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Simulation: its role in driver research and highway design

M. Gene Gilliland
Peter Kyropoulos
T.J. Hirsch

Simulation:

its role in driver research and highway design

North Carolina Symposium

on highway safety

volume eight

Simulation:

its role in driver research and highway design

M. Gene Gilliland — *General Electric Company*

Peter Kyropoulos — *General Motors Design Staff*

T. J. Hirsch — *Texas Transportation Institute*

NORTH CAROLINA SYMPOSIUM ON HIGHWAY SAFETY

Raleigh, N. C.

Volume eight **Spring 1973**

The University of North Carolina Highway Safety Research Center
Chapel Hill, North Carolina 27514 • B. J. Campbell, Director

a few words about the symposium topic . . .

Since there are many driver studies that cannot be conducted on the road because of legal and safety considerations, researchers are interested in developing a simulated driving environment that can be used in a laboratory. A number of techniques are being investigated. Computer-generated visual scenes, in particular, show great promise for rendering a dynamic driving environment. Such a controlled driving environment would also be useful in driver training.

Highway design engineers are also keenly interested in simulation. Testing a new roadway design would take many years of real-time observation, but by employing mathematical simulation, engineers can rapidly run the gamut of factors that might possibly affect (or be affected by) a particular design element. Such factors might include the types of accidents a design could conceivably prevent (or cause), the effects of weather, stress, etc.

Simulation has a major contribution to make to highway safety research in the years ahead.

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About the Center . . .

At the request of the Governor of North Carolina, the 1965 North Carolina State Legislature provided for the establishment of the University of North Carolina Highway Safety Research Center. Dr. B. J. Campbell, then Head of the Accident Research Branch of Cornell Aeronautical Laboratory, was invited to return to his alma mater to direct the new Center. He accepted, and in 1966 the Center officially began operation. Since then the staff has grown to more than fifty, representing skills in experimental psychology, clinical psychology, mathematics, transportation engineering, computer systems, journalism, library science, biostatistics, graphic arts, epidemiology, experimental statistics, general engineering, human factors engineering, and health administration. The University of North Carolina Highway Safety Research Center is the first institution in the South devoted exclusively to research in highway safety.

About the Symposium . . .

The North Carolina Symposium on Highway Safety is a semiannual event sponsored by the North Carolina State University School of Engineering, the University of North Carolina School of Public Health, and the University of North Carolina Highway Safety Research Center. First held in the fall of 1969, the symposium has three major purposes. First, it is designed to attract students to acquaint them with the problems and possibilities for research in the field of highway safety.

Second, it is a means of bringing together professional workers in the greater North Carolina area whose interests are related to this field.

And, third, the published papers from the symposium will provide on a regular basis major positions and summaries of research in the field of highway safety. It is hoped that these volumes will provide ready resource material for persons interested in this field.

INTRODUCTION

Webster defines "simulation" as "the act of feigning; pretense" and "false resemblance, as through imitation." Despite the somewhat negative connotations of these definitions, simulation is becoming an increasingly important and valuable tool for those associated with highway safety research. In much of the work presently being done in this field, it is either impractical or impossible to use real-life situations because of cost, safety, and time factors. Therefore, the capability to substitute a simulation or imitation of the that real-life situation has become a significant concern for those individuals interested in the continued progress of highway safety research.

The three papers contained in this volume consider the contributions that simulation is making in several aspects of highway safety research. Mr. M. Gene Gilliland, of the General Electric Company, primarily discusses the development of visual simulation during the past several decades, and describes its potential contribution to all aspects of highway safety research, but particularly to driver training programs. Dr. Peter Kyropoulos, of the General Motors Design Staff, examines both the benefits and drawbacks of simulation as it is presently being used throughout the field of highway safety. And Dr. T. J. Hirsch, of the Texas Transportation Institute, describes the present application of mathematical simulation to the process of designing highway and roadside features.

Although each speaker's presentation has a specific and directed focus, none is confined solely to such a limited consideration. Because each also touches upon matters brought up by the others, they comprise, when taken together, a comprehensive overview of the current role of simulation in highway safety research.

Mr. Gene Gilliland begins his presentation by defining simulation as "an imitation of a real event." These imitations can reconstruct numerous factors of an actual event and manipulate them so that its characteristics can be better evaluated.

Of the many aspects of an actual event that are imitated by the simulation process, Mr. Gilliland is most interested in the visual. Historically, the development of visual simulation has been one of increasing sophistication. One of the earliest and least complex examples was a movie projector and screen system used to train aircraft gunners in World War II. The major drawback of such a system was that the trainee's responses had no effect upon the pattern of projected images—the film proceeded in the same way regardless of what the trainee did.

Another, more sophisticated, means of visual simulation focuses a television camera, whose motion is controlled by an operator, upon a scaled mock-up of an environment. Although this method is a more accurate means of simulation, it too has critical deficiencies: the physical restrictions of the mechanism, by which the camera scans the model, determine the extent to which the scene can respond to the operator's actions.

These and other drawbacks have been overcome by CGI (Computer Generated Imagery) — the technological process which translates electronic impulses from a digital computer into an image on a cathode ray tube. Although the technical problems of CGI are extremely complex, continuing developments have refined the technique considerably. Mr. Gilliland feels that the development of CGI offers a solution to a pressing problem, namely, the need for a low cost simulator that responds to the behavior of the operator. It is not necessary for such a simulator to have high fidelity: relatively simple forms, instead of photographic realism, can be used to represent objects. With the advent of CGI, the technology for a simple, effective, low cost simulator is currently available. Should such a simulator be developed, it would have important application in major areas of highway safety endeavor. By adding the simulation of motion, various vehicle designs could be tested; by monitoring an image in slow time, experimental highway designs could be tested; and, by controlling "traffic conditions," student drivers could be trained safely. To develop such a simulator, however, requires the coordinated efforts of the various government, industry, and university communities.

Dr. Peter Kyropoulos feels that although simulation is capable of contributing a great deal to the field of highway safety research, too often the focus is upon the hardware and not upon the problems for which the hardware was supposedly developed: "In some instances one gets the impression of a sophisticated solution in search of a problem."

Dr. Kyropoulos is primarily interested in simulation as it pertains to product development. He describes the range of activities that can be subsumed under the heading of simulation. One of the simplest forms of simulation involves only a modified production car, or mock-up, and a questionnaire. The investigator asks questions and records the subject's responses. This method of simulation can be so simple because it is used only to test the effectiveness of very elemental aspects of vehicle design (such as the placement of a headlight switch), and for such matters it is unnecessary to simulate external conditions in any great detail.

Much more elaborate forms of simulation using more complex devices have been developed to reproduce the actual driving experience. One of these, the moving base simulator, presents two coordinated movies (one of the view through the front windshield and one of the corresponding scene in the rearview mirror), and provides appropriate motion. Although this simulation method is inflexible, it is useful for testing drivers' reactions to hazardous situations. Greater flexibility can be achieved by using computers to generate driving scenes, but a considerable measure of fidelity is lost in the process. One of the most recent developments in driving simulation, which uses a TV camera mounted in an unmanned test car that is guided by remote control, has done much to provide both fidelity and flexibility.

The purpose of all forms of simulation is to determine under controlled conditions how something will actually function under real conditions. To make the correspondence between the test and the actual conditions only as close as necessary should be the ultimate goal of all simulation processes: to seek unnecessary higher fidelity is to miss the real point of simulation. If simulation functions as a tool to achieve a goal, and not as a goal in itself, Dr. Kyropoulos sees it as a boon. If, however, simulation becomes a goal in itself, with efforts chiefly devoted to the development of ever-increasingly sophisticated hardware, then it becomes a boondoggle.

Dr. T. J. Hirsch examines the way in which the process for developing safer highway designs is using simulation by relying upon mathematical models. He quickly points out that the highway engineers who do the actual designing are often skeptical of the mathematical models developed either by their research colleagues or by members of the academic community. Frequently, such models are confusing jumbles of sophisticated mathematical formulae which, although complex, fail to take into account the intricacies of many real-world problems. However, Dr. Hirsch recognizes that, despite such shortcomings, the effective use of mathematical simulation can efficiently produce better highway designs: "Mathematical simulation provides a rapid and economical method to investigate the many parameters involved as an automobile traverses some defined roadway configuration. Once the limiting parameters are identified, it may be desirable to conduct a limited number of full-scale tests prior to final selection of a particular design. This approach, in contrast to a full-scale trial-and-error approach, will yield more meaningful results with considerably less resource expenditure."

The mathematical formulae used in this type of simulation are derived in two basic ways — by observing high-speed films and sequence photographs of full-scale tests, and by using the laws of physics to define the situation to be simulated. By altering the variables in these formulae, it is possible to examine a broad range of conditions and to anticipate what the structural needs of both the vehicles and the highway fixtures will be. Such mathematical models have been used to simulate several types of impacts.

Dr. Hirsch illustrates the simulation of a number of impacts, including vehicle/rigid-barrier, vehicle/vehicle, vehicle/traffic railing, and vehicle/call box. Because mathematical simulation can be used to describe the attenuation of the impact of a vehicle with a given object, it is possible to predict with reasonable accuracy the severity of damage that can be expected in a real world crash. Once a mathematical model has been developed for a type of crash, it must be verified through full scale crash tests. However, the use of the model makes it possible to run relatively few such tests, and to thus save time and money.

The mathematical modeling of a fairly standard vehicle has led to computer simulation of what happens when a car leaves the road and goes down an embankment. By varying the slope and height of the simulated embankment, one can establish which embankment configurations should be protected by guardrails and which do not require such barriers.

Dr. Hirsch clearly illustrates how the intricacies of mathematical modeling have readily understandable application to problems confronted by the highway engineer. Through the use of simulation, more informed decisions can be made about spending tax dollars in the most effective manner.

Mr. Gilliland provides a brief history of the development of simulation and how it has become increasingly sophisticated, particularly with the advent of CGI, or computer generated imagery. Dr. Kyropoulos discusses some philosophical aspects of simulation, that is, what do we want to accomplish through its use and how much is needed to serve any particular purpose. Dr. Hirsch shows how mathematical modeling of the vehicle and certain environmental features can be employed as a time and money saving device in making critical decisions about highway design. All three speakers have stressed that simulation need not aspire to conform to reality in as much detail as possible. Rather, only those dimensions of the real world that are relevant to the problem under investigation need be simulated. Once this principle is accepted, it should be possible to develop simulation more efficiently and more economically than is generally supposed.

Patricia F. Waller

Section I

Applications of Computer-Generated Imagery To Driver Training Highway Research and Design

M. Gene Gilliland

M. GENE GILLILAND

Mr. Gilliland has for several years been involved in Computer-Generated Image Technology. As manager, System Design, of General Electric's Apollo and Ground Systems Department, he is responsible for design of visual simulation systems. He participated in the design and construction of the first three-dimensional computed image system, completed in 1967. He has also been involved in computer-generated image simulation of spacecraft, aircraft, ship operations and, to a lesser extent, highway traffic.

APPLICATIONS OF COMPUTER GENERATED IMAGERY TO DRIVER TRAINING, HIGHWAY RESEARCH, AND DESIGN

By M. Gene Gilliland

What Is Simulation?

Very generally, a simulation is an imitation of a real event. Simulation is used in cases where it would be expensive, dangerous, or impossible to perform the real event. For example, it might be important to simulate the operation of a rocket engine before building and testing it, since the actual building and testing might be both expensive and dangerous. The simulation of a process taking place under zero gravity conditions would be an example of use of simulation where the real event is impossible to perform.

Roughly speaking, there are two different categories of simulation: real time and non-real time. Most non-real time simulations proceed at a slower rate in time than the actual event, but there are some super-real-time simulations — those that proceed faster than the real event. An example of such is the simulation of physiological processes that occur in the human body.

Most non-real time simulation is done in slow time. This means that the simulation of the event might take several hours to run to completion, whereas the actual event might take place in a matter of a few seconds. The reason for doing slow time simulation is simple: it allows trading time for computational capacity in whatever is doing the simulation. By means of this technique, a small or medium size general purpose computer can be used to simulate an event that would require many rooms full of special purpose electronic hardware to simulate at the rate at which the actual event occurs.

Some examples of non-real time simulations, both slow time and super-real-time, are the processing of economic models, the exercising of the world model (which has gotten a lot of publicity lately), and the simulation of automobile crashes. Figure 1 shows schematically how these types of simulations can be represented. This type of simulation consists primarily of a set of equations describing the behavior of the system being simulated. These equations are set to some initial condition and are then exercised in an iterative manner under the influence of input stimuli, which may change during the process of the simulation. The results can appear after the entire run is complete or during the process of running the simulation.

Real time simulations are distinguished by the fact that the simulator process runs at the same rate as the actual process. Figure 2 shows what the elements of such a real time simulator might be. An operator is either driving or flying some type of vehicle. The movements of his controls are sensed and used to determine the performance of various parts of the simulation system. One part is a computer, called the simulation computer, which determines what the vehicle will do on the basis of its current status and the motions of the controls. This simulation computer is processing a mathematical model of the dynamics of the vehicle itself. The results of this simulation are used to drive the vehicle instruments and a motion system which moves the cockpit in which the operator sits. This motion is controlled in such a manner as to accurately simulate the accelerations to which the operator's body would be subjected if he were in the actual vehicle.

A second process performed by the simulation system is the creation of the visual scene. In Figure 2, the scene is shown being produced by a visual computer. There are many ways to produce the visual for a simulator. In any event, the scene presented to the operator should represent what he would see if he were looking out the windshield of the actual vehicle.

There are numerous kinds of simulators, many of which do not possess all of the features shown in Figure 2. Some may, in fact, possess only one or two. The discussion of this paper will center primarily on the creation of the visual scene by computer-generation techniques.

Types of Visual Simulation

There are many different ways of creating the visual scene for a simulator. Figure 3 shows a highly simplified way that was actually used for training during World War II. In this situation, an individual being trained as an aircraft gunner practiced aiming a weapon (hopefully without real bullets) at a screen on which a movie was

