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FOREWORD

This RECORD presents an interesting variety of problems in highway design and operation and offers several examples of innovational solutions to those problems. The papers included illustrate how decision-making can be made easier and with more confidence through the use of new techniques in preliminary design and operation.

Two of the papers deal with the use of graphic arts techniques. Berrill and Feeser describe the photo-computer plot montage, a composite picture made up of a computer-drawn perspective and a photograph. There are several systems for producing highway perspectives, but the entirely machine-drawn view does not realistically picture the highway in its environment. The montage allows the designer to evaluate the roadway as it will actually appear against the backdrop of existing landscape and vegetation. Photographs may be taken at random and used later by photogrammetric resectioning. Smith and Holmes demonstrate the use of highway design scale models and offer the results of tests concerning appropriate horizontal and vertical scales to use in preparing such models. The design models discussed are partial interchange and alignment models without cosmetic details. The paper also investigates some of the methods and equipment recently developed in model preparation and use.

The other two papers deal with specific problems of highway design and operation. Heimbach, Khasnabis, and Chao point out the need for a method to determine where no-passing zone spot improvements can be made economically to increase throughput traffic service. They investigated the relationships between the independent variables of traffic volume and percentage of no-passing zone restrictions in a given length of highway and the dependent throughput variables. Investigations of one or several spot improvements can be made with a computer simulation model to assist in making the decision on where and how funds should be expended to make no-passing zone spot improvements for maximum cost-effectiveness. Weaver, Marquis, and Luedecke discuss the importance of selecting the proper ditch and side slope characteristics to improve out-of-control vehicle traversal of the ditch. The research method used to investigate the results of various ditch characteristics was to conduct full-scale testing of off-the-road operating characteristics of a vehicle and then to compare the test results with predictions made using the highway-vehicle-object simulation model, a computer-simulated vehicle. The results of the full-scale tests and the modeling were used to suggest desirable and maximum ditch characteristics for safe vehicle operation.

There is no question that continued research into new design techniques will greatly benefit design decision-making quality. The papers included in this RECORD are clear illustrations of the advantages of continuing the search for new tools in preliminary design.

—B. H. Rottinghaus

PHOTO-COMPUTER PLOT MONTAGES FOR HIGHWAY DESIGN

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A photo-computer plot montage is a composite picture made up of a computer-drawn perspective and a photograph. The purpose of the montage is to depict a proposed construction work, in this paper a highway, as well as its surroundings as it will appear when completed. It is the contention of the authors that, although a perspective drawing or an artist's sketch may not be detailed and extensive enough to be used for aesthetic judgments, the photo-plot montage is; and, with the system described, which introduces photogrammetric resectioning as a means of finding the photograph perspective parameters, photo-montage is brought within the reach of the design engineer for everyday use.

•AS THE SCALE of engineering works increases, so does the visual impact they have on their surroundings. The modern highway, with its high-speed alignment and wide carriageway, is, of necessity, a massive structure that tends to dominate all but the most rugged scenery.

The highway engineer should evaluate carefully the finished appearance of his design and its harmony with the landscape. He needs visual aids to depict the finished work and its surroundings for his own work in design and also for presenting his design to others.

Over the past few years much effort has gone into the development of computer systems to make perspective drawings. A number of fields, including mathematics, molecular chemistry, flight training, and, quite notably, highway engineering, now use computer-generated perspectives more or less routinely. The linear form of a highway lends itself to this process, and, when terrain and design data are already available from an automated design process, perspectives can be generated readily and economically. A drawing can be computed from the terrain and template data, from a specified perspective center and direction of line of sight, and drawn by incremental plotter or projected onto a cathode ray tube (CRT).

Several researchers (1, 2, 3, 4, 5) have systems for generating highway perspectives. Of these, Godin et al., using the TE.GI program (4), and the joint Federal Highway Administration-University of Colorado group (5, 6, 7) have also made animated movies by photographing a succession of views drawn from a moving "driver's eye" viewpoint.

However, the entirely machine-drawn view is not complete enough to realistically picture a highway and its surroundings. It is in fulfilling this needed environmental role that the photo-montage has promise. A photograph of surrounding terrain (Fig. 1) can be merged with the machine-drawn perspective of the construction (Fig. 2) to form a photo-montage of the completed work (Fig. 3).

The problem in making the montage is to match the two component pictures without relative distortion. This requires that both have the same scale, perspective center, and line of sight. Inasmuch as these three parameters are required data in the computer generation of a perspective, it is necessary to determine them for the photograph to be used in the montage. This can be done in two ways. First, the photograph can be taken by phototheodolite, with the parameters measured by careful surveying for each photograph. This procedure has been used successfully in a University of Tokyo system and has been described by Nacamura (8).

Figure 1. Photograph of existing terrain and old highway, Colo-7.

Figure 2. Computer-generated perspective.

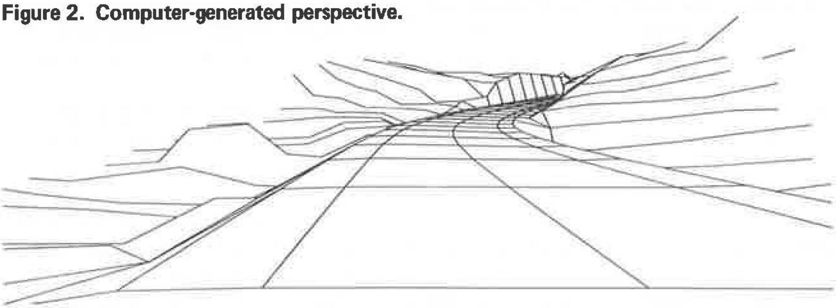


Figure 3. Montage of Figures 1 and 2.

A second method, developed at the University of Colorado (9), allows photographs to be taken at random and the perspective parameters recovered later by photogrammetric resectioning. Resectioning requires only that the position of three well-defined points in the photograph be known. This approach allows much more freedom in selecting views and reduces the capital investment and field time required to produce montages. The authors believe that this development brings photo-montage within the reach of the practicing engineer. The steps in the Colorado process are shown in Figure 4.

MATCHING THE PERSPECTIVE AND THE PHOTOGRAPH

Exact matching of the two component parts of the montage is achieved, excluding lens and film distortion, if they have the same scale, perspective center, and line of sight. These terms are defined in Figure 5, which shows the geometry of the perspective projection. The position of the perspective center and the orientation of the picture plane, described by the direction of the line of sight, which is normal to it, determine the perspective of the drawing. The scale is directly proportional to the focal length, which is the distance between the picture plane and the perspective center. Thus the perspective and scale of the drawing are completely described by the three parameters: focal length, perspective center, and line of sight. They also serve to describe the identical geometry of the photograph.

Acceptable tolerances, to produce a satisfactory montage, must be established for each of these three fundamental perspective parameters. These tolerances will then be used as a standard for the resectioning program.

Errors in scale do not present a practical problem, inasmuch as the focal length of the photograph is generally known to sufficient accuracy for a particular camera. If not, it can be determined as an additional unknown in resectioning. Small errors in the line of sight also cause no difficulty. It can be shown (9) that, for a photograph of focal length f and with an angle $\delta\alpha$ between the two lines of sight, an image displacement Δ_{max} given by

$$\Delta_{max} = 1.16 f \delta\alpha \tag{1}$$

is produced. Consequently, for a large error of 1 deg in the line of sight, the resulting maximum image distortion on an 18- x 24-in. enlargement (f = 25 in.) is 0.05 in., which is tolerable.

However, the montage is quite sensitive to errors in the perspective center coordinates. It can be shown (9) that an error in the perspective center in a direction transverse to the line of sight, say the x-direction, will produce an image displacement Δ_x in the corresponding x-direction in the photograph. Image displacement is also produced in points off the line of sight by an error in the perspective center in the direction of the line of sight, the D-direction, but to a lesser extent. The total image displacement in the x-direction is given by the expression

$$\Delta_x = \frac{f}{D} (\delta C_x + \beta \, \delta C_D) \tag{2}$$

where

D = distance to the object point in space,
δC_x = perspective center error in the x-direction,
δC_D = perspective center error in the direction of the line of sight, and
β = angle subtended at the camera by the object point and the line of sight.

β is limited by the camera field of view to about 20 deg or approximately 0.35 rad. Thus, the contribution of an error along the line of sight is limited to, at most, about one-third of that due to the same error in a transverse direction. Also, inasmuch as the distortion is inversely proportional to the object distance, the foreground will be affected much more than distance points. For example, an error of 1 ft in the x-direction would cause distortion of $\frac{25}{50} \times 1 = 0.5$ in. in the image of a point 50 ft distant

Figure 4. Photo-plot montage system.

