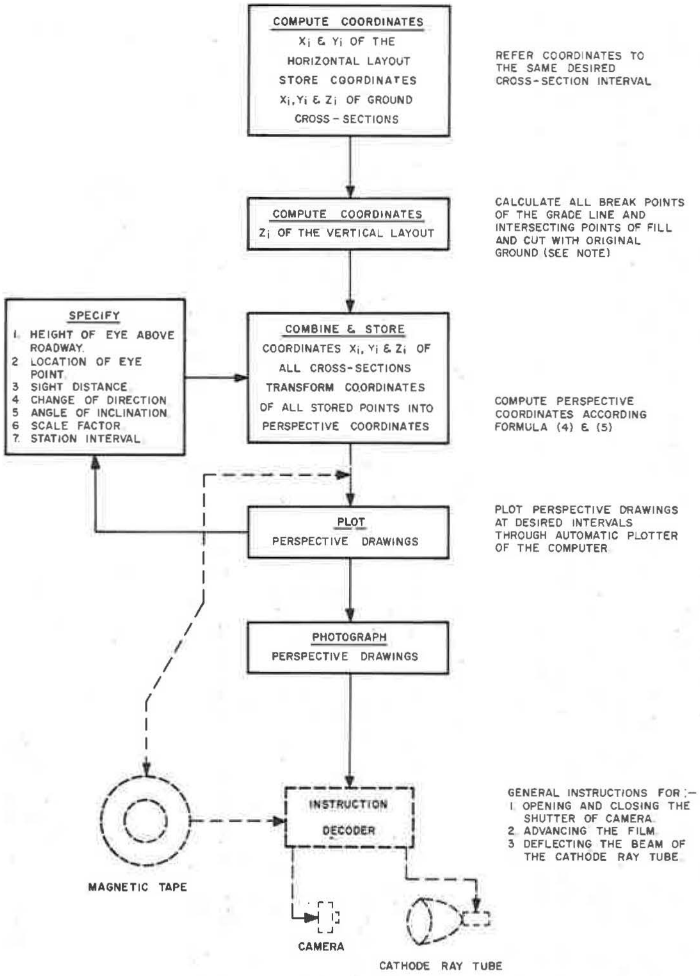
All three types of motion pictures can be produced by either the cross-section method or by the grid method (or even by a combination of the two). In the first case the perspective pictures are derived from cross-section of the ground; in the latter one, from grid points.

Perspective movies have been applied very recently in Europe but are restricted to the roadway only. In this paper, a much broader approach and application is made to use the electronic computer for a progressive staging to optimize the problem. The input data consist of the digital model and the geometric data of the horizontal and vertical alignment.

COMPUTER PROGRAM

Perspective movies can be obtained by feeding three-dimensional coordinates of terrain points into the electronic computer and transforming them into perspective drawings at desired intervals which are finally photographed. Instead of a time-consuming plotting device, an instruction decoder can be used in connection with a cathode ray tube to trace the picture on the face of the tube.

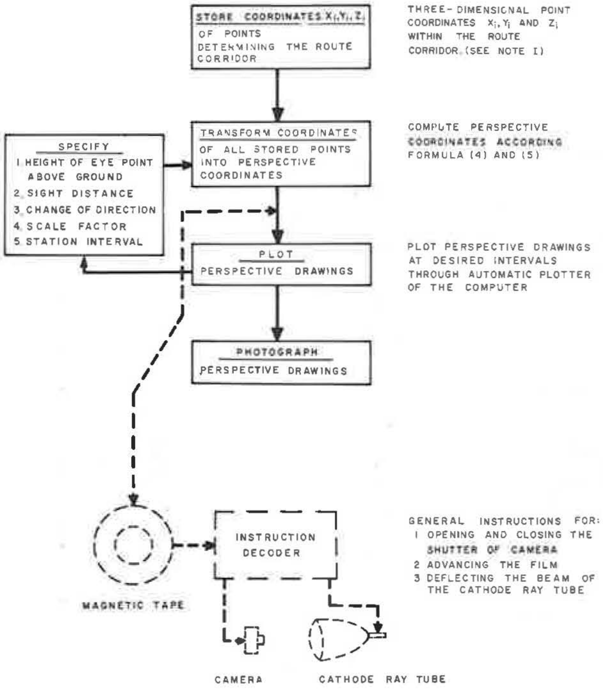
The computer program itself can be introduced by a general block diagram which explains the procedure of various steps. Since the motion pictures are based on either the cross-section method or the grid method, two different programs are necessary. Figures 10 and 11 show the flow chart for these two methods which are self-explanatory.



NOTE: ONLY TO BE APPLIED FOR ROAD MOVIE

: [ ] FUTURE IMPROVEMENT

Figure 10. Block diagram for cross-section method.



NOTES: I. DUAL PROGRAM:
1. GRID POINTS (X-SECTION).
2. TOPOGRAPHICAL FEATURES AND OTHER POINTS OF INTEREST.
3. SUPERIMPOSING FILM OF TOPOGRAPHICAL FEATURES ONTO SCREENED FILM OF GRID POINTS.

II. [ ] TO BE APPLIED IN FUTURE.

Figure 11. Block diagram for grid method.

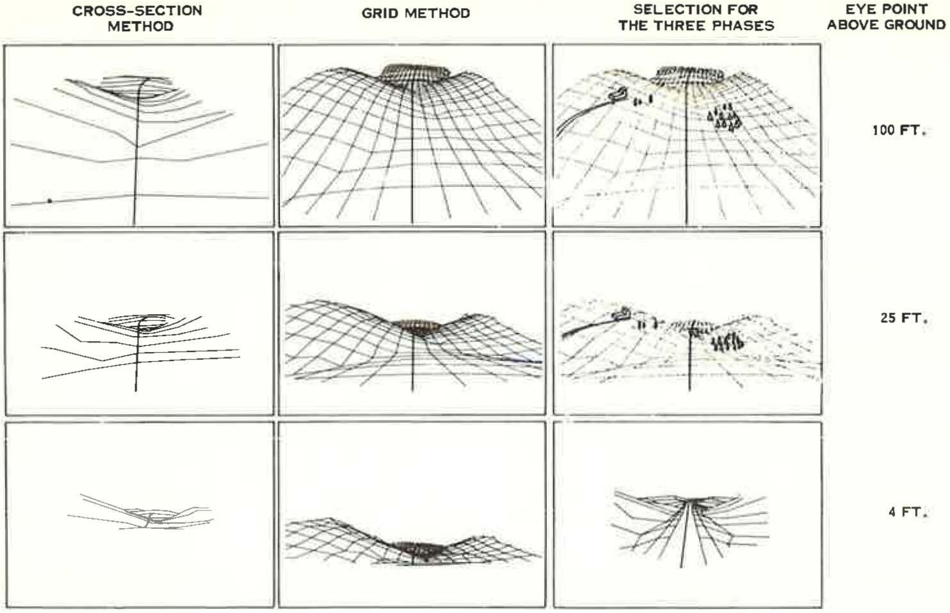


Figure 12. Staging of the dual problem.

In the first two stages, the perspective projection of the surface and significant topographical features of the route corridor are illustrated. These two features interfere with one another and influence the quality of the perspective view drawings. This disadvantage can be avoided by a separated process which results in two different view drawings. The perspective picture of the surface is then screened and superimposed on the one showing the topographical features.

A similar procedure can be applied when the grid method and the cross-section method are combined. Figure 12 shows both methods and their combinations and a selection for the staging into three phases.

STEREOSCOPIC PROJECTION

An additional improvement can be obtained by stereoscopic projection of a pair of perspective drawings of the same object, seen from two slightly different positions. When a person looks simultaneously at these two drawings, viewing one with each eye, or using a stereoscope, he can see in three dimensions. This depth perception, already known in photogrammetry and other fields, can be successfully used for perspective drawings. Figure 13 shows this stereoscopic projection of a spatial object onto two picture planes with eye point left and right.

The calculation of the coordinates of these two projections can be done in one unit. Equation 6, which refers only to one spatial object, is then extended accordingly:

$$\Delta Z'_{i(L)} = \Delta Z'_{i(R)} = \frac{1}{\cos\alpha\,\overline{(E_{(L)O} - I_O)}}(Z_{E(L)} - Z_I) = \frac{1}{\cos\alpha\,\overline{(E_{(R)O} - I_O)}}(Z_{E(R)} - Z_I)$$

$$\Delta X'_{i(L)} = \frac{1}{\cos\alpha\,\overline{(E_{(L)O} - IO)}}\sin\alpha\,\overline{(E(L)O - IO)} \qquad (6)$$

$$\Delta X'_{i(R)} = \frac{1}{\cos\alpha\,\overline{(E_{(R)O} - I_O)}}\sin\alpha\,\overline{(E_{(R)O} - I_O)} \qquad \text{(stereoscopic)}$$

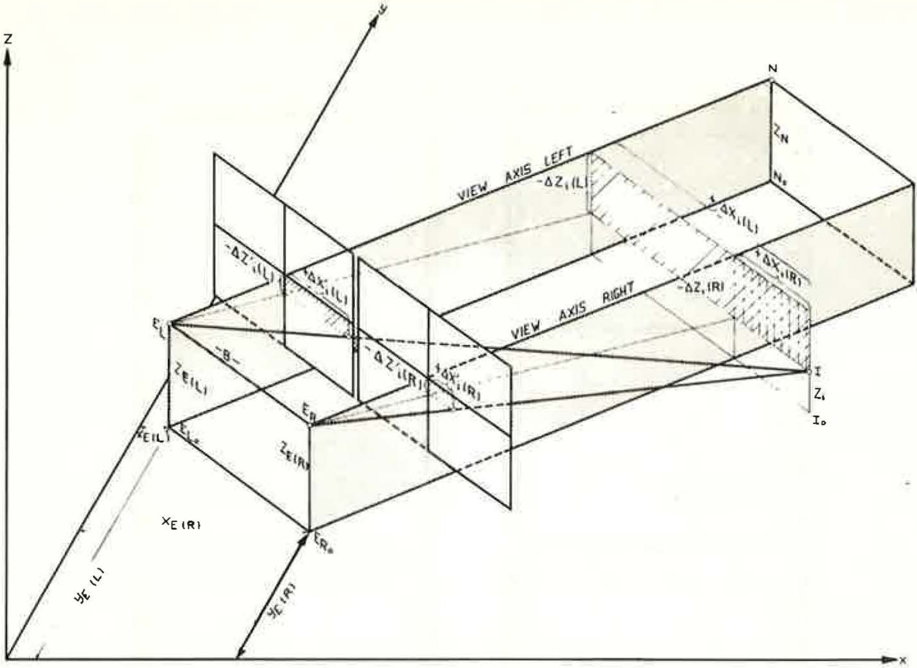


Figure 13. Stereoscopic projection of a spatial object.

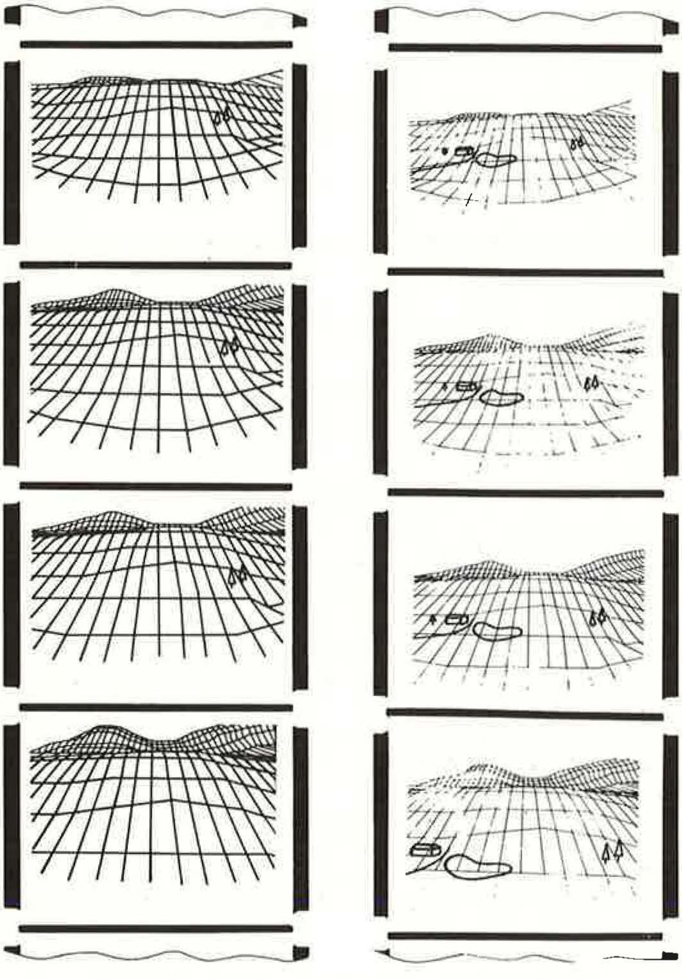


Figure 14. Spatial movie based on grid method.

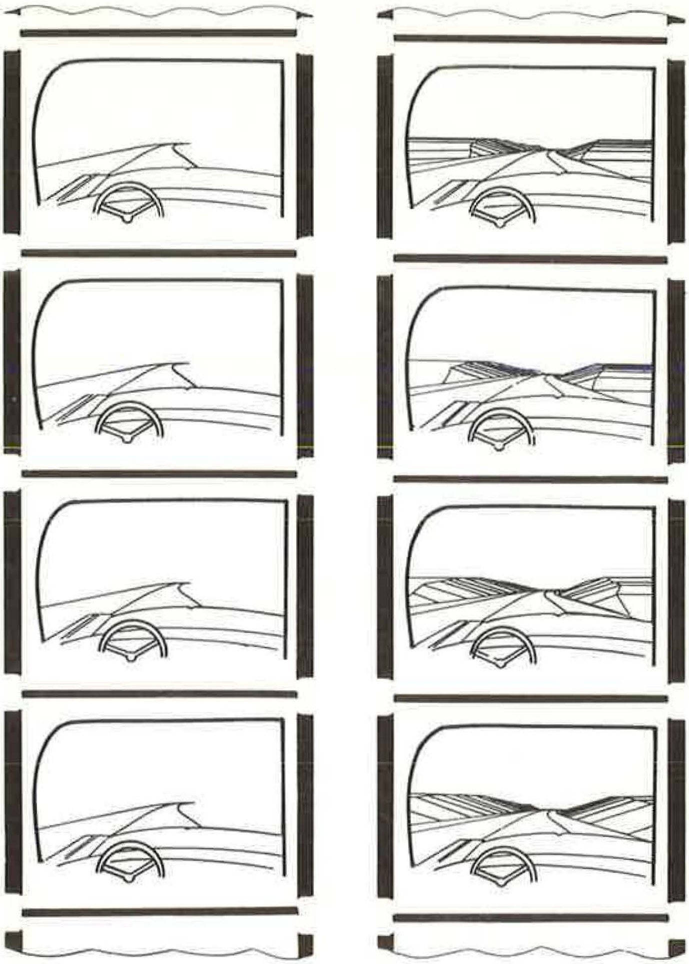


Figure 15. Roadway movie based on cross-section method.

The block diagram is similar to the previous one, with the exception that the transformation of three-dimensional coordinates are separated in perspective coordinates of the left and right perspective plane.

EXAMPLES OF MOTION PICTURES

The central perspective can be applied for various types of drawings: (a) single illustrations, (b) stereoscopic illustrations, (c) motion pictures of single perspective drawings, and (d) motion pictures of stereoscopic illustrations.

Several examples of perspective movies have been developed by the planning branch in cooperation with the electronic computing branch of the Ontario Department of Highways. The previous program has been carried out with the IBM 7044 computer and the EAI 3500 plotter; the production of the film was done by photographing the perspective plottings. However, the program is in the process of being improved and simplified and steps are already under way to perform the work with the much faster IBM 360 and an attached cathode ray tube.

For reasons of comparison, these typical examples are presented by two projectors with syncronized filmstrips. The first pair of pictures (Fig. 14) illustrates a short section of a spatial movie with the eye point 100 ft above the ground, based on the grid method. A second section of film (Fig. 15) deals with the roadway itself where the

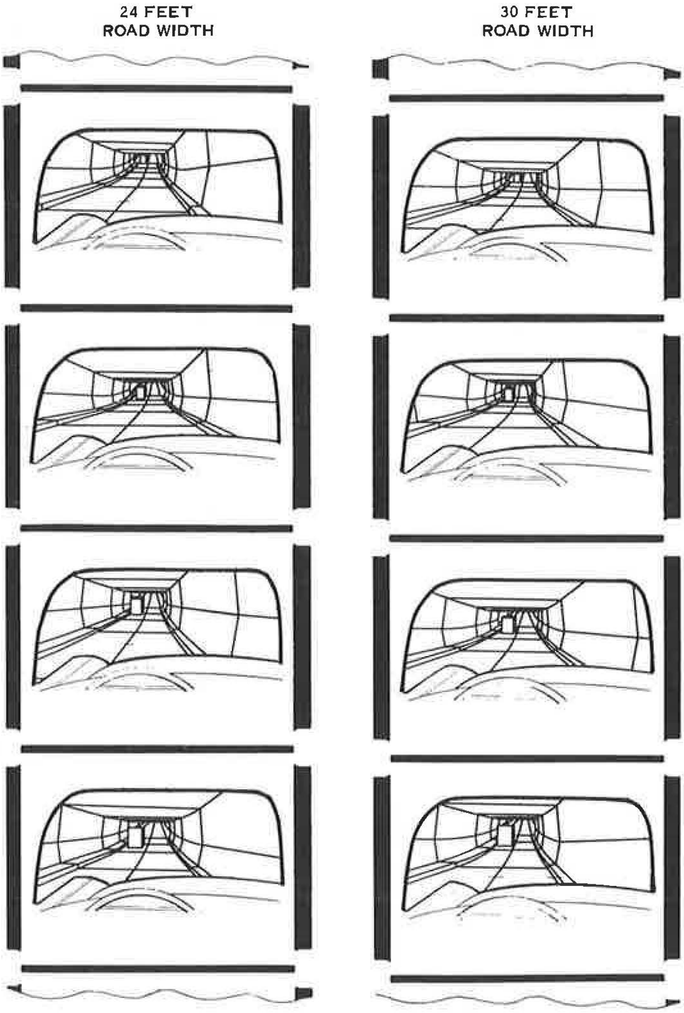


Figure 16. Tunnel movie with varying road width.

cross-section method was applied. Both sections exhibit on the left side the first approach and on the right side an improvement. Both types of motion pictures can be further developed to stereoscopic projections.

Motion pictures can also be made for very special projects. To investigate the effect on the driver in relation to various tunnel cross-sections and to opposing traffic, a tunnel movie was produced for a 24 ft and 30 ft road width, incorporating traffic from the opposite direction (Fig. 16). For perceptional reasons, the presentation was made by two projectors so that the two proposals could be observed by a group of people at the same time. In addition, each movie was copied twice and spliced together so that the observer perceived each scheme simultaneously.

FURTHER RESEARCH

This new approach in highway engineering opens up further application in the environmental and operational field. However, more experimentation and research is desired. In the further study we have undertaken, the following points are of special interest:

1. Road movies and single drawings of special locations, of complex interchanges and ramps, including merging and diverging operations;

2. Road movies to check the highway user's perception of signs and signals in regard to various locations;
3. Scale relation between horizontal and vertical alignment;
4. Relation between alignment, landscaping and rhythm of the roadway; and
5. Spatial motion pictures to test the external view of the road.

CONCLUSIONS

The application of the central perspective is able to assist the highway engineer in optimizing the dual problem of the location corridor and alignment design. With this new tool, function and form can be equally considered by evaluating various routes in the corridor through progressive staging of two sets of spatial motion pictures.

The final testing of the selected route can be carried out by a road movie, seen from the driver's eye, along a designed roadway whereby the vertical alignment is combined with a three-dimensional layout.

Any fault of the design, the appearance and disharmony with the landscape can be detected not only by one person but by a group of people. Since it is not difficult to define the location of any section which needs to be improved, the adjustable section can be replaced by a new design and the whole movie presented again. In this way, an optimum solution can be obtained.

This technique can be used for both internal and external alignment and further improved by the stereoscopic approach to provide depth perception.

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A Computer Technique for Perspective Plotting of Roadways

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The Texas Transportation Institute conducted an investigation of the possibility of developing a means whereby the highway designer may view his design before construction, thus permitting the designer to view his project from the position of the driver. In the past, this has been possible only through the use of rather expensive models.

The digital computer has been used to prepare perspective views of the roadway. An attempt has been made to provide a workable tool based on engineering principles which can be easily understood and used by designers having little or no previous computer knowledge. The IBM 7094 digital computer was used in the numerical methods of the research, and a Calcomp Model 565 digital plotter linked to an IBM 1401 digital computer was used to draw the individual roadway plots.

The methods developed provide a useful new tool to be used in the design of roadways to fit the driver's need. Any object along the roadway, as well as the roadway itself, may be viewed in perspective. With data collected from typical roadways, perspective pictures have been plotted using the developed algorithms. In instances where such were available, the computed results were checked with existing data and a reasonable accuracy of representation was evident in all cases tested.

•IN conventional design procedures, the highway designer depends on his ability to envision the roadway in perspective based on plan and profile views of the roadway. Considering the complexity of modern highways, it is truly a formidable task to visualize the roadway in complete detail. Invariably there are details which would improve the safety and efficiency of operation substantially if they had been detected at the design stage. Therefore, it is highly desirable that some means be developed whereby the designer may view his design before construction. Models of complex interchanges have been constructed to satisfy this need, but models are expensive and generally cannot be justified for extensive application. For the less complex design applications, the perspective drawing can be an effective alternate. However, several perspectives on each approach to a highway feature could be expensive and time consuming unless manual means of drawing were replaced by more modern techniques.

In this investigation, the digital computer has been used in the development of a means of preparing perspective views of a roadway. The technique developed could have application in general roadway design, interchange design, and in the location of signs and other traffic control devices for greatest effectiveness. An attempt has been made to provide a workable tool based on sound principles which can be easily understood and used by designers having little or no previous computer knowledge. The numerical methods were developed and checked on the IBM 7094 digital computer. The program package was organized as a 7094 Fortran main program which links several 7094 subroutines to perform the various manipulations required. A Calcomp model 565

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digital plotter linked to an IBM 1401 digital computer was used to draw the individual roadway plots.

BACKGROUND

Several approaches have been taken in studying driver reaction as related to the driving task and to traffic operations in general. In most cases, these investigations have dealt only with single elements of the roadway or traffic stream in relation to driver reaction or behavior and traffic operation. Recently, however, increasing emphasis has been placed on the driver's view of the roadway or the total vision input as related to the driving task.

Various mechanical devices have been employed in studying the driver's reaction in relation to his visual input. Counters and measuring devices have been used on test drivers to determine driving patterns over specifically designated test roadways. One such study was conducted at the Transportation Institute at the University of Michigan. The driving patterns of more than 950 drivers were observed over a selected 5½-mi route. Measuring devices yielded information concerning stopping time, acceleration actions, steering reversals, brake applications, speed changes, and direction changes. Photographic equipment mounted in the test vehicle was used to record the visual input of the driver. These visual inputs were classified into two classes: those relating to the driving task, and those unrelated. An unrelated event was defined as one that had no potential for requiring the driver to change the motions of the vehicle.

An interesting method of studying the isolation of visual input was investigated by Gordon (2). An apparatus was developed to be worn by the test driver which restricted his vision and recorded his visual fixation points. The apparatus, an aperture observation tube equipped with an 8-mm camera and mounted on a helmet, can be adjusted to allow various angles of vision. It was found that all drivers guide their vehicles by reference to the road edges and the centerline. Two factors which seem to limit this method are (a) the accuracy of questionnaires answered by test drivers for indicating the driver's visual input, and (b) the limiting effect imposed by the small aperture of the head apparatus. Gordon reported that the driver should always be given a sufficient unimpeded view ahead to satisfy his anticipation requirements. Further research is needed in the field of perceptual requirements in the many situations encountered on the roadway.