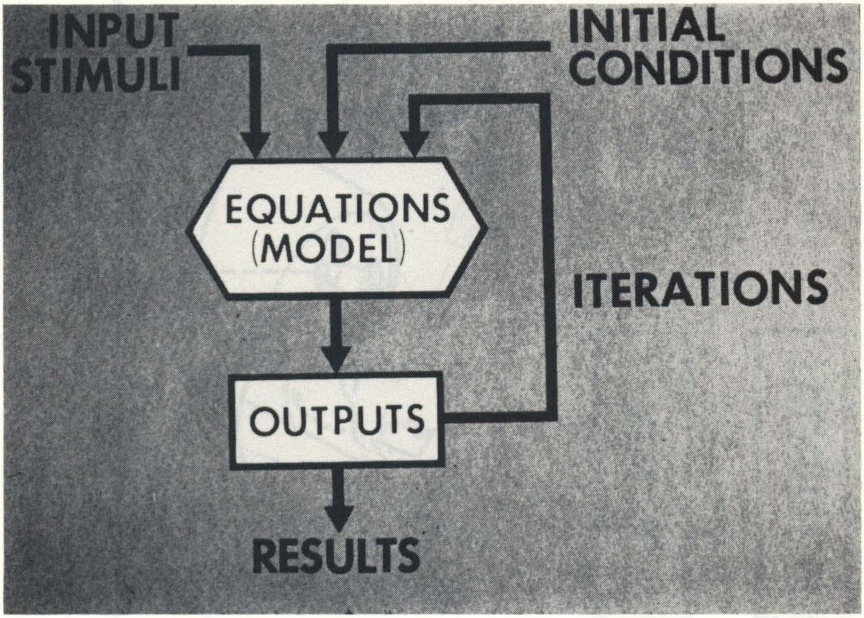

FIGURE 1. *Schematic representation of a non-real time simulator*

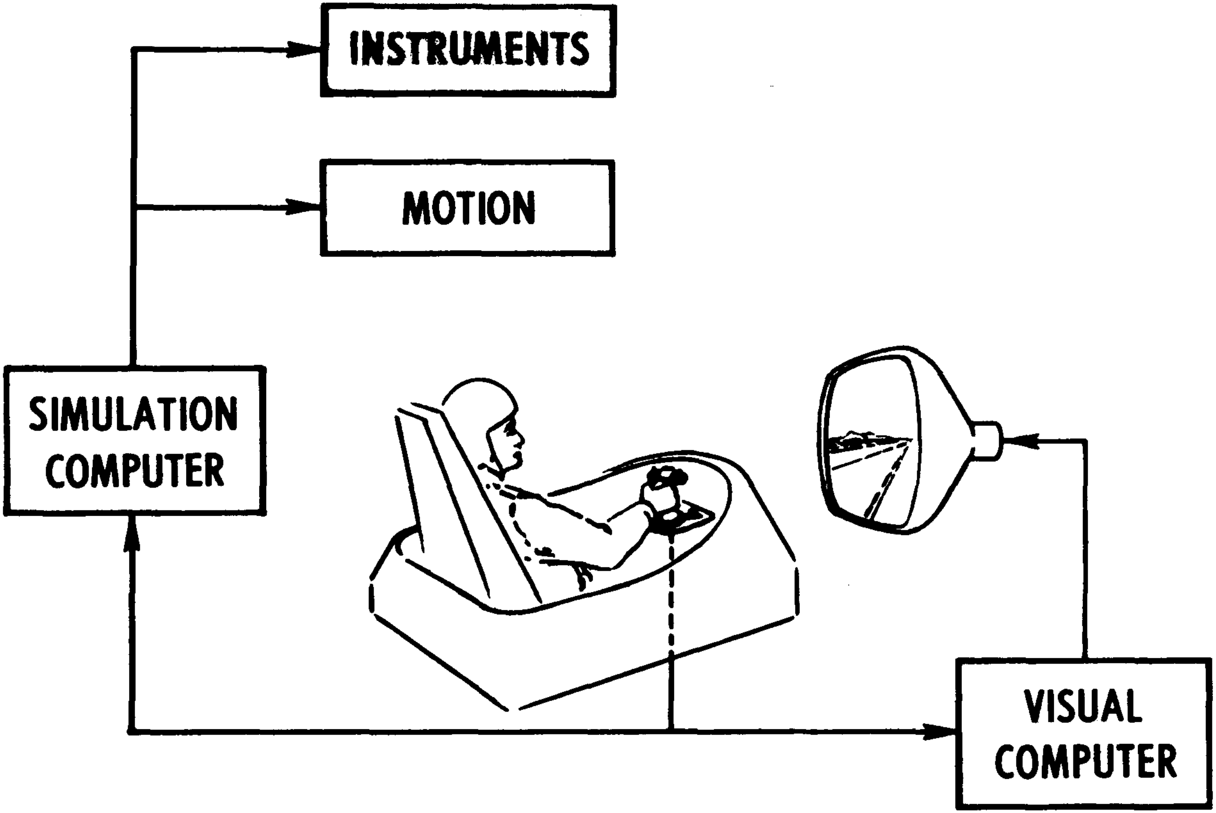

FIGURE 2. *Schematic representation of a real time simulator*

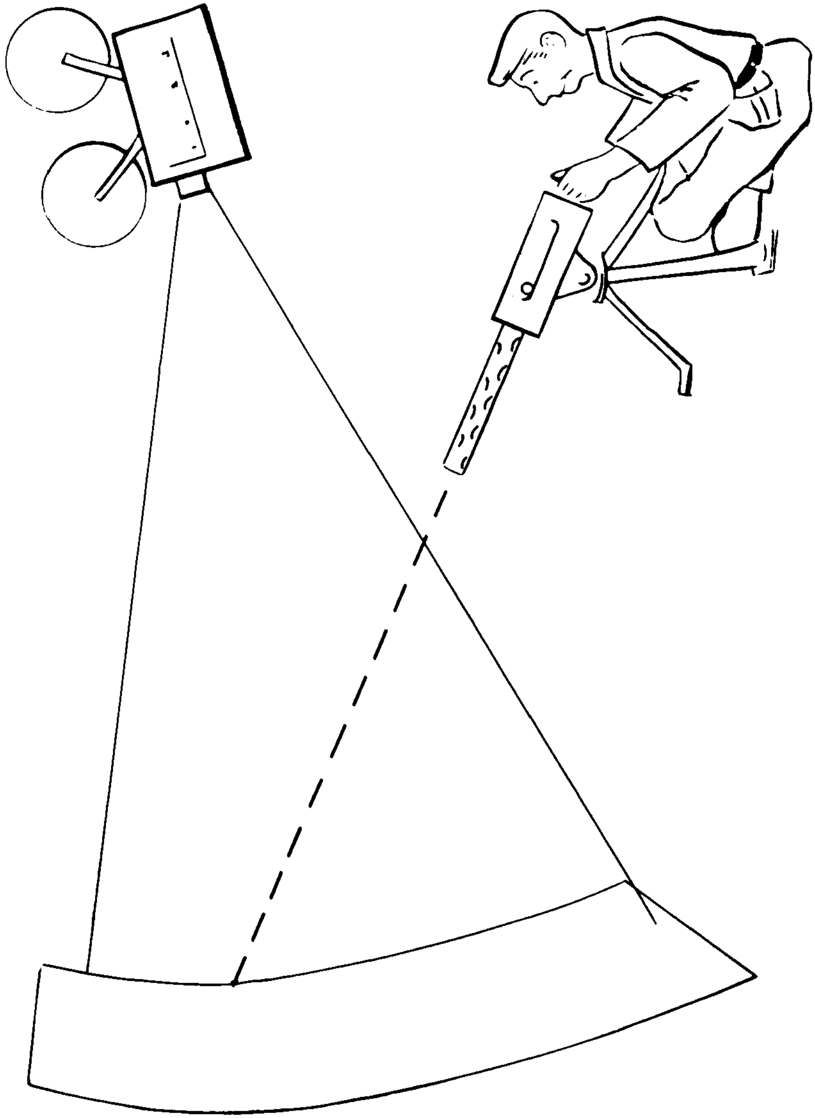

FIGURE 3. *Simulation process used to train aircraft gunners in WW II*

projected. The movie might show enemy aircraft approaching and flying past. Although the trainee in these simulators learned about the mechanical operation of the device on which he was training, one important element in the training process was missing. The scene that he saw did not respond to his actions. Whether he aimed properly or improperly, the result was always the same: namely, that which was recorded on the movie film.

Figure 4 shows another means for producing the simulated visual scene which has been used extensively. In this technique, a scale model of the environment to be used for operation is built. A television camera is suspended over this model on a track which allows motion with respect to the model. In advanced versions of this type of visual system, the apparatus for suspending the camera will allow motion along all three axes. The responses of the operator are used to control the camera transport mechanism so that it presents to the operator a scene which is closely related to what he should see through his windscreen. This technique offers interaction with the environment and provides a great advance over a movie technique. However, it suffers from significant dynamic limitations. The rates at which the camera can be driven back and forth and rotated with respect to the model are limited by the power of the servos which are used for camera transport. In addition, there are significant limitations on where the camera can go and in what directions it can look. For example, it can't look up or it will see the track mechanism and the motors that are used to move the camera. Also, because the trainee's mental scale is adjusted to the tiny size of the model, it might be fairly upsetting to him if the camera points off the edge of the model and he sees a gigantic person standing out there.

The use of digital computing equipment to produce the visual scene is a technique that successfully overcomes the disadvantages inherent in most other methods. This technique utilizes a special purpose digital computer in conjunction with a stored numerical description of the environment to synthesize a video signal for presentation on a cathode ray tube (or a television projection device) for viewing by the trainee.

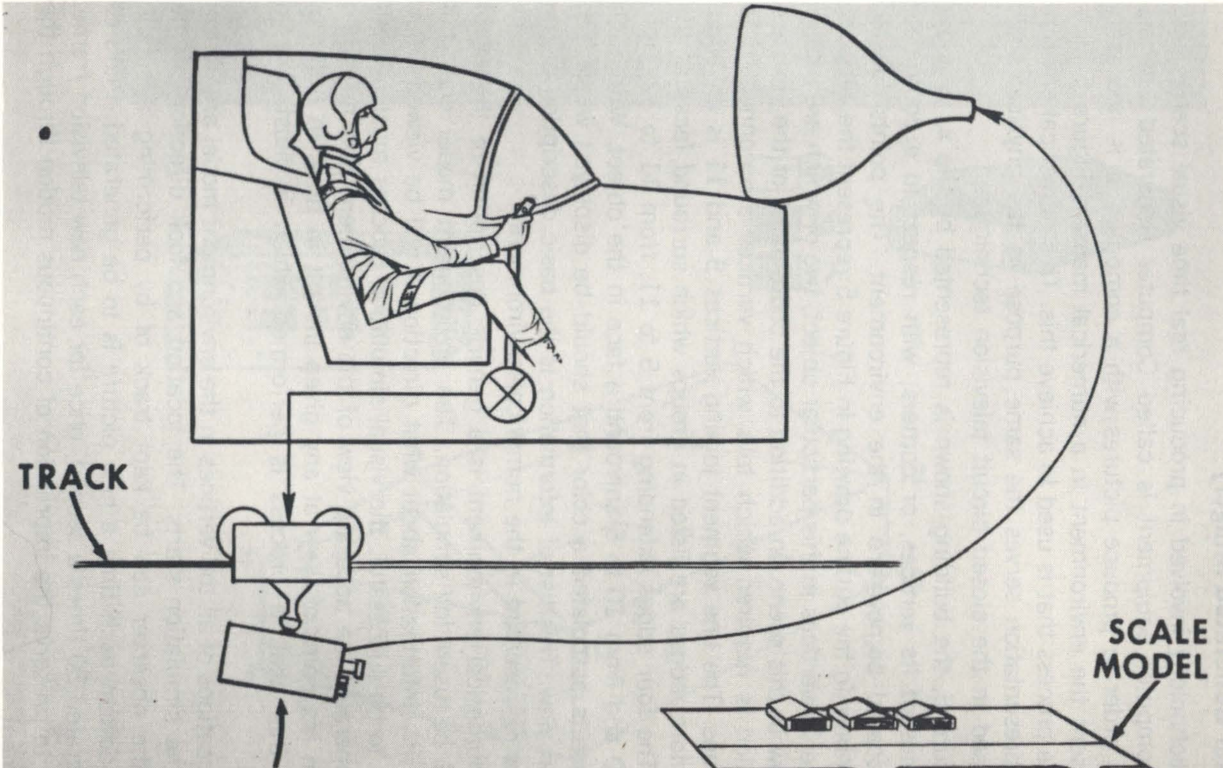

FIGURE 4. *Simulator with scale model of environment and TV camera*

Computer Generated Imagery

The technology involved in producing real time visual scenes with digital computer equipment is called Computer Generated Imagery (CGI). In order to produce pictures with a computer, it is necessary to represent the environment in a numerical manner. Figure 5 illustrates the process that is used to achieve this. This numerical environment representation serves the same purpose as the physical scale model used in the closed circuit television technique.

In Figure 5, the building shown is represented by the x, y, and z coordinates of its vertices, or corners, with respect to a coordinate origin located somewhere in the environment. The points labeled with numbers in the outline drawing in Figure 5 represent the vertices. There are 15 vertices in this particular object, two of which are hidden from view in this scene. In addition to the coordinates of the vertices, information is required which tells which vertices are connected to form edges. The line segment joining vertices 5 and 11 is an edge. Furthermore, edges are listed in groups which surround faces of the object. The four edges extending from 5 to 11, from 11 to 12, from 12 to 10 and from 10 to 5 surround a face in the object. With each face there is associated a color that should be displayed when that face is in view. This list of information is the basic description of the object as represented in the numerical environment.

The numerical environment is a generic description of the world that will be used for simulation. The environment model does not contain any information about what direction it will be viewed from. In order to be successful, the visual simulation process must present to the operator the accurate view of the environment that he would see from his point of view at any given instant in time. In order to achieve this goal, a process is performed which is illustrated in Figure 6.

The locations of all the vertices in the environment model are known before the simulation starts. The location and look direction of the eye of the observer can be kept track of by performing a simple vector addition each time a new picture is to be generated. Pictures are generated 30 times a second, once for each new television frame, in order to preserve the impression of continuous motion through the environment.

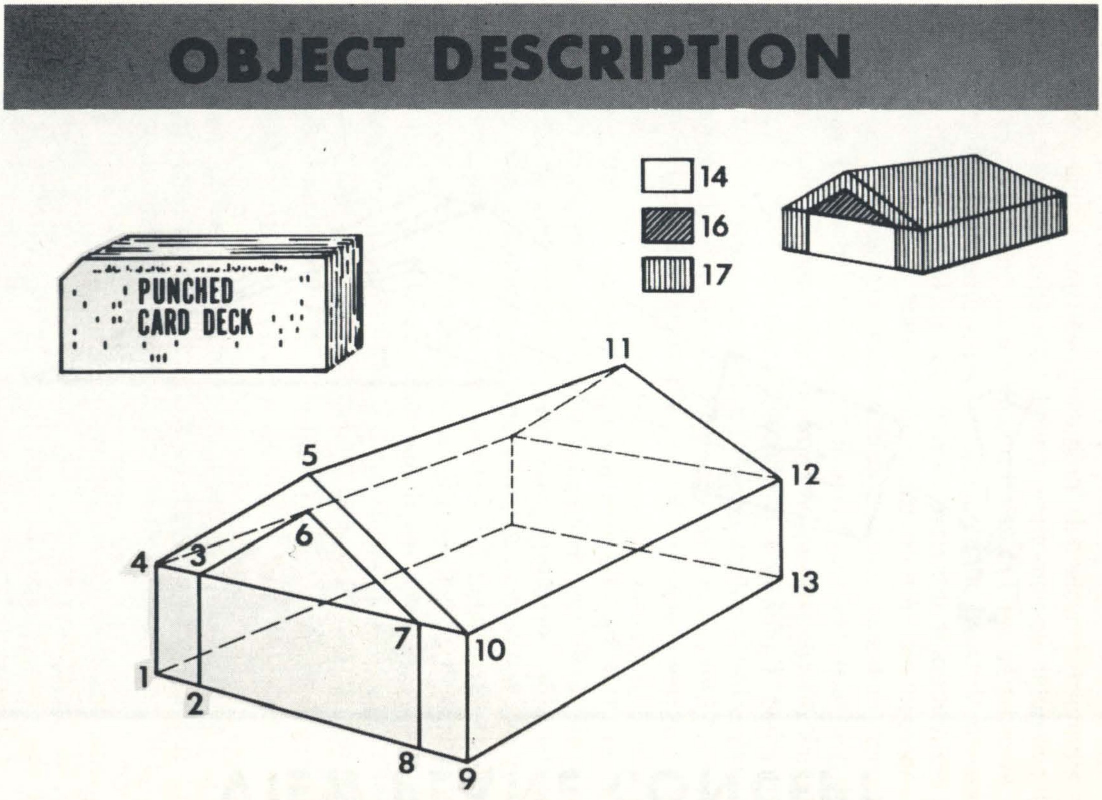

FIGURE 5. *Illustration of representation of environment for use in CGI*

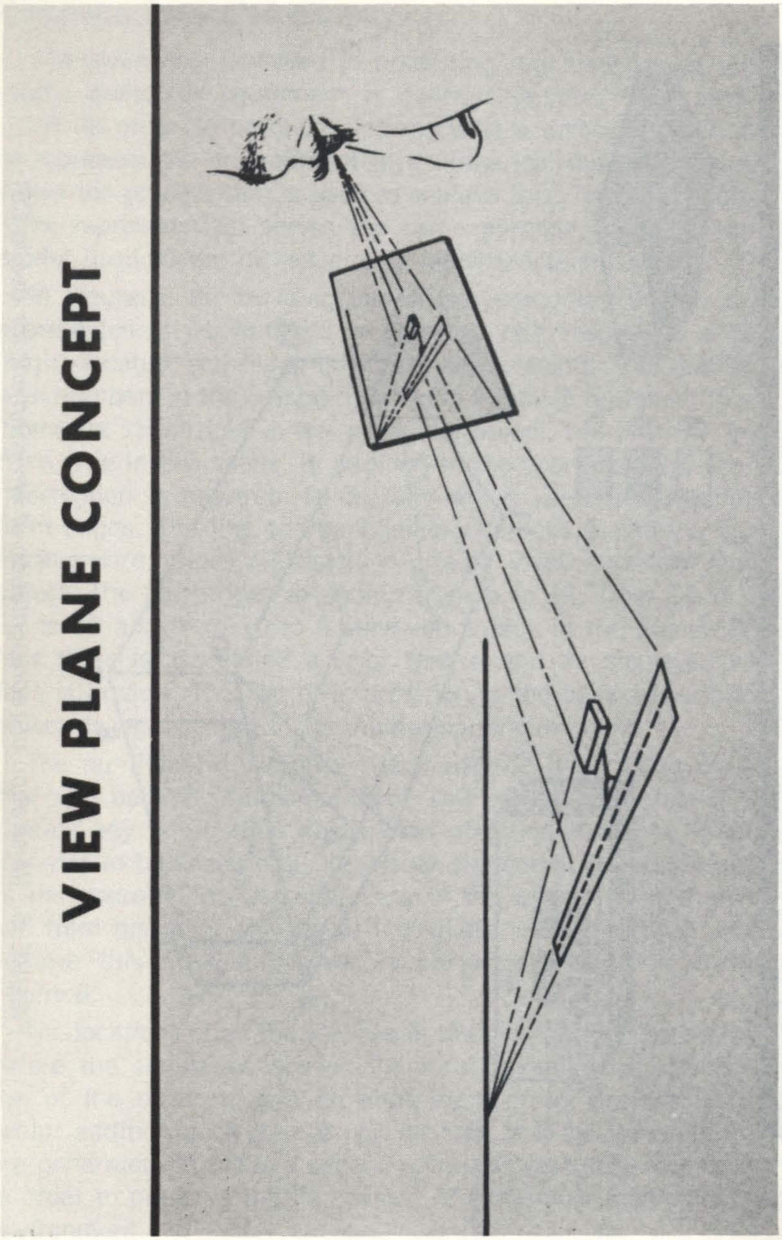

FIGURE 6. *View plane concept: How environment is presented to viewer from appropriate angle*

Two steps are involved in the process of creating the updated picture on the viewplane. The first process is a perspective transformation which moves the images of the vertices from the three-dimensional environment into the currently-valid position of the two-dimensional viewplane. Since this projection is a perspective transformation, the vertices are projected along the sight lines extending from the mathematical eye position through the display plane to the vertices in the environment. The second part of the process is the scanning of the two-dimensional image which has been created in the display plane by the projection process. This scanning is performed in such an order and at such a rate that the points scanned on the display plane are processed at the same time that the electron beam in the television output device is scanning corresponding points in the picture. In this way, a television signal is synthesized which can be displayed directly on the television output device.