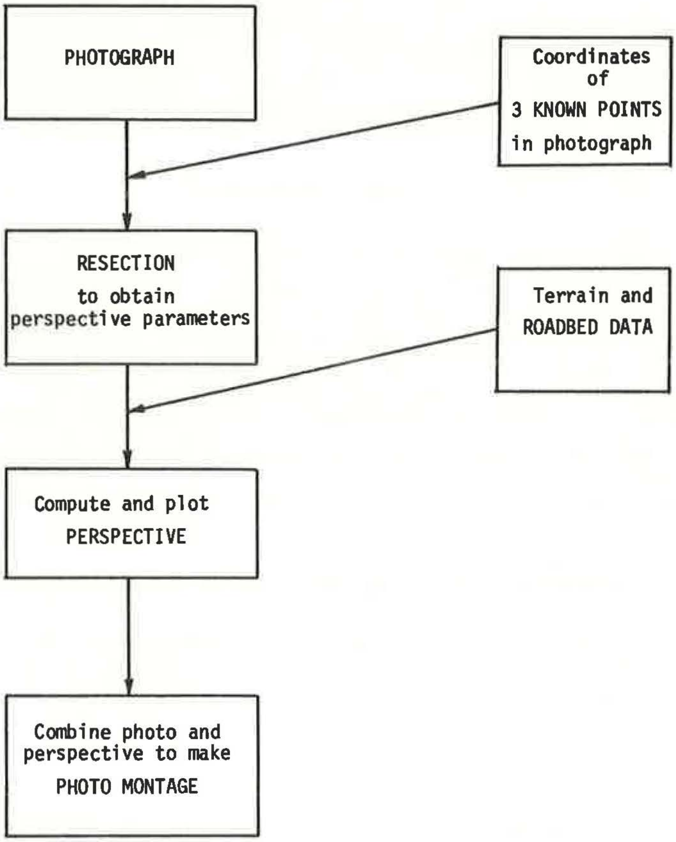
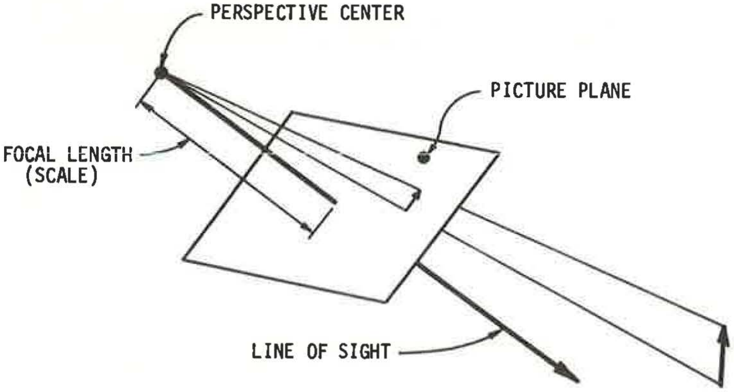


Figure 5. Perspective projection.



but only $\frac{25}{500} \times 1 = 0.05$ in. in the image of a point 500 ft distant. This accentuation of foreground distortion is partly compensated for by the eye, which is more critical of mismatching in the distance than it is in the foreground.

From the foregoing, it would seem reasonable to propose the following tolerances: line of sight, ± 1.0 deg; and perspective center location, ± 0.5 ft transverse to line of sight and ± 2.0 along the line of sight.

THE PHOTOGRAPH

The photographs shown were taken on glass plate negatives using a Wild P-30 theodolite in order to eliminate film and lens distortion as variables while developing the system. However, such a high-precision camera and film are not necessary. A $2\frac{1}{4}$- x $2\frac{1}{4}$-in. Rollei roll film camera, with a glass plate added to carry fiducial marks and to keep the film flat, has been used successfully in Sweden (10) for architectural mapping that required precision similar to that of photo-montage. Being able to use such a camera that is compact and easy to handle makes the method all the more attractive. In addition, montages have been made using a 4- x 5-in. sheet film camera with good results.

All the trial montages made used commercial 18- x 24-in. enlargements, and the resectioning points in the photograph were measured from contact prints by a vernier rule reading to $\frac{1}{1,000}$ in.

RESECTIONING

The procedure of calculating camera position and orientation from the known position of three points and their image in a photograph is called resectioning. It has been known in photogrammetry since about the turn of the century and has been widely used in analytical photogrammetry, particularly since the advent of the digital computer.

The coordinates of a point in space, the coordinates of its image in a photograph, and the position and orientation of the camera are related by a pair of equations, known as the projective transformation equations. Because there are six unknowns in the resectioning problem, three camera coordinates and three angles defining the line of sight, three pairs of equations must be solved simultaneously. Because these equations are nonlinear and involve trigonometric functions, the solution is not a trivial task.

In photogrammetry it is usual to take more than the necessary three points and use a least-squares method of solution. However, because the camera is much closer to the known points in the photo-montage application, a least-squares error reduction is not necessary. Newton's method of solving nonlinear equations has been used in the Colorado program (11).

Tests in typical photo-montage situations showed that, given normal surveying accuracy and provided the resectioning points are not bunched too closely together (as are the group of points shown in Figure 6), the camera position could be obtained to within ± 0.10 ft and the line of sight to ± 0.1 deg. These tolerances are well within those proposed above.

For a history of resectioning, the reader is referred to Doyle (12) and, for more details of the procedure, to any standard textbook of photogrammetry, such as Hallert (13).

COMPUTER-DRAWN PERSPECTIVES

The Colorado perspective programs (14, 15, 16, 17) take terrain and road template data in the form of the Federal Highway Administration's earthwork output (18), together with the perspective parameters obtained by resectioning. The perspective program generates a file of plot data that may be read by either a CRT display driver program or an incremental plotter driver to produce a pen-and-ink drawing. The known points are marked on the plot to enable it to be aligned with the photograph.

Completing the montage is then a matter of cutting off the areas of plot that do not depict new construction and pasting the plot over the photograph. Figure 7 shows a montage of the highway pictured in Figure 6.

Figure 6. Photograph of existing highway with resectioning points.

Figure 7. Photo-montage of Figure 6.

The cost of producing montages such as those shown in this paper includes a number of components whose individual costs highly depend on the particular organization involved and on the computer system used to perform the necessary computations. The following five components are identified:

1. Photographs that contain identifiable points on the ground;
2. Ground survey work to obtain coordinate information for the ground points;
3. Resectioning to obtain perspective-photograph information;
4. Cost of generating perspective view, including data file preparation, actual perspective generation, and plotting of perspective view; and
5. Fitting of the perspective plot to the photograph.

Our experience has shown that the computer costs using a CDC 6400 system range from $1 to $5 per view, depending on the availability of the needed design data files.

CONCLUSIONS

There is a need in highway engineering for graphic aids to depict the finished appearance of proposed highways. This need is heightened by the increasing concern in all quarters for environmental quality. With the use of resectioning to simplify and increase its versatility, the photo-montage system presented here goes a long way toward meeting this need.

Recently, some color montages have been produced, and it is obvious that the addition of color has made the process very valuable for communication with interested parties outside of the design group.

ACKNOWLEDGMENTS

This work was supported by the Federal Highway Administration, and the authors are grateful for the assistance they have received both from the Office of Development, Washington, D.C., and from Region 9, Denver. The computer programs described are documented and have been published by the Federal Highway Administration (11, 14, 15, 16, 17) and are available from the National Technical Information Service, Springfield, Virginia.

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RELATING NO-PASSING ZONE CONFIGURATIONS ON RURAL TWO-LANE HIGHWAYS TO THROUGHPUT TRAFFIC

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Because the roadway designer has no satisfactory technique to evaluate the traffic flow consequences of making selective passing sight distance improvements at spot locations on two-lane, two-way rural highways, a study was undertaken to investigate the relationships between the two independent variables (percentage of total length of a section of highway marked with no-passing barriers and the traffic volume input to the section of highway) and the dependent throughput variables (mean speed, speed variance, volume, travel time, and completed passes). Additional dependent variables investigated, but not verified with field observations, were attempted passes, delay, and speed change cycles. A digital computer traffic model is used to simulate traffic flow over 5- to 6-mile sections of highway at nine field locations in North Carolina. Volumes ranged from 175 to 650 vph. The model is calibrated to generate simulation throughput data that statistically match the throughput data observed at the field sites. The calibrated model is then used to analyze simulated systematic changes in no-passing barriers, over volume ranges of 175 to 1,200 vph. The conclusions are that the model is sensitive to these changes, as reflected by the throughput statistics, and that the dependent variables can be correlated with the independent variables in a statistically reliable manner, using multiple linear regression.

•TWO-LANE rural roads in rolling or hilly topography pose a problem for the motorist. Extended sections of restricted horizontal and vertical sight distance, coupled with inadequate passing opportunities, can make the overtaking and passing of slowly moving vehicles difficult or impossible. This type of highway environment not only promotes unsafe passing attempts by the driver but also tends to decrease average vehicle speed for the traffic stream. From the roadway designer's viewpoint, extensive no-passing barriers and the consequential inability of motorists to pass slower vehicles can cause reductions in throughput and level of service, while at the same time increasing delay, traffic interference, and accident potential.

The problem of up-grading a two-lane rural highway is more often one of making selective improvements at spot locations because of fund limitations or because these highways are not expected to develop traffic volumes in the future large enough to warrant complete reconstruction. But where and how should the funds be spent on improvements at spot locations for maximum cost-effectiveness? To answer this question, one must know the manner in which passing zone configurations influence traffic volumes, speed, delay, and level of service. The highway design manuals indicate only general guidelines relative to the provision of passing zones on two-lane roadways (1). It is apparent that there is a need to establish more specific relationships between no-passing zone configurations and the resulting throughput traffic performance. For this reason, a study was undertaken to investigate the relationships between the two independent variables—percentage of the total length of a 5- to 6-mile section of two-lane highway marked with no-passing barriers and the traffic volume input to the section of highway—and the dependent throughput variables—mean speed, speed variance, travel time, traffic volume, and completed passes. (Throughput variables are defined as traffic statistics that have been calculated using only data for those vehicles, moving in both directions, that have traversed the entire length of a specified section of highway.) Additional dependent throughput variables related to the independent variables, but not verified through observation, were delay (calculated on the basis of the time consumed while a vehicle is prevented by other vehicles from traveling at its desired speed), speed change cycles, and attempted passes. A speed change is a measure of the change in operating speed for a vehicle. A speed change cycle is a measure of the change in operating speed from and back to an initial speed (e.g., from 50 mph to 30 mph and then back to 50 mph).

METHODOLOGY

Various methodologies for achieving the research objectives were reviewed, including empirical techniques, mathematical models, and computer models. The large number of highway geometric and traffic variables, along with many no-passing zone configurations, that have the potential to influence throughput traffic suggests that the cost of obtaining statistically reliable observations at field sites would be prohibitive. Technical literature indicates numerous mathematical models, but the majority describes only a particular aspect of traffic flow (2), and in none of the models is the passing maneuver of primary importance. Computer simulation models have been written to describe traffic behavior on a vehicle-by-vehicle basis. Moreover, input data for the variables used in the computer model can be systematically altered and the consequences noted in the output statistics. Implicit in the use of any computer model for analysis of traffic flow behavior relative to passing zone configurations are the requirements that the simulation roadway incorporated into the model be a reasonably accurate representation of the field site, that the movement and interactions of individual vehicles generally approximate actual driver behavior, and that the vehicles moving over the simulation roadway interact and respond to the simulated highway environment.