Finally, the use of simulation has become effective in the study of driver behavior (3). The simulation must always strive to represent completely the visual, auditory, and sensing stimuli to which the driver is exposed. Full-scale simulators are still a thing of the future but part-time simulators have been developed to simulate particular parts of the driving task. The part-time simulator provides an ideal laboratory that allows flexibility and modification to meet the changing requirements and insights to a research program. The Institute of Transportation and Traffic Engineering at UCLA has been conducting research for a number of years using a driving simulation laboratory. An operating vehicle mounted on a chassis dynamometer was utilized with motion picture films to give the operator actual driving sensation. Both speed and steering wheel movements indicated that drivers responded appropriately to different roadway and environmental conditions.

It is felt that the plotting scheme of this investigation can very effectively supplement existing techniques in this field. An accurate picture of the driver's visual input is needed as a basis for design decisions. Gordon has indicated that when man's input has been specified, driving itself will be, to a considerable extent, described (2).

GENERAL CONCEPTS

The basic concepts involved in the study are fundamentals of elementary geometry and highway engineering principles. The description of the roadway in perspective as the driver sees it is produced by projecting selected points from a three-dimensional roadway onto a common two-dimensional reference plane (Fig. 1). The selected points, represented by X and Y coordinates on a two-dimensional reference plane, are joined to represent the driver's visual input. Although the underlying principles of the per-

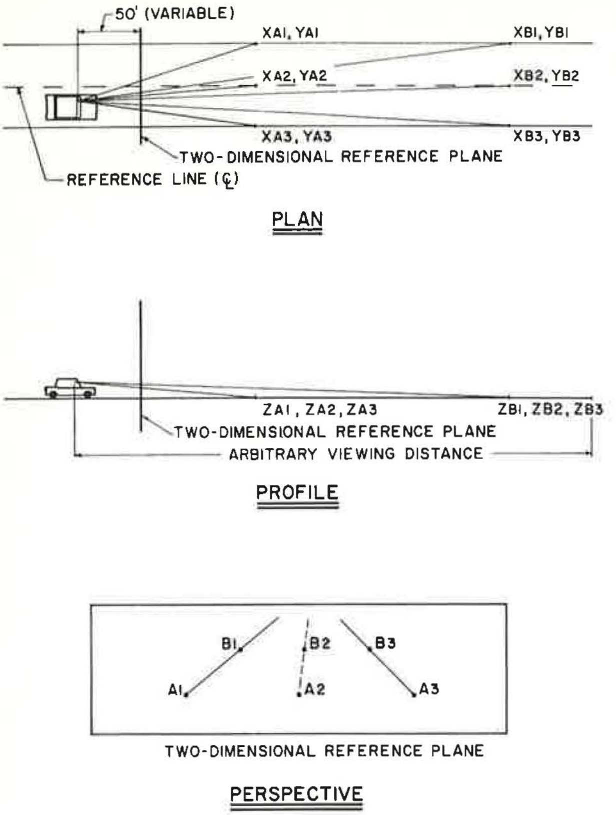


Figure 1. General concept of perspective plotting program.

spective plotting technique are familiar to all highway engineers, it is considered desirable at this point to review these principles in order to establish the basic concepts of this study.

VERTICAL ALIGNMENT

The common parabolic vertical curve with length controlled by minimum stopping sight distance is used in this study. For computational purposes the rate of vertical curvature, which is based on stopping sight distance in relation to the height of object, is defined by K, the horizontal distance in feet required to effect a 1 percent change in gradient. An an example, the normal rate of curvature, K, for a 70-mph design speed is 257 for crest vertical curves and 145 for sag vertical curves.

The length of vertical curve can be calculated using the relation

$$L = KA \tag{1}$$

where L is the length of the vertical curve, K is the design control for curvature, and A is the absolute algebraic difference in grades.

In Figure 2a, G1 and G2 represent the grades of the tangent sections on each vertical curve. The station and elevation of the beginning of the curve and the station of the end of the curve are now accessible. The offset from the gradient to the curve can be computed using the characteristic of the parabola that the offset from a parabola to its tangent varies as the square of the distance from the point of tangency.

$$\text{OFFSET} = \frac{(G1 - G2)\, X^2}{2L} \tag{2}$$

where X is the distance to the station point in 100-ft stations, and L is the horizontal length of the curve in 100-ft stations. The equation of the curve then becomes

$$Y = E + \frac{G1}{100} X - \frac{G1 - G2}{2L\ (100)} X^2 \tag{3}$$

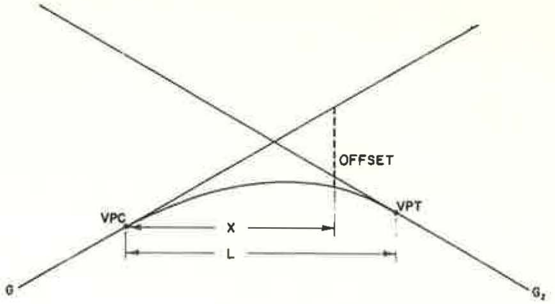
where E is now the elevation of the vertical point of curvature (VPC) and Y is the elevation of the station point in feet. Again, X is the distance to the station point in 100-ft stations. The slope at any station point on the roadway is obtained from the first derivative of Eq. 3 with respect to X.

$$\frac{dy}{dx} = \frac{G1}{100} - \frac{G1 - G2}{100\ (L)} (X) \tag{4}$$

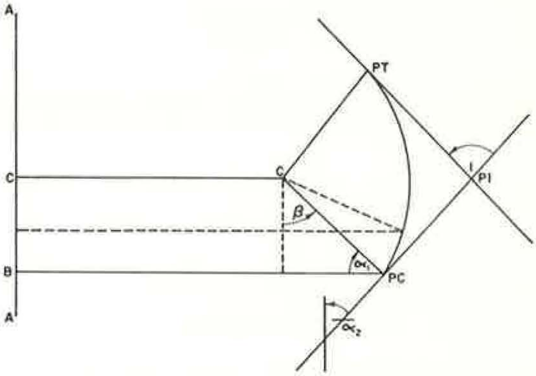
Since the driver's eye is assumed to be parallel with the roadway directly beneath his vehicle, the angle between the driver's eye and the horizontal is given by

$$\theta = \arctan \frac{dy}{dx} \qquad (5)$$

When the VPC lies beyond the VPT of the preceding curve, the slope is known to be constant and equal in magnitude to the slope at the prior VPT. The elevation of the station points must be calculated using points defined earlier. The distance in feet may be calculated between the two tangency points and, from the tangent grade of the preceding curve, the total vertical change in elevation may be calculated. After determining the rate of change of elevation, the elevations of the station points are readily accessible.



2a TYPICAL VERTICAL CURVE



2b TYPICAL HORIZONTAL CURVE

Figure 2. Horizontal and vertical curves.

HORIZONTAL ALIGNMENT

To describe the horizontal alignment of a roadway so that it may be used in the perspective plotting technique, it is necessary to describe all tangent and curve sections in relation to an assumed reference plane. This is done in the same manner and for the same reason that all vertical curves and tangents are referenced to a horizontal line in conventional design practice. An illustration of relating a horizontal curve to the assumed reference plane is shown in Figure 2b. A - A represents the assumed reference plane, and B-PC is the horizontal distance from the reference plane to the point of curve. Since the radius of the circular curve is perpendicular to the tangent line, $\alpha 1$, the angle between the radius of the curve and the horizontal line B-PC, is equal to $\alpha 2$, the angle formed by the tangent line and a parallel to the reference plane A-A. Line C-C which is the distance from the reference plane to the center of the curve is calculated as

$$C - C = B \pm (R) \cos |\alpha 1| \qquad (6)$$

with the negative sign applying if the curve is to the left (as in Fig. 2b) or with the positive sign applying if the curve is to the right. The angle β is termed the reference angle and is obtained as the complement of angle $\alpha 1$. By successive additions to the reference angle, the horizontal distance from the reference plane to all station points may be calculated.

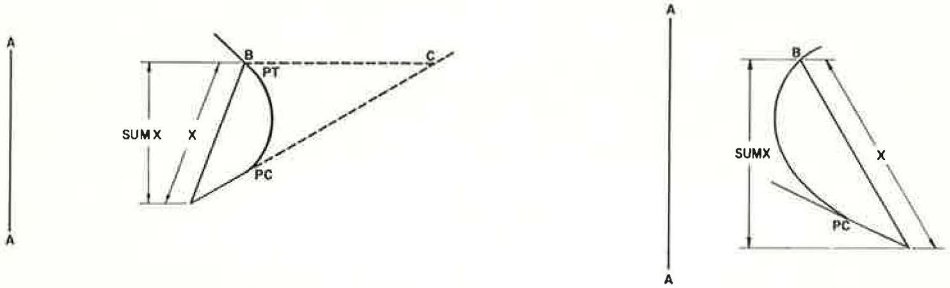
SIGHT DISTANCES

For this study, minimum sight distances are based on stopping sight distance where the driver's eye is considered to be 3. 75 ft above the surface of the roadway. On crest vertical curves the sight distance is limited by a point on the roadway surface; on horizontal curves it is limited by lateral obstructions along the roadside.

CASE I

3a TRANSLATION OF STATION POINTS

3b DRIVER AND POINT ON TANGENT LINE



CASE II

3c DRIVER AND POINT NOT ON TANGENT LINE

CASE III

3d MAXIMUM VISUAL POINT IN CURVATURE

Figure 3. Perspective concepts.

PERSPECTIVE CONCEPTS

To reproduce accurately the driver's image of the roadway, it is necessary to translate the individual station points to the driver's eye and measure their relative perspective distances on a common reference surface. By translating both the horizontal and vertical measurements of a station point, a new set of data points is derived and these may be plotted to give an accurate roadway image.

A common reference line is arbitrarily chosen to be perpendicular to the driver's line of vision and a constant distance in front of the driver's eye. In Figure 3a, A-A represents the reference plane; B-B represents the reference line, termed perspective reference line, that is perpendicular to the path of the vehicle; C-C represents the vision line of the driver. Lines to successive station points are drawn back across the perspective reference line to the driver's eyes and a perspective horizontal value is derived by measuring the distance between the point and the driver's vision line. A perspective vertical value can be calculated by measuring the elevation of the projected line as it crosses the perspective reference line. By plotting the different station values, the continuous roadway line maps the image as seen from the driver's eye.

Before a plot can be made, a relation between the driver, his visual cutoff point, and the horizontal curvature in the roadway must be established. Five cases are considered.

Case I (Fig. 3b) is that for which both the driver and the maximum point of vision are positioned on the same tangent line, but neither lies in a horizontal curve. A-A represents the reference plane, and B, the maximum point of vision. Angle $\alpha 2$ is the angle formed by the tangent line and the reference plane A-A. The distance X in feet is calculated by subtracting the position of the driver from the maximum point of vision. The distance along the reference line is

$$SUMX = \cos |\alpha 2| \ (X) \qquad (7)$$

Case II (Fig. 3c) is that for which neither the driver nor the maximum visual station lie in a curve, nor on the same tangent line. The distance X is calculated to the point of curve as in Case I. The tangent from the point of curve to C is derived as

$$T = (R) \sin I \tag{8}$$

where T is the tangent length, R is the radius of the horizontal curve and I is the intersection angle of the two tangents. The reference plane distance may be calculated using Eq. 7 with the substitution of T for X. The driver has effectively been advanced along the roadway from point of curvature to point of tangency. A comparison is needed to see whether the new driver position and the maximum point of vision now lie on the same tangent line. If not, the process is repeated, but if so, distance X becomes the difference between the maximum visual station and the driver location; Eq. 8 is again used. The various segmented reference plane distances are added.

Case III (Fig. 3d) arises when the maximum visual station lies on the curve, but the driver does not. The driver is advanced according to Cases I and II and the respective reference plane A-A distances are evaluated until the point of curve is reached. The arc distance between station point B and the point of curve gives the distance along the curve to the maximum point of vision. The angle subtended by the arc is determined as

$$A = \frac{(D) \cdot (X)}{100} \tag{9}$$

where D is the degree of the horizontal curve and X is the distance along the arc.

Case IV and Case V are variations of the preceding cases in which either the driver or the maximum visual station are positioned along the lengths of horizontal curvature. If the driver's position lies in the curve but the visual point does not, Case IV is considered. Repeated applications of Eqs. 7 and 8 are used to obtain the horizontal distance.

Next, the driver's vision line must be considered. All perspective distances are to be calculated as perpendicular distances from this sight line. By knowing the reference plane distance from the driver to his visual cutoff and the angle of the driver's sight line, we may calculate the distance from the driver to his visual cutoff according to

$$\text{DIST} = \frac{\text{R Dist}}{\cos \alpha_2} \tag{10}$$

where α_2 is the angle formed by the driver's sight line and the reference plane. R Dist is the reference plane distance from driver to vision cutoff. This scheme may also be used to determine the distances from the driver to any station point in his visual input. By a succession of angle measurements, the angle formed by the reference plane and a station point projection can be calculated. By addtion, we now have the angle formed by the projection and the driver's vision line. Having chosen the perspective reference plane as a constant distance in front of the driver, the perspective horizontal value may now be obtained.

In similar manner, by replacing reference distances by the respective station point elevations the perspective vertical values may be calculated. This procedure may be repeated to include all the necessary projections.

ROADWAY SIGNING

The typical section of roadway contains many obstructions that are visible to the driver. To describe the roadway accurately it is necessary to represent these obstructions as the driver sees them. A limitation exists at present in the nature of the signing routine as the object must be represented by X and Y coordinate points. Curvilinear surfaces must be represented as successions of straight lines. As before, these points may be referenced to the roadway and their respective projections calculated to determine perspective values. This aspect becomes quite interesting since one is able to determine the visibility of signs under ideal conditions, using height, shape, and position as variables. Large objects such as bridge segments may be calculated in the same manner, using X and Y coordinates to describe their position in relation to the roadway.

HORIZONTAL SIGHT DISTANCE

The driver's horizontal field of vision is controlled to a great extent by the presence of objects in his visual path. For example, if a large sign is placed near the roadway, the driver can certainly be limited in his view of the roadway if any horizontal curvature is present. To represent the driver's view of the roadway accurately, his pictured visual input must be limited by these obstructions. For each obstruction minimum and maximum values must be formed, and the perspective values from each projection must be compared with these values.

COMPUTER ALGORITHMS

Roadway Alignment

The basic algorithms of this plotting scheme are especially adaptable to computer use since the numerous calculations necessary to align both the roadway and the driver can be performed accurately and rapidly by the computer. Also, the large amount of design data needed to describe the roadway adequately can be readily stored. It also gives the engineer the flexibility to study many designs using the same basic algorithms and, if changes are necessary, the data may be quickly and easily altered to provide the changed parameters.

The algorithms are combined into one basic package consisting of a Fortran IV program that calls a number of Fortran IV subprograms as they are needed to accomplish the various steps. The fundamental principles of these routines have been presented previously.

Initially, the basic roadway characteristics must be supplied to the computer with the test roadway stationed in some convenient increment. Design data are usually available in 100-ft station increments, but it was felt that these increments did not provide an accurate picture of the roadway for plotting purposes, so a simple interpolation scheme was utilized to provide the necessary information to the plotting program for 25-ft stations. A reference line must be established along the roadway, and in most cases, the centerline of the roadway serves as an adequate reference line. Horizontal measurements to the roadway edges are entered as positive or negative perpendicular distances from the reference line. These distances must be supplied at each successive station point along the distance of the test roadway. The perpendicular distances to all continuous lines, including lane lines, medians, or curbs, may be entered for each station point if they are desired in the output drawing. The perpendicular distances are entered successively for each station point and each continuous line until all the horizontal distances are entered.

The main calling routine transfers control to the subprogram ELEVAT to determine the elevations of the various station points along the reference line. The plotting package assumes all gradient changes along the test roadway to be parabolic in shape and of the form

$$Y = KX^2 \tag{11}$$

with vertical distances as the Y coordinates, and the horizontal distances as the X coordinates. The rate of vertical curvature is entered for each vertical curve along the roadway and for each design speed. The tangent grades are entered in percent, plus for upgrades and minus for downgrades, for each successive vertical curve along the test roadway. The elevation of each station point along the reference line is then calculated using tangent grades as they are needed. The general procedure of the elevation calculations is outlined in Figure 4.

Using Eq. 3 for vertical curvature, the elevations of all the station points along the reference line are stored for later use. Also computed is the angle θ between the driver's eye and the horizontal plane at each station point. The θ angle is recorded as positive for angles above the horizontal and as minus for angles below the horizontal.

The data are needed later in the program to determine maximum vision point from the driver's eye.

After completion of the elevation calculations of station points along the reference line, subprogram HEIGHT is called to calculate the elevations of all points along the continuous lines of the roadway. Variable ASLOPE is the value for the side slopes of the roadway perpendicular to the reference line and must be entered in the form feet-per-twelve feet. Utilizing the perpendicular distances to the continuous roadway lines, the station point elevations are calculated successively and control is again transferred to subprogram ELEVAT. Output from the elevation subprograms includes vertical points of curvature and tangency for each vertical curve, the tangent grades in percent for each vertical curve, the perpendicular distances to each continuous line at each station point, the elevation in feet of all station points on each continuous line, and the angle between the driver's eye and the horizontal plane at each station point.

After all elevations are calculated on the test roadway, the plotting program now must orient the roadway horizontally. An imaginary reference plane is designated to lie adjacent to the roadway and subprogram CURVE is used to find the horizontal distance from the reference line to the reference plane at all station points along the roadway.

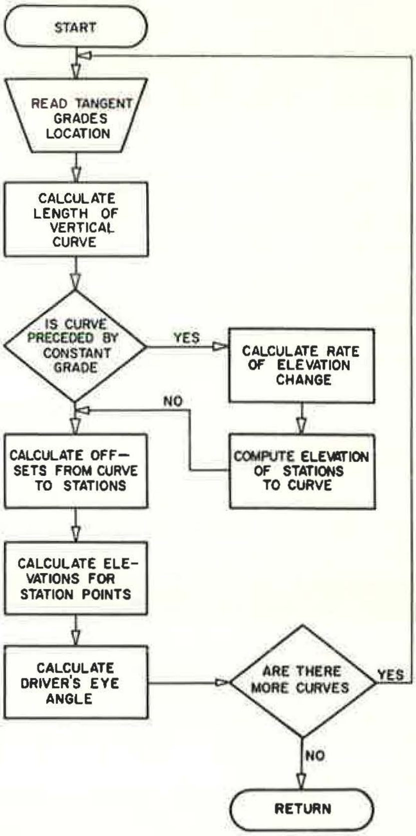


Figure 4. Elevation subprogram.

By simply entering the points of intersection of all the horiozntal curves and the corresponding tangent angles as related to the direction of the reference plane, the horizontal distance to the reference line at all station points may be calculated. The point of intersection in stations and the radius of curvature in feet are needed. The tangent angles as related to the reference plane are entered in radians. For example, if the tangent moves in a direction to the right of the reference plane, it is entered as a positive quantity and if the tangent moves in a direction to the left of the reference plane, it is entered as a negative quantity. An indicator is needed to designate the concave side of the horizontal curve.

The tangent length is computed to determine the point of curve. If the point of curve lies beyond the point of tangency of the previous horizontal curve, the line of constant slope yields the reference distance according to

$$\text{DIST (I)} = \text{DIST (I-1)} \pm 25 \text{ (SIN } \theta) \qquad (12)$$

where DIST (I) is the perpendicular distance to the reference plane and θ is the tangent angle. The minus sign holds if the tangent angle is negative in direction. After the point of curve is reached, the reference angle, formed initially by the radius vector and the reference plane, is computed. By successive additions to the reference angle (Fig. 2b), the reference distance may be calculated. These computed reference distances are stored in memory at each station point. For 25-ft incremental stationing, the angle to be added to the reference angle for each station point corresponds to the degree of the curve divided by four. This algorithm will allow angles to a maximum of 180 deg. Figure 5 illustrates the sequence of steps in determining reference plane distances.

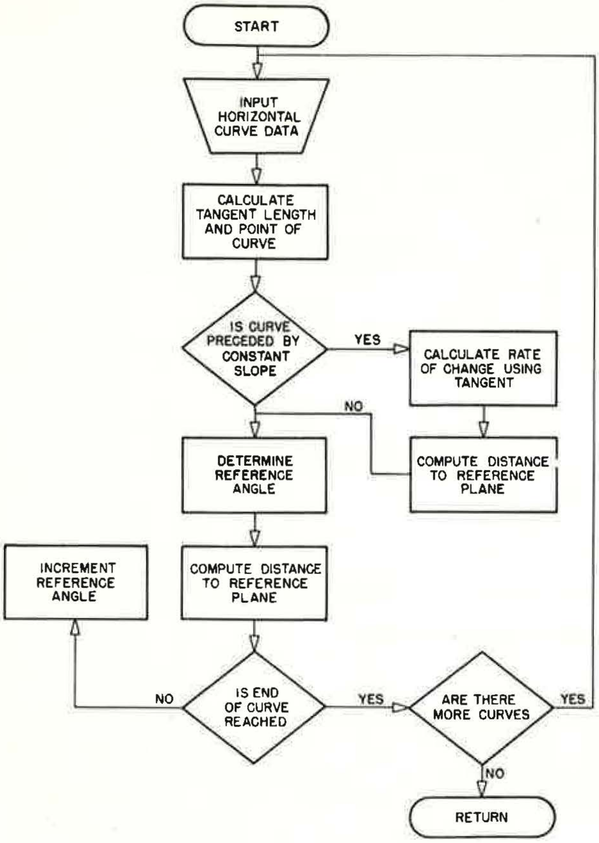


Figure 5. Horizontal curvature.

An optional feature of the plotting package allows the designer to obtain the α_2 angle of Figure 2b formed by the driver and the reference plane, if it is necessary. The angle is obtained by successive additions or subtractions from the original α_2 angle. Then it is saved for later use in the perspective calculations. By entering horizontal curve data as they are needed and making the subsequent calculations, the reference line becomes oriented horizontally to the reference plane. Subprogram SDIST is now utilized to adjust the station points on each continuous roadway line by adding their respective perpendicular distances from the reference plane to the oriented reference line.

Sight Distance Calculation

The roadway is now aligned in a Cartesian coordinate system and we are ready to consider the driver on the roadway. The driver is positioned by a data entry giving his location in station points. The first problem encountered is the sight distance of the driver. The plotting routine transfers control to subprogram CUTPT to determine the sight distance on vertical curves. Initially, the program has entered a maximum value of sight distance that may be shortened by the presence of limiting objects on the roadway. By a systematic comparison of angles between the driver's eye and roadway points in front of him, the maximum point of vision is calculated. Four cases are tested in this algorithm.

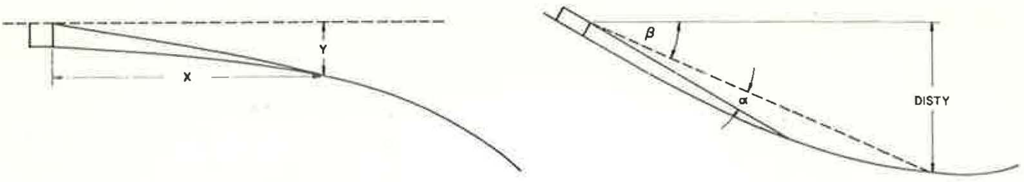
Case I (Fig. 6a) is considered when the angle between the driver's eye and the horizontal is negative. This angle is the stored angle θ from the elevation calculation described earlier. DISTY, the change in elevation between the driver and the station point, is calculated by

$$\text{DISTY} = \text{EYEH} + \text{ELEVD} - \text{ELEVP} \tag{13}$$

where EYEH is the height of the driver's eye above the roadway surface. DISTX is the difference in feet between the point in question and the driver location, ELEVD is the elevation of the driver, and ELEVP is the elevation of the point in question. Consequently, the angle β is calculated for each station point as

$$\beta = \arctan \frac{(\text{DISTY})}{(\text{DISTX})} \tag{14}$$

where DISTY is the change in elevation between the driver and the station point. Successive station points are tested until the angle β becomes larger in magnitude than the preceding one. This indicates that the point in question is not visible to the driver and the previous station point is designated the maximum sight distance for the driver.