Figure 7 shows a schematic representation of the equipment which would perform this image generation process in real time. The data base contains the entire mathematical model of the environment. From this, the selection equipment extracts information describing those items which, on the basis of their size and distance from the observer, should be considered for display during the current television frame. Certain special computations are then performed, including the vector updates mentioned previously. These computations are followed by the transformation and scanning processes previously described, and the results are passed on to the television display device.

Two parts of the process have not been mentioned up to this point. The first is represented by the box labelled, "Hidden Parts Removal," and can be the most difficult portion of the CGI process. It amounts to determining, for each portion of the display, which faces should be displayed and which should be obscured. The second, represented by the box labeled, "Special Effects" in Figure 7, refers to certain features which can be included in the CGI system. These include the production of limited visibility effects, such as those resulting from fog and haze, and the generation of special purpose blinking or rotating lights.

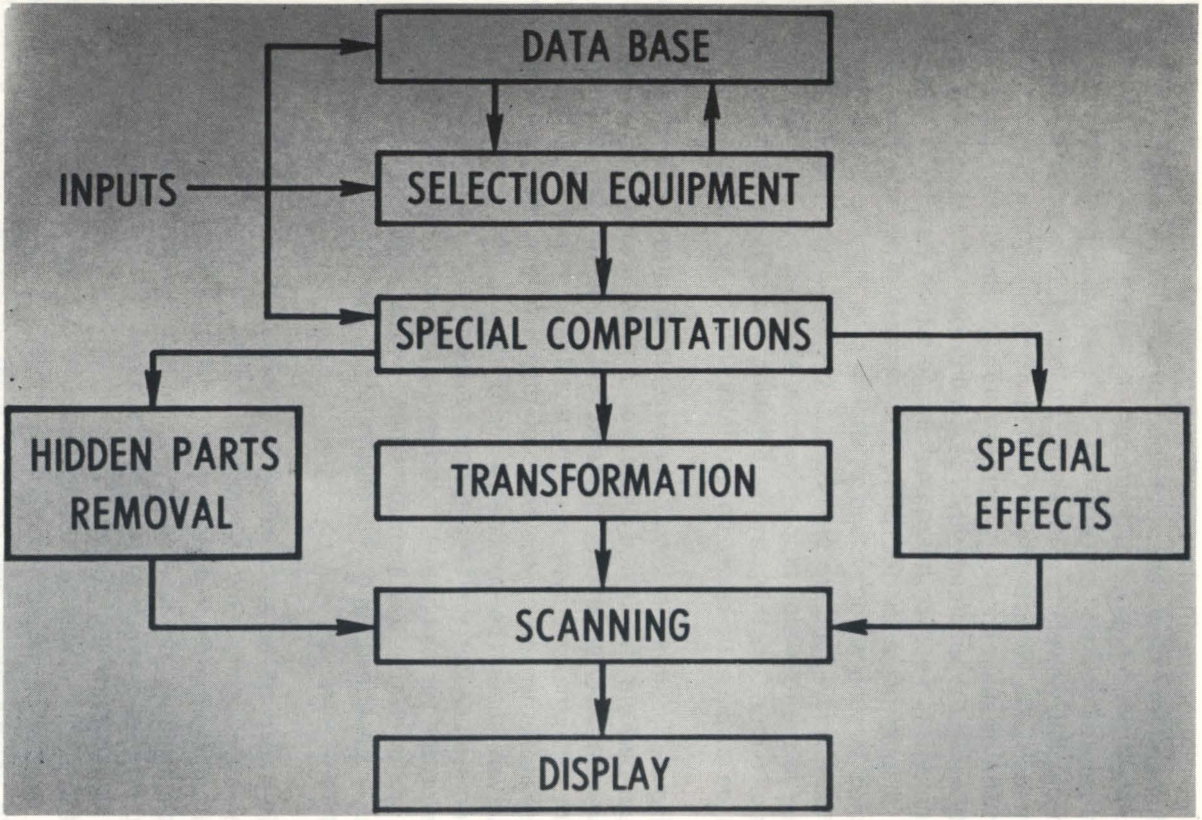

FIGURE 7. *Schematic representation of elements for CGI in real time*

CGI History

The development of CGI technology has been under way at General Electric since 1959. Throughout this time, concentration has been on the production of a visual system able to produce true perspective pictures in real time for various types of training simulation. A system was delivered in 1964 to NASA's Johnson Space Center in Houston, Texas, which had the capability for generating a textured plane surface in true perspective and real time. Later this system was updated to include the first capability for generating full color images of three-dimensional objects. The scene shown in Figure 8 was photographed from that system. This first system had the capability for handling scenes modeled with up to 240 edges in real time. It has since been augmented to a 500 edge capacity.

Developments have continued to both improve the special effects and features that could be accommodated by the system and to increase the edge capacity of systems. A system has now been installed at the Naval Air Station in Kingsville, Texas, which operates with up to 500 edges in the field-of-view from a total environment modeled with up to 2000 edges. This system, which utilizes three side-by-side projection screens to produce a 180° wrap-around field-of-view, was used to produce the photograph shown in Figure 9. This photograph was taken through a wide angle lens in order to compress as much as possible of the 180° field of view into the picture. As a result, some distortion of the picture is apparent.

Another system is now under construction which will provide up to 2000 edges within the field of view and operates in a total environment modeled with up to 600,000 edges. This system will use seven viewing channels to cover 240° in the horizontal and 180° in the vertical dimension of the field of view.

Application of CGI in Driving Simulation

In addition to training, CGI has numerous applications in driving research and design.

Research

One valuable use of CGI in driving simulation is in man-in-the-loop simulation. This research technique, illustrated in Figure 10, involves

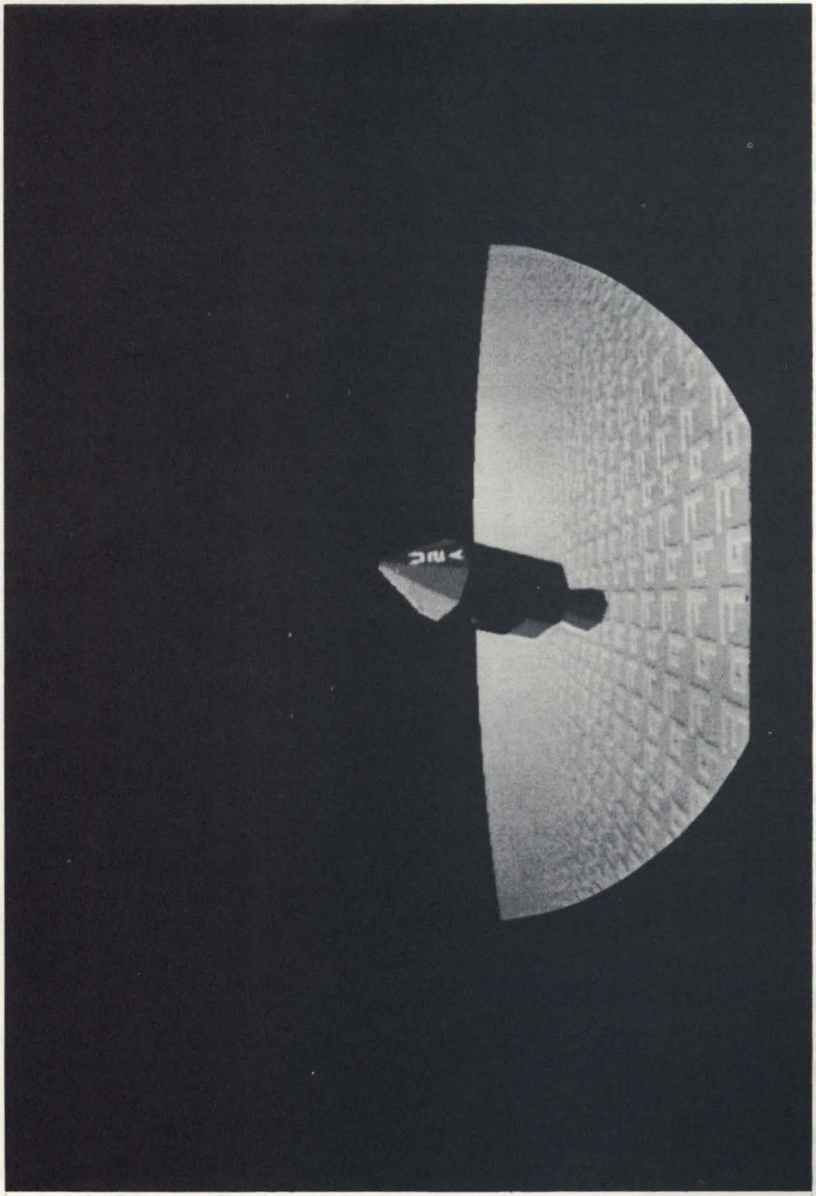

FIGURE 8. *Scene from CGI system developed by GE for NASA*

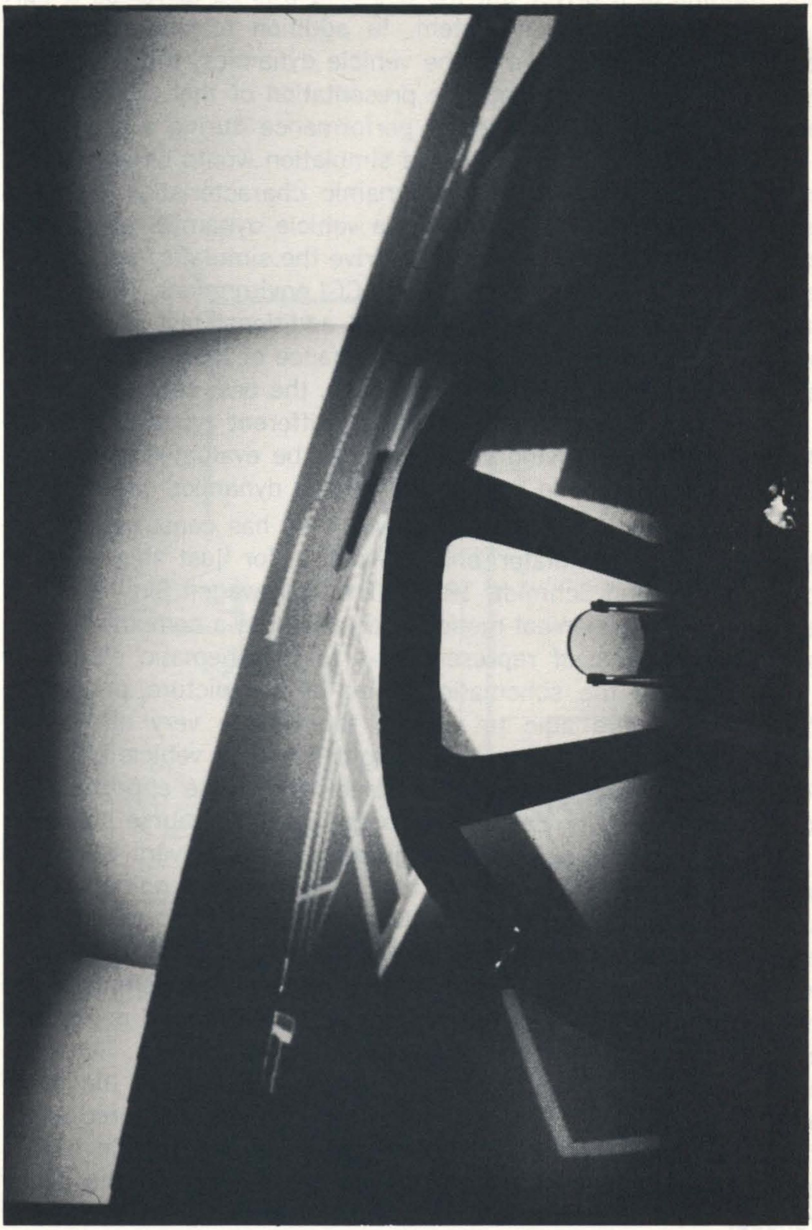

FIGURE 9. 180° scene from CGI system used to train pilots

not the training of a driver but the use of a trained driver as a part of a closed-loop simulation system. In addition to the driver, the system includes a simulation of the vehicle dynamics, the generation of a real-time computed scene, the presentation of that scene to the driver, and a means for monitoring performance during a simulation run. An example of using this type of simulation would be as follows. A vehicle with a proposed set of dynamic characteristics is represented by a mathematical model in the vehicle dynamics simulation. A number of experienced drivers then drive the simulator, negotiating a predesigned course represented in the CGI environment. The vehicle characteristics can then be changed and additional test runs made. Eventually, through monitoring the performance of the various drivers under differing vehicle dynamics conditions, the best set of dynamics can be selected. Similarly, the effects of different types of environments or of different driving conditions can be evaluated by varying the CGI environment while holding the vehicle dynamics constant.

A group of scientists at Volkswagenwerk AG has constructed a sophisticated driving simulator and utilized if for just this purpose (Lincke, Richter, and Schmidt, 1973). The Volkswagen Simulator has three degrees of mechanical motion and possesses a computer driven visual display capable of representing a fairly schematic picture in real time. Despite the schematic nature of the picture presented, ordinary drivers were able to operate the vehicle very effectively. Eight drivers were used to evaluate eight different vehicle dynamic configurations by driving over a simulated test course approximately 10 kilometers in length. Each driver negotiated the course six times with each of the eight vehicle configurations. The drivers were told to cover the course as quickly as they could without going off the road or having an accident. Subjective evaluations from each of the drivers were collected at the end of each test run. These were compared with the measured results (time required to complete the course and number of times the wheels went off the road or crossed the road center line) for each of the vehicles. In addition, live tests were performed on a test track with vehicles possessing the same dynamic characteristics. The correlation between the measured simulator results, the subjective judgments, and the live vehicle test is extremely high. Details of the correlation are covered in the paper referenced.

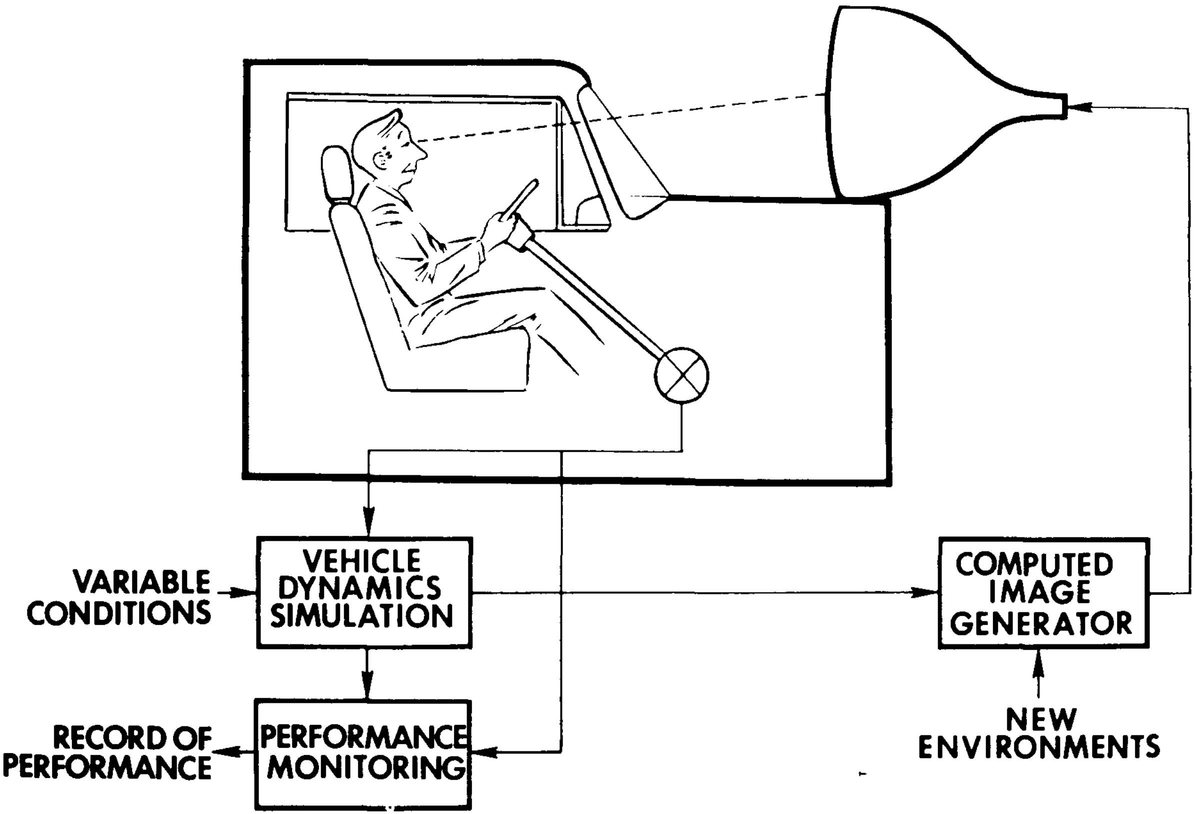

FIGURE 10. *Elements of man-in-the-loop simulation*

Design

CGI can also be used in a variety of ways in highway-related design tasks. Design applications differ from other CGI driving applications in that design applications can usually be performed in slow time.