During the early phases of this investigation, the authors were notified of the availability of a recently developed computer simulation model for traffic flow on two-lane roadways; the model simulated actual passing maneuvers. This computer model had been developed by Janoff and Cassel at the Franklin Institute Research Laboratories (FIRL) (5). Because of the unique characteristics of the FIRL model, coupled with the overall advantages of computer simulation in the analysis of no-passing zone configurations, computer simulation was chosen as the fundamental analytical tool.

The overall strategy in the investigation was to utilize the basic FIRL model and to develop additions or changes to it as dictated by roadway design requirements. The testing and calibration of these revisions utilized data from nine locations. After calibration, the revised model was employed to analyze the consequences of changes in no-passing zone barriers at an actual field site. The experience gained in this exercise was then used to formalize a set of procedures for the application of the model to a typical roadway design or redesign alternative.

Development of Revised Computer Simulation Model

Although the immediate objective of this project was to analyze no-passing zone configurations relative to throughput traffic performance, a larger objective was to provide the roadway designer with a tool that would assist him in making decisions regarding optimal locations for passing zones. Because it was anticipated that any computer model developed would be employed to simulate and analyze traffic flow on North Carolina rural highways, it was essential that the model be capable of simulating a wide range of field conditions, including those normally found on these highways.

Collection of Field Data—The development of a set of computer programs that will model roadway conditions and simulate traffic behavior on North Carolina rural primary two-lane highways requires a set of field observations from these highways so that (a) the simulation model can be properly calibrated and (b) simulation throughput can be compared with actual highway throughput for the purpose of checking the realism and accuracy of the output data from the computer model. Field observations were made at nine sites on the rural primary system during the summers of 1969 and 1970. The field sites selected were 5 to 6 miles long and had no major intersecting highways or traffic signals. The data developed from these observations were used to calibrate input variables to the simulation model and to verify simulation throughput (Table 1).

Functional Specifications—When the range of traffic and geometric variables utilized by the roadway designer was reviewed, it appeared that a traffic simulation model should have the following functional capabilities, insofar as this investigation was concerned: (a) to simulate any specified two-way traffic volume from 150 to 1,200 vehicles per hour (vph); (b) to simulate any individual traffic lane volume from 75 to 1,000 vph; (c) to simulate any specified percentage distribution of passenger cars, medium trucks, and heavy trucks; (d) to simulate acceleration and deceleration characteristics of medium and heavy trucks on gradient sections ranging from -8 to +8 percent; (e) to utilize different speed distributions, if desired, for the three classes of simulation vehicles; (f) to generate, for any specified traffic lane volume per hour, an ordered list of headways that when added cumulatively will equal 3,600 sec at the point in the ordered list when the number of headways added cumulatively is equal to the specified hourly traffic volume; (g) to generate input queues of vehicles for the simulation roadway in which the individual speed and headway assigned to each vehicle are a part of a distribution of speeds and headways normally found on rural primary highways; and (h) to simulate two-way volumes as high as 1,200 vph for nominal real-time computer costs.

It should be noted that the FIRL traffic model permits the user to specify no-passing zone locations in almost any type of configuration.

Summary of Revised Computer Simulation Model—Because it is not the purpose of this paper to report the details of the development, testing, and calibration of the revised computer model, only an abbreviated flow chart is shown in Figure 1. The speed-headway program generates an ordered list of vehicles, which in turn is input to the NCSU modified model. The latter handles all vehicle simulation routines and the calculation of output statistics.

The FIRL traffic model consisted of a main routine and three subroutines. These programs have been incorporated into the NCSU modified model with only minor modifications. However, two additional subroutines have been written and added to the main program of the FIRL model. The speed-headway program and its integration into the total simulation procedure were developed at North Carolina State University as a part of this investigation.

The major input data for the NCSU modified model related to the roadway are length of highway section, no-passing zone barriers and coordinate locations for beginning and end, vertical gradients and coordinate location, and coordinate locations for restricted stopping sight distance. The input data related to traffic and vehicles are traffic lane volumes in vehicles per unit of time; percentages of medium and heavy trucks; mean and standard deviation for an input (i.e., desired) speed distribution for passenger cars and medium and heavy trucks; nominal rate of acceleration and maximum rate of deceleration for passenger cars (acceleration and deceleration characteristics for trucks are stored in the truck-on-grade subroutine); maximum attainable speed for all vehicles; maximum headway in simulation traffic stream; and minimum stopping distance. Input data related to simulation are percentile value from the throughput speed distribution to be used as the operating speed, length of real time to be simulated, and number of intermediate update reports desired between start and end of simulation.

Conclusions Regarding Revised Computer Simulation Model

The development, testing, and calibration of the revised computer model, consisting of the NCSU modified model and the speed-headway program, occupied a major portion of the time and effort expended on the project. This preliminary but essential work provided the necessary verification for the following facets of the revised computer model:

1. That data input to the model can be quantitatively related to model output;

Table 1. Roadway and traffic for nine North Carolina sites.

Site No.	Location	Road Length (ft)	No-Passing Zone (percent)	Largest Grade (percent)	Two-Way Volume (vph)	Directional Distribution of Traffic (percent)	Trucks in Traffic Stream (percent)	Average Speed (mph)	Range of Individual Travel Speeds (mph)		Posted Speed (mph)
									Fastest	Slowest	
1-69	US-1, south of NC-55	26,442	0	1	208	43-57	13	62.7	75.0	48.0	60
2-69	US-1, south of site 1	30,571	10.2	3	177	46-54	19	62.7	77.0	49.5	60
3-69	US-64, 13.7 miles west of US-1	27,361	46.3	7	227	49-51	15	51.7	70.0	43.0	60
1-70	US-15,501, 3 miles north of Creedmore	28,692	36.7	5	686	45-55	17	51.0	73.5	38.5	55
2-70	US-15,501, 3 miles north of Pittsboro	28,846	49.1	5	291	43-57	11	50.0	66.0	38.5	55
4a-70	NC-54, 1 mile west of Morrisville	16,329	51.0	4	268	53-47	8	48.5	67.5	37.0	55
4b-70	NC-54, 1 mile west of Morrisville	16,329	51.0	4	762	83-17	2	48.0	65.5	42.0	55
5-70	US-64, 1.43 miles west of I-40	29,416	61.0	6	506	54-46	21	50.0	67.0	37.0	55
6-70	US-301, 1.95 miles south of I-95	34,821	10	3	642	46-54	15	50.0	63.5	40.5	55

Figure 1. Flow chart for NCSU modified model and speed-headway program.

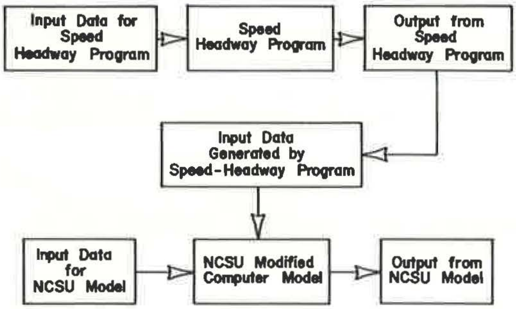
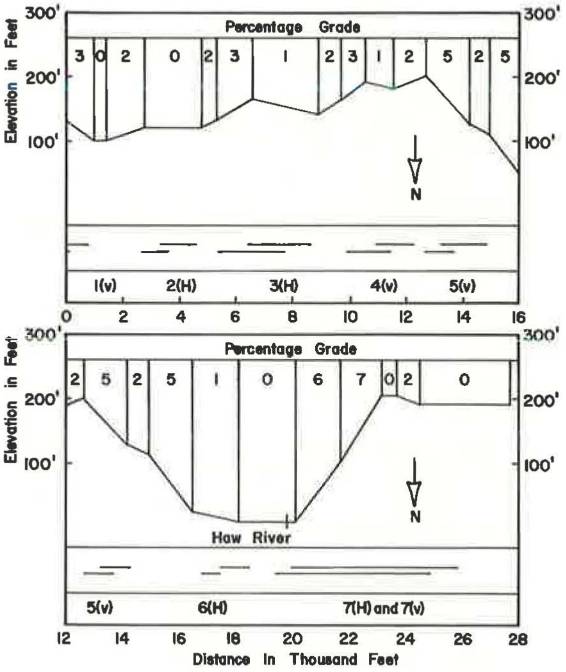


Figure 2. Vertical profile and no-passing barriers for a section of US-64.



2. That selective changes in input will produce predictable changes in output;
3. That, given a set of field conditions for simulation, the necessary computer input data can be specified to produce simulation throughput data that will statistically match throughput data from the field site over volume ranges of 175 to 650 vph;
4. That the revised model appears to be realistically simulating two-lane, two-way traffic flow; and
5. That, on large-scale computer systems such as an IBM 370/165, the computer time for simulation appears quite reasonable (for a 5-mile section of roadway and a two-way traffic volume of 600 vph, approximately 3 min of computer time is required for simulation of 1.2 hours of real time).

APPLICATION OF THE REVISED COMPUTER MODEL TO A HIGHWAY REDESIGN PROBLEM

The problem outlined in the introduction suggested that there was a lack of satisfactory methodology to calculate the overall traffic flow consequences resulting from spot design improvements on two-lane, two-way rural highways. One of the nine field sites at which traffic lane input, output, and throughput data had been collected was utilized for the purpose of indicating the manner in which the computer model can be used to estimate the overall consequences of spot highway improvements, using computer simulation of traffic flow.

Description of Field Site

The site selected is a 5.3-mile section of US-64, southwest of Raleigh, that crosses the Haw River Valley. The maximum grade is 7 percent, and 46 percent of its length is zoned with no-passing restrictions. Figure 2 shows a schematic plan and profile for the sections with the location of the no-passing zone barriers. No-passing restrictions are identified by numbers marked with a suffix of (V) or (H). These labels designate whether the restriction is due to horizontal or vertical sight distance limitations. In the case of restriction 7, the limitation is due to both horizontal and vertical restrictions. Figure 3 shows photographs of the passing restrictions on this highway at locations 1(V), 3(H), the Haw River Bridge, and 7(H, V).