CASE I
6a SIGHT DISTANCE ON NEGATIVE GRADE

CASE II
6b SIGHT DISTANCE ON NEGATIVE GRADE

CASE III
6c SIGHT DISTANCE ON POSITIVE GRADE

CASE IV
6d SIGHT DISTANCE ON POSITIVE GRADE

Figure 6. Sight distance concepts.

Case II (Fig. 6b) is also considered when the angle between the driver's eye and the horizontal is negative. DISTY, DISTX, and the beta angle are calculated as before using Eqs. 13 and 14. The driver's sight distance is not impeded by the roadway surface, but headlight sight distance becomes somewhat of a controlling factor. General practice allows a 1-deg upward divergence of the light beam from the longitudinal axis of the vehicle (1). If the angle β becomes more than 1-deg less than the angle θ for the present driver location, a visual maximum has been reached and the station point becomes the maximum sight distance for the driver.

When the angle between the driver's eye and the horizontal is positive, the program utilized is Case III (Fig. 6c). DISTY is now calculated as

$$\text{DISTY} = \text{ELEVP} - \text{ELEVD} - \text{EYEH} \tag{15}$$

with ELEVP and ELEVD defined as in Eq. 13. Again the headlight sight distance becomes a factor, and the Case II method is repeated to yield the maximum distance.

Finally, Case IV (Fig. 6d) is considered when the angle θ is positive with DISTX and DISTY derived as in Case III. The successive β angles are compared as in Case I until the driver's vision is hindered by the roadway surface. Again, this station point is stored as a maximum sight distance.

In all these cases, the difference between the station point in question and the driver location is compared to the maximum allowable sight distance. If this maximum sight distance is reached, further β angle comparisons are terminated.

Perspective Subprograms

To arrive at the perspective picture of the roadway, the program transfers control to subprogram XPERSP. Since the test roadway may contain sections of horizontal curvature, all measurements of distance must be first translated to the reference plane established earlier in the program. The location of the driver is checked by subprogram PLACE as to his position relative to any horizontal curvature. The station point of the vehicle is compared to the point of curve and point of tangent of any horizontal curves calculated earlier in the program, and appropriate indicators are set. An identical scheme is utilized to indicate the position of the maximum visual point.

Subprogram DISCAL is now employed to calculate the distance along the reference plane from the driver to the maximum visual point. Five options are handled in DISCAL according to the positions of the driver and maximum sight distance as indicated by PLACE with indicators, set by PLACE, determining which option is needed to calculate the reference plane measurement. All horizontal curve data have been saved from earlier calculations and are available to subprogram DISCAL.

The designer is allowed one of two choices in determining the vision line of the driver: (a) the driver's vision line is directed at the maximum visual point, or (b) the driver's vision line is directed along the path of this vehicle. Considering the first choice, distance X (Fig. 7a) is calculated by taking the difference in the perpendicular distances from the reference plane to the station points. SUMX is the previously derived distance along the reference plane from the driver to the maximum visual point; α_1, termed the reference angle, is determined by

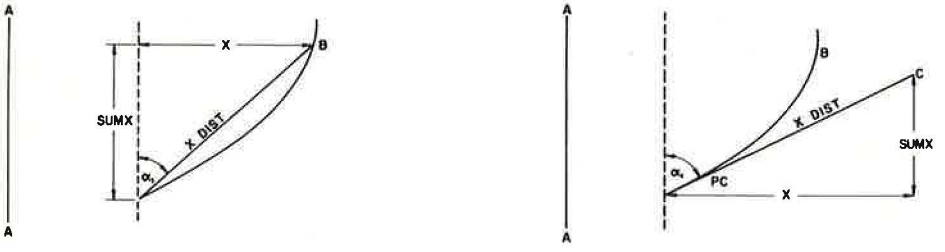
$$\alpha_1 = 90^0 - \arctan \left|\frac{\text{SUMX}}{\text{X}}\right| \tag{16}$$

and this angle describes the relation between the vision line from the driver's eye and a parallel to the reference plane. The slope of the vision line is also calculated at this point and saved for later comparisons. The distance along the driver's vision line from the driver to the maximum visual point is obtained by use of the Pythagorean theorem.

Now, consider the choice of the driver's vision line along the path of the vehicle (Fig. 7b) in which case the reference angle, α_1, is a previously defined quantity. The distance along the driver's vision line is calculated using the reference plane distances SUMX. The perpendicular difference between the two station points is calculated as

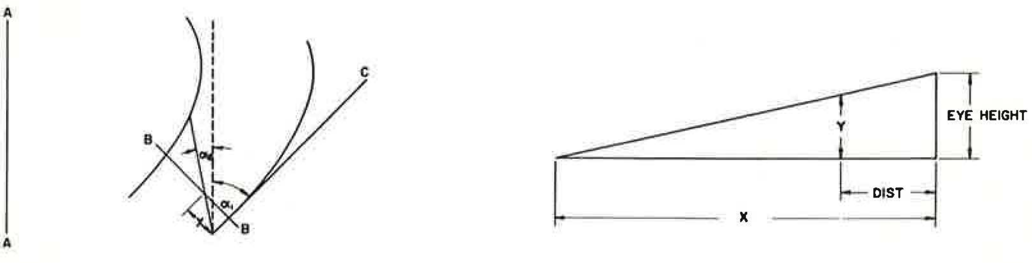
$$\text{X} = (\text{XDIST}) \sin |\alpha_1| \tag{17}$$

where XDIST is the distance along the vision line. The perpendicular distance from the reference plane to the maximum point C (Fig. 7b) is derived as the sum of the perpendicular distance to the vehicle plus the distance X.



7a SIGHT DIRECTION AT MAXIMUM VISUAL POINT

7b SIGHT DIRECTION ALONG PATH OF VEHICLE



7c ANGULAR RELATIONS

7d POINT LYING BELOW EYE LEVEL

Figure 7. Sight distance concepts.

The program now begins a successive translation of the points along each continuous line between the perspective reference line and the maximum visual point. Each point in turn is positioned relative to any existing horizontal curvature and its distance along the reference plane from the driver is calculated using subprogram DISCAL. The perpendicular distance from the driver to the point in question is determined from the reference plane. The slope of the line from the driver to the station point is now calculated and the related angle formed by the line and the reference plane is determined using Eq. 14.

A comparison is made to determine the relation between the point in question and the maximum visual point. If they lie on different sides of the driver (Fig. 7c), the two relative angles add to give the total angle formed by the driver's vision line and the line from the driver to the point. Since the perspective reference line B-B is perpendicular and is taken to be 50 ft in front of the driver, the perspective distance X for the point is calculated as

$$X = \tan \alpha_1 (50) \tag{18}$$

and if the slope of the line from the driver to the station point is less than the slope of the driver's vision line, the perspective distance X becomes negative indicating the point lies to the left of the driver. If the relation between the station point and the maximum visual point is such that they lie on the same side of the driver, their respective reference angles are subtracted and calculations are made as before.

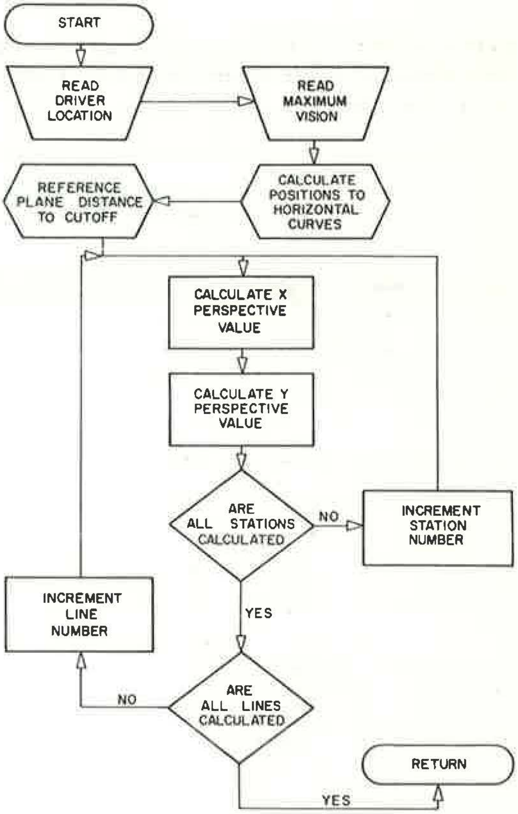


Figure 8. Perspective model.

Control is now transferred to subprogram YPERSP to calculate the perspective elevation of the selected station point. From the angular relations derived about the station point it becomes a simple matter to calculate the distance along the line from the driver to the point. The distance from the driver to the perspective reference line, DIST, is given as

$$\text{DIST} = \frac{50}{\cos |\alpha|} \tag{19}$$

where α is the total angle formed between the line from the driver to the station point and the driver's vision line. From these two distances a relation is formed to yield the perspective elevation.

Figure 7d illustrates the case where the elevation of the object B lies below the elevation of the driver's eye. DIST represents the distance from the driver to the point. The relation

$$Y = \frac{(\text{EYE HEIGHT})\ (X - \text{DIST})}{X} \tag{20}$$

yields the perspective Y value in feet. This value is added to the elevation of the station point B to produce the desired perspective elevation for the station point. If the elevation of the station point is higher than the elevation of the driver's eye the perspective Y value must be added to the elevation of the driver's eye to yield the perspective elevation.

The equations are used repeatedly until a perspective X distance and a perspective Y elevation are calculated for each station point along the continuous lines of the roadway within the limits of the driver's vision. Figure 8 illustrates the general outline of the perspective calculations.

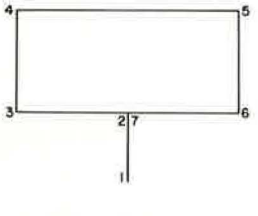
Obstruction Plotting

Methods tested in this plotting program to represent obstructions along the roadway are very similar to those previously described. The individual objects are entered as data with the appropriate station point and the number of data points as header words. For example, the typical roadway sign (Fig. 9a) would contain 7 data points. For each data point X and Y values must be supplied with the X value being distance between the point and the reference line of the roadway, and the Y value being the height of the point above the roadway. It is obvious that almost any roadway object may be broken into X and Y points and thus may be represented in this manner. Subprogram SDIST is called to align the object with the reference plane previously established in the program. This is simply done by addition or subtraction to the existing roadway points.

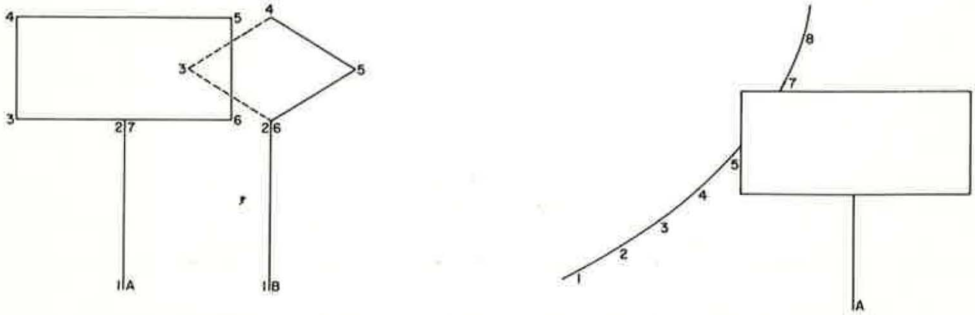
After the driver's position has been established and the basic roadway points have been drawn in perspective, subprogram SVALUE is called by the plotting program to determine perspective values for the roadway objects. SVALUE compares the station position of each object with the driver location and his maximum visual point to determine whether the object lies within the visual field of the driver. If the object is visible to the driver a similar scheme described earlier is used to determine the perspective calculations of each data point of the object. The perspective points are stored in a like manner to the original data points with the two header words being object position in stations and number of data points. Each object is checked in turn and control is transferred to the main calling program.

Plotting Program

The plotting programs are governed by a parameter card allowing plotting of a profile, plan, or perspective view of the roadway, or any combination of these. No attempt is made to plot the roadway obstructions in plan or profile views. The plotting



9a VISUAL LIMITATIONS



9b VISUAL LIMITATIONS

9c CONTINUOUS LINE HIDDEN BY ROADWAY SIGN

Figure 9. Sign plotting concepts.

program generates an output tape of pen movements sufficient to plot the desired view on the Model 565 digital plotter connected to an IBM 1401 system.

If a plan view is desired, the aligned roadway values at each station point are plotted versus the distance of the roadway. Continuous lines are drawn through the station points along the length of the roadway. If a profile view is desired, the elevation of the reference line is plotted versus the distance of the roadway. Again, a continuous line is drawn through the station points along the length of the roadway.

If a perspective plot is desired, the scheme becomes more involved because of the limit in sight distance due to the presence of objects on the roadway. Subprogram CALPLT is used to plot the perspective values. Initially, the roadway objects that lie within the driver's visual field must be plotted. A maximum and minimum X value and a maximum and minimum Y value are determined for each object. The nearest object to the driver's eye that lies within his visual field is plotted with a continuous line connecting the X and Y values to represent the object in perspective. A comparison of coordinates of the next object is made to see whether they lie within an area not visible to the driver because of the presence of the nearer object. If the points are visible, they are plotted and a continuous line is drawn connecting all visible points. This comparison is repeated until the visible points of all the objects within the driver's visual field have been plotted. For example (Fig. 9b) point 3 is not visible to the driver from his particular location. Sign A would be plotted but only points, 1, 2, 4, 5, and 6 of sign B would be plotted.

When all the objects have been plotted, the basic roadway may be drawn. Each continuous line along the roadway is entered in turn and the perspective X and Y values of each station point are compared with the minimum and maximum values of the objects to determine whether the station point of the roadway is visible to the driver. If the points are visible, they are plotted and a continuous line is drawn through them. If the point is not visible, the continuous line is broken until further comparisons indicate a visible point.

Because of the presence of object A (Fig. 9c), station point 6 of the roadway line is not visible to the driver, and the plotted line becomes discontinuous at station point 5.

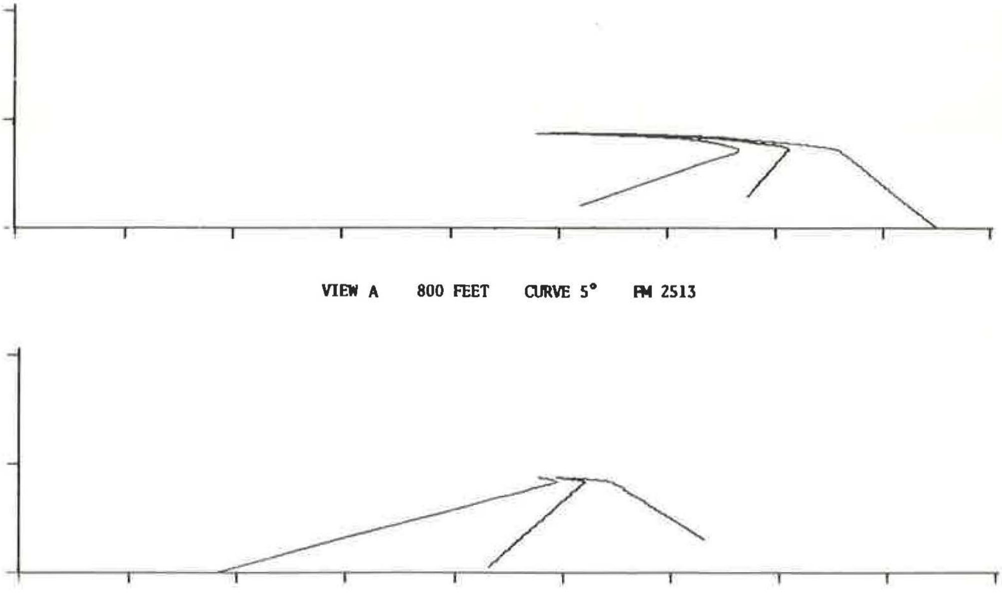
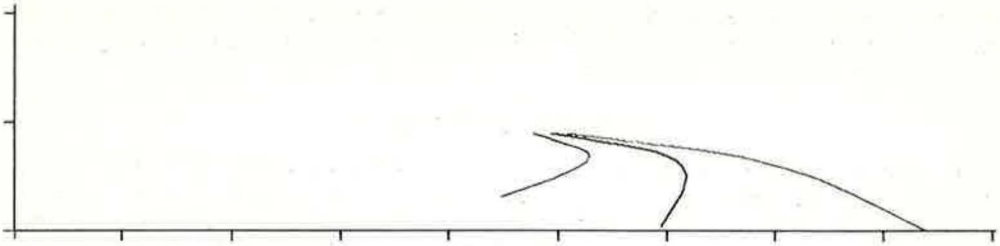
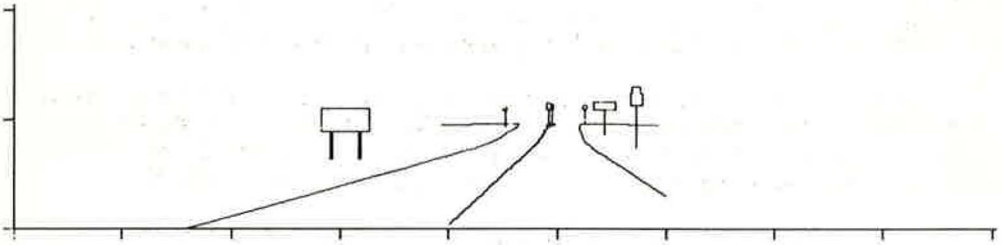


Figure 10. Sample plot.

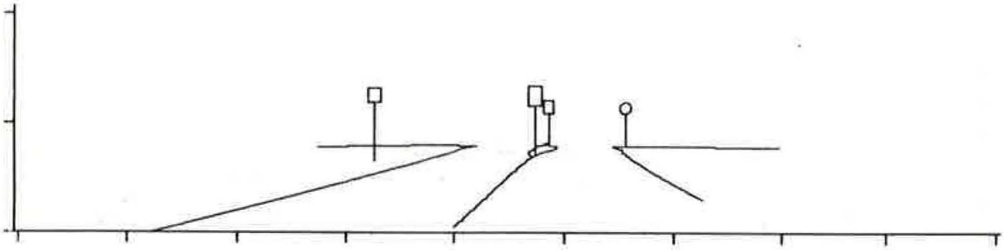


VIEW C 800 FEET CURVE 2° FM 2513

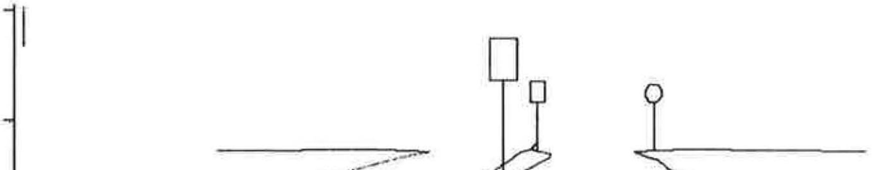


VIEW D 750 FEET INTERSECTION FM 60 - FM 2513

Figure 11. Sample plot.



VIEW E 350 FEET INTERSECTION FM 60 - FM 2513



VIEW F 250 FEET INTERSECTION FM 60-FM 2513

Figure 12. Sample plot.

Comparison indicates that station point 7 is visible, and the line continues from this point. Plotting is continued until all the visible station points of the roadway lines within the driver's visual field are drawn.

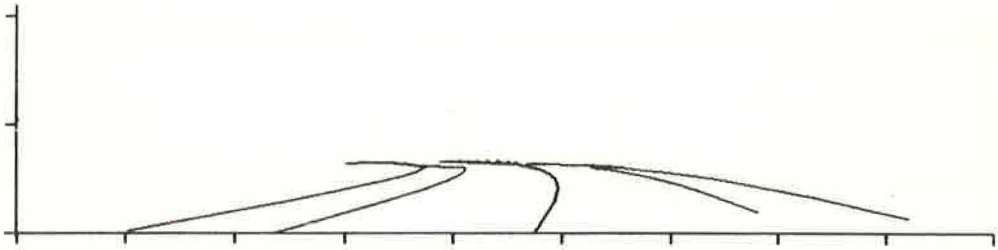
SUMMARY OF RESULTS

This study concerned the development of the necessary plotting algorithms to represent graphically the configuration of a roadway as seen from the driver's eye using design information as data. These algorithms were developed and evaluated, and their applications to the problem were studied. The following is a summary of results.

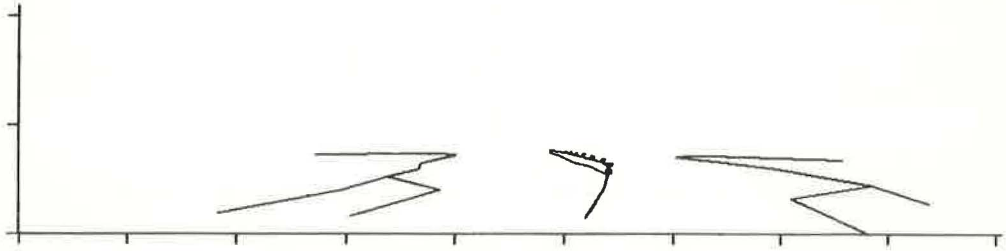
1. It is felt that the methods described provide a useful new tool to be used in the design of roadways to fit the driver's needs. Any object along the roadway that may be represented in X and Y coordinate values may be viewed in perspective.
2. Sections of roadway can be segmented into 25-ft station lengths and a typical driver advanced along its length yielding graphical displays of his visual input at each station.
3. With data from typical roadways, perspective pictures have been plotted using the algorithms. The computed results were checked with existing installations and a resonable accuracy of representation was evident in all cases tested. Sample graphs utilizing data from existing roadways are shown in Figures 10 through 13.

SIGNIFICANCE OF RESULTS AND APPLICATIONS

The significance of this research is that a new tool has been developed that can be used by all geometric designers in making design decisions. Although using the present methodology is expensive, it represents a substantial savings when compared to either hand drawings of perspective views or models. At present, approximately three minutes of computer time and four minutes of plotter time are needed to calculate and draw



VIEW D 550 FEET CURVE 4.77° 6" x 6" DELINEATORS



VIEW E 350 FEET CURVE 4.77° 6" x 6" DELINEATORS

Figure 13. Sample plot.

twenty perspective views of a typical test roadway. These requirements represent a cost of approximately $25.00.

The algorithms are immediately applicable to the less complex design situations. However, further refinement of the algorithms is needed to represent bridge layouts or multi-lane, multi-level interchanges accurately. This further refinement will also lead to reduced computer storage requirements and running time resulting in increased efficiency.

It is also feasible to utilize the results of this research to describe graphically objects not related to the transportation field. The visual inputs to an observer of an object not having curvilinear sections may be represented. For example, the field of architectural design might utilize the methods to view proposed architectural constructions in perspective. Thought is being given also to the use of the methods to draw certain anatomical features of dissected biological specimens in a similar method.

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Visual Quality Studies in Highway Design

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Modern conditions require increasingly higher standards in highway design. Faults can no longer be tolerated. In particular, studies in highway perspective are necessary at the design stage. Traditional techniques are inadequate for the volume of drawings and calculation needed.