CGI techniques could be applied, for example, to the design of an interchange to allow observation of the physical roadway that will result before construction is started. Working from input data normally available as a part of the civil engineering design, such as that shown in Figures 11A and 11B, the numerical description of the interchange elements can be constructed. The resulting computer-generated scene shown in Figure 12 could be viewed from any position in order to determine, for example, potential interference with other physical objects in the actual environment. The resulting roadway is pictured in Figure 13.

The composition and placement of signs is another example of a CGI application in the highway design area. The interaction of the driver with roadway markers and signs is an extremely complex process, particularly in the presence of heavy accompanying traffic. By utilizing a CGI-equipped simulator in a real time mode it would be possible to model various sign configurations and to experiment with a number of drivers until the best configuration is determined. This iterative approach would yield much more accurate results than standard computer simulation of the situation using a random traffic model. This fact results from the interaction of actual drivers with the scene.

Figures 14 and 15 illustrate an automated process for producing CGI roadway models from coordinate and elevation data. The spacing of the lateral boundaries crossing the proposed roadway is defined, along with the location of the first boundary and of the extremes of the project. Based on the required accuracy for approximating the actual terrain and roadway, the computer automatically models the environment with a succession of triangles. Colors can then be assigned interactively to these triangles to delineate the grass, shoulder, and pavement areas. The result is shown in Figure 15. This model can be viewed from any of a large number of vantage points in order to examine it fully.

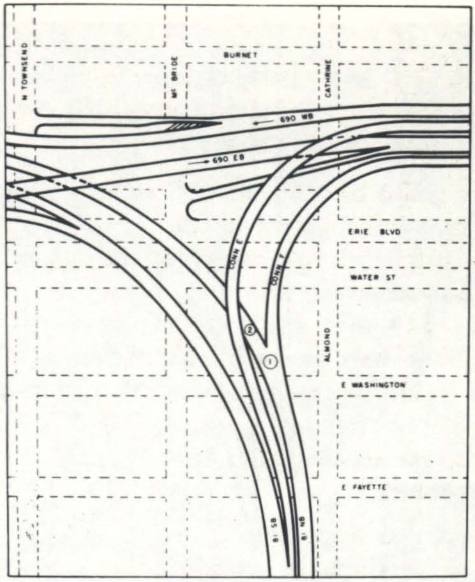

FIGURE 11A.

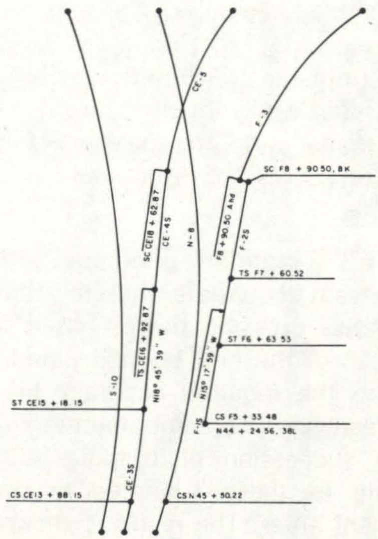

FIGURE 11B. *Civil engineering input data for roadway*

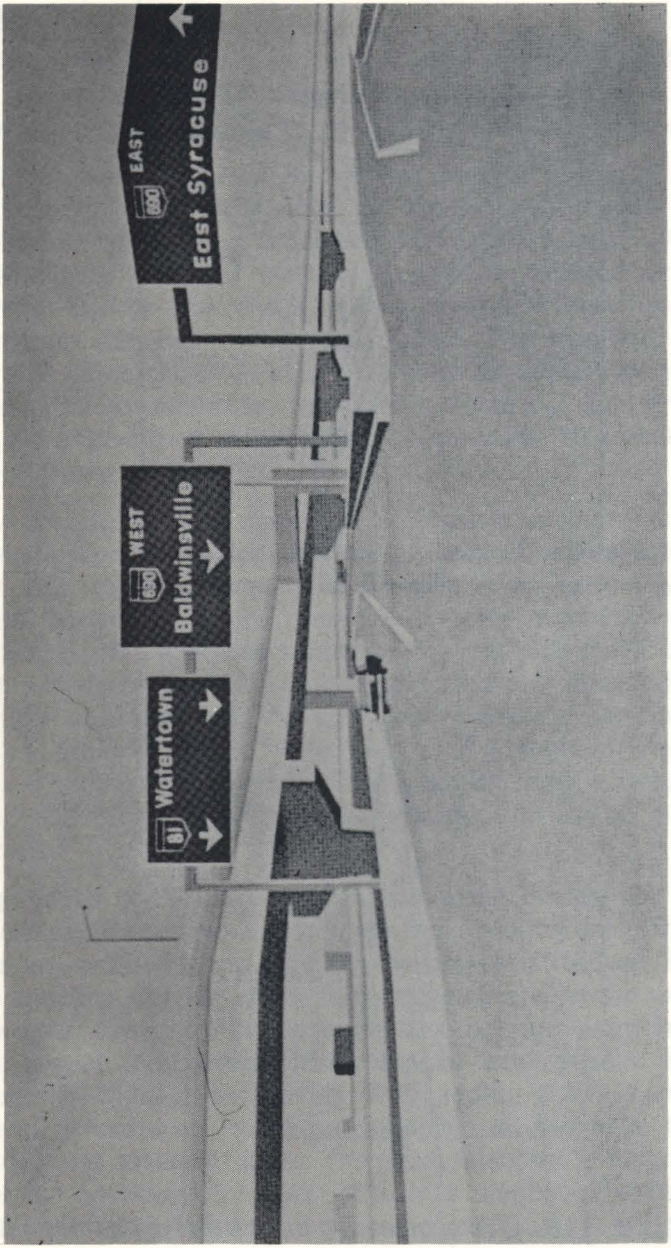

FIGURE 12. *CGI of proposed roadway based on in-put data from Figure 11*

FIGURE 13. *Roadway as built*

Training Drivers Through Simulation

The use of simulation in training of all types offers significant advantages over live training. In particular, the training to be performed can be accomplished in a controlled environment. The influences that are brought to bear on the trainee can be controlled to support the intended learning task. Furthermore, repetition can be used. A given event can be done over and over again without difficulty in setting up the initial conditions. Finally, stress can be introduced. Situations which would be difficult to reproduce or perhaps dangerous to experience in the real world can be incorporated into a simulated training program without danger to the trainee.

The value of these characteristics of training simulation in a driver training environment can be readily understood. For example, the ability to produce a controlled environment allows instructors to control and reproduce repetitively a traffic pattern involving a significant number of accompanying vehicles. In addition, the roadway characteristics, driving conditions, and vehicle performance can all be controlled. Repetition is of great value where a particular maneuver is being learned, such as a driver going around a righthand corner. Finally, stress situations, such as interaction with oncoming traffic, can easily be introduced. This last factor is perhaps the most valuable aspect of simulation training as applied to the driver training task.

It should be noted that the incorporation of a CGI image in the driving simulator creates unprecedented flexibility for providing interaction with traffic and producing varied environments and environmental conditions. Alternative approaches are severely limited in this regard.

A subject that has received a great deal of discussion is the effectiveness of high school driver education in reducing accidents and improving the quality of drivers. The information shown in Table I describes the results of one study on this subject (Solomon, 1970). This study covered 10,000 students, 6000 of whom were offered behind-the-wheel driving training in addition to classroom instruction. The three groups covered in Table I are: those among 6000 who took and passed the course, those among the 6000 who elected not to take the course, and the 4000 who were not offered the course. Solomon draws the conclusion from this information that, at least

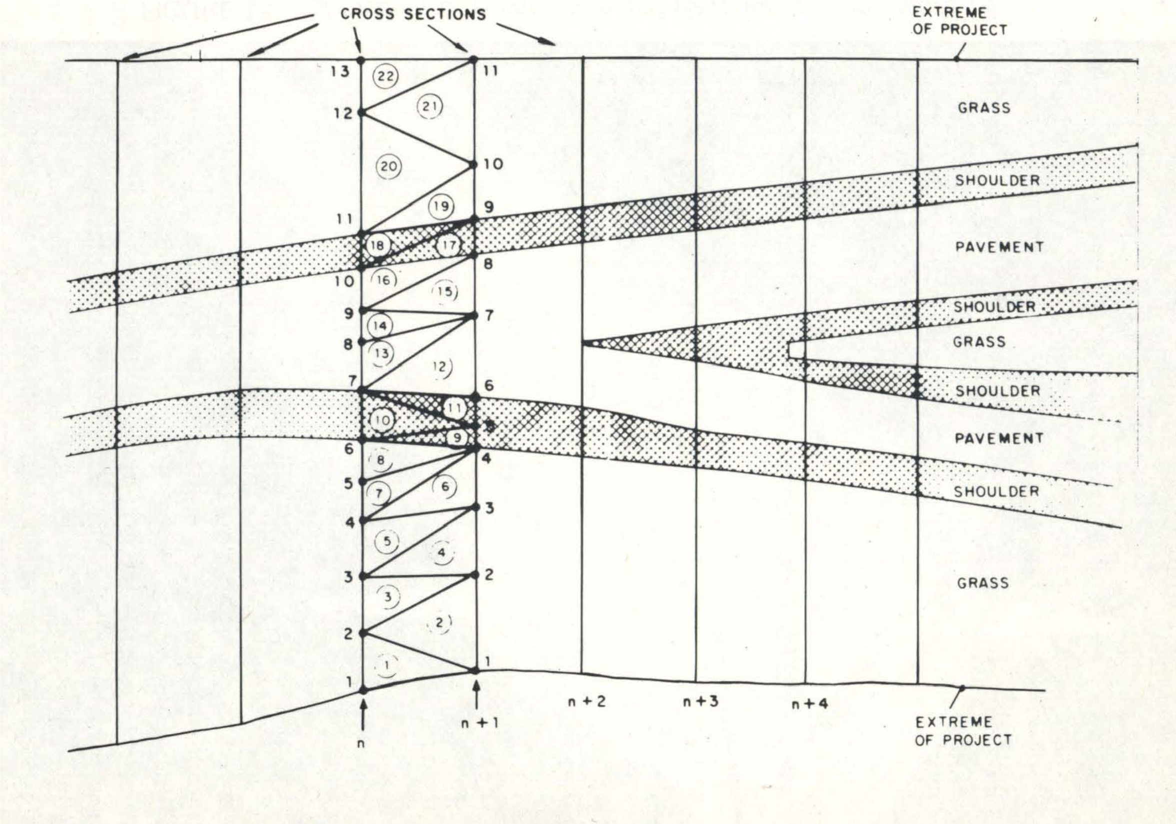

FIGURE 14. *Coordinate and elevation data for roadway*

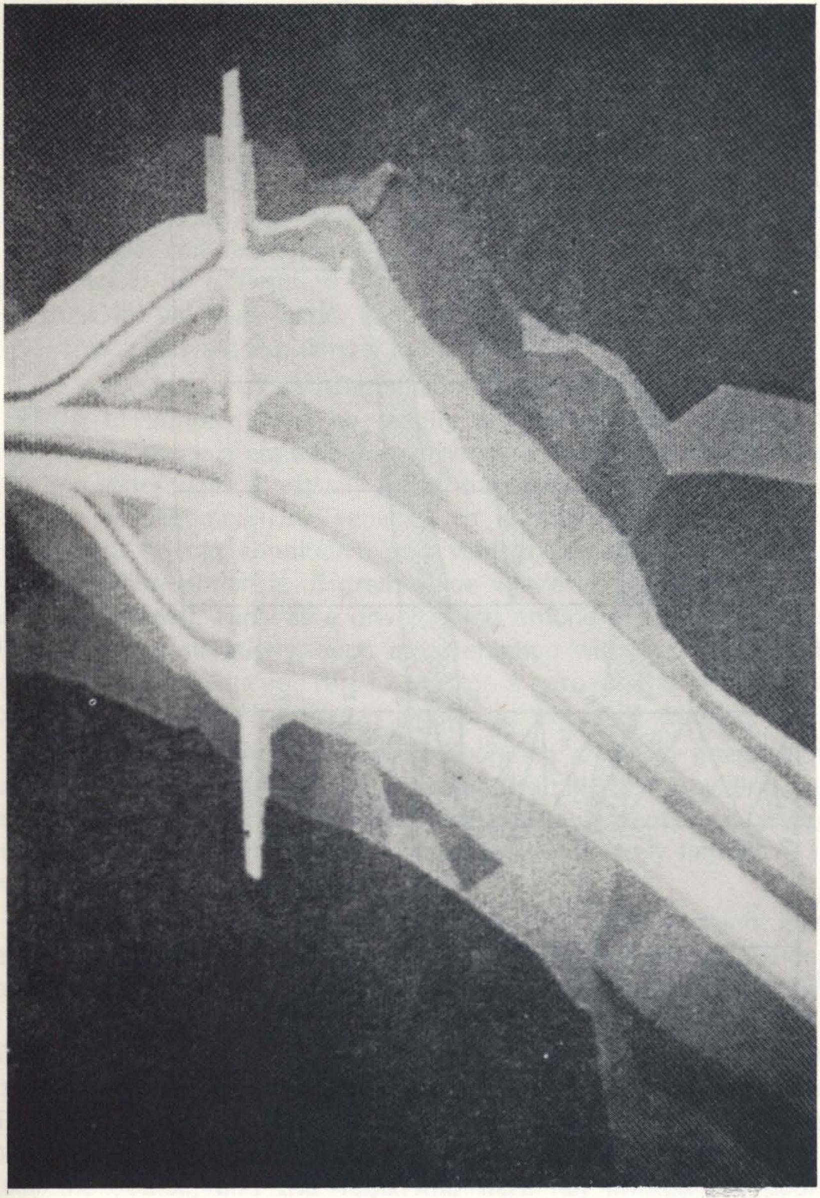

FIGURE 15. *CGI model from coordinate and elevation data in Figure 14*

in this study, the effectiveness of driving education in reducing accidents was not demonstrated. Without commenting on the overall effectiveness or value of driver education, it is fair to state that the inclusion of high-quality simulation in the training program should vastly improve the results of driver education.

Solomon's paper states, "Driving is basically a skill, and most skills are best learned by practice at a relatively early age." He goes on to speculate about the possibility of having young children participate in an extensive program of driving practice, perhaps in specially designed safe vehicles on a closed course, in order to develop driving skills. Of course it would take a great deal of money to set up such a program and a great many years to prove its effectiveness. Possibly the same thing is true of an extensive program of simulation in driver training. The important point is that whatever could be done with the specially-designed vehicle approach could also be done with CGI simulation, but more effectively, faster, and at lower cost. The safety requirements for allowing very young drivers to participate in this simulation program could easily be met.

Figure 16 shows a representation of a simplified driving simulator with the incorporation of the capability for programmed instruction. The term programmed instruction refers to the process of adjusting the course of the simulation based on the performance of the driver. For example, if the driver successfully negotiates a particular maneuver, it might be eliminated from the program after a few repetitions. If he has difficulty with it, it could be inserted into the program to appear again at a somewhat later time during the simulation run. All of this can be performed under the control of the computer, since it involves simple logical decisions based on information that is available. All quantities describing vehicle performance and interaction with the environment are contained within the vehicle simulation computer and the image generator. On the basis of this information, it can be determined what the performance of the driver is and what exercises he needs to repeat. Performance analysis itself could be performed in the same computer that does the vehicle simulation.