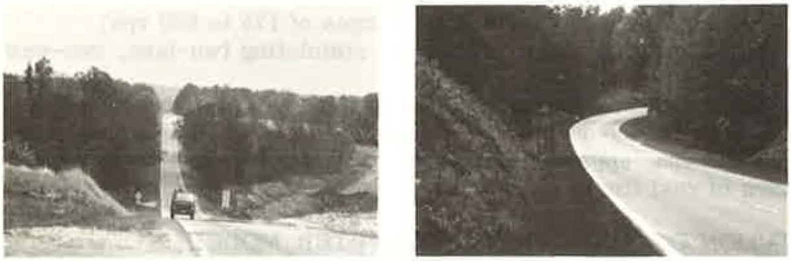
Spot Highway Improvements

The roadway designer, with access to detailed maps and records, can evaluate each of the no-passing locations shown in Figure 2. He can then prepare engineering estimates outlining the extent of spot improvements and their respective costs. Table 2 gives the design improvements used in this example problem. However, it should be noted that many other alternatives can be generated for each of these restricted passing locations.

The selection of specific spot improvements to be utilized in simulation is at the discretion of the roadway designer. For the purpose of this example problem, it is assumed that all of the redesign alternatives given in Table 3 are feasible, not only from an engineering point of view but also from the standpoint of cost.

Column 2 in Table 3 lists the redesign alternatives by noting the specific no-passing zone restrictions removed. As these restrictions are removed, the level of service and the construction costs both increase. Thus, simulation sequences 16 and 17 would be expected to provide the highest level of service and, at the same time, would cost the largest amount of money to implement. Column 8 in Table 3 indicates the mean travel time for the base condition with the travel time for each of the 17 alternatives. Column 9 shows the increase in overall mean speed as the magnitude of the spot improvements increases. In column 11, the value of t denotes whether there is any significant statistical difference between travel time for a particular simulation run and that for the base condition without any passing restriction removed. Table 4 gives additional throughput data for delay, passing, and speed change cycles. The data in both tables indicate a regular change in simulation output as the magnitude of the spot improvements increases. Although not shown here, the other five volume levels used for

Figure 3. Examples of horizontal and vertical passing sight distance restrictions on US-64.



view looking east—restriction 1(V) view looking west—restriction 3(H)

view looking west—Haw River Bridge view looking west—restrictions 7(H, V)

Table 2. Explanation of original and modified no-passing zone barriers for field site 3-69.

No-Passing Zone Barrier	Reason for Restriction	Engineering Basis for Modification
1(V)	Crest vertical curve	Barrier attributable to crest vertical curve, only a part of which is included in the actual field site selected for simulation; therefore, no modification or removal implemented.
2(H)	Limited visibility due to horizontal curvature	Horizontal curvature flattened to provide necessary passing sight distance for 70-mph design speed.
3(H)	Limited visibility due to horizontal curvature	Horizontal curvature flattened to provide necessary passing sight distance for 70-mph design speed.
4(V) 5(V)	Crest vertical curve and approach to an intersection	(These two vertical curves were treated together in removing the no-passing barriers because they are within 1,000 ft of each other.) Removal accomplished by replacing existing grades with flatter ones (1 and 2 percent) and placing a single crest vertical curve between the new tangents; the 500-ft no-passing barrier established in both directions because of the intersection left intact and not modified.
6(H)	Limited visibility due to horizontal curvature	Horizontal curvature flattened to provide necessary passing sight distance for 70-mph design speed.
7(H,V)	Limited visibility due to a horizontal curve, a crest vertical curve, and a narrow bridge	Existing steep 6 and 7 percent grades replaced with a uniform flatter grade (3 percent); a single crest vertical curve introduced to provide passing sight distance for 70-mph design speed.

Table 3. Summary of traffic data resulting from computer simulation of selected changes in no-passing barriers on rural two-lane highway with input volume of 226 vph.

		No-Passing Restrictions (percent)			Input Data		Throughput Data			
Simulation Sequence Number (1)	No-Passing Restrictions Removed (2)	Actual (3)	Less Than 1,500 Ft (4)	Sight Distance Greater Than 1,500 Ft (percent) (5)	Mean Speed[a] (ft/sec) (6)	Standard Deviation (ft/sec) (7)	Mean Travel Time (sec) (8)	Overall Mean Speed (ft/sec) (9)	Throughput Volume (vph) (10)	t-Value (11)
0	None-base condition	46.28	68.46	31.54	85.27	9.5	340.77	81.09	230	—
1	6(H)	43.50	53.62	46.38	85.86	9.7	333.27	82.91	230	2.30[b]
2	2(H)	42.51	62.30	37.70	86.01	9.7	337.70	81.82	230	0.89
3	7(V)	42.30	61.58	38.42	86.04	9.7	337.41	81.88	230	0.95
4	2(H), 6(H)	39.73	47.47	52.53	86.43	9.8	335.54	82.35	230	1.49
5	4(V), 5(V)	38.13	56.87	43.13	86.67	9.8	331.07	83.46	230	2.85[c]
6	3(H)	38.04	58.33	41.67	86.68	9.8	338.40	81.65	230	0.68
7	2(H), 3(H)	34.27	52.17	47.83	87.25	10.0	331.88	83.26	230	2.55
8	4(V), 5(V), 7(V)	34.15	50.00	50.00	87.26	10.0	330.81	83.53	230	2.86[c]
9	2(H), 3(H), 6(H)	31.49	37.33	72.67	87.66	10.1	329.62	83.83	230	3.36[c]
10	7(H)	30.24	53.25	46.75	87.85	10.1	331.77	83.28	230	2.71[c]
11	6(H), 7(H)	27.46	38.42	61.58	88.27	10.2	328.66	84.07	228	3.85[c]
12	7(H), 7(V)	26.26	46.38	53.62	88.44	10.2	328.58	84.09	228	3.60[c]
13	2(H), 3(H), 4(V), 5(V)	26.12	40.59	59.41	88.46	10.2	324.46	85.16	230	4.68[c]
14	2(H), 3(H), 6(H), 7(H)	15.45	22.13	77.87	90.06	10.6	320.49	86.22	231	5.67[c]
15	4(V), 5(V), 6(H), 7(H), 7(V)	15.32	22.67	77.33	90.08	10.6	321.58	85.92	232	5.64[c]
16	2(H), 3(H), 4(V), 5(V), 7(V), 7(H)	6.10	18.52	81.48	91.42	10.9	310.34	89.04	232	8.97[c]
17	2(H), 3(H), 4(V), 5(V), 6(H), 7(H), 7(V)	3.48	6.39	93.61	91.84	10.9	312.86	88.32	231	8.26[c]

[a] Mean input speed calculated from regression model: U = -0.65335 + 1.05718 x (posted speed) - 0.14964 x (percentage of no-passing zone).
[b] Denotes significant difference at 95 percent level of significance.
[c] Denotes significant difference at 99 percent level of significance.

Table 4. Summary of delay and passing data resulting from computer simulation of selected changes in no-passing barriers.

				Throughput Data Per Hour Per Mile of Highway				
Simulation Sequence Number (1)	No-Passing Restrictions Removed (2)	No-Passing Zone (percent) (3)	Mean Speed (ft/sec) (4)	Delay (sec) (5)	Number of Attempted Passes (6)	Number of Completed Passes (7)	Number of Cars Passed in Multiple Passes (8)	Number of 1-mph Speed Change Cycles (9)
0	None-base condition	46.28	85.27	813.08	21.21	19.10	1.34	5,908
1	6(H)	43.50	85.86	867.35	24.84	23.31	3.65	5,081
2	2(H)	42.51	86.01	800.47	21.98	19.87	1.34	3,751
3	7(V)	42.30	86.04	789.77	19.68	18.34	1.91	3,967
4	2(H), 6(H)	39.73	86.43	781.17	26.18	22.93	2.68	5,803
5	4(V), 5(V)	38.13	86.67	616.46	21.78	19.68	1.15	3,925
6	3(H)	38.04	86.68	707.80	25.22	22.55	1.72	5,899
7	2(H), 3(H)	34.27	87.25	745.44	27.52	22.16	1.34	5,318
8	4(V), 5(V), 7(V)	34.15	87.26	693.46	26.56	23.12	1.72	6,747
9	2(H), 3(H), 6(H)	31.49	87.66	711.04	29.43	23.88	2.87	5,977
10	7(H)	30.24	87.85	816.14	27.90	25.41	2.68	2,910
11	6(H), 7(H)	27.46	88.27	715.44	32.29	29.81	2.48	5,526
12	7(H), 7(V)	26.26	88.44	750.98	25.03	23.12	1.91	3,871
13	2(H), 3(H), 4(V), 5(V)	26.12	88.46	571.54	31.72	29.42	2.29	5,455
14	2(H), 3(H), 6(H), 7(H)	15.45	90.06	638.81	36.69	31.91	3.44	5,524
15	4(V), 5(V), 6(H), 7(H), 7(V)	15.32	90.08	682.19	24.65	21.98	2.29	3,271
16	2(H), 3(H), 4(V), 5(V), 7(V), 7(H)	6.10	91.42	384.85	46.05	34.21	2.10	4,699
17	2(H), 3(H), 4(V), 5(V), 6(H), 7(H), 7(V)	3.48	91.84	566.19	31.53	24.08	2.10	3,975

simulation also resulted in regular changes in the output data relative to input changes in the percentage of no-passing zones.

The underlying relationships between the dependent simulation output variables—speed, travel time, delay, passing, and speed change cycles—and the independent input variables—percentage of no-passing zone and traffic volume—are difficult to discern by eye. Therefore, the next step is to develop regression equations relating dependent and independent variables. Finally, the regression relationships can be expressed in a graphical form that is easier to use.