This report describes a highway design computer program, TE.GI (imposed geometry automatic alignment calculations), which carries out all numerical calculations for a project, and produces a full set of drawings including accurate perspective views. The program uses an original representation of the ground, the numerical ground image, which allows the interpolation of any ground level within the defined zone to a precision of about 5 in., at a rate of 900 points interpolated per minute. The necessary interpolation programs form part of a program package composed of seven sections, treating the various design aspects, with automatic data transfer between sections. The package can be used section by section to keep pace with design phases, and is well adapted to the study of several different alternatives.

Particular emphasis is placed on the use of the perspective drawings to correct faulty designs. The most common errors are illustrated, with comments on how corrections could have been made; before and after examples are given for an access point where the design was changed when perspective drawings showed that the new design would be inherently less likely to cause accidents.

The use of the program to obtain the perspective views is explained, and the available types of view are given with their approximate costs. An independent program based on the perspectives phase of the TE.GI package is also explained, along with its use for studying interchanges and other aspects of design that cannot be handled directly by TE.GI. Both of these programs can be used to obtain a large number of closely spaced perspective drawings that can be photographed using cartoon film techniques to obtain animated views of the project as seen by a driver following any trajectory at any speed. The cost of these cartoon films will be reduced by modifications to the program, adapting it to new equipment coming onto the market, such as a small high-performance computer coupled to a cathode-ray tube and an automatic camera.

•THE basic aim of a projected highway is to provide the most comfortable and safest conditions for the flow of automobile traffic. Traditional design methods based on horizontal and vertical alignments are no longer adapted to such modern traffic conditions

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Paper sponsored by Committee on Geometric Highway Design.

as high vehicle densities, relatively higher speeds, and numerous interchanges. The designer must now be able to study directly the visual appearance of his project, putting himself in the driver's seat and simulating driver reactions. He must be aware of all defects in his design and of the dangers which they bring, and he must know what improvements can be made to insure optimum safety, notably through improved signposting.

TE. GI PROGRAM IN HIGHWAY DESIGN AUTOMATIZATION

Development of the TE. GI (imposed geometry automatic alignment calculations) program was started at the end of 1962. The first version was brought into service progressively from 1963 to 1965, and an improved and enlarged version was available in March 1967. From 1965 on, the TE. GI program has been used to calculate and draw nearly 700 miles of highway projects yearly.

General Description

TE. GI, an integrated computer program for highway design, automates most of the numerical and graphical work involved in preparing an alignment project for a long-distance throughway.

The geometry of the project is "imposed": the project is conceived by the designer, and not by the computer. The designer must make all of the basic choices fixing the project's geometrical parameters, and must take into account all factors bearing on his research: geometrical, geological, orographic, technical, safety, climatic, economic, political, human, etc.

For these reasons studies of perspective views represent one of the major phases in highway design. Through the use of "perspectographs," perspective drawings have been prepared in various countries since 1960. These machines, which use optical methods to provide a perspective projection from horizontal and vertical alignments, have been invaluable in eliminating alignment errors and, consequently, in avoiding a large number of accidents which otherwise would have occurred.

However, a systematic perspective drawing of all projects would require a large stock of perspectographs, as well as the availability of large numbers of operators, who are not easy to find and train. Simulation of the reactions of the highway driver, through the use of cartoon techniques, would be impossible with these costly, slow, manual methods. Fortunately, computer techniques have taken over and provide a high volume of output at fairly low costs, and industrial output of perspective views has now been achieved thanks to TE. GI.

Besides, the machine carries out for the designer all of the repetitive work which does not require intelligence, but which is still essential to the preparation of the project, such as numerical calculations (earthwork volumes, for example), and automatic drawings (such as perspective views of the throughway).

The use of the "numerical ground image" as a terrain model and the simplicity with which the computer produces drawings and calculations, opens the way for comparative studies of several variations, which are entirely calculated and easily visualized; the chief designer can select the best solution at his leisure, using whichever criteria seem to apply.

Acting as a real assembly line for road alignments, the TE. GI program lowers design costs while improving technical quality, overcomes difficulties due to the scarcity of qualified personnel, optimizes personnel, requires no displacement of manpower, and frees the designer from trifling jobs that prevent him from looking full-time for the best solution.

The Numerical Ground Image

Since a computer can process only numerical information, ground information must be transformed into numerical figures. The problem is how to transform the ground into a discrete numerical image. The most widely used solution has been that of defining the ground after and along the project alignment. An air or ground survey used to be carried out along the proposed alignment, using more or less equally spaced cross-sections as survey lines. Obviously, this method covers the whole project, but it does not allow the study of any important variations without carrying out further surveys.

A much more rational solution is provided by the numerical ground image. All survey work is carried out before starting the project design, using a study strip that is large enough to allow for alternative solutions. Thus the same ground model is used for all calculations, major alignment modifications can be handled without going back to new surveys, and the designer is no longer tied to an a priori alignment which is sometimes a disastrous choice.

The numerical ground image is a set of points on the ground, suitably distributed along the project study strip, and represented by their orthogonal coordinates X, Y, Z in the chosen reference system. The points are held in memory through their cartesian coordinates X, Y, Z and the computer will work directly in a three-dimensional geometry.

To calculate a particular alignment, the computer places points along the cross-sections using X, Y plane coordinates, and then interpolates the gound elevation Z at each point. This is done by first picking up all image points close to the interpolated point, and weighting them according to the exact distance; next, the computer bases a second-degree surface on these points, using a weighted least-squares method. This surface hugs the ground around the interpolation point; its value at this point is taken as the ground elevation.

The interpolation speed is about 900 points per minute. Accuracy is good: the standard deviation of error is usually less than 5 in. —hardly significant in projects of this nature.

Computer Calcuations and Automatic Drawings

The general TE. GI program consists of seven sections linked together, although some of them can be used separately.

Section 1 (horizontal alignment) calculates basic element characteristics for a horizontal alignment, working from the geometric parameters of the circular and straight sections. If required, progressive spirals (clothoids) can be tabulated, and a machine drawing of the alignment can be produced.

Section 2 (structural zones) is used to define and record for the following sections numerical values for certain geometric, geological and economic parameters (such as tabulation distance, cross-section templates, ground types, and earth-works costs), which vary along the project but which can be considered constant within zones, called "structural zones." The program also calculates and produces drawings of the superelevation diagrams.

Section 3 (ground interpolation) applies the numerical ground image to the calculation; it is used with Sections 1 and 2 to calculate and draw the ground section along an alignment calculated by Section 1 and along the cross-sections prepared by Section 2.

Section 3b (staking-out) converts general coordinates to local polar, semipolar or orthogonal coordinates based on a polygonal or on a local triangulation. The results are supplied to the surveyors responsible for marking the alignment on the ground to be used such as they come out of the computer.

In the same way that Section 1 handles the horizontal alignment, Section 4 (grade line), prepares detailed drawings and the exact calcuation of a project grade line. The vertical alignment automatic drawing can be superimposed on the ground alignment section drawing prepared by Section 3.

Section 5 (earthworks) provides three series of results: (a) calculation and automatic drawings of cross-sections of the ground, project and subgrade level; (b) earthworks volume calculations, with costs for fill, pavement, topsoil, and three layers of cut; and (c) toeline and earthworks surface area, used for land acquisition.

Section 6 (perspective views) prepares two types of drawings: (a) an automatic plan drawing of the complete alignment showing the center-line, pavement edges, platform edges and toelines; and (b) automatically prepared perspective views at requested points.

If the user wishes, this section can be used to make a cartoon film of a driver's view of the road while advancing at a given speed.

PERSPECTIVE VIEWS AND VISUAL QUALITY

Rural Highways

It is customary to carry out separate studies for horizontal and vertical alignments. As a result the road, once constructed, is often a let-down although both alignments are, considered separately, prepared according to design standards and correctly integrated with the ground relief. This is because the alignment is, in fact, a three-dimensional curve whose perspective appearance depends not only on the vertical and horizontal projections, but also on the combination of both.

For an expressway, the perspective appearance of the alignment, as seen from every point along the road, must let the user:

1. See clearly the pavement and all obstructions which could be on it, over a long enough distance for him to take avoiding action or to stop (classic visibility conditions);
2. Distinguish clearly particular points such as forks and interchanges;
3. Foresee direction of the road ahead; and
4. Enjoy the alignment as forming part of the countryside without his being abused by artificial devices or annoyed by elbow bends, breaks and discontinuities which destroy the driver's psychological comfort.

Let us look at some of the most common errors caused by a poor combination of horizontal and vertical curvature. A horizontal curve is deformed in perspective if a high point lies on it. A short, low hump can completely transform the alignment's appearance, and the horizontal curve can even be completely hidden if it starts at about the position of the hump.

An alignment which has no point of inflexion in its horizontal or vertical components may have a point of inflexion in the two considered together. This happens when the ocular plane at an alignment point passes through the observer's eye. These artificial inflexion points are extremely common, produced either by combining horizontal and vertical curves with radically different radii or, worse, by putting vertical and horizontal curves in sequence or with a slight overlap. Artificial inflexion points are disagreeable and misleading when marked, as they will make people think that there is a real point of inflexion on the alignment.

The road may also disappear behind a vertical hump only to reappear further on in line with the original platform. The difference in platform widths and alignment directions makes such a loss of view of the road ahead disagreeable and often dangerous because it modifies the driver's appreciation of distances and can give him the impression that vehicles coming toward him from far away are in the same lane as he is.

The accompanying photographs show some of the most important well-known alignment errors, and certain extremely dangerous errors in horizontal and vertical coordination near interchanges and forks.

Urban Freeways, Multilevel Interchanges and Underpasses

On urban and suburban freeways or on interchanges, perspective studies are even more useful, despite the lower design speed. Not only can visibility be correctly studied, together with landscape integration and the location and correction of optical errors, but also advance studies can be made of overhead and conventional signposting, acceleration and deceleration ramps, and crossing zones.

The alignment errors already discussed for alignments in open country are now even more serious: alignment losses, inflexions, and curvature changes on humps often produce an anxiety reflex in the driver who, consciously or unconsciously, slows down, and starts a wave of decelerations in the dense traffic behind him—thus, during peak hours, jams and multiple accidents.

Poor signposting—badly studied, badly placed or badly written—coupled sometimes with defective visibility at forks and interchanges, is bound to slow down the traffic flow and prompt dangerous lane changes and a breakdown in the regularity of the flow, leading to a reduction in capacity.

Figure 1. A winding alignment visible over a considerable length appears artificial unless the natural features responsible for the curvature are visible.

Figure 2. An example of sight loss and a poor combination of vertical curvature.

Figure 3. An example of a bayonet in a vertical alignment.

Figure 4. Sight loss near a fork: the driver cannot see the decision point shown by the signposting; this visual defect gives him a feeling of insecurity.

Figure 5. The same fork (farther on): the exit ramp aligned with the previous roadway seems to be the main road, while the main road is hidden by an inflexion on the left and is nearly invisible—the driver can be misled by the appearance of the exit into making dangerous maneuvers.

Figure 6. Poor visibility at a fork: in this case, the minor fork is on the left (this disposition should never be adopted); the straight, horizontal alignment hides the fork, which only appears at the last moment for a driver who is not concentrating.

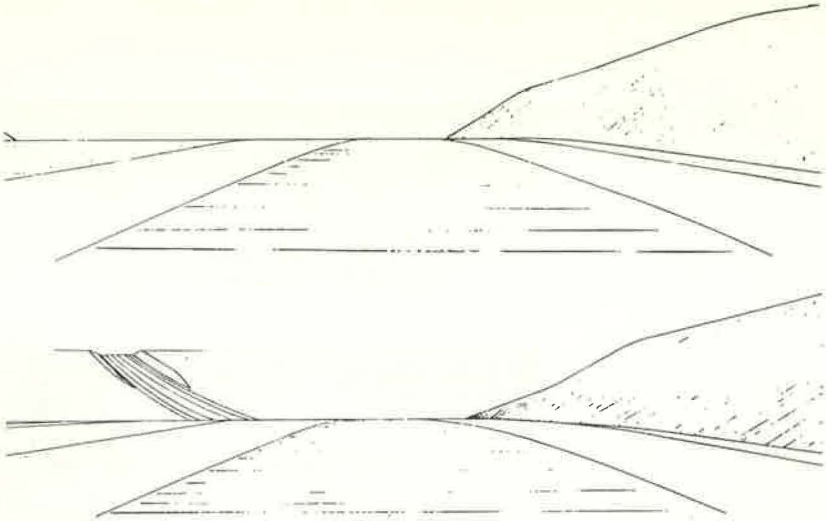

Figure 7. Poor visibility at a fork at the design stage: the fork is invisible at 500 yd (top), and still invisible at 300 yd (bottom), although the left arm can now be seen behind the masking hump.

Figure 8. The same after correction by offsetting the alignment: both arms can be seen at 500 yd (top), and the division itself is clearly visible at 300 yds (bottom).

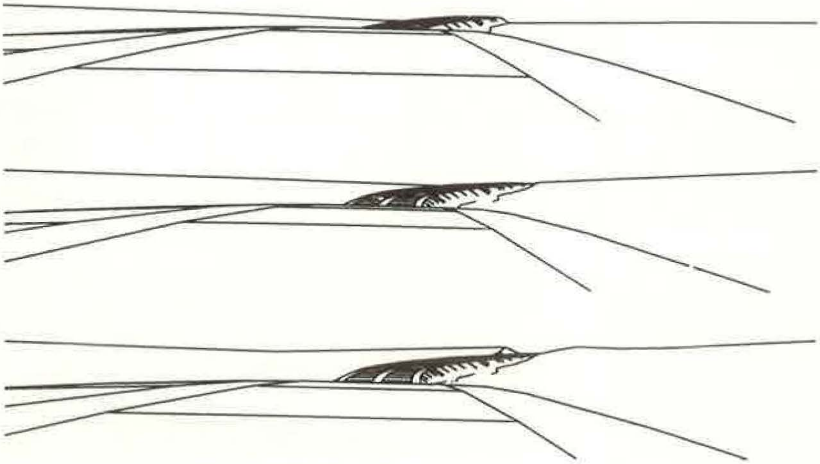

Figure 9. Automatic perspective example—characteristic sight losses.

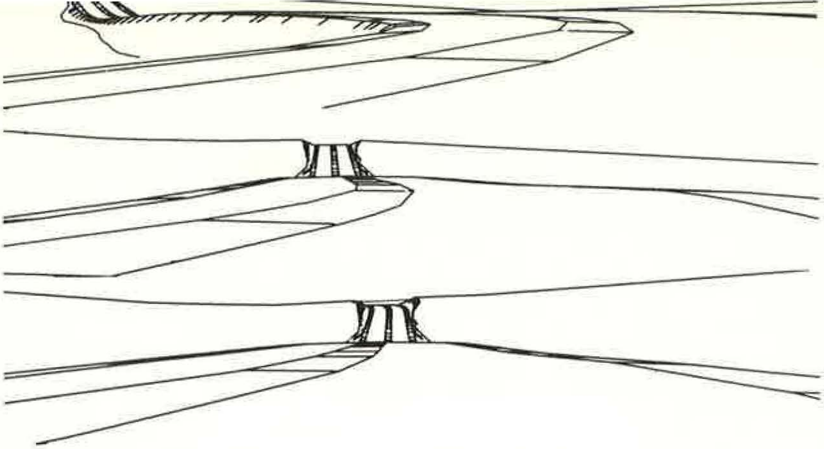

Figure 10. Automatic perspective examples—characteristic sight losses.

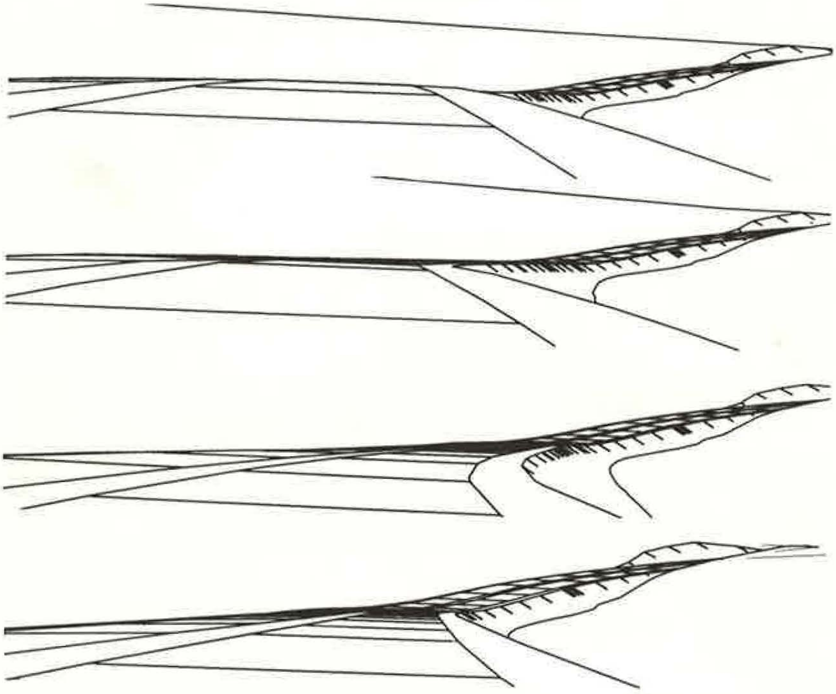

Figure 11. Automatic perspective examples—sight losses and inflexions.

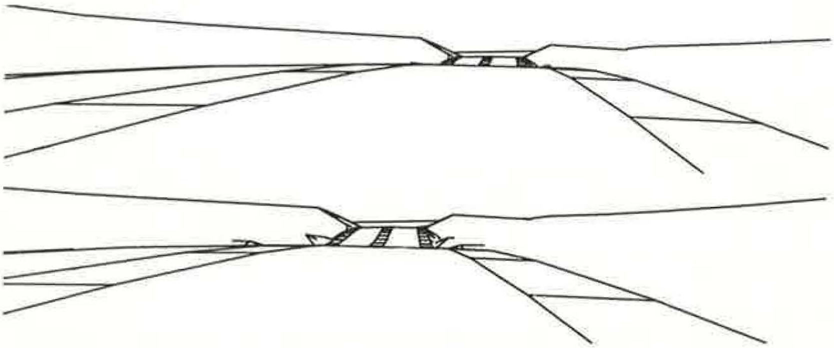

Figure 12. Automatic perspective examples—bayonet on the vertical alignment.

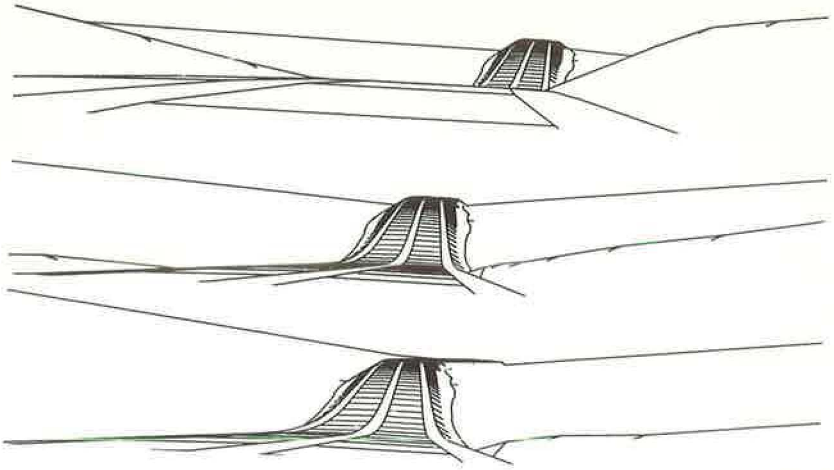

Figure 13. Automatic perspective examples—bayonet on the vertical alignment; the left carriageway seems to be a continuation of the right.

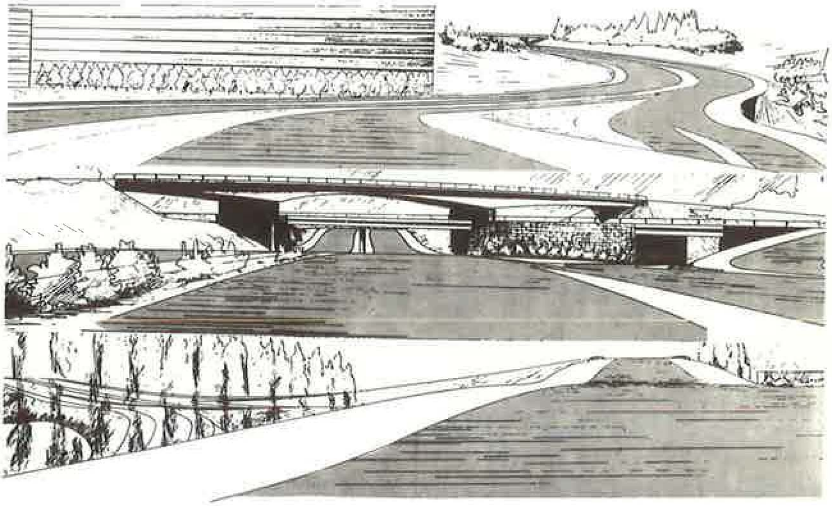

Figure 14. Perspectives in suburban zones: (top) inflexion; (middle) bayonet on the vertical alignment; (bottom) sight loss which could be corrected by masking the reappearance behind a curtain of trees.

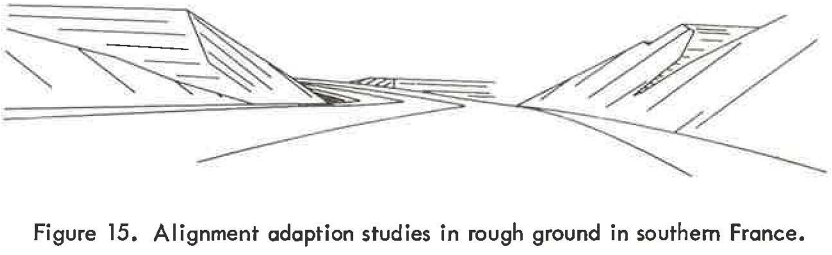

Figure 15. Alignment adaption studies in rough ground in southern France.

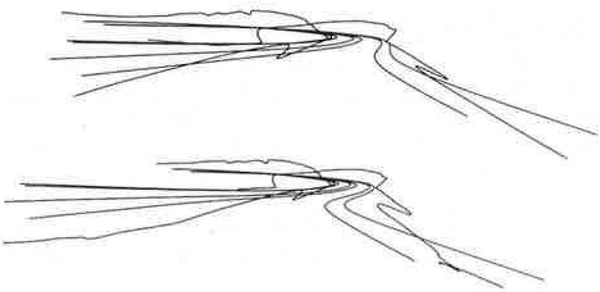

Figure 16. Extracts from an animated perspective film (rural expressway).

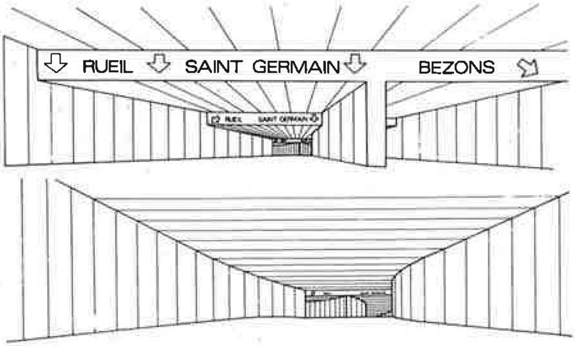

Figure 17. Extracts from an animated perspective film (underpass).

In the same way, crossing zones that have not been correctly studied in perspective may give reduced capacities and lead to incidents in the circulation and to accidents.

Underpasses are particularly delicate from the point of view of traffic flow; steady-flow conditions, lane guidance and fluid merging control the hourly capacities of these points. All this implies a very careful study of the geometrical dimensioning, the spatial coordination and the signposting, which can only be made by studying perspective views. Studies of crossing zones may even require the preparation of animated cartoons from the perspectives to simulate merging traffic.