Figures 17A through D show a sequence that might be viewed by the driver in a driving simulator. These four scenes were generated by CGI techniques and represent four points in what would be a

High School Driver Education in California, 1965 Study

Driver Education	Average Number of Accidents Per Year		Average Travel Per Year	
	Males	Females	Males	Females
Took and Passed Course	.158	.076	9,500	4,600
Did Not Take Course	.154	.074	10,800	4,400
Could Not Take Course*	.186	.080	10,600	5,000

* Course was not available in that school or for that student.

TABLE I

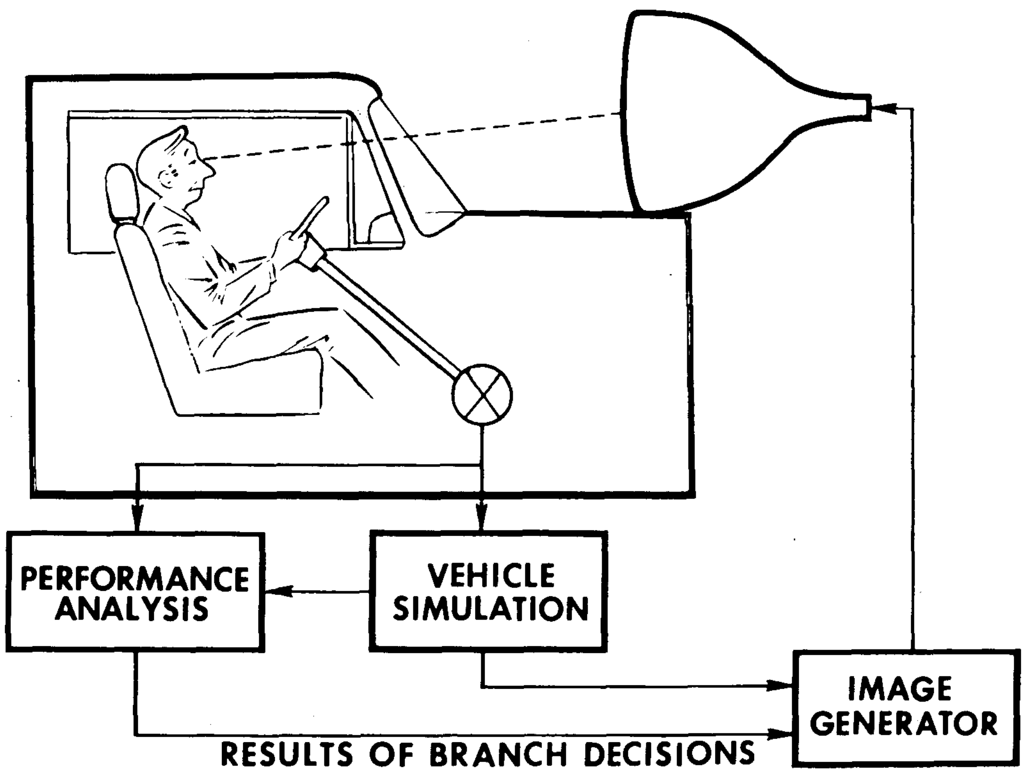

FIGURE 16. *Driving simulator with capability for programmed instruction*

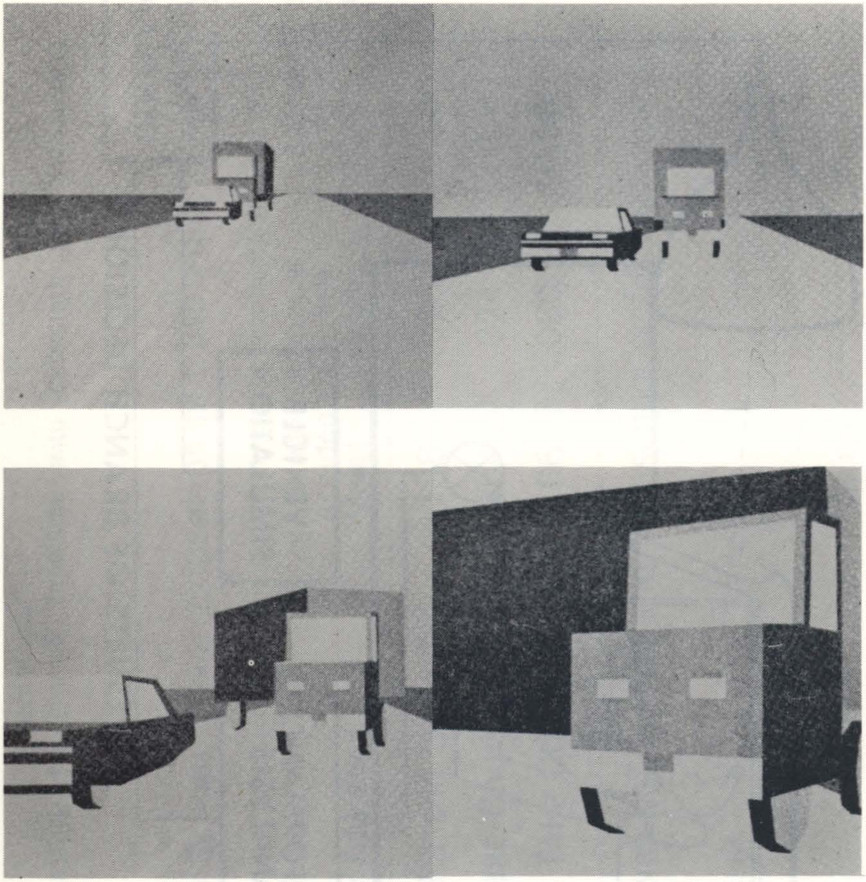

FIGURE 17. *CGI sequence from driving simulator*

continuous scene presented to the simulator driver. What would the driver's reaction be to the jackknifing semi-trailer? Perhaps the best thing to do would be to get off on the shoulder on the right. Whether he does this can be detected. In any event, this type of exercise can be completed without danger to the driver, except perhaps to his emotional state of mind.

What's Holding Us Back?

The technology for producing a satisfactory simulator for driving simulation now exists. In particular, the technology of CGI has advanced to the point where all of the required events described above can be successfully represented. What, then, prevents the large scale utilization of driving simulators for the purposes outlined above? Efforts in the past at determining what kind of driving simulator should be built, if any, have resulted in extremely high estimates of the cost of producing such a system. While these estimates might have been accurate several years ago for the highly sophisticated simulator capable of performing practically every task that anyone could imagine, they do not currently apply to the production of a special purpose simulator for driver training. Nonetheless, these high cost estimates have led potential users to believe that the system is many orders of magnitude more expensive than they could afford.

Technology in CGI visual systems has progressed to a point where a cost-effective driving simulator could be built today. In order to produce such a simulator, however, it is necessary to know several things. First, what tasks can be done most effectively on a CGI-equipped simulator? Second, what training is most cost effective on the simulator? An effective driver education program would undoubtedly involve a combination of classroom instruction, live driving tasks, and simulation. It would not be worthwhile, for example, to teach a student how to start a car and how to manipulate the controls with a simulator. The actual vehicle can be used for that in a very economical way. Parallel parking also could be taught on a closed course at very low cost. Initial traffic contact experience, on the other hand, should probably be taught on a simulator. In addition, such things as collision avoidance and building self-confidence in being able to handle the vehicle under adverse conditions would most certainly have to be done on a simulator. At present, however, a division of tasks among the various educational approaches is purely speculative. What is needed is attention to the problem of how a curriculum should be designed, based on the capabilities of the various approaches.

In addition, several questions arise concerning the capabilities of the Image Generator itself. For one thing, how much image detail is required? Early attempts at specifying a CGI visual have usually tended in the direction of requiring as much image detail capability as could possibly be handled within the limits of technology. This has resulted primarily from the fact that there has been little experience with the utilization of CGI visuals until recently. For example, it was never apparent to anyone what the effect on training would be if an oncoming vehicle were represented by a box as opposed to looking like a real vehicle. Naturally, making an airplane, an automobile, or a fire plug look like a photographic reproduction of the real article involves a great deal of computational capacity and expense. If slow-time CGI techniques were used for the production of movies or cartoons, photographic realism would be very important. However, high-realism approaches are completely out of place in a training simulation system which is to provide a maximum amount of learning per dollar. The trainee would very clearly understand what was going on if he were confronted with a real time, dynamically-accurate sequence similar to that represented by the truck photographs in Figure 18, even though photographic realism is not achieved.

Although it is apparent that schematic representation of images within the scene can do an effective job, the actual degree of realism required is unknown. The experiments at Volkswagen, as described in the above referenced paper, are a valuable step forward in answering the image detail question. Much more research is needed, however, in this area and in related areas such as determination of the required fidelity of simulator motion.

Conclusion

All of the ingredients for the effective application of simulation to driver training, highway research, and design are currently available. What is needed is a cooperative effort which is officially organized and involves the work of many parts of the Government, industrial, and university communities. The time has arrived when such a cooperative effort should be undertaken to determine the answers to the questions that remain before us.

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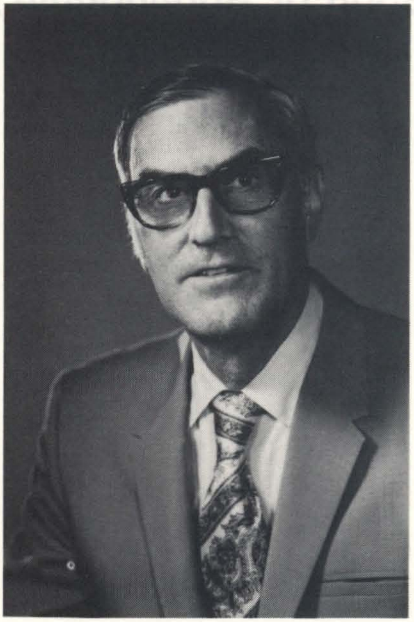
Section II

Simulators: Boon or Boondoggle?

Peter Kyropoulos



PETER KYROPOULOS

Dr. Kyropoulos was named technical director of the General Motors Design Staff in 1957. His work with simulators has spanned a number of years, and he is not only familiar with the technology of simulation but has also given considerable thought to the philosophy underlying it. Dr. Kyropoulos was associated with the California Institute of Technology (from which he received his doctorate) from 1941 through 1957. In 1953, he became a consultant to the General Motors Research Laboratories, assuming his present duties in 1957. Dr. Kyropoulos holds membership in a number of professional engineering associations and sits on advisory councils of four major universities.

SIMULATORS: BOON OR BOONDOGGLE?

By Peter Kyropoulos

Assuming that you have overcome the shock of the title, and assuming furthermore that the high priests of simulation have either left the room or have allowed their hackles to subside, we may proceed to define the subject as I am going to treat it.

I am involved in automobile design, and hence I am concerned with driver-vehicle-environment relations. The driver may be anyone who is legally licensed to drive. I shall, for the present discussion, *exclude driver training and driving under the influence of alcohol and drugs.* I shall have to depend on reseachers in these fields for my inputs.

The driver interacts primarily with the interior components of the vehicle, i.e., the controls and displays.

What are the criteria to be met?

How does the driver interact with these controls and displays?

What is the simplest and fastest way to examine many alternative solutions?

What is useless from the driver's point of view?

Can we identify *equivalent* solutions?

Is the solution technologically and economically feasible?

Is it realistic with respect to the *driver* population?

The literature is full of opinions — not necessarily data — on astronauts, fighter pilots, rhesus monkeys, and octopuses. This is well and good, but how does it relate to drivers? If the association *is* obvious, why not say so. If it *is not* obvious, somebody (preferably the author) better tell us what to make of it.

In addition to the problem of insufficient data, the hardware designer has the following constraints, which the researcher does not generally have:

Time is always short ("If I wanted the answer tomorrow, I would have asked you tomorrow!").

The goal may be a moving target: regulations change, tastes and idiosyncrasies change, problems go away or become academic ("The driver did not know it could not be done and did it anyway").

I have spent some time on the characterization of the problem for a good reason. In my review of the very extensive literature on simulators and simulation, I find little mention of the problems which concern the design of the vehicle but much exposition and discussion of the elegance of the device. In some instances one gets the impression of a sophisticated solution in search of a problem.

First of all, let me assure you that I know that simulation and simulators are capable of making very substantial contributions to vehicle design. They are indeed doing so all along, albeit in a manner different from that reflected by the literature on simulators.

We do not pay much attention to the official jargon, which may be examined in most technical articles (I never can remember that CGI stands for *C*omputer *G*enerated *I*mage and is not a gastrointestinal disorder, nor can I remember whether TBTV is a hard-to-cure disease, a TV station or *T*errain *B*oard *T*elevision).

We use the following forms of simulation:

1) A mock-up and questionnaire.
   Such a test is illustrated in Figure 1 and 2. Since this represents an international effort, similar tests were made in England, France and Germany. Everyone uses the same set of symbols and the same questionnaire (except for language). The statistical evaluation is being done by the chairman of the committee, Mrs. Alice Heard of my laboratory. In this test, no attempt is made to simulate the driving environment (outside the car) or car motion. The subject is told: "Imagine that you are driving this car. Please respond to my request (e.g. turn on the headlights)."

2) A mock-up of driver controls.

   The command and the secondary task are displayed in front of the driver. Such a test is shown in Figure 3.

The test subject is shown what the control does. In this case the control is a headlight beam switch for a three-beam system (as contemplated in Docket 69-19, a proposed amendmend to MVSS 108: Lamps, Reflective Devices, and Associated Equipment). This switch is incorporated into the turn signal lever (an accepted practice in

FIGURE 1. *SAE—ISO Committee on Control Identification, test control symbols. Real cars, mocked up control symbols, test subjects selected from visitors to the Ford Motor Company Visitors Center, Dearborn. Test Cars: American Motors, Chrysler, Ford, General Motors.*

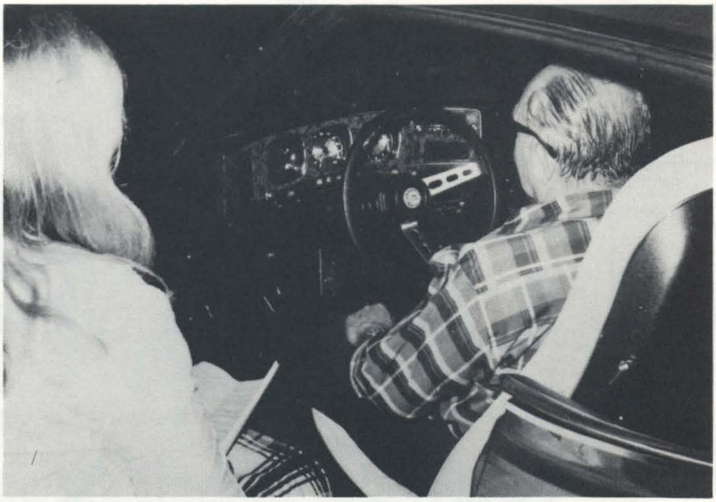


FIGURE 2. *Test subject in car, experimenter with questionnaire, asking questions and recording response.*

FIGURE 3. *Test subject being instructed*

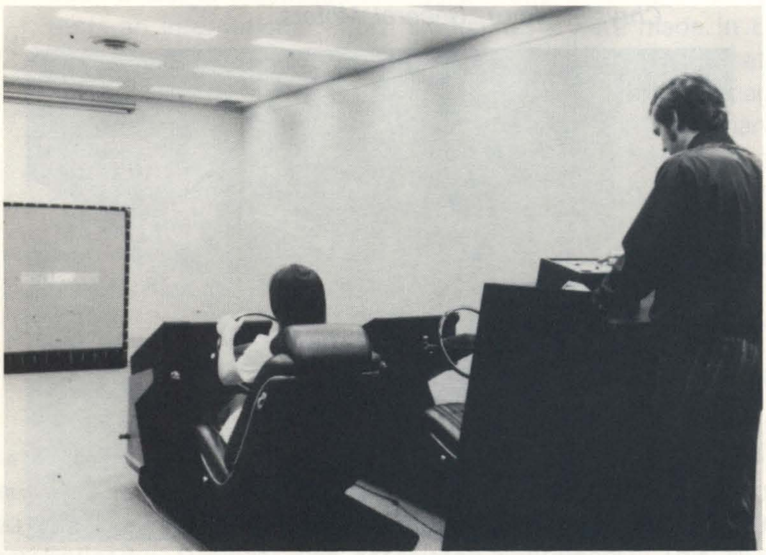


FIGURE 4. *Overall view of the mockup and test equipment*

Europe). The name of the beam selected is displayed on the instrument panel.

Figure 4 shows an overview of the test setup with the driving mock-up, the experimenter, the projected command, and the secondary task. The secondary task consists of a circle of lights which light up at random. The test subject turns the steering wheel until the pointer corresponds with the light. The switch action, the response time, and an appropriate identification code are punched automatically on tape, which is then used in data processing.