Correlating No-Passing Restrictions and Vehicular Volume Levels With Throughput Traffic Data

In Table 4, a regression equation was developed for the independent variable in column 5 and the dependent variable in column 9. A second independent variable consisting of input traffic volume over the range of 200 to 1,200 vph was also included in the regression equation.

Five additional regression equations were developed by using the independent input variables of traffic volume and percentage of no-passing zone and the dependent variables of delay, number of completed passes, number of attempted passes, number of cars passed in multiple passes, and number of 1-mph speed change cycles. Table 4, columns 5 through 9, shows the dependent variables resulting from simulation for a volume level of 226 vph. These five regression equations were also developed by using simulation output data for input volume levels of 200 to 1,200 vph.

The regression equations are easier to interpret and use if they are expressed in graphical form. Figures 4 through 7 show the graphical equivalents for four of the six regression equations developed. Figure 4 shows speed-volume-sight distance relationships for the 5.3-mile highway section in the example problem. For the roadway designer, this is the most important graph of the set, for it represents the trade-off between speed and volume for any given level of sight distance greater than 1,500 ft. It also represents the trade-offs between sight distance and volume and sight distance and speed. Figure 5 shows a measure of delay as it is related to three input volume levels and the percentage of no-passing zone restriction. Figure 6 shows the number of completed passes per mile per hour, and Figure 7 shows the number of 1-mph speed change cycles per mile per hour, with both statistics also related to the same three input volume levels and percentage of no-passing zone.

Use of the Graphical Relationships

To illustrate the application of Figures 4 through 7 to the example problem, let it be assumed that the 30th highest hourly volume on this 5.3-mile section of highway is 600 vph. The base condition sight distance greater than 1,500 ft is 31.5 percent, as given in Table 4, column 4. Let it be further assumed that planning studies indicate that the 30th highest hourly volume will increase to approximately 800 vph over the next 5 years. Some construction funds may be available for spot improvements, but no money will be available for extensive reconstruction. It is also assumed that roadway designers would like to maintain the existing overall operating speed at its present level or better as the traffic volume increases over the 5-year period. Two questions arise: What spot improvements will satisfy these problem specifications, and what overall benefits accrue in relation to construction costs?

In Figure 4, point a on the graph is the existing situation at 600 vph, with a mean speed of 52 mph and a sight distance greater than 1,500 ft of 31.5 percent. The intersection at point c of a horizontal line through 52 mph and a vertical line through 800 vph yields the necessary sight distance percentage to satisfy the problem requirements. This value is approximately 52 percent. Point b indicates that, after the spot improvements have been completed, the mean speed will rise to approximately 54 mph, at a volume level of 600 vph. However, the mean speed will decrease over the 5-year period as the throughput volume increases from 600 to 800 vph, with the speed decrease following the 52 percent sight distance line b-c.

Column 5 in Table 4 indicates that simulation sequences 4 and 9 and 11 through 17

Figure 4. Relationship between average overall travel speed and input volume for various sight distances.

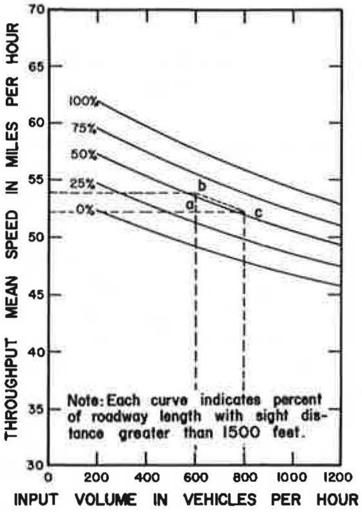


Figure 5. Least square curves relating vehicular volume and percentage of no-passing zone to vehicle delay.

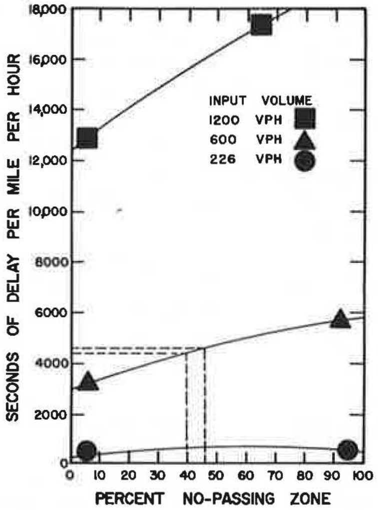


Figure 6. Least square curves relating vehicular volume and percentage of no-passing zone to number of completed passes.

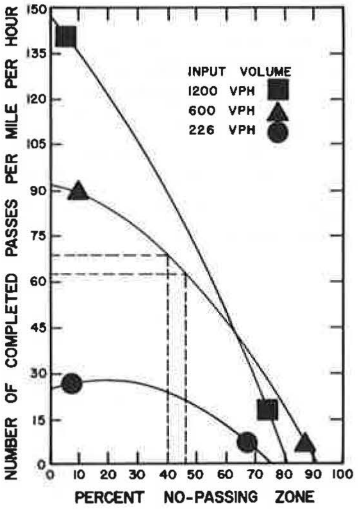


Figure 7. Least square curves relating vehicular volume and percentage of no-passing zone to number of 1-mph speed change cycles.

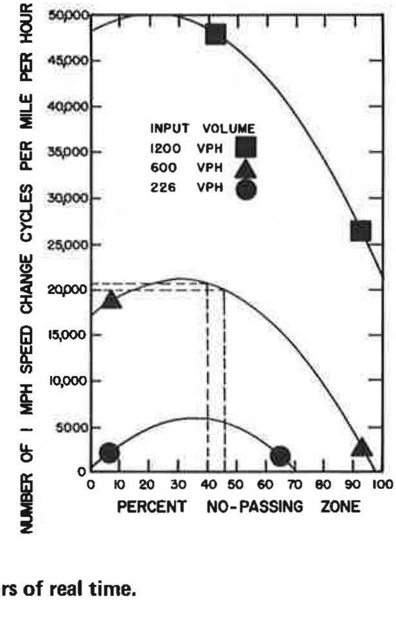


Table 5. Computer simulation time required for 1.2 hours of real time.

Volume (vph)	Computer Time (min)		
	IBM 370/165	IBM 370/145	IBM 360/40
200	1	12.5	50
600	3	37.5	150
1,200	7	87.5	350

will all satisfy the sight distance specification. Let it be assumed that sequence 4 is selected for additional investigation because it has the lowest construction cost. Let it be also assumed that the roadway designer desires to amortize the construction costs for sequence 4 over the 5-year period.

Column 3 in Table 4 indicates that, if the spot improvements in sequence 4 are implemented, the percentage of sight distance restriction will drop from 46 percent to approximately 40 percent. If each of the 1-hour volumes that compose the 24-hour ADT is used, the reduction in delay per hour per mile can be obtained by using the regression equation plotted in Figure 5 but for the appropriate volume level. The sum of the 24-hour delay per mile multiplied by the 5.3-mile length of the section and then by the number of days in the year will yield the total yearly savings in delay. Assuming that the ADT can be estimated for each year in the 5-year period, the total savings in delay can be calculated and then converted to a dollar value. To illustrate the use of Figure 5, assume that one of the 24 hourly volumes in the ADT is 226 vph. The reduction in delay in moving from 46 percent sight distance restriction to 40 percent is approximately 100 sec/hour/mile. For an hourly volume of 600 vph, the savings in delay read from Figure 5 is approximately 300 sec/hour/mile.

Figure 6 can be used to estimate the number of additional completed passes associated with the reduction in percentage of no-passing zone from 46 to 40. For a volume of 600 vph, Figure 6 shows that the number of completed passes will increase from 64 to 69/hour/mile. Increases in passing can be estimated for other volumes in a similar manner.

The additional completed passes noted in Figure 6 for a volume level of 600 vph and a reduction in no-passing zone percentage from 46 to 40 will cause an increase in speed change cycles. The increase read in Figure 7 is approximately 850 one-mph speed change cycles. This increase can be converted to dollars of additional operating costs for the 5-year period in a manner similar to calculating the savings in delay and should be offset against the dollars of savings for delay.

Computer Processing Time

For a 5-mile section of two-lane, two-way roadway, the computer simulation time for 1.2 hours of real time is related to throughput volume as given in Table 5.

In reference to Figures 4 through 7, the data used to plot the curves were generated by using six input volume levels—200, 400, 600, 800, 1,000, and 1,200 vph. In Table 5, the redesign alternatives selected for simulation included the base condition, simulation sequence 0, sequence 17, and three intermediate alternatives. Thus, the data necessary to analyze the example problem can be generated in 30 computer runs. The total computer processing time will depend on the hardware available.

CONCLUSIONS

From the results and findings of the investigation, the following conclusions were drawn:

1. Based on statistical comparisons of throughput data from nine field sites with throughput data resulting from computer simulation of these nine sites, the revised computer simulation model can be calibrated to produce simulation throughput for traffic volumes, mean speed and its associated standard deviation, mean travel time, travel time distribution, and number of completed passes that match the same field throughput values, over volume ranges of 175 to 650 vph.
2. Based on computer simulation and input traffic volume levels of 175 to 1,200 vph, statistically reliable quantitative relationships exist between the two independent variables, percentage of highway marked with no-passing zone barriers and input traffic volume, and the dependent throughput variables, mean speed, delay, attempted passes, completed passes, number of passed cars in multiple passes, and number of 1-mph speed change cycles.
3. Over the input volume level of 175 to 1,200 vph, on the average, the input traffic volume is equal to the throughput volume.

4. The revised computer model, consisting of the NCSU modified model and the speed-headway program, can be employed to develop data useful to highway designers desiring to evaluate improvements in passing sight distance on two-lane, two-way rural highways.

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DESIGNING SAFER ROADSIDE DITCHES

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ABRIDGMENT

The dynamic response of a vehicle during an off-the-road maneuver depends on many roadway and vehicle parameters. Of primary importance are such factors as speed and exit angle, slope steepness, slope of the ditch, and other related geometric and operational features. This research approach to investigating roadside traversals involved use of the highway-vehicle-object simulation model in conjunction with 24 full-scale vehicle tests. This paper presents the results of the study. Included are descriptions of the full-scale methodology and a discussion of the results obtained. Tentative recommendations are presented for design of V-ditches and small-radius round ditches for various combinations of side and back slope.