In designing airport runways, architectural and urban projects, the perspectives also have many applications.

These examples of the uses that can be made of perspective views for project designs are certainly not the only ones that can be imagined; no doubt, in the future the visual aspect of human achievement will take on, in the design stage, the importance that it merits.

SOME APPLICATIONS OF THE TE. GI PROGRAM TO VISUAL QUALITY CONTROL

The key role of perspectives for improving roads was seen some years ago and one of the declared aims of the TE. GI program was the production of perspective drawings for the designer.

For this purpose, TE. GI Section 6 links onto the output of preceding sections, while leaving viewpoints and distances between views open to the designer's choice, to produce a perspective drawing where readability is increased by computer-added shading on the center reserve and berms, and by marks on the high side of the side slopes.

Awareness of the Visually Disturbing Elements

A design engineer usually asks for perspectives spaced every 200 yd along the alignment in both directions. Marked perspectives are immediately readable, while the complete perspectives with all lines are used to detect alignment faults. This systematic use of perspectives allows the engineer to track down all alignment errors, however small, showing him exactly what the results of his design will be.

The independent version of Section 6 lets the designer study all problems which are not covered by the rural expressway possibilities of TE. GI. It is being used more and more for urban expressways, with their multiple accesses, interchanges, and complex signposting.

Other uses that have been made of the program, outside of its normal applications, include views of a runway as seen from the aircraft and views of a bobsled run.

Improvement of Visual Quality

What can be done for this? The simple answer is to increase vertical radii of curvature; this, however, leads to enormous embankments, deep cuttings, and the highway becomes a slash across the countryside destroying the landscape. Therefore, the designer has an aesthetic and monetary interest in modifying the horizontal alignment as well, fitting it as best as he can to the countryside. In general, he should replace straight sections by fluid curves following the lines of the ground and integrated with the landscape to give a harmonious overall effect. It must be emphasized that this is not only advisable from an aesthetic viewpoint, but also from a hard economic standpoint, since accident risk plays an important part in the user's cost function. For roads as elsewhere, a well thought out product with a harmonious design is, in the end, a source of economy.

The adaptation to the environment must be designed by the engineer, but the TE. GI program will help him by cheaply and rapidly showing the finished effect, and allowing comparative studies of a number of different projects.

Simulated Driving Through the Use of Animated Cartoons

The best way of checking visibility and visual guidance is obviously to simulate the behavior of a driver traveling along the highway at a given, though not necessarily constant, speed. This requires the preparation of a large number of closely spaced perspectives, which are then used to prepare an animated film cartoon. Two such projects have already been run in two different fields. The first was prepared on a rural expressway to find out the effect on the driver of completely separating the dual carriageways. The second was for an urban expressway running underground. Each roadway had six lanes, and the film checked on the behavior of a driver leaving on the extreme left lane after traversing three successive merge areas. The main objective of the film was to control overhead signposting limited, obviously, by the height of the tunnel roof.

This design technique, because of its efficiency and its appeal for nonspecialists, will certainly be considerably developed. For this, it will be necessary to reduce the cost, made up of computer cost and the cost of refining the perspectives and preparing the film views.

The cost of refining can best be reduced by making the process automatic, as has already been done for rural perspective drawings in TE. GI. Research is going on for the introduction of bridges, trees and other objects in these perspectives, so as to give maximum possibilities of automatic completion. This technique, coupled with the use of an electro-optical plotter "drawing" on a cathode ray tube, will be able to give us directly, without other manipulation, a movie film.

These are the aims toward which we are working, and we hope that, before long, all the major road projects will include a film simulating driver's reactions on the highway.

CONCLUSIONS

These examples show the enormous changes in our way of thinking which have been forced on us by computer techniques, particularly by the generalization of spatial visualization by perspective views. General appearance, access points, signposting—all can be foreseen and verified as though the designer were in the driving seat of an automobile driving along the road two or three years later. Moreover, the road can be tried out at a series of different speeds.

These amazing design tools need a greater degree of thought and reflection from the engineer if they are to be of the greatest use, but the tools themselves free the engineer from rote tasks. Safer, less expensive, more beautiful highways are now possible and, because they are possible, they are necessary.

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Extending Control Surveys by Photogrammetry

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The U.S. Forest Service is interested in improving its methods and techniques of extending (bridging) horizontal and vertical control surveys by use of photogrammetry. The purpose of this paper is to report the results of a series of tests on production projects, carried on in cooperation with the Virginia Department of Highways. These tests were divided into two phases: (a) evaluating the extension of control by analog and analytic bridging and (b) expanding topographic mapping control to highway design photography by photogrammetry.

Twenty-five aerial photographs, at a scale of 350 ft/in., containing 77 horizontal and 210 vertical control points, were used in the first test. This material was bridged using measurements made with the Zeiss Stereoplanigraph, model C8, and the Mann Monoscopic Comparator, and each bridge was computed with identical varying amounts of control. Two scales of photography were used in the second test: 2,000 ft/in. (used for standard topographic mapping on a quadrangle basis) and 500 ft/in. (used for highway design mapping). Common image points were selected between the two scales of photography, and the small-scale photography was bridged, thereby establishing X, Y, Z coordinates for the common image points. The design photography was then bridged, using the common image points as control.

The standard deviation for the analytical bridging, with control every sixth model, was 0.59 ft horizontally and 0.47 ft vertically. The analytic method showed that errors are reduced about one-third horizontally and one-fourth vertically, as compared to the analog method.

Design mapping can be accomplished, using horizontal control established for the small-scale topographic mapping, to an accuracy of 1:4,700, but a datum shift can be expected.

•THE U. S. Forest Service is interested in improving its methods and techniques of extending (bridging) horizontal and vertical control surveys by use of photogrammetry. It is required to make engineering surveys throughout rugged topography and during adverse weather conditions; therefore, manpower must be used wisely to keep ahead of the ever-increasing demands on the engineers. For example, if photogrammetrically determined coordinates are used for targets along a preliminary route location, the engineer checks the "L" line each time he "ties" to a target, thereby saving "double measurement" of the line to ascertain its survey accuracy.

Photogrammetry has developed to the stage where coordinates determined for points by aerial triangulation can be used in lieu of coordinates for the same points measured by field control surveys. Too often errors in field control surveys are made because the photogrammetrist requests control where the topography or ground cover is not compatible with field methods or conditions. Together with good bridge planning, the photogrammetrist will request control in areas where it can be established accurately and

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identified correctly. Aerial triangulation can be used to establish control where the classic field surveys are not practical.

When the two types of surveys (field and photogrammetric) are planned simultaneously, the field survey will take full advantage of the terrain and consequently be a better control survey; and the flight plan will enhance the photogrammetric survey. The field survey should be in two parts (horizontal and vertical) and should be planned separately. The photogrammetric survey will wed the two together. Most of the time, the two field surveys will require different types of terrain for efficiency and accuracy.

The Forest Service is continually testing bridging equipment and methods to obtain guidelines for planning future projects. The purpose of this paper is to report the results of two production project tests. The first was to compare analog and analytic bridging, with varying control spacing, and the second was to expand topographic mapping control to design photography, by use of photogrammetry. The first test was divided into two parts:

1. Analog Plotter—The Zeiss Stereoplanigraph, model C8, with Ecomat (automatic readout device) was used to obtain bridge coordinates. This method was used to obtain two complete sets of measurements. Contact printed photographic transparencies (photographic images printed on glass) were used for the first set. The same diapositives were used for the second bridge, but the photographic image control points were drilled with a Wild PUG (stereoscopic point marking and transfer device).
2. Comparator (Analytic)—The Mann Monoscopic Comparator was used to measure X and Y coordinates on the diapositives of the PUG marked photographic image control points.

The tests were made on a production project using production methods. The Virginia Department of Highways furnished test material (camera report, flash plate, photographs, glass diapositives, and horizontal and vertical control) for a portion of Interstate 81 near Christianburg. This material consisted of 25 photographs (24 stereoscopic models) at a scale of 350 ft/in. (1:4, 200) taken with the Wild, RC8, 6-in. focal length, aerial camera, using a shutter speed of $^1/_{300}$ 0.03-sec. Aircraft speed was 168 ft/sec, or 0.62 ft of forward movement during exposure. The strip bridged by use of the aerial photographs was 29, 764 ft long, along a bearing of N66° 30′E. The 77 horizontal control points (spaced about 400 ft apart) were identified by targets; about 40 percent of the 210 vertical control points were targeted, and the remaining 60 percent were identified by natural images. Photographic exposures were printed through the film base on photographic glass plates which had a thickness of $^1/_4$ in.

This material was used by two instrument operators using the Stereoplanigraph to make the measurements for computing each separate photogrammetric bridge:

1. Operator A measured each point once for bridging from west to east.
2. Operator A measured each point once for bridging from east to west.
3. Operator A measured each point four times for bridging from west to east.
4. Operator B measured each point once for bridging from west to east.

Each of these four bridges was computed five times by varying amount of control as follows:

Adjustment A—Control on every stereoscopic model; i.e., 25 horizontal and 50 vertical control points were used to compute the bridge.
Adjustment B—Control spaced every second model; i.e., 13 horizontal and 26 vertical control points were used to compute the bridge.
Adjustment C—Control spaced every third model; i.e., 9 horizontal and 20 vertical control points were used to compute the bridge.
Adjustment D—Control spaced every fourth model; i.e., 7 horizontal and 16 vertical control points were used to compute the bridge.
Adjustment E—Control spaced every sixth model; i.e., 5 horizontal and 12 vertical control points were used to compute the bridge.

TABLE 1

STANDARD DEVIATION IN FEET

Bridge Number	Adjustment	All Control Points	
		Horizontal (77 points)	Vertical (210 points)
1	A	0.74	0.54
	B	0.78	0.55
	C	0.78	0.56
	D	0.79	0.60
	E	0.87	0.62
2	A	0.74	0.64
	B	0.75	0.65
	C	0.77	0.66
	D	0.85	0.66
	E	0.92	0.67
3	A	0.88	0.88
	B	0.91	0.90
	C	0.95	0.91
	D	0.97	0.95
	E	1.15	1.03
4	A	0.87	0.71
	B	0.91	0.71
	C	0.95	0.71
	D	0.99	0.76
	E	1.11	0.73

Table 1 summarizes results by standard deviation in feet. The results are similar except for Number 3, which is somewhat ou of line. Ordinarily, measuring each point four times would produce better results. These results (1) are approximately the sam as obtained on the Interstate 66 test.

The Forest Service continued the test by negotiating a contract with a private compan to do the bridging, using the same material. The contractor was furnished a set of photographs and all points were identified and labeled. The contractor used the Wild PUG to drill an 80-μ diameter hole (0.003 in.) for each photographic point on the diapositives. Point coordinates of the drilled holes were measured with the Mann Monoscopic Comparator. The aerial analytic triangulation computations were based on the U. S. Coast and Geodetic Survey's equations. The bridges were computed using the same varying amoun of control as used in the analog instrument bridging.

After the contractor furnished the results of the five bridges, the Forest Service bridged the photographs, using the same glass diapositives and identical control.

Table 2 gives three bridge results: Mann with PUG, Stereoplanigraph, model C8, b Operator A (1), and Stereoplanigraph, model C8, with PUG Operator A.

These results are not a true comparison of instruments, as the computation equation for the analytical procedure, using comparator measurements, are more sophisticated than those used for the analog bridging, using Stereoplanigraph measurements, althoug both sets of equations were developed by the USC & GS.

The analog bridge computations are based on the USC & GS Technical Bulletin No. 1 (Jan. 1958) and Technical Bulletin No. 10 (Sept. 1959). In 1963, Olin D. Bockes combined the equations and programmed them for use in an IBM 7074 electronic computer. Aerial analytic triangulation equations (USC & GS Bulletin No. 21) include corrections for film distortion, perspective center, symmetric and asymmetric lens distortion, atmospheric refraction, and relative orientation and adjustments for earth curvature, all of which are not included in the analog bridging program for use in the IBM 7040. The analog bridging procedure arbitrarily considers: perspective center by aligning th diapositive on the fiducial marks, film distortion by changing the focal length, lens distortion by using a correction plate, refraction and earth curvature by predetermined tip, and relative orientation by the parallax solution; but does not consider cross tilt (averaging the Stereoplanigraph measurements of carry-over points as they affect the total bridge) in the bridge computations. All of these arbitrary corrections would tend to make the bridging results from Stereoplanigraph measurements less accurate than those from analytical bridging. Another factor which tends to improve the accuracy of the comparator is that blurred images, due to movement during exposure, are better "centered" monoscopically when compared to stereoscopic "pointings."

Jesse R. Chaves of the Bureau of Public Roads recomputed these same analog C8 bridges, using the Stereoplanigraph measurements and the new USC & GS equations (Technical Bulletin No. 23), and the results were approximately the same. The unanswered question is: Why didn't Bridge 3 (each point measured four times) give better results than single measurement for each point? The only apparent answer is that with this number of check points (77 horizontal and 210 vertical), single measurements averaged more accurately than multiple measurements.

These results show the possibility of using photogrammetry to establish control. Existing ground control, as well as new control, should be targeted. Photogrammetry can be used to determine control position for natural image points, but some of the

TABLE 2

EXTENDING CONTROL SURVEYS BY PHOTOGRAMMETRY

BRIDGE [24 MODELS-SCALE OF PHOTOGRAPHY 1:4200-FLIGHT HEIGHT 2100 FEET]	INSTRUMENT	AVERAGE ERROR IN FEET $\left(\frac{\text{SUM OF ERRORS}}{\text{NUMBER OF POINTS}}\right)$		B FACTOR $\left(1:\frac{\text{FLIGHT HEIGHT}}{\text{AVERAGE ERROR}}\right)$		STANDARD DEVIATION (S) IN FEET $\left(S=\sqrt{\frac{\Sigma d^2}{N}}\ \ d=\text{ERROR}\ \ N=\text{NUMBER OF POINTS TESTED}\right)$		90% ACCURACY IN FEET (1.65 X S)	
		HORIZONTAL (77 POINTS)	VERTICAL (210 POINTS)	HORIZONTAL	VERTICAL	HORIZONTAL (77 POINTS TESTED)	VERTICAL (210 POINTS TESTED)	HORIZONTAL	VERTICAL
ADJUSTMENT "A" [CONTROL EVERY MODEL; I.E., 25 HORIZONTAL (H) AND 50 VERTICAL (V) CONTROL POINTS USED TO COMPUTE BRIDGE]	MANN/PUG	0.46	0.32	1:4565	1:6562	0.52	0.45	0.86	0.74
	C-8	0.67	0.42	1:3152	1:4954	0.74	0.54	1.22	0.89
	C-8/PUG	0.65	0.54	1:3231	1:3889	0.72	0.64	1.19	1.06
ADJUSTMENT "B" [CONTROL EVERY SECOND MODEL; I.E., 13 H AND 26 V CONTROL POINTS USED TO COMPUTE THE BRIDGE]	MANN/PUG	0.47	0.33	1:4468	1:6364	0.52	0.46	0.86	0.76
	C-8	0.68	0.43	1:3099	1:4886	0.76	0.55	1.25	0.91
	C-8/PUG	0.70	0.56	1:3000	1:3750	0.75	0.66	1.24	1.09
ADJUSTMENT "C" [CONTROL EVERY THIRD MODEL; I.E. 9H AND 20 V CONTROL POINTS USED TO COMPUTE THE BRIDGE]	MANN/PUG	0.48	0.32	1:4375	1:6562	0.52	0.46	0.86	0.76
	C-8	0.69	0.43	1:3031	1:4836	0.78	0.56	1.29	0.92
	C-8/PUG	0.75	0.55	1:2800	1:3818	0.80	0.66	1.32	1.09
ADJUSTMENT "D" [CONTROL EVERY FOURTH MODEL; I.E., 7 H AND 16 V CONTROL POINTS USED TO COMPUTE THE BRIDGE]	MANN/PUG	0.49	0.34	1:4286	1:6176	0.54	0.47	0.89	0.78
	C-8	0.71	0.47	1:2971	1:4461	0.79	0.60	1.30	0.99
	C-8/PUG	0.81	0.57	1:2593	1:3684	0.87	0.67	1.44	1.11
ADJUSTMENT "E" [CONTROL EVERY SIXTH MODEL; I.E., 5 H AND 12 V CONTROL POINTS USED TO COMPUTE THE BRIDGE]	MANN/PUG	0.53	0.35	1:3962	1:6000	0.59	0.47	0.97	0.78
	C-8	0.78	0.49	1:2709	1:4272	0.87	0.62	1.44	1.02
	C-8/PUG	0.89	0.60	1:2360	1:3500	0.97	0.72	1.60	1.19

accuracy will be lost to both the photogrammetrist and the field engineer when a finite point is not established. The analytic approach shows that errors will be reduced about one-third horizontally and one-fourth vertically, as compared to the analog method. The X corrections (E-W) were much larger than the Y corrections (N-S), which could be attributed to camera motion during exposure, as the flight direction was N66° 30'E.

The purpose of the second test was to determine if material (photography and control) from recent standard topographic mapping on a quadrangle basis can be used to control design photography at a scale of 1:6,000 (500 ft/in. for design mapping at a scale of 1:1,200; i.e., 100 ft/in.). For this test, we chose a project in the George Washington National Forest in Virginia, on which had been used the mapping photography (1:24,000— ft/in.) and control for making route investigations leading to route selection and preliminary design. This preliminary location was based on the use of a 1:4,800 (400 ft/in.) scale topographic map with a 10-ft contour interval.

This 1:4,800 scale topographic map was used to locate targets for both the control survey and preliminary (P) road location. Intervisible control targets were located some distance from the proposed route for identification of a field-surveyed traverse. This traverse extended back and forth across the South Fork of the Shenandoah River and had very limited use for route location. Intervisible targets were also set near the preliminary location for the road.

Again, the Virginia Department of Highways cooperated and furnished the photography, using the same camera as on the first test.

A spirit level elevation was measured for each targeted point along the preliminary location for the road. Positions, with vertical angle elevations, were measured along the control traverse.

Common image points were selected between the mapping photography (1:24,000 scale) and the design photography (1:6,000 scale), using the Zoom stereoscope. The Zoom stereoscope was also used to transfer the target positions from the 1:6,000 to the 1:24,000 scale photographs. This was quite difficult, as some of the ground cover (trees and bushes) had been cleared to set the targets.

The mapping photography was bridged using only the control established for the topographic mapping done on a quadrangle basis. This bridge established X, Y, and Z coordinates for both the common image points and the targets transferred from the 1:6,000 scale to the 1:24,000 scale photography. Thus 35 targets were transferred from the design photography to the mapping photography. All 35 targets had field measured elevations (either spirit level or vertical angle), of which 14 had field measured horizontal position. A comparison of field surveyed and bridged results showed an average elevation (Z) error of -2.8 ft. The average X (E-W) error was +8.6 ft, and the average Y (N-S) error was +14.7 ft. The datum shift in X was +8.1 ft, Y +12.3 ft, and Z -0.7 ft. When a ground measured distance of 11,788.8 ft was compared with the photogrammetrically measured distance between the same points, the error was 6.2 ft, or about one part in 1,900.

The design photography was then bridged, using only common image points as control. Thirty-seven targets, with field measured elevations (26 by spirit levels and 11 by vertical angles), and 15 targets with field measured horizontal position, were used to evaluate this bridge. The average X error was +3.3 ft, Y +13.8 ft, and Z +2.0 ft. The datum shift was X +3.3 ft, Y +13.8 ft, and Z +0.5 ft. When the same ground measured distance of 11,788.8 ft was compared with the photogrammetrically measured distance, the error was only 0.7 ft, or one part in 16,800. The datum shifts were similar to the preceding bridged results.

The bridge was recomputed using only the targets along the preliminary road location; i.e., those with spirit level measured elevations. Eleven targets, with vertical angle field elevations, were used to evaluate this bridge. The average error in Z was -0.8 ft, of which -0.4 ft was datum. It should be remembered that none of these targets were located along the proposed road, but were located near the pass-point (edges of the photographs) area. The X and Y errors for this bridge were the same as for the previous bridge, as the same common image points were used to compute the horizontal portion of both bridges.

TABLE 3

TRAVERSE RESULTS

	Bridge Computed Using Ground Surveyed Control		Bridge Computed Using Common Image Points as Control	
	Station in Feet	Delta Angle	Station in Feet	Delta Angle
T-1	0		0	
T-2	462.79	20°04'27" Rt	462.75	20°04'16" Rt
T-3	1,294.19	12°17'57" Rt	1,294.08	12°18'02" Rt
T-4	2,065.88	2°09'40" Rt	2,065.66	2°08'51" Rt
T-5	2,800.77	0°36'02" Lt	2,800.55	0°36'07" Lt
T-6	3,800.13	17°47'04" Lt	3,799.87	17°47'23" Lt
T-7	5,093.96	30°08'13" Lt	5,093.65	30°08'27" Lt
T-8	6,389.37	17°46'43" Lt	6,389.04	17°45'01" Lt
T-9	7,354.68	23°08'23" Lt	7,354.00	23°09'46" Lt
T-10	8,034.67	25°01'08" Lt	8,034.08	25°00'49" Lt
T-11	8,484.59	11°25'13" Lt	8,484.04	11°26'25" Lt
T-12	8,990.94	0°43'35" Lt	8,990.33	0°43'02" Lt
T-13	9,333.44	0°16'07" Rt	9,332.80	0°16'37" Rt
T-14	9,998.61	1°09'42" Lt	9,997.88	1°04'38" Lt
T-15	10,428.67	20°02'01" Lt	10,427.60	20°08'08" Lt
T-16	10,786.42	18°01'15" Lt	10,785.25	17°59'57" Lt
T-17	11,167.79	5°18'35" Lt	11,166.45	5°19'10" Lt
T-18	11,708.61	4°01'12" Rt	11,707.05	4°01'07" Rt
T-19	11,952.60	13°17'55" Lt	11,950.93	13°17'28" Lt
T-20	12,815.54	1°37'10" Rt	12,813.29	1°37'08" Rt
T-21	13,290.78	4°38'43" Lt	13,288.18	4°39'04" Lt
T-22	13,732.09		13,729.17	
			2.92	
			(1:4,771)	

For the final test, the bridge using the design photography was recomputed, using the field surveyed control; i.e., the 37 vertical and 15 horizontal control points, which were identified by targets. This bridge was compared to the bridge using common image points as control. The comparison was made by computing a traverse of the 22 targets along the P line. This was an important test, as the L line is usually staked by use of computed offsets from the P line. Table 3 indicates what errors can be expected.

These results are most promising, and the traverse checks show that an accuracy of one part in 4,700 should be obtained. The tests indicate a datum shift; i.e., all coordinates would be shifted by 3.3 ft in X, 13.8 ft in Y, and 0.7 ft in Z, if the field surveyed control is eliminated. The datum shift becomes a problem when the surveyor determines an azimuth from a geodetic station or by making a solar or polaris observation. The only way in which this shift could be eliminated would be to increase the accuracy of the topographic mapping bridges.

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An Aerial Photographic Technique for Presenting Displacement Data

LLOYD O. HERD, Ohio Department of Highways

The modern serial aerial camera with electronic intervalometer and photographic record of the instant of exposure is a scientific apparatus for the study of moving or displaced subject matter. A novel method of using photographs of vehicular traffic to present a graphic envelope of vehicle trajectory curves is described.

•THE measurement of points in three dimensions is a routine problem of stereoscopic photogrammetry. That the method also provides a fourth dimension, time, is not so often recognized.

Time is not all important to most fixed point plotting; however, we date all maps or state the date of mapping photographs because we instinctively know that our culture and even our terrain is subject to change.

Another class of data, however, is most dependent on time—objects undergoing displacement. It will be recognized that the position of projectiles, rockets, satellites and all vehicles are dependent on their time coordinate.