A practical note is in order here: we find it very important to the outcome of the test, that the action and feel of the controls be as close as possible to that of production controls. In addition to the measurements taken, we also ask for the subject's personal reaction It will not do for engineers and human factors specialists to decide unilaterally. We need to know how people react. A good device may be rejected or cause customer complaint unless it is identified and explained. At this point, the people who will build the hardware are called in to furnish typical hardware items, to serve as test subjects, and to participate in data analysis. This procedure accomplishes two things for us:

1) It dispels the mystique of the human factors specialists which can seriously hamper effectiveness in the real world.
2) It helps us to identify simple and practical solutions and eschew complexity (known in the trade as Kettering's Principle: "The part you eliminate on the drawing board will not give you trouble later on in the field").

Figure 4 shows a relatively simple mock-up of the driver's workspace. This particular mock-up is a basic component and has been used for different tests. Often it is easier and faster for us to modify a production car and use it statically, as shown in Figure 1. The choice depends entirely on the task, the available time, and the complexity of constructing the test setup.

Figure 5 shows our moving base simulator, which was described in detail by Beinke and Williams (1968). The driving scene is a motion picture. Figure 6 shows the projector mounted on top of the simulator. The driver sees the scene in front of him and, in the rear view mirror,

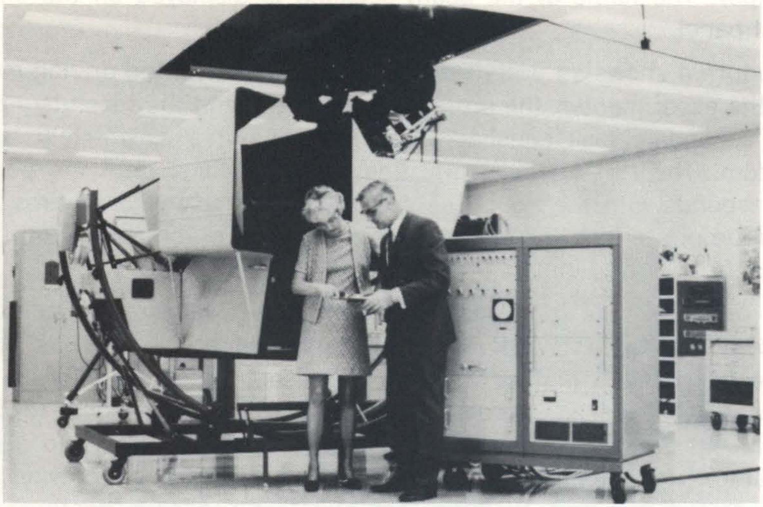


FIGURE 5. *GM moving base simulator*

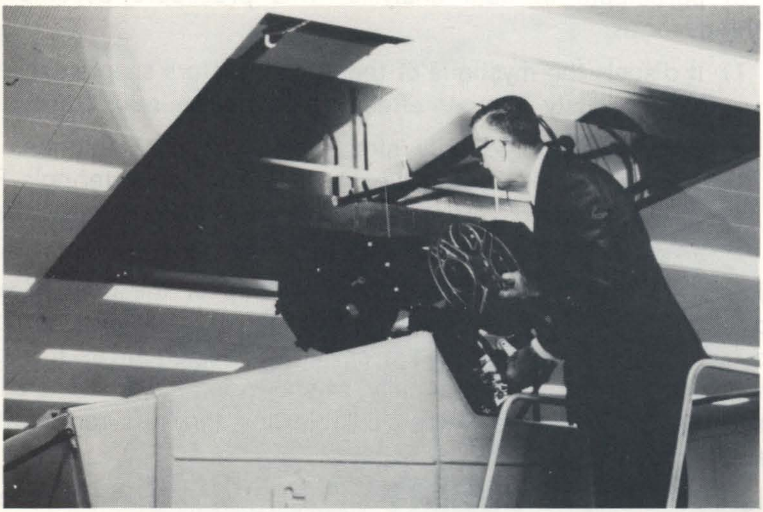


FIGURE 6. *Projection system (photographic film, image front and rear)*

the corresponding scene behind the car. Of course this is a highly structured and programmed driving task. The driver can experience only what has been recorded by the camera car. Although limited in this manner, this specific type of simulation is useful for confronting a driver with stressful situations and observing his reactions.

Figure 7 shows a simulator designed and constructed by the research laboratories of Volkswagen. In this device, the driving scene is generated by a computer and displayed on a cathode ray tube in front of the driver. Dr. Lincke of Volkswagen was kind enough to give me this picture. Generating scenes by computer offers more flexibility than any other method.

Figure 8 illustrates the type of high fidelity that can be generated. This depiction was made available to me by Mr. Ramon L. Carpenter of the General Electric Company. Images generated by computer are discussed and compared in Hulbert (1969).

Driving an instrumented car on a proving ground constitutes the next level of simulation. I still call this simulation because it is possible to set up specific controls (e.g. one way road, no counter-traffic, no other cars, etc.). It is the oldest and most traditional method of testing.

Traditionally, we have not been able to get any data (or, at best, only sketchy numerical data) on driver behavior from such tests, simply because it is difficult to get beyond subjective biases. This is not all bad, but is not sufficient in many cases. There does not really exist a good and flexible instrumentation which can readily be moved from car to car and which will survive the rigors of actual driving. Research vehicles have been built which serve only a specialized purpose. For our kind of product development work (as contrasted with research), such cars tend to become off-white elephants put on display at open house days or dog and pony shows.

For our purpose, the test car should differ from a normal production car only in the detail under test. An instrumented car which looks like a Boeing 707 cockpit is an engineer's delight, but distracts most test subjects and alters their behavior. This is also true to some extent in the laboratory type simulator, but there the trade-off in cost and convenience (such as all-weather capability and being able to use standard lab equipment) makes the lack of fidelity acceptable.

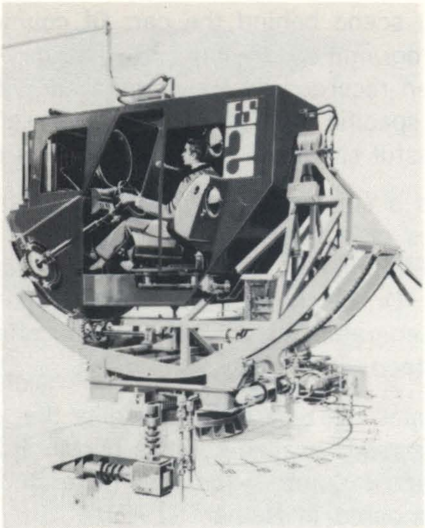


FIGURE 7. *Volkswagen moving base simulator (computer generated image) [courtesy of Volkswagenwerk]*

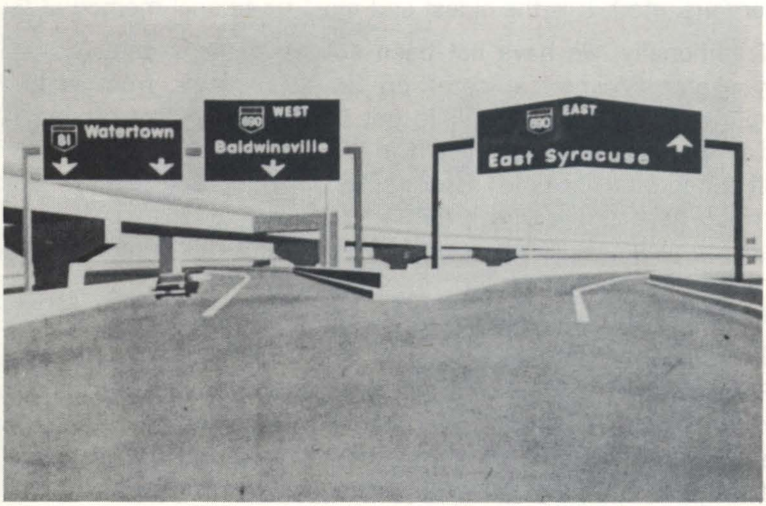


FIGURE 8. *Freeway scene generated by computer [courtesy of General Electric]*

How much fidelity is actually needed has been argued ever since simulation began. I agree with Gartner and Wernicke (1971). I shall paraphrase their conclusion simply by saying that the quest for the highest fidelity is often not justified. Generally, we compare several controls or displays, and are not directly concerned with the fidelity of the task. The ultimate test is the follow-up on a real vehicle. There are not many instances in the published literature where the experiment is carried through to a real life check. Although the need is recognized, it is easier said than done.

Wojcik and Allen have conducted studies of directional control on one of the UCLA simulators (Terrain Board Television type) and actual cars, and are satisfied with the results.

I am told that Dr. W. W. Wierwille at the Virginia Polytechnic Institute is intending to investigate driver behavior on a simulator of his design and on a vehicle.

Although actual data and experiences have not yet been reported, it is of interest to mention another type of simulation reported in Schimkat, Unterreiner, and Will (1972). Figure 9 shows an unmanned test car which carries remote controls and TV monitoring camera. Figure 10 shows the controls and TV monitor. The TV sceen presents the view from the unmanned test car.

I have discussed the simulator work done by Volkswagen because it constitutes the continuation of extensive studies begun many years ago by Dr. Fiala, who was at that time Director of the Institute for Motor Vehicle Research at the Technical University of Berlin (for further details on Dr. Fiala's studies, see Wallner (1970)). Dr. Fiala, now Director of Research at the Volkswagenwerk, has been consistently ignored in the U. S. literature on driving simulation. This oversight implies that we are the inventor and sole proponent of this technique. In conclusion, I would like to emphasize the signifance of Dr. Fiala's studies and encourage their publication in the United States.

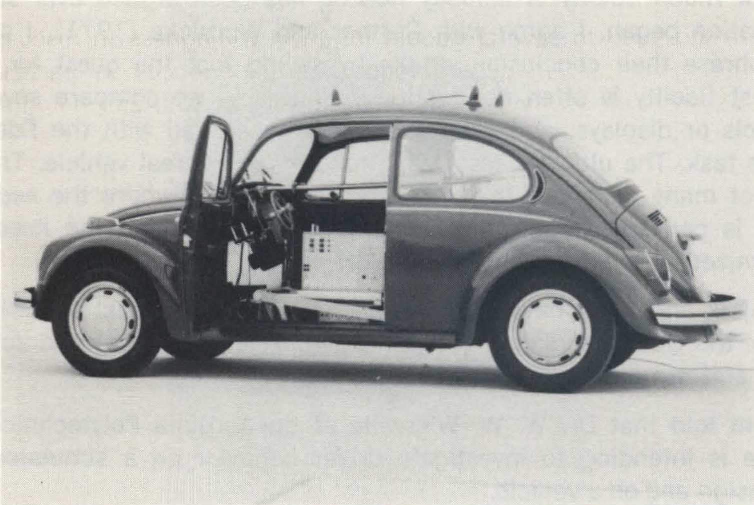


FIGURE 9. *Unmanned test car, Volkswagen accident simulator [courtesy of Volkswagenwerk]*

FIGURE 10. *Driving and monitoring control, Volkswagen accident simulator [courtesy of Volkswagenwerk]*

ACKNOWLEDGMENTS

I am indebted to several people for their willingness in discussing with me simulation in general and their experiences in particular. They have furnished me reports and reprints as well as photographs and descriptions of their simulators:

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Dr. R. Bernotat, Director, Forschungsinstitut, fur Anthropotechnik, Meckenheim, Germany.

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Last, but not least, I acknowledge the initiative and outstanding work of my co-workers in the Safety and Human Performance Laboratory of General Motors Design Staff and the Advanced Product Engineering Group of General Motors Engineering Staff.

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Section III

Use of Mathematical Simulations to Develop Safer Highway Design Criteria

T. J. Hirsch

T. J. HIRSCH

Dr. Hirsch is professor of civil engineering and head of the Structural Research Division of Texas Transportation Institute. As a research engineer, he is investigating mathematical simulation and its potential for pointing the way to safer highway design. Dr. Hirsch has received numerous honors and awards for his research and teaching, including the Texas A&M University Faculty Distinguished Achievement Award (1969); in 1971 he was named Engineer of the Year by the Brazos Chapter of the Texas Society of Professional Engineers. Dr. Hirsch's published articles have dealt primarily with the physical properties of highway construction materials and with the structural design of impact attenuation devices, including cell-type crash cushions and breakaway signs.

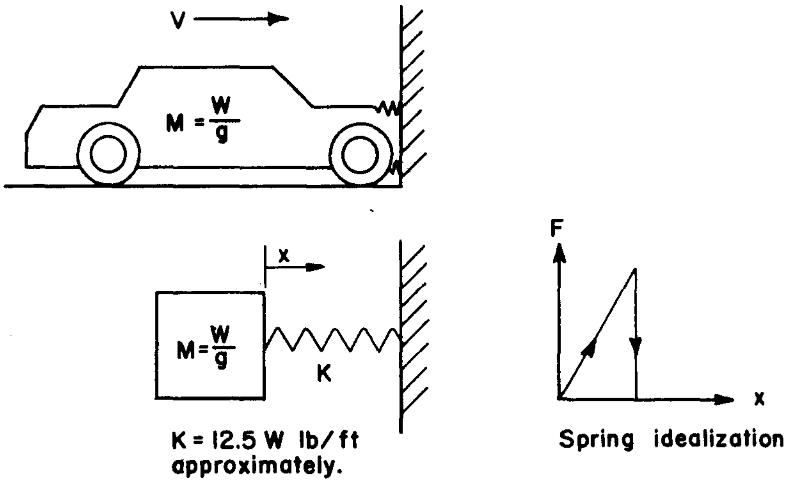
USE OF MATHEMATICAL SIMULATIONS TO DEVELOP SAFER HIGHWAY DESIGN CRITERIA

By T. J. Hirsch

Many practicing highway engineers and others are extremely skeptical of researchers and college professors who would like to have a research project to develop a mathematical model to analyze the passenger, vehicle and roadway interaction problems which can be used to design safer highways. In many cases their skepticism and distrust is well-founded, for they fear all they will get for their money is a thick complicated report which includes sophisticated mathematics that they do not understand and consequently cannot use. In most cases the researcher does not, or cannot, clearly show the sponsor how to use such a sophisticated mathematical program to solve the practical problems involved in designing safer highways. In many cases the researcher is unable to demonstrate how his complicated mathematics can solve the sponsor's problem because he does not fully understand the complexity of the highway engineer's real problem and possible alternatives.

It has been said that "one picture is worth a thousand words." It has also been said that "one full-scale test is worth a thousand expert opinions."

Before going further into the subject of mathematical models and simulations, let me point out one other philosophical point which I believe to be basically true. Most practicing engineers and others will quickly accept the results of one full-scale test as being true, accurate or representative of the phenomena observed. One man who distrusts the results of the test is the man who actually conducted it because he understands or appreciates how difficult it would be to repeat the test and obtain the same results. Usually only he understands how a small change in some of the variables can completely change the results of the test. In the case of a rigorous mathematical model or simulation of a physical phenomena, only the researcher who developed the model has confidence in its validity or ability to predict the real world phenomena. Many other engineers and researchers will view it with suspicion and distrust, either because they do not understand the complicated mathematics, or because



$-Kx = M\ddot{x}$ where B.C. are $t=0,\ x=0,\ \dot{x}=V$

$\ddot{x}+\omega^2 x = 0$ where $\omega^2 = K/M$

Solution $x = (V/\omega)\sin\omega t$

$\dot{x} = V\cos\omega t$

$\ddot{x} = -V\omega\sin\omega t$

$G_{max} = \ddot{x}_{max}/g = -V\omega/g = -.62V_{fps}$ or $-.9V_{mph} = G_{max}$

$G_{avg} = G_{max}(2/\pi) = -.58V_{mph} = G_{avg}$

FIGURE 1. *Simulation of rigid-barrier collision*

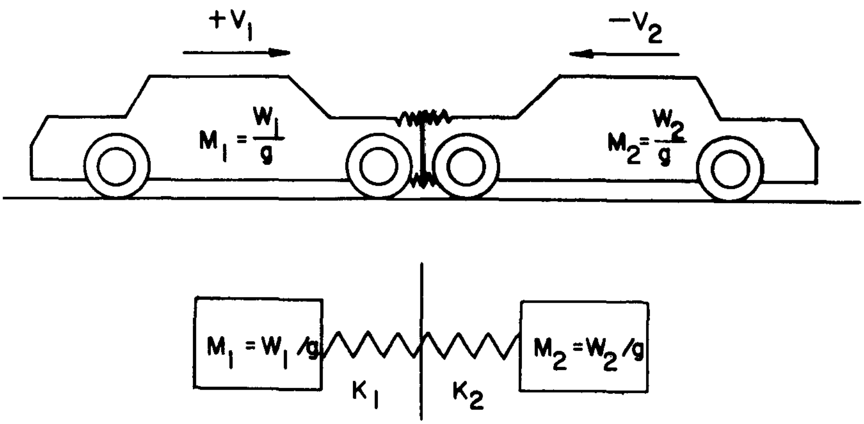
they understand them so well that they realize many simplifying assumptions must have been made to solve the problem. Consequently, engineers and researchers will distrust the validity of some of the assumptions and thus the accuracy of the predictions.