•THE highway engineer has been handicapped by the lack of objective criteria with which to select safe combinations of slopes for roadside design. To enable him to evaluate alternatives and thus achieve safety in his design, objective criteria must be available to him. The continuing NCHRP Project 20-7 (1) has as its specific objective the development of criteria for safe roadside slope design that will assist in establishing design standards and guidelines.

This paper concerns research efforts (1, 2) conducted by the Texas Transportation Institute to provide objective criteria for the design of safer roadside slopes and ditches. It is directed particularly toward the design of V- and small-radius round ditches and traversable combinations of side and back slope.

ROADSIDE CRITICAL AREAS

The sequence of events that can occur when a vehicle leaves the roadway is greatly influenced by roadside geometry. Three regions of the roadside are particularly important when safety aspects are evaluated: the top of the slope (hinge point), the side slope, and the toe-of-slope (ditch or intersection of side slope with level ground). The hinge-point and side-slope regions are particularly important in regard to the design of long slopes where a driver could attempt a recovery maneuver or reduce speed before impacting the ditch area. The hinge point adds to the loss of steering control because the vehicle tends to become airborne. A driver's normal instinct is to attempt to return to the roadway, but obviously there is a side-slope steepness at which the vehicle will roll during a recovery maneuver. Also, there are situations where the toe-of-slope is close to the roadway so that the probability of reaching the ditch is high, in which case safe transition regions between front and back slope must be provided.

Each region affects vehicle response in a different way and for a different set of operating conditions. When individual criteria are determined for each, the pieces may be put together to produce safety guidelines for total roadside slope design.

RESEARCH APPROACH

The work to date, conducted in two parts, has addressed the toe-of-slope region with particular emphasis on safe combinations of slopes forming various ditch shapes because it is here that the maximum vertical g-forces are developed. The first year was devoted to an investigation of vehicle g-forces experienced in traversing four ditch cross sections (V, round, trapezoidal, and trapezoidal with rounded corners) formed by 12 combinations of front and back slopes ranging from 3:1 to 6:1. The highway-vehicle-object simulation model (HVOSM) was used to study the effects on vehicle behavior.

To verify the model-predicted vehicle response, we conducted 24 full-scale vehicle tests during the second year on slope combinations from 3:1 to 5:1 forming round and V-ditches. The tests were run at a constant 25-deg exit angle (nominal) and four speeds: 30, 40, 50, and 60 mph. The HVOSM predicted, with remarkable consistency, the vehicle response resulting from traversal of the ditch-slope configurations. Extremely close correlation was obtained between predicted and actual resultant average accelerations.

CRITERIA

Vertical g's make up the dominant accelerations in ditch traversal and consequently contribute most significantly to the resultant g-forces. Lateral and longitudinal g's, although not exactly negligible, play only a minor role. Therefore, criteria based on literature concerning vertical g-forces were selected. Human tolerance levels of acceleration were selected for three types of occupant restraint:

Restraint	Tolerance Level (g)
None	0 to 6
Seat belt	6 to 10
Seat belt and shoulder harness	10 to 17

DISCUSSION OF PRELIMINARY FINDINGS

From the HVOSM results, it was apparent that the 3:1 side slopes produced severe vertical g-forces regardless of ditch shape or back-slope steepness. It was, therefore, recommended that 3:1 side slopes be used only when flatter slopes are not feasible. When the front slope was flattened to 4:1, vertical g-forces in most cases were reduced from severe levels to the tolerable level for seat belt restraint or less. On the other hand, flattening the front slope from 4:1 to 6:1 did not produce such a significant reduction in vertical g's.

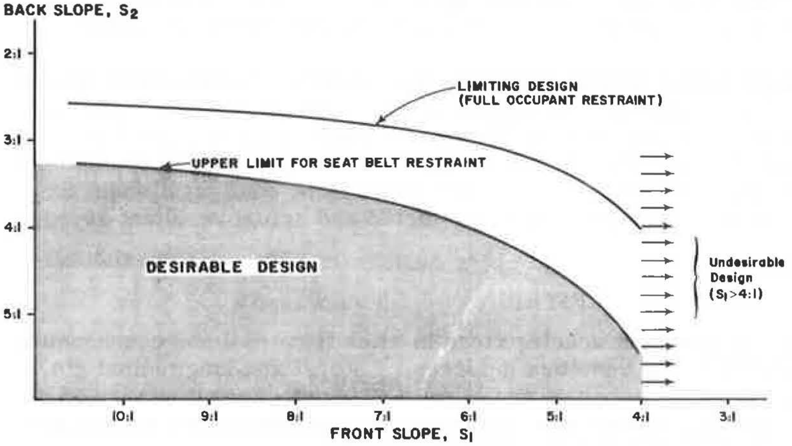
In general these results were borne out during full-scale testing. The 16 tests on the 4:1 and 5:1 back slopes with a front slope of approximately 7:1 revealed that these combinations could be safely negotiated at speeds up to 60 mph with no rollover hazard and with only moderate discomfort if the driver was adequately restrained. The 3:1 back slope (7:1 front slope) appeared quite formidable. The test vehicle was remote-controlled rather than driven; thus, the effect on an occupant can only be estimated. However, based on vehicle damage sustained during these tests and the peak g's measured, slopes of this steepness are not considered desirable design.

Vehicle dynamic response is influenced appreciably by the speed and angle at which the vehicle enters the ditch region. The test driver experienced considerable difficulty in achieving the 25-deg exit angle at speeds of 50 and 60 mph due to rear wheel drift, yet he had a 42-ft wide pavement in which to negotiate the turn. A 25-deg encroachment angle at these speeds can be executed by a professional driver under certain conditions but probably is too severe for design purposes.

The resultant g-forces were only slightly higher for the V-ditch than for the corresponding round ditch in every test but were appreciably higher than they were for the trapezoidal ditches investigated. Therefore, to design for the most critical situation, we developed recommended slope combinations based on the more severe V-ditch configuration. These tentative design curves are shown in Figure 1. Although the curves are applicable for V-ditches, design of a small-radius round ditch using these curves would not be appreciably conservative because very little difference in vehicle response was found between the V-ditch and the small-radius round ditch.

The two curves represent the upper bounds of safe combinations of slopes for two types of occupant restraint, seat belt restraint for desirable and full restraint (seat belt and shoulder harness) for the limiting curve. The curves can be entered with a

Figure 1. Tentative design recommendations for V-ditches.



known front slope (axis S_1) to select a safe back slope (axis S_2) or vice versa. For example, given a 6:1 front slope, the upper limit for limiting design would be a 3:1 back slope and more desirably would be a 4:1 back slope. Of course, a 5:1 back slope would be even more desirable inasmuch as this combination falls well within the desirable range.

CONTINUING RESEARCH

As mentioned previously, there are three areas of concern in the roadside slope design process. The work to date has provided needed information regarding the toe-of-slope region, at least with respect to V- and small-radius round ditches. Currently, design curves are being developed for the other ditch configurations investigated in the computer study. Also, a comprehensive study is being made of the effect of the hinge point and the side-slope region on vehicle rollover and driver recovery maneuvers. The final product of the individual phases will include objective design criteria with which the designer may evaluate alternatives and thus achieve optimum safety in his design for the total roadside slope region.

ACKNOWLEDGMENT

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HIGHWAY DESIGN MODELS: SCALES AND USES

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One solution to the problem of depicting a three-dimensional highway design in other than a two-dimensional form is through use of models and model photographic equipment. This paper shows the results of research aimed at resolving the problems of scale and realism in highway design models and illustrates the use of modelscopes for photographing and viewing design models. Examples are given of designs modeled to represent a variety of situations including an intersection at flat grade, an interchange with significant grade changes, and straight highway sections.

•THE DESIGN of highways has been increasingly recognized as a three-dimensional problem. Persons with the ability to form the three-dimensional picture of the finished highway in their minds simply from viewing two-dimensional plans (plan, profile, and cross sections) are indeed rare. Even if such persons were common, they would also need to possess some form of creative medium, such as artistic ability, to convey their mental picture of the roadway to others.

This physical problem is slowly being solved through the development of successful computer graphics programs (7, 8, 9), the production of more sophisticated model photographic equipment, and the availability of a greater range of model-making materials (5).

The major problems that still remain before proper visual evaluations can be made are to convince clients that these studies are indeed necessary and need not be a massive budgeting item; to demonstrate to the designer that he can readily build design models for such visual studies (or that he can have the models built economically and quickly); and to make the techniques, materials, and equipment for building, viewing, and analyzing design models readily available.

The models that are the subject of this paper are termed "design" models, i.e., models built without much concern for cosmetic details. Design models are generally used as three-dimensional aids for preliminary and final highway design.

LITERATURE

The series of nationwide seminars on Dynamic Design for Safety (7) has been instrumental in pointing out the differences between presentation models and design models and in illustrating the uses and construction techniques for design models. The concept of design models was enthusiastically received by the highway engineers attending the seminars.

Berry and McCabe (2) and Porter (6) present excellent discussions on the construction and uses of design models, especially urethane models. Butcher and Pearson (3) present an excellent discussion on model photography. Although they were concerned with architectural models, they provide considerable insight into model photography.

METHOD OF APPROACH

The approach taken in the solution of scale problems was an empirical one inasmuch as the literature survey revealed no sound theoretical approach. Locations were selected and photographed at known points along the roadway from the driver's approximate viewpoint. Plans were obtained for each location, and models were constructed at various scales. The models were built and then photographed from the same points as the actual locations using one of the two available modelscopes to place the viewpoint at approximate driver's eye level. Model photographs and color slides were compared to the location photographs and color slides to determine the vertical scale at which the model appeared most realistic.

Although the comparison of model photographs and actual location photographs was the primary means of resolving scale problems, this was not the only means used in the research. Views with the naked eye, the Optec modelscope, and color slides were also compared to the actual location views.