Photography has long been used to study complex motion by time lapse and multiple exposure techniques. Open-shutter photography also provides a method of recording the path of a lighted moving object against a background of low illumination, but to record time requires an elaborate coding of the transmitted light.

It is not generally appreciated that the modern serial aerial camera with electronic intervalometer and photographic record of the instant of exposure is a scientific apparatus for motion study.

In recent traffic studies conducted with the use of specialized equipment for the Ohio Department of Highways, it became apparent that the precision mapping camera was a tool that could be used without modification for investigating many displacement problems. For instance the minimum 2-sec cycling time available is more than adequate to demonstrate all but the micro-relations involved in traffic flow theory.

For presenting the data from many aerial photographs for direct comparison of traffic situations, a new technique was evolved which can be of use for making other investigations involving displacement.

The data are from special photography taken by the Ohio Department of Highways for a department-sponsored study conducted by Joseph Treiterer of the Ohio State University. The techniques employed were described by James I. Taylor (1) and in an abbreviated form by Treiterer and Taylor (2).

In brief, a fast cycling 70-mm camera was transported by a helicopter at a fixed height and in synchronization with a moving platoon of cars. Panchromatic, Ektachrome, and Infrared Ektachrome film were used to record the moving traffic patterns and a traverse of targeted ground control points.

Nine frames at a time were placed on the stage plate of the analytical plotter AP/C and the plate coordinates for interior orientation, the ground control points, and an identical point on each vehicle together with a complete identification of each point was printed out. The probable error of the pointing on the moving vehicle proved to be less

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Paper sponsored by Committee on Photogrammetry and Aerial Surveys.

than 10μ. The data were then processed in an electronic computer using an analytic program to obtain map coordinates for the traffic analysis.

Much tedious scientific effort, as well as equipment that might not be available to other investigations, was employed.

The largest effort was spent in reducing the data to coordinates, processing, and then replotting the adjusted coordinates for graphical presentation. A technique for reducing this effort follows:

1. Only the pertinent photographic data are printed, striped, or cut from the photographs.
2. A suitable coordinate system of position and time is selected.
3. The photographic strips are fitted on the correct time axis and fixed points fitted to position coordinates to form bar charts.
4. A set of symbols for identification of similar events is adopted.
5. By photographic interpretation, unique displaced objects are connected by identifying "trajectory" curves. Less easily identified points are then joined.
6. Each trajectory is numbered for identification.
7. Contours or grade and alignment data are plotted on one or more straight-line position bar charts.

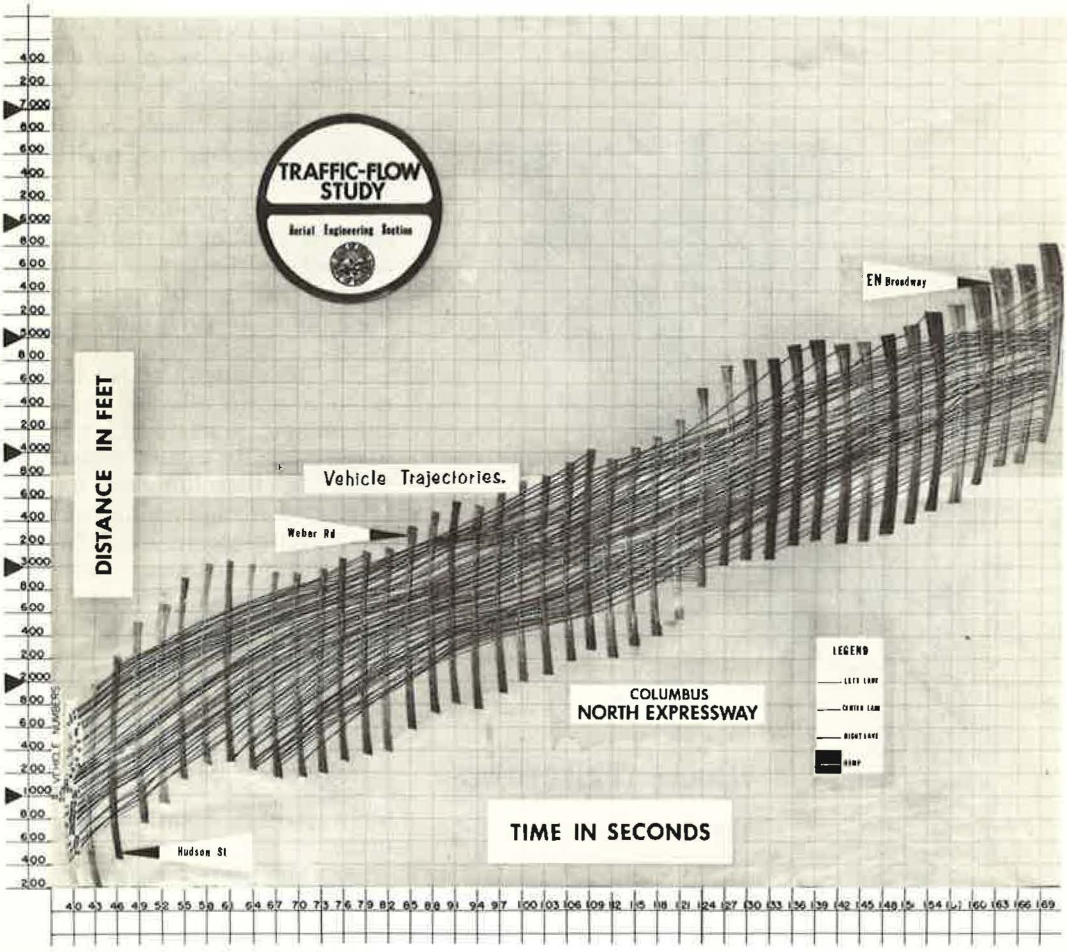

Figure 1.

Traffic data previously described and prepared according to this technique are illustrated in Figures 1 and 2. A further description follows:

1. The vertical axis of the plane coordinate system is displacement. The horizontal axis is time.
2. The photographic bar charts are the northbound lanes with their related ramps of I-71 in Columbus, between Hudson Street and North Broadway.
3. The curve connecting consecutive images of an individual vehicle represents that vehicle's trajectory. The slope of the curve is the vehicle's velocity. Acceleration is indicated by the change in the curve's slope. A horizontal line represents a zero displacement, a fixed point, or a vehicle stopped for a period of time. A vertical line represents an infinite displacement or an instant of time. The scale of the graph is so selected that the legal speed or the average speed trajectory has a slope of approximately 45 deg.
4. The trajectory of a vehicle in a single lane is assigned a distinguishing color or symbol. As soon as it crosses over 50 percent into an adjacent lane it takes on the color assigned to that lane. A trajectory of more than one color represents a weaving vehicle or a vehicle entering or leaving the mainstream of traffic.
5. Individual vehicle trajectories are identified by number.
6. The displacement axis may show contours or gradients.
7. If the bar represents a straight-line diagram the alignment curvature can also be indicated along the displacement axis.

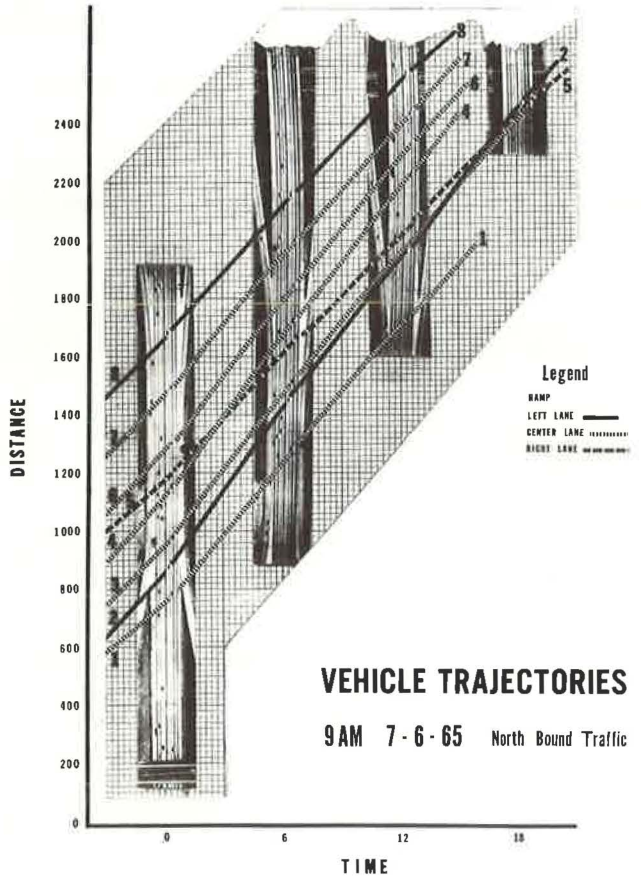

Figure 2.

A chart so prepared can be used to study most of the traffic problems of usual interest:

1. Density counts can be made by counting the number of trajectories cut by a vertical line at any desired instant. Not only the number of vehicles in a selected mile can be counted, but also the type of vehicle and the number in each lane can be noted.
2. "Headings" or the distance between vehicles in files can be seen, measured, or compared visually to an arbitrary "assured clear following distance." Average headings in individual platoons can be obtained by comparing totals of displacement and vehicle counts.
3. Volume counts can be made by counting the number of trajectories cut by a horizontal line at any fixed point. Not only the total number of vehicles in a given interval of time can be counted, but also counts of vehicle types in each lane can be made.
4. The path of a vehicle is represented by its trajectory curve.
5. The change of color of a curve represents weaving or lane changing.

6. Speed or velocity and acceleration observations are given by the slope of the trajectory curve.
7. A unique vehicle identification system can be used to provide information for comparing the changes in platoon composition.
8. The traffic record can be compared with gradients or alignment to note their effect or, for instance, the need for climbing lanes.

Variations and modification of the illustrated example are possible. For example, only the pertinent portions need be printed from the many negatives involved. The AP/C stereoscopic plotter, with an orthophotographic printing device, seems to offer advantages for implementing this technique by virtue of its versatility. It will be able to print an orthophotographic map of any portion of the negative as well as to print identification and three-dimensional position coordinates. While printing this data, it can also draw the route profile, plot the crossing contours, or compute gradients. Using color materials, this would seem to give the ultimate information except for license numbers and origin and destination. The possibilities of representing curved alignments as straight-line diagrams is limited only by the problem of computer programming.

To study the traffic flow in a network, say within the corporate limit of a small city or the inner city of a metropolis, it is only necessary to expose aerial photographs which will cover the entire network. No attention need be given to securing a suitable stereoscopic base except for a single set of mapping exposures. Problem routes in this network can then be treated as straight-line diagrams and the trajectories plotted.

Parking studies are special cases of vehicles with zero displacements and by stereoscopic examination and photographic interpretation, the identity of vehicles can be determined and counts made.

A further technique of targeting which is being researched by the Ohio Department of Highways may make it practical to premark unique vehicles or targets and pinpoint their location at the instant of exposure. Exposures could perhaps be made at such small scales that the vehicle itself would not be identifiable. The technique is to illuminate a retro-directive prism at the instant of exposure by means of a suitably synchronized and powered electronic flash. Adhesive coated targets could be set on the top of vehicles, and the position and headings, for instance, of all the operating buses in a city transportation system could be pinpointed.

Such investigations could lead to increasing the efficiency of single elements and the entire system.

The importance of traffic flow study is pointed out by an official of the Cleveland Transit System. He estimated that every increase of 1 mph in the average travel speed on that city's streets would produce an annual savings in transit operating costs of about one million dollars.

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2. Treiterer, Joseph, and Taylor, J. I. Traffic Flow Investigations by Photogrammetric Techniques. Highway Research Record 142, p. 1-12, 1966.

Super-Wide-Angle Photography for Highway Mapping With AP/C and A7

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Super-wide-angle (SWA) photography was evaluated for use in highway mapping at medium scales by experiments with the Nistri-Analytical Plotter AP/C and the Wild Autograph, model A7. By use of photography of the Arizona Test Site (USGS, AMS), error analysis and adjustment procedures were done with single models and with a multi-model strip.

Although the tests were limited in quantity, they showed that the Nistri-Analytical Plotter AP/C produces very high quality measurements and provides an effective means for controlling systematic errors. The results indicate great promise for SWA photography in highway mapping where accurate vertical data are required with both the Nistri AP/C and the Wild A7, even though the Wild A7 was not equipped to handle SWA photographs directly.

•THE super-wide-angle (SWA) single lens aerial camera is a recent development in photogrammetry. With its development has come a new family of instruments and procedures to manipulate the photography with angular coverage of 120 degrees. In some cases existing instruments and procedures have been modified to accommodate us of SWA photography.

The SWA system was studied by the photogrammetry research group at The Ohio State University particularly with its use in highway mapping in medium and large scales. The objectives were to evaluate SWA photography with special reference to the equipment presently available with the Ohio Department of Highways (particularly the Nistri-Bendix Analytical Plotter, model AP/C) with a view to improving the present mapping system. The study comprised three broad aspects:

1. A general study of the SWA system and a theoretical analysis of the obtainable observational accuracy as compared to the standard wide angle (WA) system of photography.
2. A study and analysis of the AP/C system of handling photogrammetric problems This study was required in view of the very recent developments of the AP/C which had not been thoroughly evaluated by any agency. This led to establishing a procedure for handling SWA photography at the AP/C.
3. A test of the procedure by using SWA photography taken on a controlled test are with an RC9 aerial camera (manufactured by Wild Heerbrugg, Ltd.) which is the only SWA camera commercially available in the Western World. A comparative study was made between results obtained from aerialtriangulations at the AP/C and at the Wild Autograph, model A7 stereoscopic instrument.

COMPARATIVE STUDY BETWEEN SWA AND WA SYSTEMS

In a series of tests conducted by USAE/GIMRADA (4), empirically obtained results of two systems are compared. In this study, comprising (a) grid model flatness test, (b) terrain model flatness test, and (c) stereo-triangulation test, it was established th the SWA system is better than the standard WA system. The study, however, did not

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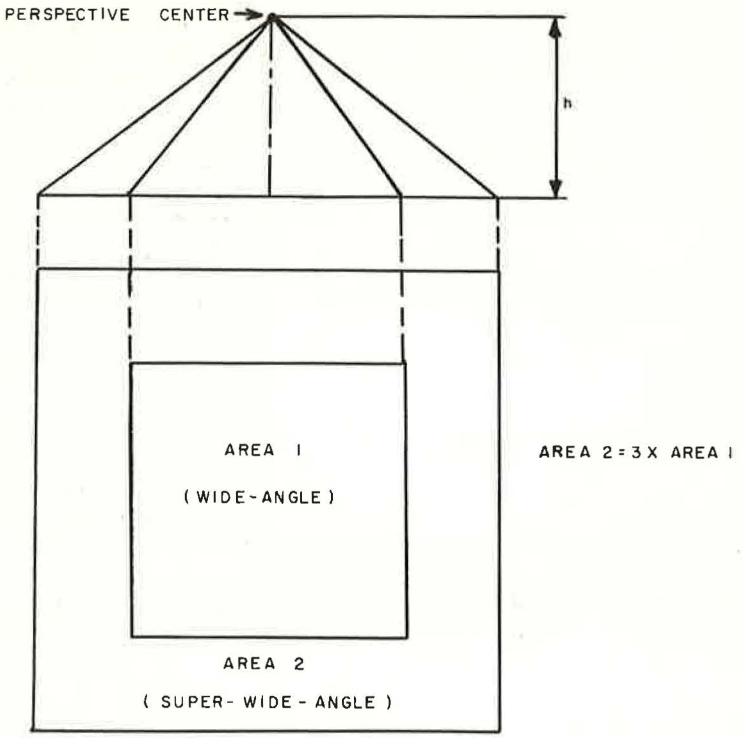


Figure 1. Comparison of areas of RC9 and wide-angle photographs.

include a thorough theoretical analytical comparison of the accuracies of relative orientation in each system. This was deemed necessary to complete the evaluation because the accuracy of the compiled map in a photogrammetric system is directly related to the accuracy or orientation (particularly, relative orientation) of individual stereoscopic models.

This study was made in two cases: (a) with six model points for orientation, and (b) with nine model points for orientation. On forming variance-covariance matrices in each case, comparative studies were made. These studies indicated that SWA photography is definitely capable of yielding better accuracy and better efficiency than the standard WA photography.

THE ANALYTICAL SYSTEM

An analytical system offers distinct advantages over analog systems in controlling error sources. This is accomplished by improving the photogrammetric measurements by use of simple, precise measuring devices which have been calibrated. Also corrections are applied better and easier for known systematic errors such as lens distortion, film distortion, and atmospheric refractions, and adjustments for earth curvature (Fig. 1).

In the present studies use was made of the Nistri-Bendix Analytical Plotter, commercial (AP/C) with the Ohio Department of Highways. There are three basic component parts of the AP/C (Fig. 2):

1. The computer with its associated electrical equipment;
2. The optical-mechanical viewing unit, essentially a two-plate comparator; and
3. The plotting table

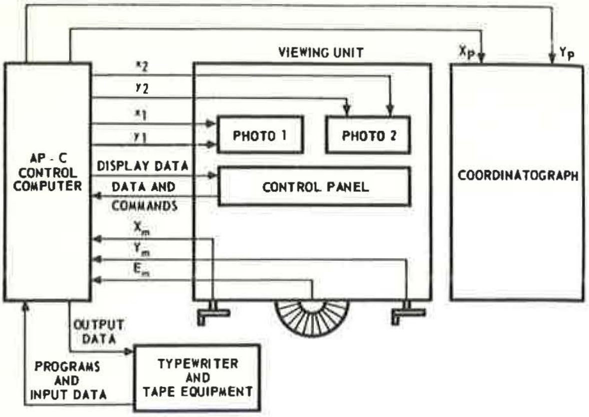


Figure 2. System diagram for AP/C.

With the computer unit is a typewriter with a punched tape reader and punch-out routines. The computer is small (approximately 2, 000 word memory), fully transistorized and very fast.

The computer receives input data as model coordinates from the hand wheels (X_m, Y_m) and the footwheel (E_m), from the operator's control panel (data commands), and from the typewriter and tape unit (generally, programs and subprograms are entered). In turn, the computer cause printout of data at the typewriter and tape unit. It sends commands to servos to keep the photographs properly positioned and oriented for viewing by the instrument operator. It might also display various data at the operator's control panel. Finally, the computer commands servos for plotting at the coordinatograph.

The photogrammetric solutions on AP/C can perhaps be shown by describing a typical operation procedure. Figure 3 shows the coordinate systems. The usual case in

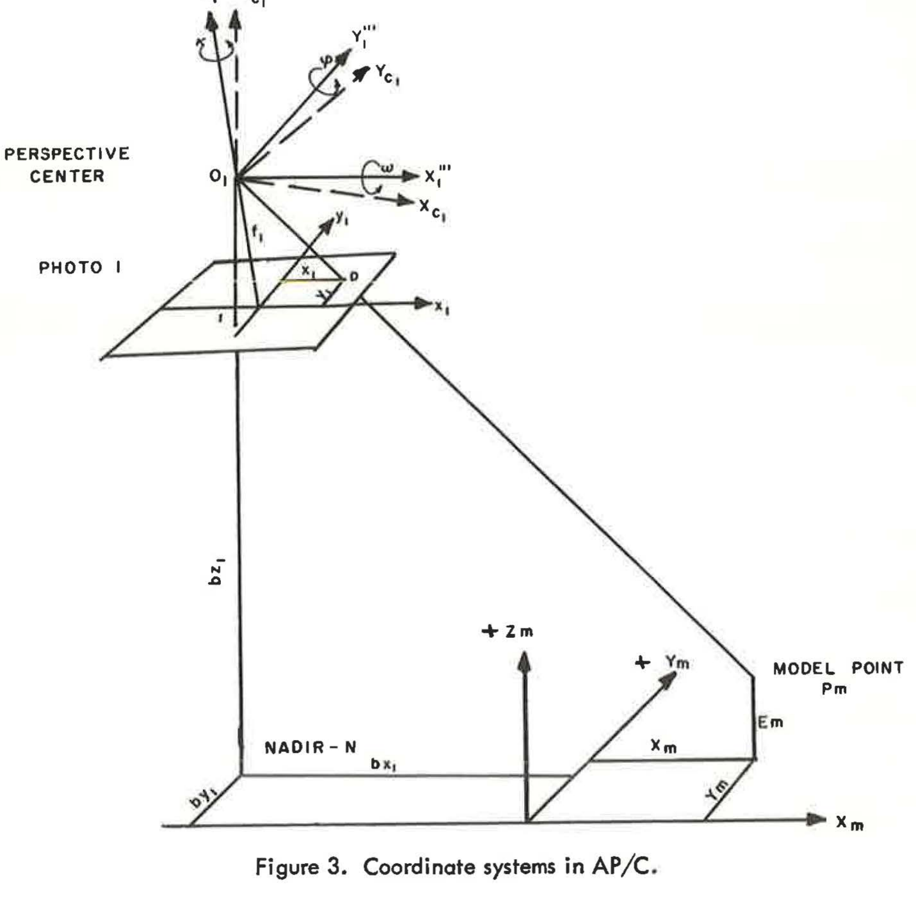


Figure 3. Coordinate systems in AP/C.

photogrammetry might begin with photograph coordinates. Then, after applying corrections and transformations, stereoscopic model coordinates are obtained. Here, with AP/C it is handled in the inverse manner as the computer is reacting to commands from hand wheels and the footwheel—the model coordinates X_m, Y_m, E_m for model point P. These coordinates are translated to the perspective center O_1 by airbase components b_x, b_y, b_z to the coordinate system X_c, Y_c, Z_c. Orientation elements κ, ω, φ are next applied sequentially in this given order to rotate to the coordinate system X''', Y''', Z''' still at model scale. A scaling by factor f/z''' converts to photograph coordinates x, y, (= f).

The systematic corrections to coordinates are applied in a similar manner as the transformations previously described. First the stereoscopic model coordinates are adjusted for earth curvature, which depends on X_m and Y_m and some scale constant S_G to correct the model coordinate E_m. The atmospheric refraction depends on the X_c, Y_c from the nadir point and on E_m. Earth curvature adjustments and refraction corrections are added to obtain Z_c. Finally, corrections for lens distortion and film shrinkage are applied to the photographic coordinates to furnish the instrument operator his correct stereoscopic model for viewing.

The cycle is performed for each photograph as the operator moves about the model space—either by hand wheels and footwheel, or by the Vetropole slewing device (which actually permits slewing accurately in any desired azimuth). These computations comprise the biggest effort of the computer and are designated as the "real-time" program. Intermixed with the cycles for the real-time program are computations with several subroutines. The real-time program is executed at the rate of 30 times per second and the operator's control panel is also interrogated by the computer at 30 times per second. The subroutines that display data, lens and film corrections for each photograph, and model corrections for each photograph cycle 5 to 6 times per second. Thus, many computations, such as for relative orientation, appear instantaneously to the operator because of the speed of execution.

It was fortunate for this study that the U. S. Geological Survey furnished diapositives printed from photography negatives exposed in one of its Wild RC9 aerial cameras of a photogrammetric test site in Arizona (joint effort of the U. S. Geological Survey and the Army Map Service). Although the scale (approximately 1:17, 000 - h = 5, 000 ft) was smaller than that generally used in large-scale highway mapping, it might be a suitable scale if more precise methods were used. Also the abundance of targeted control stations were near optimum in distribution for this test (Fig. 4).