Despite these negative viewpoints, the writer believes that mathematical models, or simulations, can be extremely powerful tools for achieving safer highway designs. In developing a mathematical simulation to describe observed physical behavior, a researcher must synthesize the problem and define the significant variables affecting the problem. By using a simulation, which has been validated by tests, a researcher is then able to investigate various combinations of variables to arrive at a more effective or economic design.

Mathematical Models

In the writers' opinion, the first attempt at developing a mathematical model to describe a physical phenomenon should be kept extremely simple. The model or simulation should contain only those variables necessary to describe the basic phenomena of concern. This is sometimes called the "Quick, Rough and Dirty Approach." To do this, one should have test results or experimental observations available; then he can attempt to synthesize the problem and describe the behavior mathematically. This quick, rough and dirty approach will allow the researcher to get a handle on the problem, and to readily determine the magnitude and significance of certain obvious variables. Additional sophistication can be added to the simulations as necessary or required to obtain the desired results. As an example of this approach, Figure 1 shows the synthesis and simulation of a vehicle/rigid-barrier collision, first published by Emori of UCLA (1968). After observing the results of many full-scale vehicle crash tests involving a rigid barrier, Emori concluded that the crushing of the vehicle front end could be simulated as a lump mass and one spring. From full-scale test data, he observed that the spring stiffness of the front end of the vehicle could be closely approximated by 12.5 times the vehicle weight. The spring exhibits no restitution. This approximation was found to be within about ± 20 percent accuracy.

Following the solution of the homogenous linear differential equation, one will find that the maximum deceleration of the vehicle is



Momentum before impact = momentum after impact

$$M_1 V_1 + M_2(-V_2) = M_1 V_1' + M_2 V_2'$$

If springs K_1 and K_2 have no restitution (plastic impact)

$$M_1 V_1 - M_2 V_2 = V'(M_1 + M_2)$$

Final velocity is

$$V' = \frac{W_1 V_1 - W_2 V_2}{W_1 + W_2}$$

The changes in velocity are

$$\Delta V_1 = V_1 - V' \quad \text{and} \quad \Delta V_2 = -V_2 - V'$$

It can be shown that the deceleration of either vehicle is

$$G_{max} = .9\,\Delta V_{mph}$$

or

$$G_{avg} = .58\,\Delta V_{mph}$$

FIGURE 2. *Simulation of vehicle to vehicle collision*

equal to 0.9 times the vehicle impact velocity in miles per hour. The average deceleration of the vehicle during the collision is 0.58 times the vehicle velocity in miles per hour. For example, in a 60 mph rigid barrier collision, the vehicle will be subjected to a maximum deceleration of 0.9 times 60, yielding 54 g's. The average deceleration of a vehicle will be 0.58 times 60, or 35 g's. If one further examines the solution to the differential equation, it will be found that the duration of the collision is 0.080 sec. This relatively simple simulation of a vehicle/rigid-barrier collision is extremely useful for comprehending the magnitude of the decelerations imposed on such a vehicle and the collision forces involved. If an engineer were required to design a rigid barrier to resist the 60 mph head-on impact of a 4000 lb vehicle, it is apparent that the barrier must resist a force of 4000 lb times the peak deceleration of 54 g's or 216,000 lb. The total kinetic energy of the vehicle is absorbed by the crushing of its front end. Knowing the approximate stiffness of the front end, one can quickly compute the maximum deformation of the front of the vehicle.

One can readily extend this simulation to that of the vehicle-to-vehicle collision as shown in Figure 2. By using Newton's third law (the conservation of momentum), it is known that the momentum before impact must equal the momentum after impact. Following the derivation, shown in Figure 2, it can be seen that the change in velocity of vehicle 1 and the change in velocity of vehicle 2 can be readily computed. It can be readily shown (as in Figure 1) that the maximum deceleration of each of the vehicles is equal to 0.9 times the velocity change and that the average deceleration imposed on each vehicle is 0.58 times the velocity change. For example, if vehicle 1 weighs 4000 lb and vehicle 2 weighs 2000 lb and they are traveling in opposite directions at 60 mph, the 4000 lb car will sustain a velocity change of only 40 mph, whereas the 2000 lb car will sustain a velocity change of 80 mph. Consequently, the smaller vehicle will be exposed to a deceleration level twice that of the heavier vehicle. In this case the peak deceleration will be 72 g's for the 2000 lb car and only 36 g's for the 4000 lb car. Using generally accepted values for the human tolerance to deceleration in such vehicle collisions (Appendix A), it becomes apparent that the occupants of the 2000 lb vehicle will almost certainly die in the crash, whereas it is possible that occupants of the 4000 lb vehicle may survive. If one further examines the simulation shown in Figure 2, it can be found that the smaller 2000 lb vehicle must absorb twice the kinetic energy in the collision as the 4000 lb vehicle. This simulation can also be used to quickly evaluate the decelerations imposed in a collision of a faster vehicle overtaking a slower vehicle, both moving in the same direction. (Both V_1 and V_2 will be positive.)

The simulations shown in Figures 1 and 2 clearly indicate the significant parameters involved in such collisions (the vehicle speed, the vehicle weight, and the stiffness (or spring constant) of the vehicle structure). If one sits down and carefully manipulates these significant variables, he can arrive at many enlightening conclusions concerning the design of vehicles to achieve greater safety.

Mathematical Model of a Vehicle/Barrier Railing Collision

An extensive review of available research literature revealed that many full-scale dynamic tests of barrier railings have been conducted by several research organizations, and much useful information has been made available in written reports and on high-speed film records. As study of this information progressed, it was evident that a rational analytical approach as a basis for the design of a barrier railing system has not been available to the highway engineer. A simple mathematical model of a vehicle/barrier railing collision evolved (Olson, Post, & McFarland, 1970). Observations of high-speed films and sequence photographs led to the development of the equations presented.

These equations assume that, at the instant of impact, the vehicle motion can be defined by an angle, θ, and a velocity, V_1, as shown in Figure 3. The following assumptions have been made:

(1) The lateral and longitudinal vehicle decelerations are constant during the time interval required for the vehicle to become parallel to the undeformed barrier.

(2) Vertical and rotational accelerations of the vehicle are neglected.

(3) The lateral component of velocity is zero after the vehicle is redirected parallel to the barrier railing.

(4) The vehicle is not snagged by the barrier railing as it is being redirected.

(5) Deformation of the vehicle occurs in the area of impact, but the center of mass (C.G.) of the vehicle is not thereby changed appreciably.

(6) The mass center of the vehicle moves as if the entire mass were concentrated at that point.

(7) A barrier may be rigid ($D = 0$) or may be flexible ($D > 0$).

(8) The friction forces developed between the vehicle tires and roadway surface are neglected.

(9) The barrier railing system does not contain discontinuities (jutting curbs, etc.) which might produce abrupt vertical movement of the vehicle.

Based on these assumptions, the motion of the vehicle that occurs during the time interval required for the vehicle to become parallel to the undeformed barrier railing can be determined from the basic principles of mechanics.

Referring to Figure 3, the lateral movement of the vehicle, $\Delta S_{lat.}$, is expressed by the equation:

$$\Delta S_{lat.} = AL\sin(\theta) - B[1 - \cos(\theta)] + D \quad (1)$$

This lateral movement of the vehicle occurs during the time interval, Δt, expressed by the equation:

$$\Delta t = \frac{\Delta S_{lat.}}{\text{Average Lateral Velocity}}$$

in which

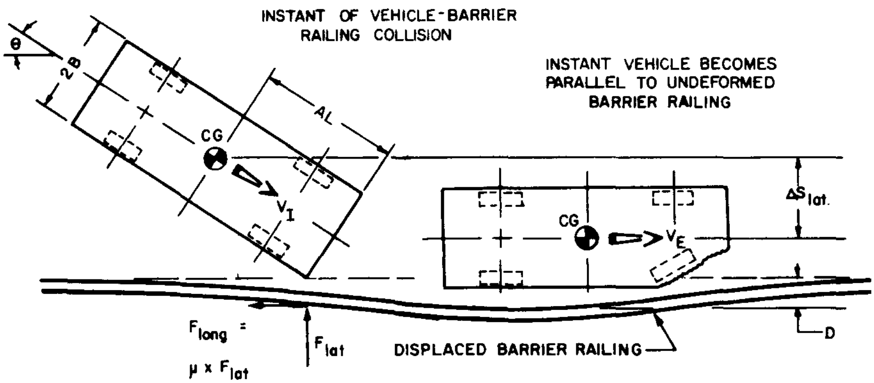
$$\text{Average Lateral Velocity} = \tfrac{1}{2}\,[V_1\sin(\theta) + 0]$$

$$\Delta t = \frac{AL\sin(\theta) - B[1 - \cos(\theta)] + D}{\tfrac{1}{2}V_1\sin(\theta)} \quad (2)$$

Having an expression for the time interval, the average vehicle decelerations, G's, are expressed by the equations:

Average Lateral Vehicle Deceleration ($G_{lat.}$)

$$G_{lat.} = \frac{a_{lat.}}{g} = \frac{(\Delta V)_{lat.}}{g(\Delta t)}$$



Avg. $G_{lat.} = \dfrac{\Delta V_{lat.}}{\Delta t \; g}$ and avg. $G_{long.} = \dfrac{\Delta V_{long}}{\Delta t \; g}$

Since $\Delta V_{lat.} = V_I \sin\theta$ and $\Delta V_{long.} = V_I \cos\theta - V_E$

and $\Delta t = \dfrac{\Delta S_{lat.}}{V_{lat. avg.}} = \dfrac{AL \sin\theta - B(1-\cos\theta) + D}{1/2 \; V_I \sin\theta}$

then

$$\text{avg. } G_{lat.} = \frac{V_I^2 \sin^2\theta}{2g\left[AL\sin\theta - B(1-\cos\theta) + D\right]}$$

$$\text{avg. } G_{long.} = \mu G_{lat.}$$

Exit speed $V_E = V_I(\cos\theta - \mu\sin\theta)$

FIGURE 3. *Simulation of vehicle — traffic rail collision*

in which

Change in Lateral Velocity $(\Delta V) = V_1 \sin(\theta) - 0$

$$G_{lat.} = \frac{V_1 \sin(\theta)}{g(\Delta t)}$$

$$G_{lat.} = \frac{V_I^2 \sin^2(\theta)}{2g\{AL\sin(\theta) - B[1 - \cos(\theta)] + D\}} \tag{3}$$

Average Longitudinal Deceleration $(G_{long.})$

$$G_{long.} = \mu G_{lat.} \tag{4}$$

in which μ is the coefficient of friction between vehicle body and barrier railing.

The vehicle exit or final velocity (V_E) can be computed by

$$G_{long.} = \frac{a_{long.}}{g} = \frac{\Delta V_{long.}}{g\Delta t}$$

$$= \frac{V_I \cos\theta - V_E}{g\Delta t}$$

substituting equations (2), (3), and (4) yields

$$V_E = V_I (\cos\theta - \mu \sin\theta) \tag{5}$$

Note that the average impact forces are:

$$F_{lat.} = WG_{lat.}$$

$$F_{long.} = WG_{long.}$$

in which

L = vehicle length (ft);
$2B$ = vehicle width (ft);
D = lateral displacement of barrier railing (ft);
AL = distance from vehicle's front end to center of mass (ft);

V_I = vehicle impact velocity (fps);
V_E = vehicle exit velocity (fps);
θ = vehicle impact angle (deg);
μ = coefficient of friction between vehicle body and barrier railing;
a = vehicle deceleration (ft/sec^2);
g = acceleration due to gravity (ft/sec^2);
m = vehicle mass ($lb\text{-}sec^2/ft$); and
W = vehicle weight (lb).

These equations express the average vehicle decelerations as a function of: (1) type of barrier railing — rigid or flexible, (2) dimensions of the vehicle, (3) location of the center of mass of the vehicle, (4) impact speed of vehicle, (5) impact angle of the vehicle, and (6) coefficient of friction between the vehicle body and barrier railing.

Tests have shown the friction coefficient to range from 0.1 to 0.7 with an average value of about 0.3 for steel rails. Peak or maximum decelerations can be two times the average values computed.

The equations developed here can be used to design safer traffic rails for a selected vehicle weight (W), impact angle (θ), and impact speed (V_I). The rail must have adequate strength to resist the collision forces (lateral and longitudinal). The rail can also be designed to be flexible to provide lateral deformation (D) which in turn will minimize the decelerations on the vehicle to provide more safety (or fewer injuries) for the vehicle occupants. Since the final vehicle velocity (V_E) can be computed, the change in vehicle kinetic energy can be computed. The crushing of both the vehicle and barrier, and the energy dissipated by friction between the barrier and vehicle must account for the change in kinetic energy. If structural analysis of the barrier indicates it is not capable of absorbing the required energy, it is obviously inadequate.

Mathematical Simulations to Describe Vehicle Impact Attenuation Concepts

In recent years, vehicle impact attenuation devices, sometimes called crash cushions, have been installed on our nation's highways in order to protect vehicles from collisions with rigid obstacles located near the travel-way. The following discussion attempts to describe, with simple mathematical simulations, the basic physical principles now used. Presently available vehicle crash cushions generally use one of the following two concepts to stop a speeding vehicle before it strikes a rigid obstacle or hazard.

The first concept involves absorption of the kinetic energy of the speeding vehicles either by using "crushable" or "plastically" deformable materials or structures, or by using hydraulic "dashpots" or energy absorbers placed in front of the hazard. Devices of this type need a rigid backup or support to resist the vehicle impact force and deform the energy absorbing material or structure. Figures 4 and 5 illustrate this principle applied to a compression type barrier and a net (or snagging) device, respectively.

In Figure 4 the stopping force (F) need not be constant, but the area under the force (F) vs deformation (D) graph of the crash cushion should equal the kinetic energy of the impacting vehicle. The crash cushion should be designed so that it will stop a small 2000 lb vehicle traveling at 60 mph with D equal to or greater than the minimum required stopping distance of 10 ft (based on 12g maximum allowable average deceleration, Appendix A). Additional material and distance should also be provided so that the device will also be capable of stopping a 4500 lb vehicle traveling at 60 mph.

In Figure 5 the metal tape tension, or "drag force," (T) will usually be constant. The designer must select the proper combination of "drag force" (T) and tape run-out distance (R) so the device will stop a small 2000 lb vehicle traveling 60 mph with a stopping distance (D) equal to or greater than the minimum required stopping distance of 10 ft. Additional tape run-out capacity (R) should be provided so the device will be capable of stopping a 4500 lb vehicle traveling at 60 mph. From the simple geometry of Figure 5 it can be seen that the relationship between stopping distance (D) and tape run out (R) is

$$D = R^2 + RL \quad \text{or} \quad R = \frac{-L + \sqrt{L^2 + 4D^2}}{2} \quad \text{(approximately)}$$

The second concept involves transfer of the momentum of the speeding vehicle to some expendable masses of material located in the path of the vehicle. The expendable masses (or weights) are