Locations and Location Photography

The locations were selected to represent a variety of design situations. These locations included one intersection at a very flat grade, one interchange with significant grade changes, and two highway sections.

The locations were photographed with a 35-mm Nikon F single-lens reflex camera equipped with a Nikkor zoom lens. A camera setting of 86 mm appeared to give the most realistic picture of a roadway section.

Model Construction

The models were constructed of profiles cut from ½- or ¼-in. sheets of foamed urethane. The profiles were then pinned to a styrofoam base. Detailed procedures for constructing urethane models at various scales are given elsewhere (2, 6, 7).

The urethane models were inexpensive and easy to construct. For example, a large scale (1 in. = 40 ft) model of a complex interchange can be built in 2 to 4 man-days at a cost of $50 to $75 for materials (7).

Model Photography and Viewing

The Nikon F camera was also used in the model photography. The modelscope, developed under the direction of William E. Hamilton of Howard, Needles, Tammen and Bergendoff, was fitted directly to the camera body (Fig. 1). A special focus screen manufactured by Nikon was utilized to let more light through the pentaprism.

A tripod was used to hold the camera and attached modelscope stationary during the time exposures, and a cable release was used for the time exposures.

The camera was attached to the tripod such that the modelscope protruded onto the models in a horizontal position (Fig. 1). This was possible because only partial models were made for this study. When models of, say, a complex interchange are photographed, it is usually necessary to arrange the tripod so that the modelscope will be vertical By doing this, the modelscope can be inserted at many points in the model. It is possible to provide a moving picture of a driver's trip through the model interchange by using either a 35-mm slide camera or a movie camera (4).

The modelscope manufactured by Optec (cost about $300) was extremely useful for quick viewing of a model. The modelscope was held with one hand and used to view a model in either the vertical or horizontal position (Fig. 2). The Optec modelscope can be readily used for photographing models.

INTERCHANGE MODELS

A location was selected that had operational problems, caused by the geometry of the situation, that were not readily apparent in the construction plans. The interchange section consisted of an entrance ramp and an exit ramp connected by a short weaving section. After construction, it was apparent that the weaving section was not readily visible to drivers entering the freeway.

To build a number of models illustrating the inherent problems, we constructed only the problem section. Hence, early in the study, an important fact was noted: To view part of an interchange did not require that the entire interchange model be built. In many cases, only the section that has probable design problems needs to be built.

Building a partial model (Fig. 3) as opposed to the entire model can result in a considerable time savings. For example, if the entire interchange had been built, the time to construct each model would have been approximately 3 man-days, whereas each partial model was built in less than $^1/_2$ man-day.

All of the models were built with horizontal scales of 1 in. = 40 ft (40-scale) with the exception of one model that had a horizontal scale of 1 in. = 50 ft (50-scale).

Construction Procedure and Materials

The procedure used in the construction of the interchange model was essentially the same as outlined at the seminars on Dynamic Design for Safety (7).

To view the problems at hand required roadway surfaces for all the interchange models. The surfaces were constructed complete with inked lane markings and curbs and were attached to the top of the urethane profiles.

Two types of material were investigated for the construction of the roadway surfaces, 0.015-in. pressboard (a hard-finish brown paper board) and 0.06-in. matboard (a durable form of cardboard). The matboard was superior to the pressboard. It was not affected by the heat of floodlamps and retained its form and shape even after remaining on a model for months.

Interchange Modeling Results

The most desirable interchange model is one that is constructed at natural scale or, in other words, at the same horizontal and vertical scale. Natural scale models produce the most realistic view of the total roadway environment and provide more realism in such design applications as contour grading, retaining wall studies, and signing (2, 6). One problem investigated in the research was whether the roadway in a natural scale interchange model would appear realistic from the driver's viewpoint.

Two models were built at natural scale, one at 40-scale and the other one at 50-scale.

The result of this experiment was encouraging. Both models closely resembled the actual location from the driver's viewpoint. Figure 4 shows series of photographs taken of the actual location (Fig. 4a) and of the scale models (Figs. 4b and 4c). These photographs were taken at approximately 200-ft intervals.

In picture 1 of Figure 4b and Figure 4c, the second structure is barely visible on the horizon as it is in picture 1 of the actual location. Although the modelscope (as used in horizontal position) placed the viewpoint somewhat above the driver's actual view, the photographs give a valid indication of vertical sight distance.

The series of photographs in Figure 4d is the result of an experiment with vertical exaggeration. The horizontal scale used in the model was 1 in. = 40 ft, whereas the vertical scale was 1 in. = 20 ft (i.e., a vertical exaggeration of 2:1). In order that the backslopes would appear realistic, the structures were constructed with no exaggeration, using both horizontal and vertical scales of 1 in. = 40 ft. This obviously had considerable effect on the apparent vertical sight distance. In picture 1 of Figure 4d, the second structure is completely out of view, whereas this is not the case in the actual location photograph.

All model photographs accurately illustrate the geometric design problem inherent in this location. The views given in picture 2 of the actual location and all of the models give no indication that a weaving section is ahead. In picture 3, which is 200 ft farther downstream, the driver is actually in the weaving section. However, a driver unfamiliar with this location might have some difficulty distinguishing the weaving section from a typical acceleration lane. Actually, close inspection of picture 3 reveals that a right off-ramp begins immediately following the structure in view. Nevertheless, a driver under normal circumstances would not have the time to make a detailed inspection of the situation ahead.

Intersection Model

An at-grade intersection was also modeled. The intersection was a high type of design with a left-turn bay located on one of the intersection legs. Even though the

Figure 1. Setup for model photography.

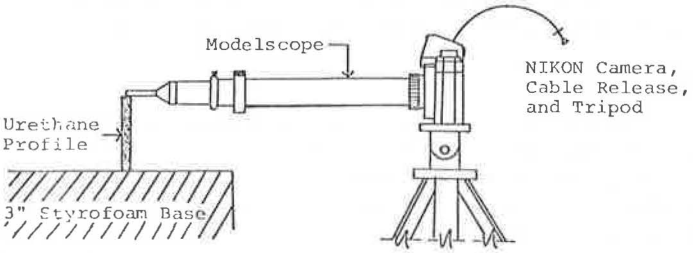


Figure 2. Use of Optec modelscope.

Figure 3. Partial interchange model.

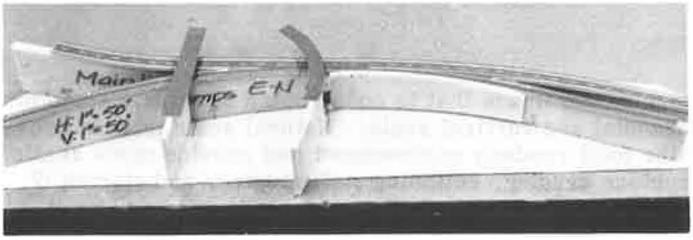
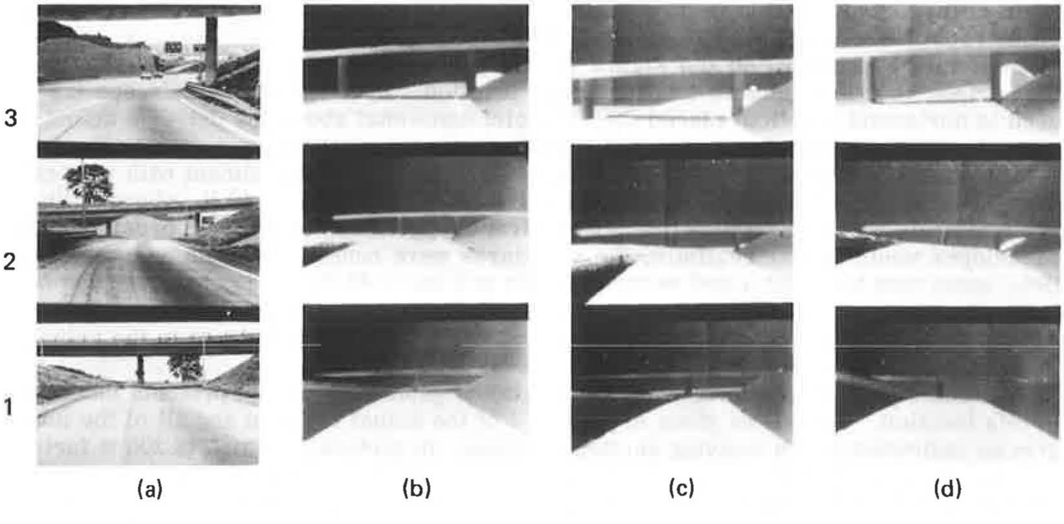


Figure 4. Photographs of (a) actual interchange location, (b) 40-scale model, (c) 50-scale model, and (d) 40-scale model with 2:1 vertical exaggeration.



intersection was built on a very flat grade (about 0.5 percent), the left-turn bay was not visible until the driver was nearly at the intersection.

Forty-scale models were built with vertical exaggeration of 2:1, 4:1, and 10:1 and with no vertical exaggeration. A plan model was also built; i.e., no urethane profile was constructed. The plan model very effectively showed the design problem. For intersections with grades of less than 1 percent, examination of plans at, say, 40-scale with a modelscope or the eye near the pavement surface works quite well. For greater grades or grade changes, one should use the scales recommended for interchange models.

ALIGNMENT MODELS

Coordination of horizontal and vertical alignment is an important but extremely difficult task (1). Using alignment models enables the highway designer to effectively preview the effects of combining plan and profile in three dimensions.

Alignment models are generally built at horizontal scales smaller than those used in interchange and intersection models; commonly used scales range from 1 in. = 100 ft to 1 in. = 500 ft. At relatively small scales, long sections of highway can be modeled in a limited amount of space. Note also that only urethane profiles (without roadways) are used in these models. Alignment models can also be used to effectively examine losses of view of the roadway ahead.

Two locations were selected and modeled for the research, a four-lane expressway and a two-lane highway. Numerous models of these locations were constructed at two horizontal scales, 1 in. = 100 ft (100-scale) and 1 in. = 400 ft (400-scale).