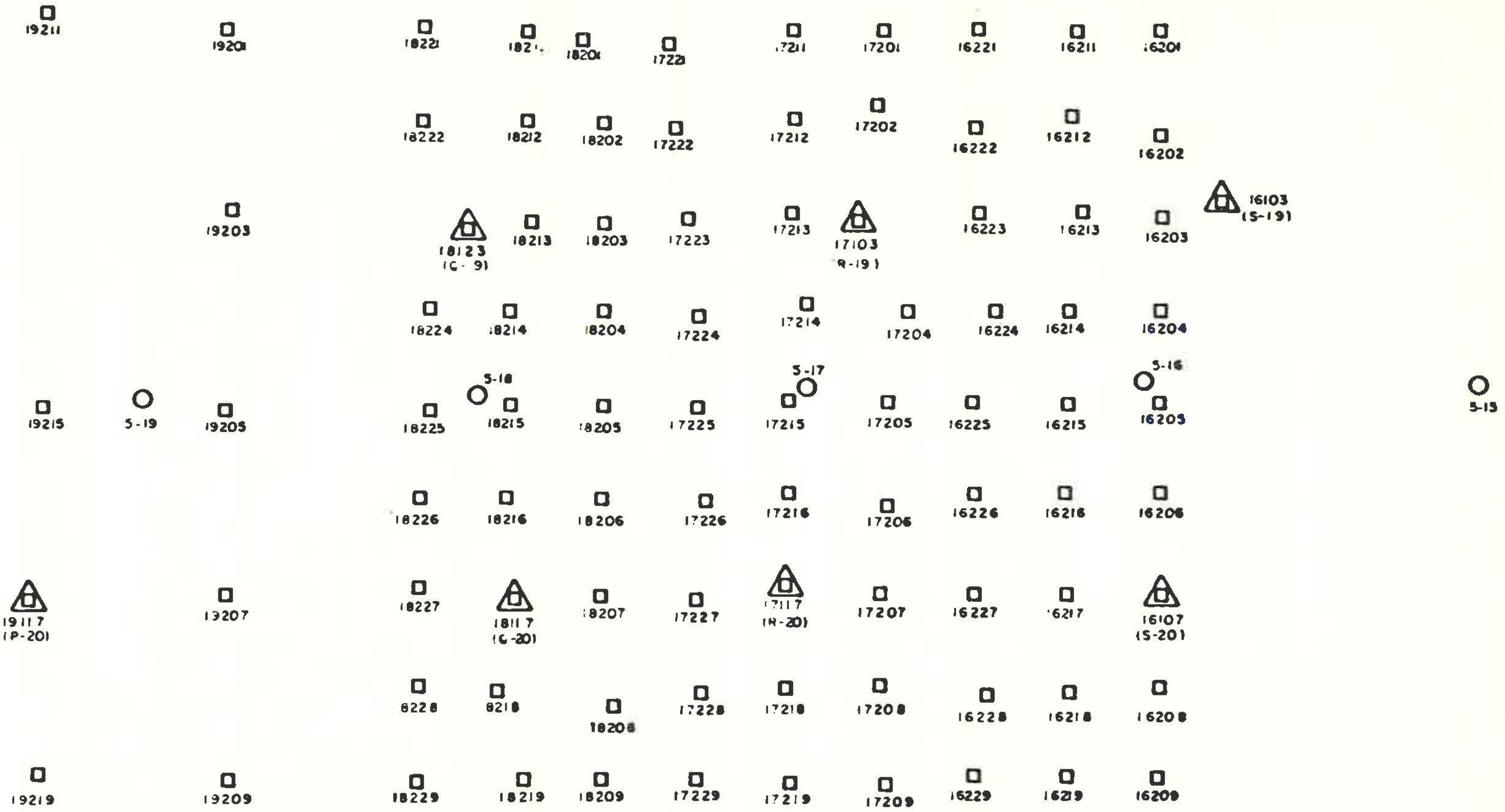
The control layout of the area was designed for photogrammetric use and was established as a joint effort of the Army Map Service and the U. S. Geological Survey. Two of the models of this strip are each controlled by 4 horizontal control stations and over 40 vertical control stations. These approximately cover the full extent of the models and are nearly ideal to study the elevation errors in the entire model area. All control was targeted in advance of photography using targets which were either 6 or 9 ft square.

The objectives of the test were to measure the inherent or residual errors in the RC9-AP/C system, and later to compare these results with those obtained from the RC9-Wild A7 system. The test was done with absolute orientation for each model in the high-density controlled area. This confined the error to within each stereoscopic model so as not to introduce any propagated error.

As a secondary step, the entire strip was done to test for propagated error in aerial triangulation. Actually, this is a small number of models for this test but it should show some pattern of error propagation, as the measurements were made to microns.

The diapositives for this test were printed with corrector plates for symmetrical lens distortion, for earth curvature, and for atmospheric refraction. The latter corrector plate used was for a flight height of 10, 000 ft, whereas, the actual flight height was 5, 000 ft. A computer correction was thus made in the AP/C system to compensate for this over-correction of the plate.

The photographs were prepared for these tests in the following manner. First, a row of three pass points were drilled approximately on a line normal to the flight line through the photograph center. A templet was used to maintain some symmetry in the



LAYOUT FOR TEST STRIP
AMS ARIZONA TEST AREA
Approx. Scale - 1:17,000
CONTROL BY AMS, USGS
Photography _ RC9 Camera_USGS

LEGEND

△ HORIZONTAL AND VERTICAL STA.
☐ VERTICAL STA.
○ PHOTOGRAPHS

(NUMBERS FOR CONTROL ARE PROGRAM CODE

location of these pass points. Coding of the photograph points was made by using a 5-digit number as follows: first two digits for the number of the photograph on which the point was identified, the next digit used for classifying the point, and the last two digits to denote the serial number within these groupings (Fig. 4).

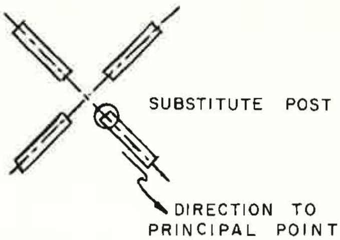


Figure 5. Substitute fiducial mark.

INTERIOR ORIENTATION

The interior orientation on the AP/C is the first step in the photogrammetric solution. The operator is "led" by the computer in a semiautomatic routine to the vicinity of each fiducial mark where the coordinates are manually measured and stored in the computer. From this, the computer unit determines the centroid of the measurements and furnishes the operator a display of coordinates for each mark.

Corrections affecting the images (the photographs), which are handled as part of the interior orientation problem, are lens distortion, film shrinkage, earth curvature, atmospheric refraction, and principal point offset.

For calibration in this test, a master glass negative was used which was exposed in the laboratory to show only the fiducial marks in their correct relationship in the camera. Using this, a set of 5 measurements on each leg of the fiducial marks, and 5 measurements on the substitute marks were made. The equation for the mean line defined by opposite legs of the fiducial marks were determined by a least-squares procedure using the 10 observations. The intersection of the lines was obtained by the simultaneous solution of the two equations.

The principal point of the photograph is generally the origin of the photograph coordinate system and is determined by the intersection of the lines connecting opposite fiducial marks. But in the AP/C system the centroid of the fiducial marks is determined in interior orientation. Thus, it is always necessary to determine the offset of the principal point from this centroid position. In this test, the principal point offset from the centroid of the substitute fiducial system was determined (Fig. 5).

FILM DISTORTION

Film distortion is corrected in the AP/C by maintaining the relative dimensions in the photograph coordinates by use of ratios of measured to calibrated coordinates for the fiducial marks. A constant for correcting for differential film shrinkage is computed for each photograph. It is based on the ratio of measured values between X and Y coordinates, to the ratio determined by the calibration routine, as outlined earlier. The correction is applied only to Y coordinates, which brings them to the correct ratio with the X coordinates. Some further change in coordinates is possible with the b_Z element; however, this introduces incorrect geometry in the photograph and could have a systematic effect in the aerotriangulation. A better procedure would be to change the focal length of the cameras. The measured increments in coordinates of fiducial marks could give data for this. Then the focal length entered in the computer would be

$$f = \frac{(\Delta X) + (\Delta Y) \text{ (measured)}}{(\Delta X) + (\Delta Y) \text{ (calibrated)}} \cdot f \text{ (calibrated)}$$

The data for computing film distortion correction are obtained at the centering phase of interior orientation. The computation is done by desk calculator for each photograph of a strip and is based on the Δx's and Δy's between the measured fiducial marks of the photographs.

LENS DISTORTION

In the AP/C system, corrections for lens distortion are computed by use of a stored function table, whereby, the distortion is expressed as a function of the radial distance from the principal point of the photograph. The correction equations are

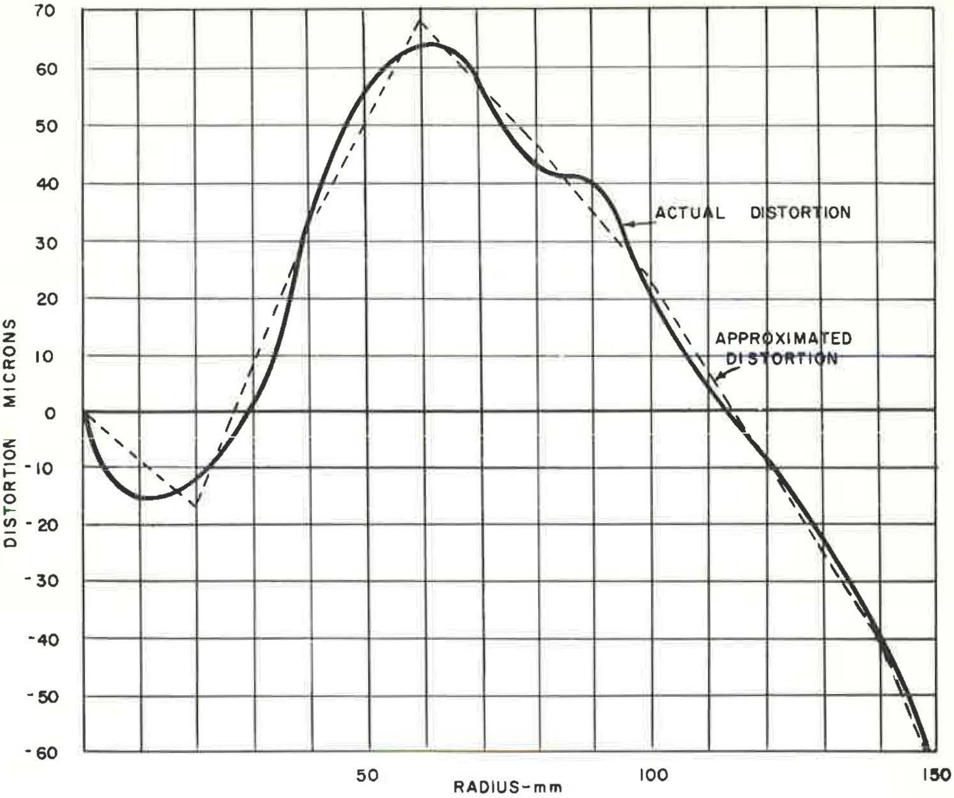


Figure 6. Distortion curve with approximation for AP/C.

$$\text{In } x : \Delta x_L = x \cdot d\,(r/D)$$

$$\text{In } y : \Delta y_L = y \cdot d\,(r/D)$$

where

r = the radial distance,
D = a scale factor,
x, y = photograph coordinates, and
d (r/D) = the distortion function.

Corrections are applied only for symmetric radial distortion, asymmetric and tangential distortion being ignored. Figure 6 shows the actual calibration distortion curv for this test and the series of linear approximations as used by the computer.

The method of approximating the lens distortion function might introduce a slight systematic error. The linear segments in this example generally approximate the actual graph (mean curve) within about 5 μ. It is more significant that camera No. 36 (used in this test) had asymmetric distortion as great as 20 microns. These distortio cannot be corrected with the present procedure of the AP/C. Also possibly significant are distortions related to errors in the principal point offset.

EARTH CURVATURE AND ATMOSPHERIC REFRACTION

The distortions resulting from earth curvature and atmospheric refraction are removed by correcting the stereoscopic model coordinate E_m (Figs. 3, 7 and 8). The distortions are corrected using the line of camera station to nadir point as reference and in shifting the direction ray to the corrected E_m in model space.

The corrections in each case are applied using model scale. Here, a scale factor S_G is entered initially during interior orientation which sets up a table of parameters for the correction equations. The earth's radius and the flight height are reduced to model scale.

The correction (of negative sign) for earth curvature (Fig. 7) is computed using the radial distance in the photogrammetric model.

Atmospheric refraction is similarly computed in model space but using the lens-nadir line for reference (Fig. 8). The equation (1) used is

$$D_{mi} = \left[A_i - B_i \cdot E_m + f\,(E_m)\right]\left[1 + \tan^2\theta_{ni}\right]$$

where

$$f\,(E_m) = LE_m{}^2 + ME_m + N$$

$$\tan^2\theta_{ni} = \left(X_{ci}{}^2 + Y_{ci}{}^2\right)/Z_{ci}{}^2$$

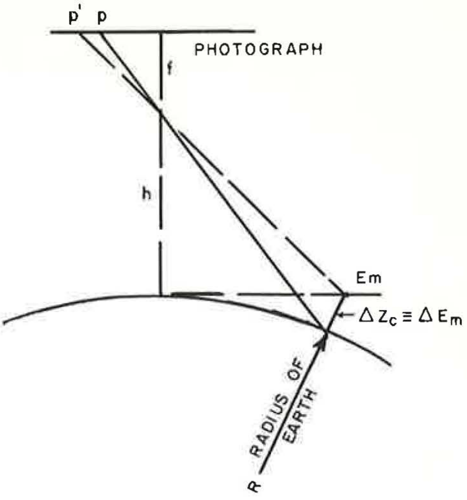


Figure 7. Earth curvature effects.

The correction terms are computed by a stored computer program. The parameters A, B, L, M and N are based on a standard atmosphere. The function f (E_m) is the parabolic representation for the refraction effect due to the ground elevation as shown by Laurila (14). The angle θ is the angle between the directions to the nadir and the model point.

Both the atmospheric refraction and earth curvature corrections are combined with the b_z to give the model correction term (1), from which a corresponding shift in the photographic image point is computed.

$$\Delta Z_{m_i} = \Delta D_{m_i} + \Delta Z_{c_i} - b_{z_i}$$

USE OF CORRECTOR PLATES

The use of corrector plates to correct for distortions for lens, earth curvature, and atmospheric refraction has limitations. To economize, agencies operate with a number of plates covering minimum flight height increments. Thus for this test, the corrector plate was for a flight height of 10,000 ft, whereas the actual flight height was 5,000 ft. Such an application introduces significant systematic effects which were corrected for this test.

The residual effects from use of the corrector plate were computed and entered as corrections to the lens distortion curve (Fig. 6). This is a valid, though simple, procedure for near-vertical photography but it might introduce a significant error for convergent photographs. It is readily apparent from Figure 9 that the effects were very significant for this case.

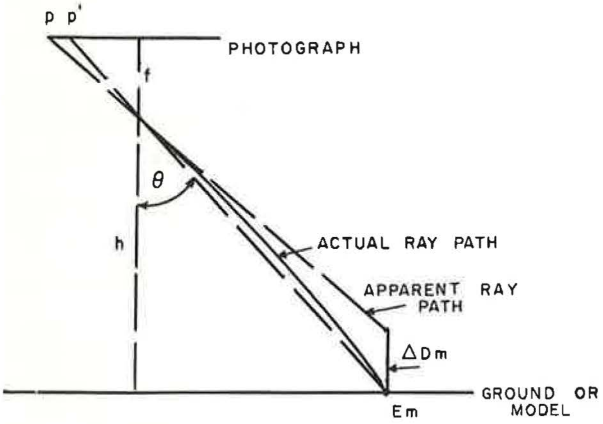


Figure 8. Atmospheric refraction effects.

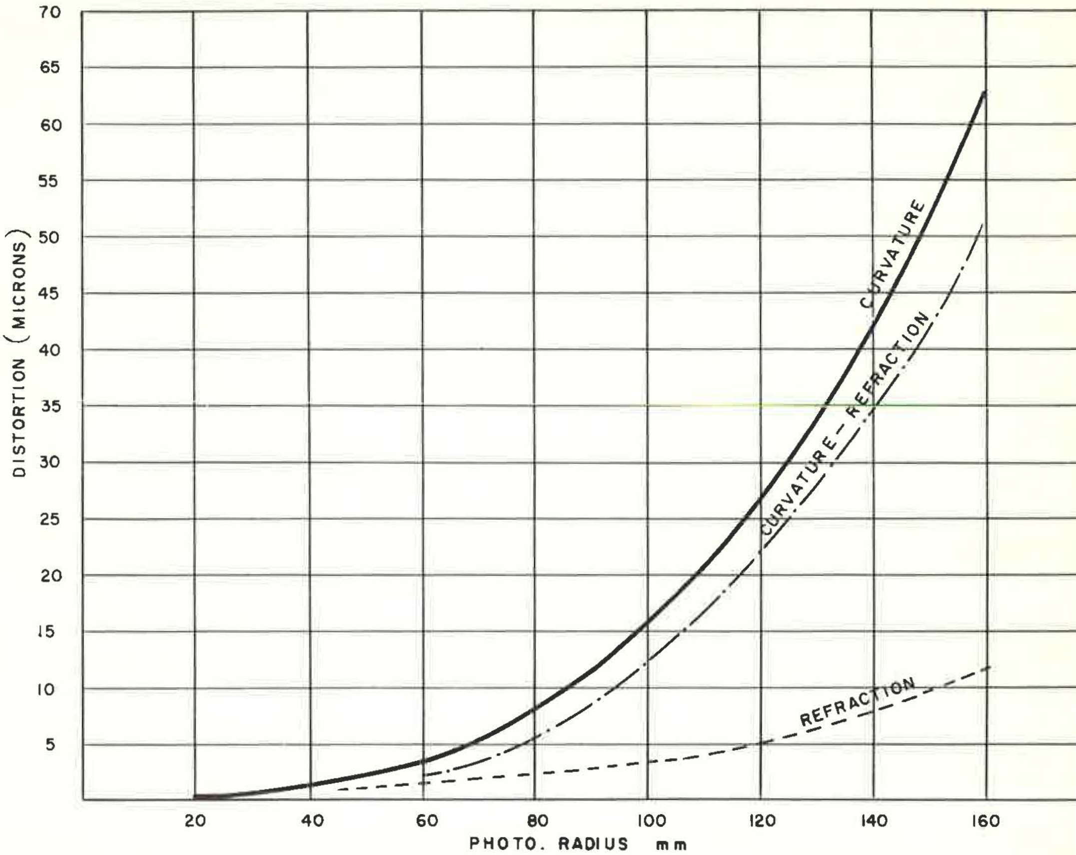


Figure 9. Residual effects from improper corrector plate.

Of further significance in this test example are the residual errors in the use of the corrector plates themselves. Based on some calibration data of the U. S. Geological Survey in which grids were used, these residual errors are as large as 15 μ. Such corrections can be made in the AP/C if calibration data are available.

RELATIVE ORIENTATION

The solution of relative orientation in the AP/C supplies a set of corrections for u dating the orientation elements for one or both of the photographs of the stereoscopic pair. These corrections are obtained by an iterative procedure employing a least squares solution with parallax data from six points (Fig. 10).

The computation procedure requires an input of scaled values for b and d and focal length. A single set of these values will suffice for an individual strip but a separate program tape is required for the "base-in" and "base-out" modes of operation.

Each numerical orientation computation is practically an instantaneous operation with the AP/C and is a very convenient facility. It requires rough approximate orientation to begin the solution and this is best handled by the operator using similar pr cedures as with other stereoscopic plotters. The corrections, however, are applied by the computer to the orientation element selected by the operator. (Since this test, procedures for relative orientation and absolute orientation have been revised.)

ABSOLUTE ORIENTATION IN THE AP/C

The absolute orientation, comprising scaling and leveling the model, is accomplished using a least squares technique. It requires at least three control points, all with X, Y and Z coordinates, but it can have a possible input of many control points. In order to prevent an overflow in the summation of coefficients for the normal equations, the practical upper limit of the number of control points is 30. In operation, the ground coordinates must first be reduced to the working model scale.

The program, as at present, seems limited on the minimum condition because it does not provide for inclusion of partial control—that with only horizontal (plan), or only vertical (elevation) coordinates. However, the instrument operator can level the stereoscopic model by conventional methods. For this the automatic computer is not to be used initially.

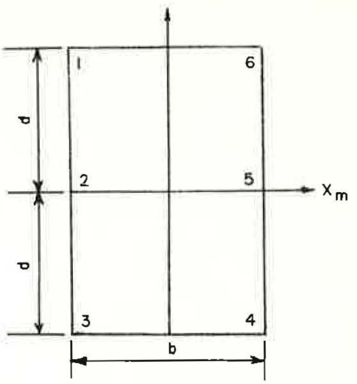


Figure 10. Designation of model points in AP/C system.

Absolute orientation does not comprise any translation of coordinates—the model coordinates get changed due to scaling and leveling but they remain in the same model system as before absolute orientation was begun. Next, the model may be translated n elevation by applying a common b_z correction through the operator's panel.

There is no printout or display of residuals from absolute orientation but the operator has an excellent facility to test his results. He can initialize "D" scale to the No. 1 control point and directly obtain a model distance, to microns, to any other control point. This value is then compared to the previously computed distances. (Since this est, procedures for relative orientation and absolute orientation have been revised.)

TEST OF PROCEDURE

Two adjacent models 16-17 and 17-18 each had four control points (for both planimetry and elevation) and about 40 additional vertical control points (Fig. 4). These were well distributed in the model to furnish data on the elevation accuracy of the system. Measuring the points in individually controlled models did not introduce any propagaion of error as might occur in strip triangulation. Thus, it furnished some measure f the inherent accuracy of the system. One of the models was measured twice with different operators so as to furnish a comparison and to validate the program.

RESULTS OF ORIENTATION TEST IN AP/C

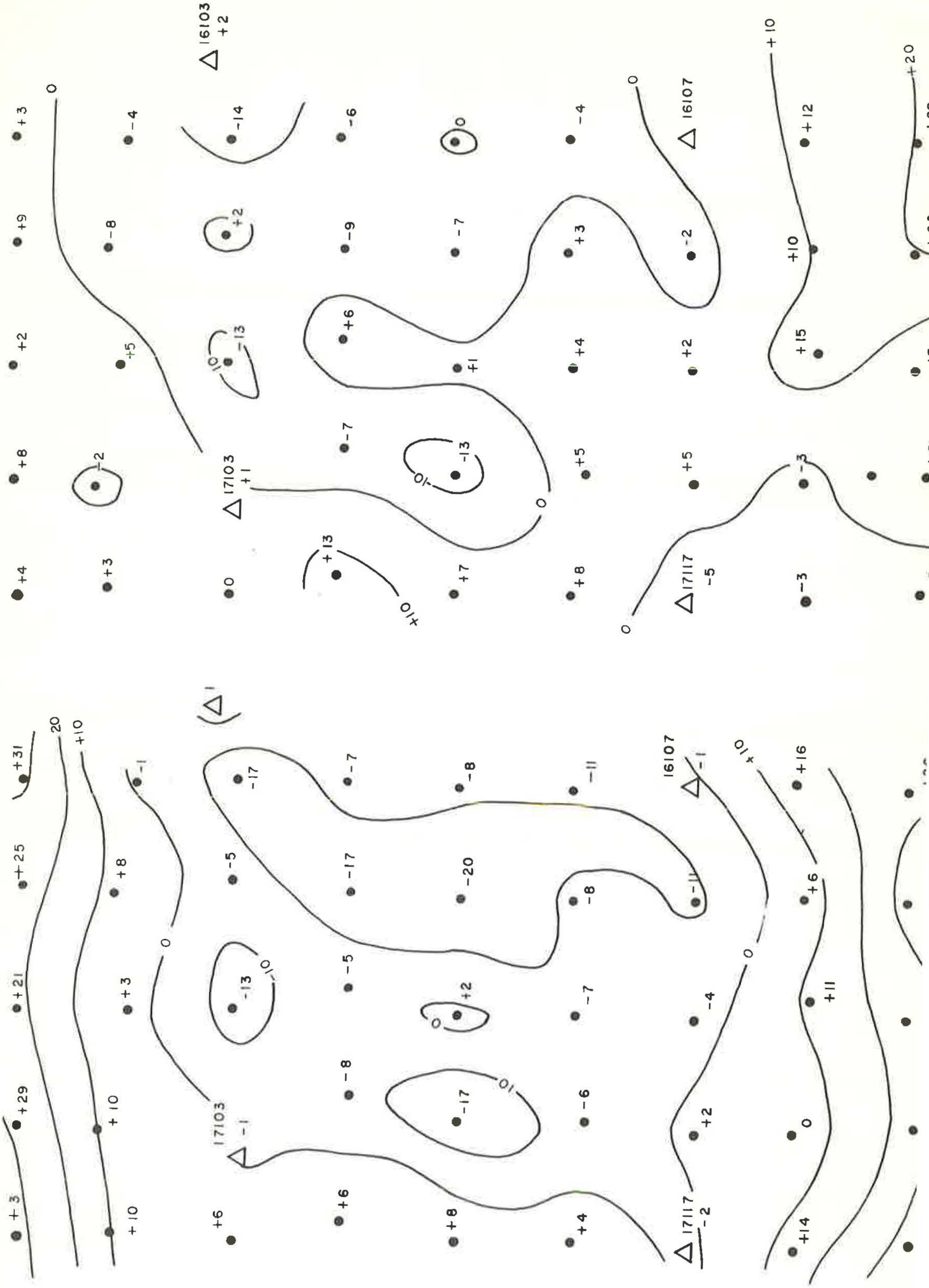
The stereoscopic model scale was 1:17,200. Only elevation errors were considered or this test in absolute orientation.