It was extremely difficult to cut profiles with short vertical curves in building the alignment models. It was noted that some of the vertical curves that were difficult to cut at 100-scale were virtually impossible to cut at 400-scale. To construct the 400-scale models accurately required that the profile be cut "high" and then sanded, with another piece of urethane, to the correct elevation. Thus, it appeared that simply constructing alignment model profiles, especially at very small scales, was one of the best ways to locate possible discontinuities in the alignment caused by short vertical curves.

100-Scale Modeling Results

As in the intersection and interchange models, an alignment model built at natural scale was considered the most desirable. Accordingly, a 100-scale model of the four-lane expressway was constructed with no vertical exaggeration. However, the results clearly indicated that vertical exaggeration was needed at this scale. Not only were profiles difficult to plot and cut at 100-scale, but also the grades in the location simply appeared too flat on the model.

Models were built with 5:1 and 10:1 vertical exaggerations. The resulting photographs of the models of the two-lane highway location are shown in Figure 5.

The model with 5:1 vertical exaggeration (Fig. 5b) was the most realistic. The downgrade in the model with a 10:1 vertical exaggeration (Fig. 5c) appears extremely steep. Also, in picture 1 of Figure 5c, the crest vertical curve appears to conceal the downgrade, whereas this is not the case in either the actual location or the model with 5:1 vertical exaggeration. Note in Figure 5 that picture 1 of each series was taken from the same highway stationing; the same is true for pictures 2 and 3.

400-Scale Modeling Results

Two models of each location were built at a horizontal scale of 1 in. = 400 ft. Because it was found that 100-scale models were not realistic without vertical exaggeration, no attempt was made to construct 400-scale models without vertical exaggeration. Vertical scales of 4:1 and 10:1 exaggeration were used. Figure 6 shows series of photographs of the actual two-lane highway location and the models with vertical exaggerations of 4:1 (Fig. 6b) and 10:1 (Fig. 6c).

The models with 4:1 vertical exaggeration, or vertical scale of 1 in. = 100 ft, did not accurately simulate the real situations. The long downgrade in both locations simply appeared too flat on these models. The models with 10:1 vertical exaggeration, on the other hand, were quite realistic. The long downgrade in both locations looked as steep on the models as in the actual situations.

SMALL-SCALE ALIGNMENT MODEL APPLICATIONS

Small-scale alignment models have some distinct advantages that set them apart from the other types of models discussed in this paper. Because of the relatively small horizontal scales used in these models, such as 1 in. = 400 ft or 1 in = 500 ft, long sections of highway can be modeled in very little space. Also, the time required to build such a model is minimal. Given the plan and profile, along with the necessary materials, two persons can construct a small scale model of a 4-mile section of highway in less than 1 hour.

This section of the paper illustrates a few applications of small-scale alignment models. Several hypothetical design situations were fabricated and modeled.

All of the models built were at 400-scale. Models at this scale were considered to be representative of all small-scale alignment models.

According to Smith, Yotter, and Murphy (9), there are three primary rules for coordination of the profile and plan of a highway. These rules are as follows:

1. The point of intersection (PI) of the horizontal curve and that of the vertical curve must nearly coincide (within about 10 percent of the length of horizontal curve), i.e., the curves should be "in phase."
2. The horizontal and vertical curves must be nearly the same length (within about 10 percent).
3. If the conditions in rule two cannot be met, the horizontal curve should slightly precede the vertical curve.

Three models were constructed to test the effectiveness of 400-scale models in indicating violations of rule two. The geometry of all the models was essentially the same with the length of vertical curve being the only variable. The geometry of the three models is summarized as follows:

Item	Value
Horizontal	
PI station	200+00
D, deg	1
Δ, deg	30 right
Length of curve, ft	3,000
Vertical	
PI station	200+00
Back tangent grade, percent	-3
Forward tangent grade, percent	+3
Length of curve	Variable

The first model constructed had a vertical curve length of 900 ft, which is slightly longer than the length recommended by AASHO (1) as the absolute minimum for a design speed of 70 mph. Using this length of vertical curve clearly violated the conditions set forth in rule two.

Figure 7a shows a series of photographs taken of the first model. The photographs depict the expected visual dip or artificial inflection most vividly. Furthermore, the dip is more apparent as the distance from the observer to the point of curvature (PC) is increased, which is the same conclusion drawn by Smith, Yotter, and Murphy (9).

To further test the effectiveness of 400-scale models, we constructed a second model. The length of vertical curve L_v in this model was twice that of the first model, 1,800 ft. Although L_v was significantly greater than the absolute design minimum, it still violated the conditions in rule two.

A series of photographs of the second model is shown in Figure 7b. Again, the expected visual dip was clearly apparent, even at the PC of the horizontal curve.

Figure 5. Photographs of (a) actual two-lane highway and of 100-scale model with (b) 5:1 vertical exaggeration and (c) 10:1 vertical exaggeration.

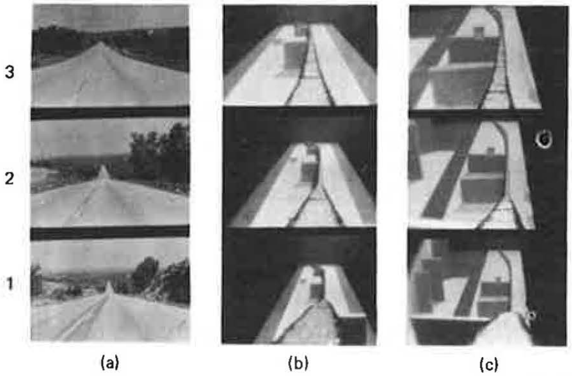


Figure 6. Photographs of (a) actual two-lane highway and 400-scale models with (b) 5:1 vertical exaggeration and (c) 10:1 vertical exaggeration.

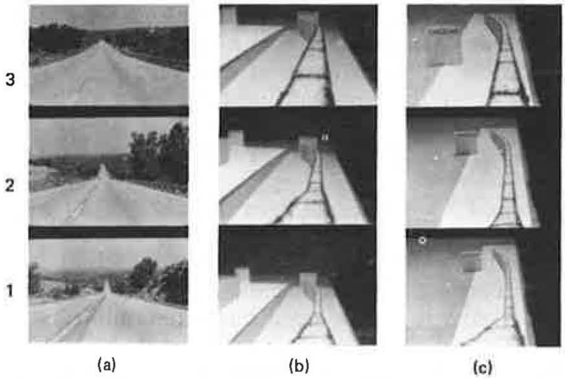
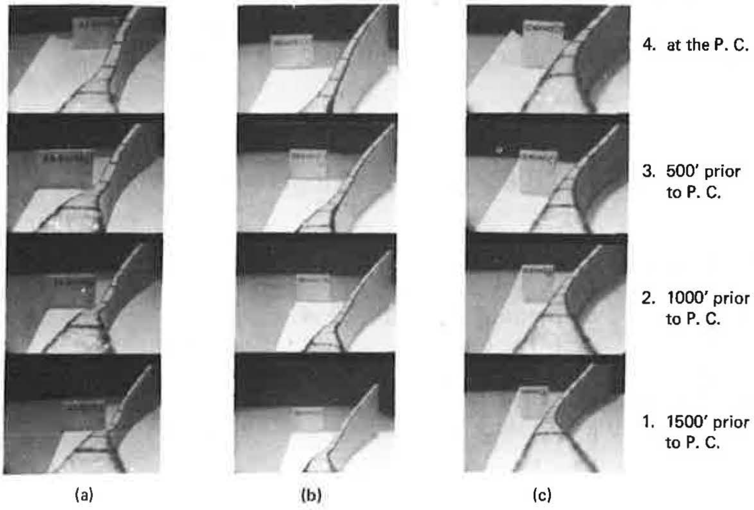


Figure 7. Photographs of visual dip models with L_v equal to (a) 900 ft, (b) 1,800 ft, and (c) 3,000 ft.



Having established the fact that 400-scale models are sensitive to visual discontinuities caused by violations of rule two, we built a third model. This model was in keeping with the rules for coordination of plan and profile. Both the horizontal and vertical curves were 3,000 ft long. The resulting photographs are shown in Figure 7c. As expected, the photographs depict a much smoother and more flowing alignment with no artificial inflections or vertical dips.

Similar studies were made with the vertical and horizontal curves being both in and out of phase. The visual discontinuities in the out-of-phase case were very apparent and agreed with similar studies that used computer graphics (9). The models also graphically indicated problems involving "losses of sight" of the roadway.

CONCLUSIONS

The following was concluded from this study:

1. There is no real need to introduce vertical exaggeration in interchange models built at 40-scale, 50-scale, or larger.
2. In the study of an intersection with very flat grades (i.e., less than about 1 percent), a simple plan model consisting of the roadway surface alone would most likely be sufficient.
3. If the profile of an intersection is dictated by the topography and if the grades are greater than 1 percent, a model should be constructed in the same manner as an interchange model.
4. To study a particular area or problem requires that only a partial model of the intersection or interchange be constructed rather than the entire model.
5. Interchange or intersection models built with some vertical exaggeration (say, 2:1) can be used effectively to study problems involving vertical sight distance. The exaggeration would thus act as a safety factor.
6. Alignment models built at 100-scale need a vertical exaggeration of 5:1 (i.e., 1 in. = 20 ft) in order to appear realistic.
7. Alignment models built at 400-scale need a vertical exaggeration of 10:1 (i.e., 1 in. = 40 ft) in order to appear realistic.
8. Because it was difficult if not impossible to cut profiles with short vertical curves, especially at 400-scale, simply constructing alignment model profiles, especially at very small scales, is one of the best ways to locate possible discontinuities caused by short vertical curves.
9. 400-scale models give valid indication of artificial inflections or vertical dips.
10. Small-scale alignment models are effective in examining losses of view of the roadway ahead.
11. Modelscope devices are essential for studying small scale models from the driver's vantage point.
12. Photographs (especially color slides) of design models, taken through the modelscope, are of great aid in studying a wide variety of highway design problems.
13. Design models are versatile, economic, and significant aids to the highway designer.

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