A comparison was made in the two sets of measurements of model 16-17. The standard deviation m from the mean, for a single measurement of these two sets, is $\pm 3.7\mu$ where $m = \pm\sqrt{([dd]/2n)}$ and d is the difference between sets). The differences were andom. Thus, the m of 3.7μ indicates a reliable value for the standard error of obervation for a single observation.

Another similar comparison was made for a partial set with 28 points of the same model, by the same operator, on different days (the partial set resulted from computer malfunction). Here the standard deviation from the mean was $\pm 3.1\mu$.

The models were then examined for closure to control. The model measured withut any corrections entered in the AP/C, or with the partial corrections for distortions y use of the corrector plates in the printing process, showed a remarkable systemaic pattern of distortions (Fig. 11).

The standard deviation to control (misclosure at control points) was 16μ. The aplication of further corrections in the AP/C much improved this pattern (Fig. 12) with he standard deviation of about 8μ.


16103
+2
16107
17103
+1
17117
-5
17103
-1
17117
-2
16107
-1
0
+10
+20
-10
20

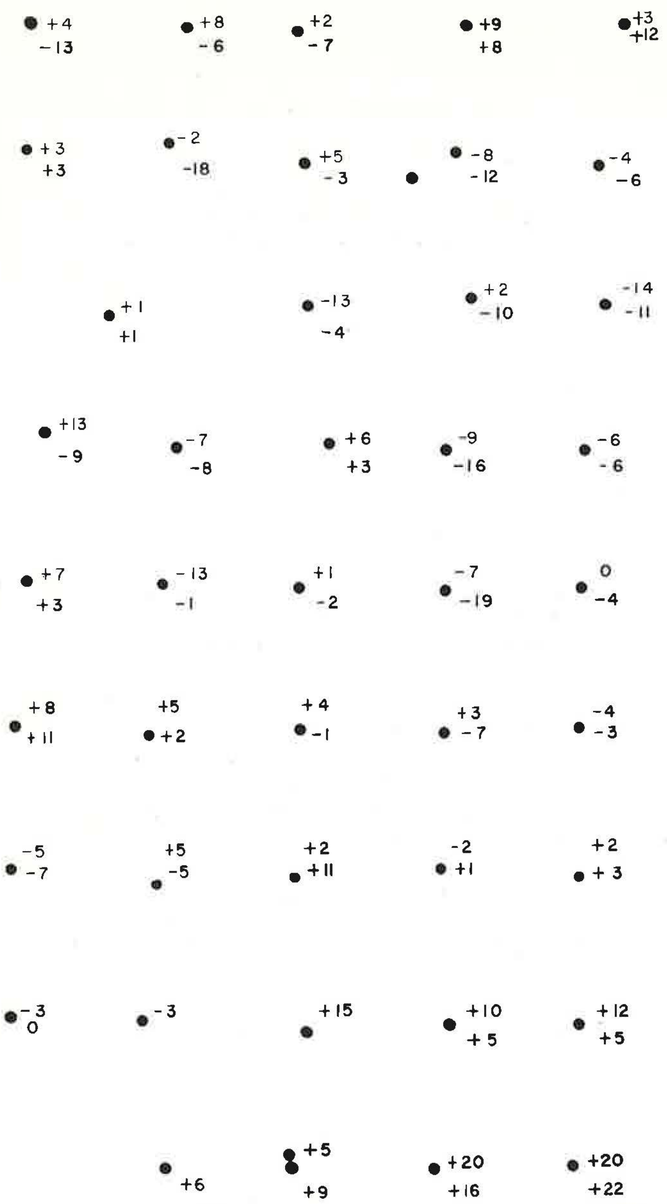


Figure 13. Comparison of errors in different models; the upper values are model 16-17 and the lower values are from 17-18—all values are in microns in the model scale.

The juncture of adjacent models was at times rather poor, with differences as great as 25μ. However, if the models are superimposed by fitting the rectangular patterns of control, the correspondence of error pattern is remarkable (Fig. 13). The pattern is noticeably asymmetric. This pattern also prevails in the aerial triangulation adjustment. Thus, to minimize the propagation of errors, the junctioning of models should be weighted to favor points at the center axis of the photographs.

STRIP TRIANGULATION ON AP/C

Aerialtriangulation procedures with the AP/C closely parallel those with a first-order, optical train, analog instrument. Base-in and base-out models are achieved by a single switch located just above the operator's control panel. Junctioning of models is done by first setting the E_m for a common point by the footwheel. The measuring dot is then brought to ground level in the model by changing the b_x element by means of the incremental switch. These steps are done after dependent relative orientation is accomplished.

The adjustment program used is that of the Coast and Geodetic Survey as amended by Horsfall (11). To conserve computer storage, a ceiling is imposed on the number of control points for adjustment, 5 for horizontal and 7 for vertical. Thus, the selection of these stations should be made with care to obtain the best solution. The factors to strive for are an even distribution along the strip and one covering the extremes of the strip. Although the first stereoscopic model is controlled absolutely in scale, it should not be heavily weighted in the solution as it might introduce an erroneous slope in the polynomial adjustment curve.

Formulas used in the adjustment are

$$x' = x - \Delta z\ (21x + J) + Ax^3 + Bx^2 + Cx - 2Dxy - Ey + F$$

$$y' = y - \Delta z\ (Lx + M) + 3Ax^2y + 2Bxy + Cy - Dx^2 + Ex + G$$

$$z' = z\ [1 + (21x + J)^2 + (Lx + M)^2]^{1/2} + Ix^2 + Jx + Lxy + My + N.$$

Here, x', y', z' are the newly transformed (or adjusted) coordinates; x, y, z are strip coordinates transformed to an axis-of-flight system.

Δz is the increment in the z-coordinates of a point from the reference datum of the strip.

x', y', and z' must undergo an inverse transformation (translation, rotation, and scaling) to ground coordinates. The coefficients A, B, C, . . . , N are the parameters of the transformation and are determined for the strip from the control stations.

The test strip comprises only four models with control (Fig. 4). The strip was can tilevered by adding successive models by coorientation (i. e., dependent relative orientation and scaling). A close fit to 3 transfer (tie) points generally could not be achiev because a large amount of systematic error was evident. So, scale transfer was mad by using the center tie point with an approximate fit to the other two points.

The closures to control before adjustment are shown in Figure 14. Very little propagation of error is evident; only 44μ in planimetry and 29μ in elevation. The pattern o systematic effect is evident.

The closures to control after adjustment are shown in Figure 15. The standard deviations to control at stereoscopic model scale of 1:17, 200 were as follows:

in x: ±4μ
in y: ±6μ, i. e., ±7μ in planimetry
in z: ±10μ

It is evident that the NW corner of the strip was improperly controlled. So, for el vation a separate adjustment using the method by Brandenberger (2) was performed wi 9 control points. This resulted in a standard deviation of ±7μ in $\bar{z}$.

AERIAL ANALOG TRIANGULATION AT THE WILD A7

With a view to study the workability of SWA photography at a stereoplotter, not equipped for this kind of photography and with a view to compare the results with those obtained from the AP/C, the same test strip was triangulated at the Wild Autograph, model A7 in the Ohio State University, Department of Geodetic Science. The aeropolygon method of aerialtriangulation was performed in this case.

The calibrated focal length 88. 23 mm cannot be introduced into the projector camera of the Wild A7 because the range of focal length column here is 98 to 215 mm. In this case a focal length of 105. 88 mm was used. This means that an increase of 1/5 times the actual (88. 23 mm) is used. The photography being vertical (i. e., the camera axis

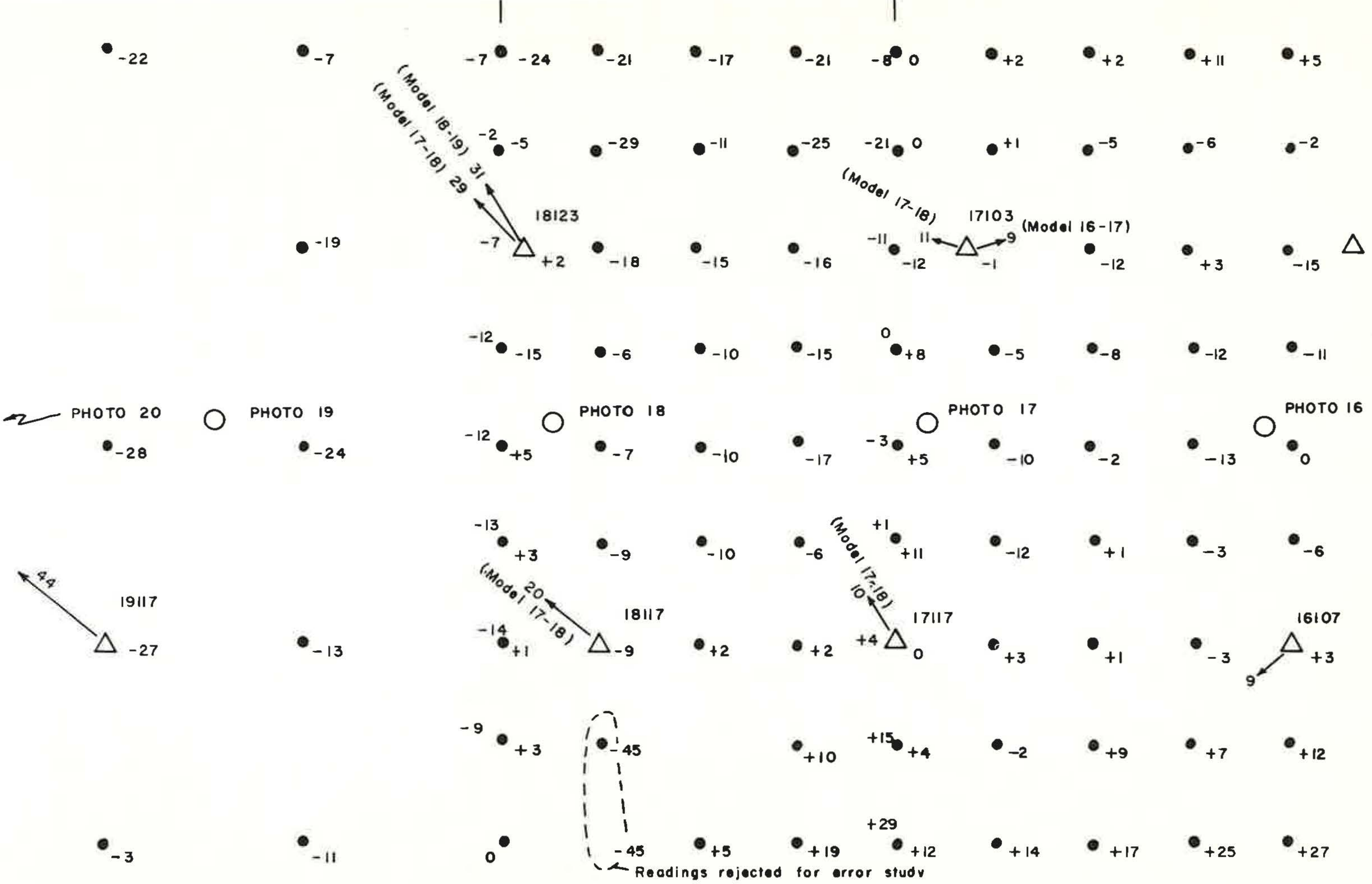


Figure 14. Aerialtriangulation closures to control before adjustment (horizontal misclosure shown at arrowheads, others are vertical misclosures; all values are in microns at scale of the model).

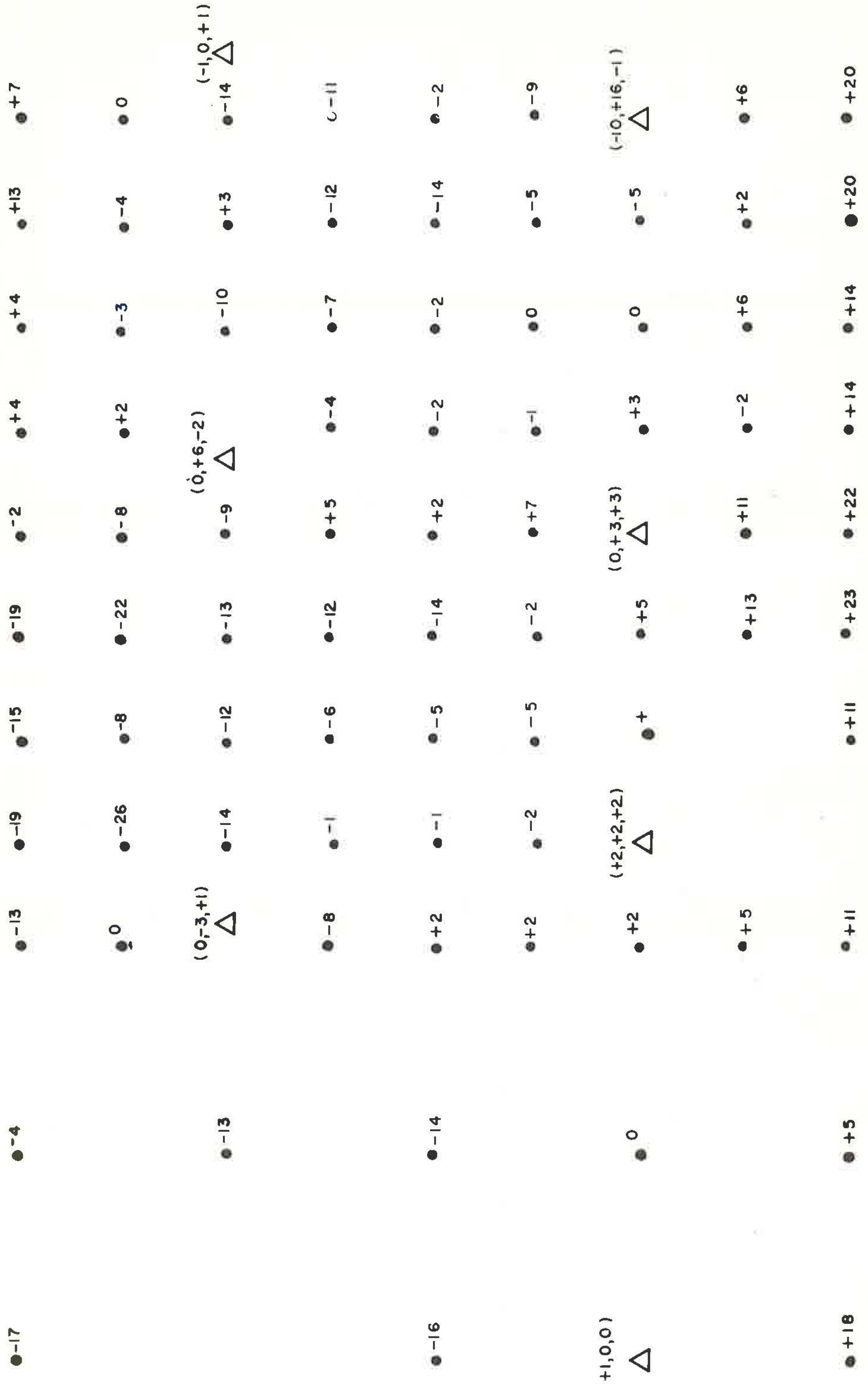
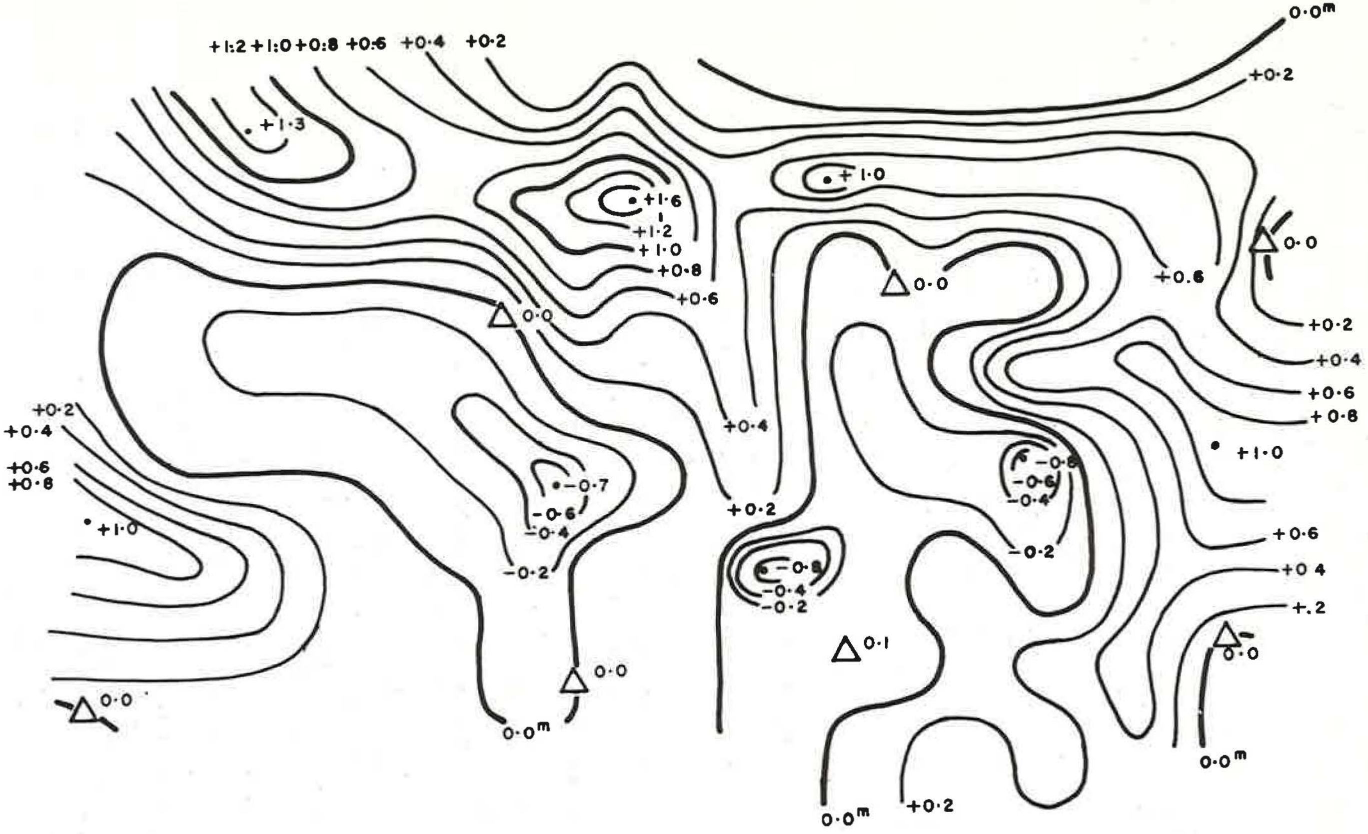


Figure 15. Aerialtriangulation closures to control after adjustment.



Interval : 0.2 m Scale 1 : 34000

Figure 16. Elevation differences between A7 and AP/C, in meters.

being nearly coincidental with the Z-coordinate direction) this increment in the focal length of the cameras would cause an affine deformation in the stereomodels. Thus, the planimetric coordinates (X and Y) will have a scale different from that of the eleva tion coordinate (Z) which in this case is enlarged by 1/5 times.

The least count of the coordinates in the model was 0. 01 mm. Further, each coor dinate was measured in two rounds of observation. Considering that the model scale, 1:6, 000, was approximately three times the scale of the photograph (i. e., the same a the model scale in the AP/C) it may be considered that the measuring accuracy of all the coordinates was about the same (±3μ) in this case as well as at the AP/C.

The relative orientation of each model was performed by the numerical method (6). After the relative orientation was performed the residual y-parallaxes were measure at 8 different locations in each of the 5 models. From these 40 observations was com puted the standard residual error in y-parrallax which was ±0. 019 mm. This reduce to the photograph scale approximately ±0. 006 mm, i. e., 6μ. This is reasonably goo for any analog system.

The observed coordinates (X, Y and Z) were next reduced to the ground system by performing linear transformation based on the ground coordinates of points 16107, 19117, 16103 and 17102 (Fig. 4). Only at this stage could the closing errors be found in the observed coordinates at the points. An analytical-graphical method of adjustment was performed for each of the coordinates.

The adjusted ground coordinates of all points in the strip were compared to those obtained from the AP/C. The standard deviation between the AP/C and A7 (adjusted) data are as follows: in X, ±0.14 m; in Y, ±0. 98 m; and in Z, ±0.14 m. The differen in elevation are shown in Figure 16.

It may be pointed out that in the Wild A7 no attempt was made to compensate for th residual errors in refraction and earth curvature. It is also apparent that those effec were of little consequence in this test. (General note: Since this test was done, the procedures for relative orientation and absolute orientation have been revised.)

CONCLUSIONS

Although the test and outlined procedures were limited in amount of data and in co trol of error sources, some conclusions are evident:

1. Very high quality measurements can be obtained with the AP/C system. Measu ments could be further improved by calibration of the comparators and other allied photogrammetric components of the system. In fact, the test demonstrates the value of accurate calibration data.
2. The AP/C analytical system provides a means to measure and control systema errors in the photograph. Thus, in this test, the standard deviation was reduced one half that with the corrector plate.
3. Results with the AP/C system, both in absolute orientation and in aerial triang lation, were superior to those that could normally be expected by an analog system.
4. SWA photography can produce very high quality results with the AP/C. Thus, the standard deviation to vertical control was less than ½ ft with 1:17,000 scale photographs.
5. The test with the Wild A7 indicates that the SWA can be handled satisfactorily i analog instruments for normal aerial stereophotogrammetric mapping when affine deformations are properly corrected. However, this has not been validated with double projection type instruments such as the Kelsh stereoscopic plotter.
6. The test was considered adequate to validate the AP/C system for SWA photography. It might be more feasible to perform aerial triangulation with the AP/C to yie control for compilation instruments. Also, possibly the orientation elements for com pilation instruments can be readily obtained in this procedure (15). The need for mor testing is indicated for these procedures.

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