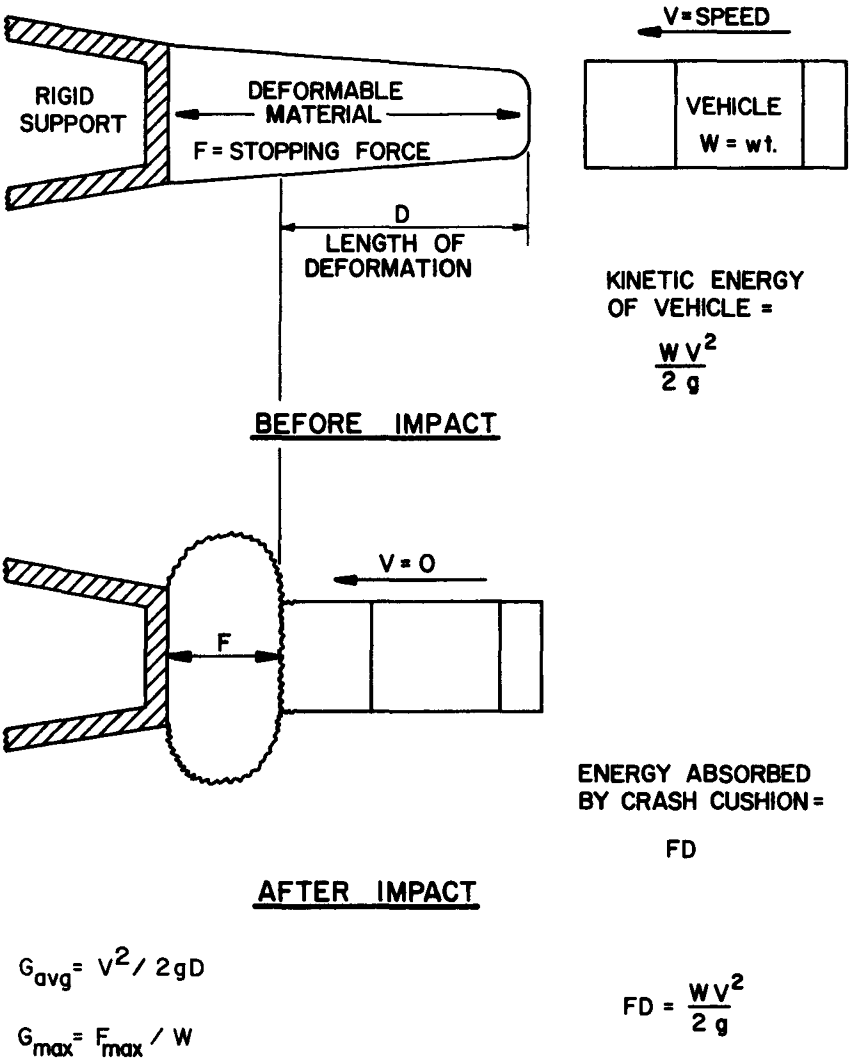


FIGURE 4. *Principle of absorbing vehicle kinetic energy — compression device*

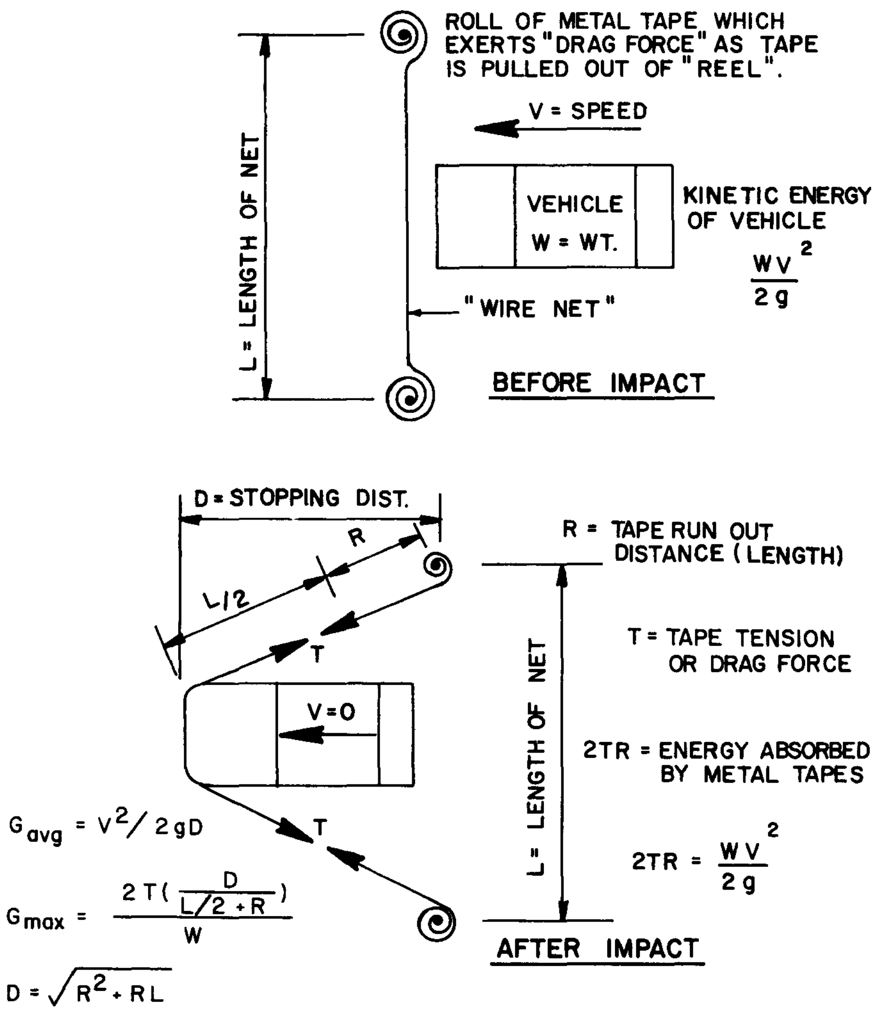


FIGURE 5. *Principle of absorbing vehicle kinetic energy — nets or snagging devices*

usually containers filled with sand, although water and other materials can be used. Devices of this type need no rigid backup or support to resist the vehicle impact force since the kinetic energy of the vehicle is not absorbed but merely transferred to the other masses. This type of crash cushion is sometimes referred to as an "Inertia Barrier."

Figure 6 illustrates this principle applied to a speeding vehicle impacting a series of 5 masses or containers filled with sand.

By the law of Conservation of Momentum, the vehicle speed after first mass impact (assuming rigid body plastic impact) is

$$V_1 = V_0 \left(\frac{W}{W + W_1} \right)$$

The vehicle speed after second mass impact is

$$V_2 = V_1 \left(\frac{W}{W + W_2} \right)$$

The final speed after fifth mass impact will be

$$V_5 = V_4 \left(\frac{W}{W + W_5} \right)$$

To obtain a constant change in velocity as the vehicle strikes each container (W_1 through W_5) it can be seen that containers must increase in weight (or mass) as they get closer to the hazard.

Thus

$$\Delta V_1 = V_0 - V_1 = V_0 \left(1 - \frac{W}{W + W} \right)$$

and

$$\Delta V_2 = V_1 - V_2 = V_1 \left(1 - \frac{W}{W + W_2} \right)$$

and so forth. It is apparent that theoretically the vehicle cannot be stopped completely by this principle. Practically, however, it is usually adequate to design the Inertia Barrier to reduce the vehicle speed to 10 mph after the final container is impacted.

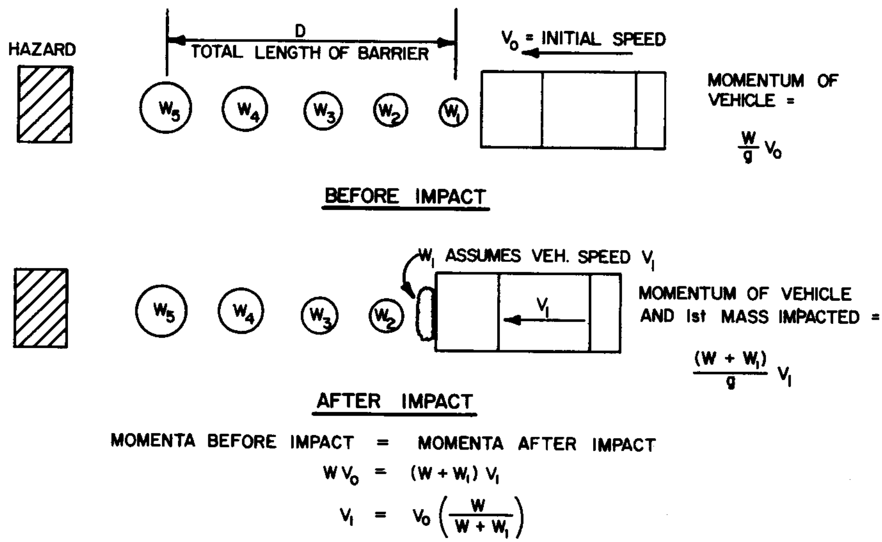


FIGURE 6. *Principle of transferring vehicle momentum to expendible masses — assuming plastic rigid body impact*

If the Inertia Barrier illustrated by Figure 6 were designed to slow a 2000 lb vehicle traveling at 60 mph down to 10 mph with 5 containers (each slowing the vehicle 10 mph), the containers should each weigh:

$$W_1 = 2{,}000 \left(\frac{60}{50} - 1\right) = 400 \text{ lb}$$

$$W_2 = 2{,}000 \left(\frac{50}{40} - 1\right) = 500 \text{ lb}$$

$$W_3 = 2{,}000 \left(\frac{40}{30} - 1\right) = 667 \text{ lb}$$

$$W_4 = 2{,}000 \left(\frac{30}{20} - 1\right) = 1{,}000 \text{ lb}$$

$$W_5 = 2{,}000 \left(\frac{20}{10} - 1\right) = 2{,}000 \text{ lb}$$

As in the design of any vehicle crash cushion, the weight and number of containers and length of the barrier should be proportioned to stop a small 2000 lb vehicle traveling at 60 mph with a stopping distance (D) equal to or greater than the minimum required distance of 10 ft. Additional containers and distance should be supplied so the device can also stop a 4500 lb vehicle traveling 60 mph.

VEHICLE IMPACT ATTENUATION — GEOMETRIC AND DESIGN DETAILS

In the preceding sections the basic design criteria and concepts used in the development of most vehicle impact attenuation devices presently available were presented. To make a crash cushion work as intended by the design, however, requires careful attention to several other geometric and design details.

A vehicle may ramp and jump over the vehicle impact attenuation device if the resultant stopping force provided by the crash cushion is considerably lower than the vehicle center of gravity (C.G.). The energy absorbing material may deform more at the top than at the bottom and thus form a ramp for the vehicle.

A vehicle may also flip end over end due to the couple formed by the eccentricity of the resultant stopping force and vehicle inertia force.

On the other hand, a vehicle may submarine under the vehicle impact attenuation device if the resultant stopping force is considerably higher than the vehicle center of gravity. To guard against such behavior, the resultant stopping force provided by the energy absorbing material or inertia masses should be located approximately 22 to 24 inches above the roadway or ground. (This is the approximate location of a passenger vehicle's center of gravity.) In addition, the energy absorbing crash cushion materials are usually stabilized by a cable or other anchoring system to prevent the material from moving up, down or sideways during the collision.

Use of Computer Simulation to Evaluate the Impact Response of Various Motorist-Aid Call Systems

The motorist-aid call system has been installed on some urban freeways in an effort to aid the problem of freeway inefficiency resulting from disabled vehicles and also to serve as a convenience to distressed motorists. Typical installations have the call-boxes spaced at approximately one-quarter mile intervals on each shoulder and in each direction of travel so that a motorist is not required to cross main lane traffic to place a call.

Since these installations are usually situated next to the roadway, collisions with these installations may be hazardous to the motorist if adequate safety features are not incorporated in the call system design. This also applies to sign posts, light poles, etc. (Martinez, 1968: Martinez, et al., 1970: and Martinez, Olson, and Post, 1971). For example, a nonfrangible base attachment could cause large vehicular deceleration rates and possible injury to the occupants. Also, a call-box improperly secured to the support post could come loose after impact and go through the windshield of the impacting vehicle. In addition, the dynamic characteristics of the call-box may be such that, upon impact, the entire system rotates and strikes the vehicle compartment in the area of the windshield causing a hazardous situation for the occupants.

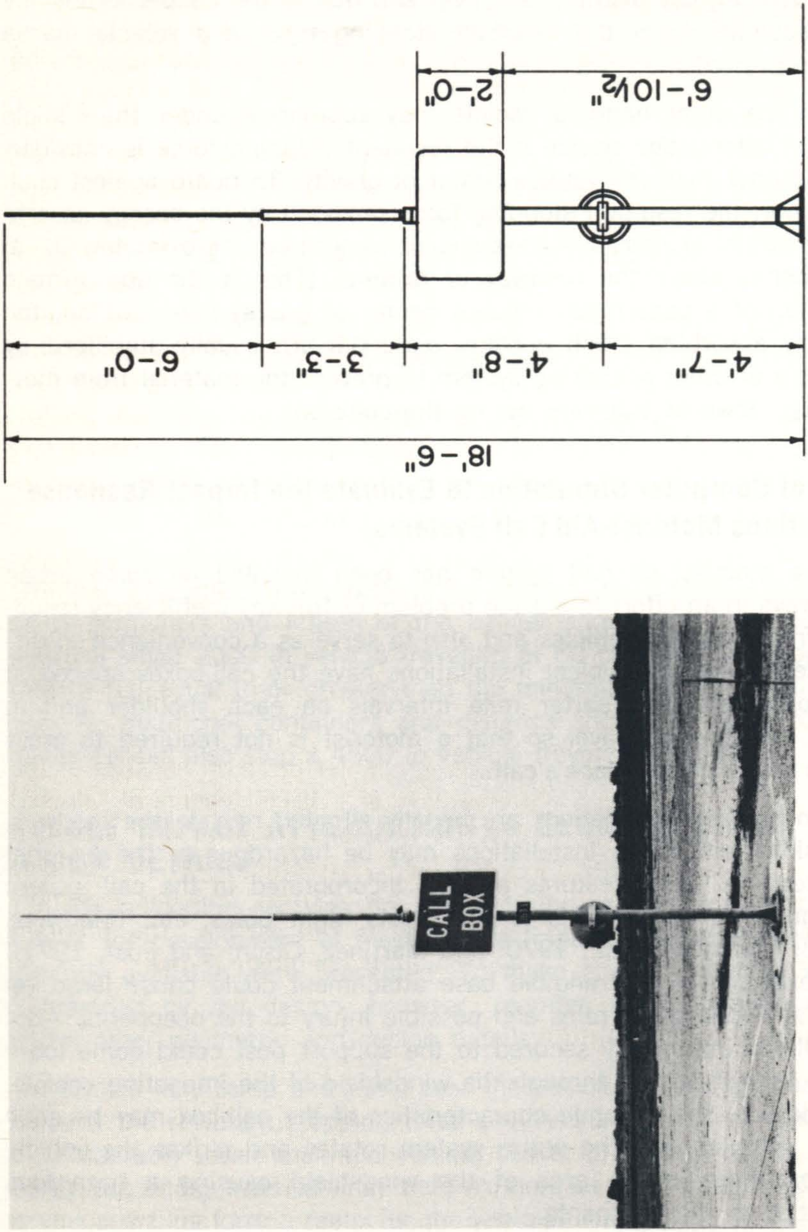


FIGURE 7. Maryland call-box assembly

Computer Simulation

Each call-box assembly was idealized as a rigid body possessing three degrees-of-freedom; two translational and one angular. The assumptions are that the call-box assembly undergoes rigid body planar motion after being struck by a vehicle and that the vehicle behaves as a single degree-of-freedom spring-mass system. This type of vehicular representation has produced satisfactory results in the analysis of roadside signs (McHenry and Segal, 1967), luminaire supports (McHenry and Deleys, 1968), and overhead sign bridge structures (Young et al., 1969). It is recognized that the planar motion assumption is not correct for off-center collisions on the structures under consideration; however, the analysis presented here is directed to central impacts and small vehicular approach angles. Under these circumstances the model should yield a satisfactory phenomenological behavior for the dynamic response of the structure and the vehicle.

The computer program established for the structural and vehicular response solved the equations of motion numerically and required knowledge of both the structural geometric and inertia properties, and the vehicular mass and geometry. Further, the base resistive force variation for the structure was required and was obtained from pendulum test data on this hardware.

The output information from the computer program consists of the vehicular displacements and velocities, and displacements of selected points of the call-box assembly. These values are printed at specified time intervals, and when (1) the base is fractured, (2) the support post loses contact with the vehicle and (3) the call-box assembly either strikes the ground or re-contacts the vehicle. The program automatically terminates when the third condition is met.

Experimental Evaluation

Pendulum Tests

Pendulum tests were conducted in order to provide information for the computer simulation. The pendulum consisted of a 1,000 lb concrete-filled cylinder supported by 4 cables. These cables supported the ram in such a manner that upon release the ram swung as a pendulum from a height of approximately 15 ft and contacted the call-box support at a distance approximately 1.5 ft from the bottom, the normal bumper height for most vehicles. The purpose of the tests was to supply base force-deformation data that could be used to simulate a vehicle crash test.

Parameter Study

Based upon the mathematical model verified by the full-scale crash tests, a parameter study was conducted in order to obtain the response of the assemblies and the impacting vehicle for a variety of cases. The study employed vehicles varying from 2000 lb to 5000 lb in weight and considered impacting speeds of 20 mph, 40 mph and 60mph. The results obtained for the 2000 lb and 5000 lb vehicles are shown in Figures 7 and 8.

The findings of the study reveal that, for all the cases considered, the vehicular velocity changes, deceleration rates and momentum changes are quite low and always remain well below the limits that have been suggested as being tolerable. These limits are 11 mph for the vehicular velocity change (Patrick, 1967) and 1000 lb-sec for the momentum change (Edwards, et al., 1969).

The study of the Illinois assembly revealed that the point of secondary impact by the post on the roof of the vehicle tends to move toward the rear windshield area as the speed and weight of the vehicle are increased. For the lighter vehicles, the tendency is for the post to strike somewhat farther toward the front of the vehicle.

The information presented in Figures 7 and 8 indicates that the Maryland call-box assembly behaves similarly to the Illinois assembly. The point of secondary impact by the post on the top of the vehicle tends to move toward the rear windshield area as the vehicular speed of the heavier vehicle is increased and strikes above the front windshield area for most lightweight vehicles traveling at low and medium speeds. Thus, it appears that for the vehicles and speeds considered, a collision with a Maryland call-box assembly does not create a hazardous situation. However, due regard must be given to the possibility of component parts of the assembly becoming detached during the collision and striking the windshield of the vehicle. As indicated in Figures 7 and 8, the Ohio call-box system rides the vehicle

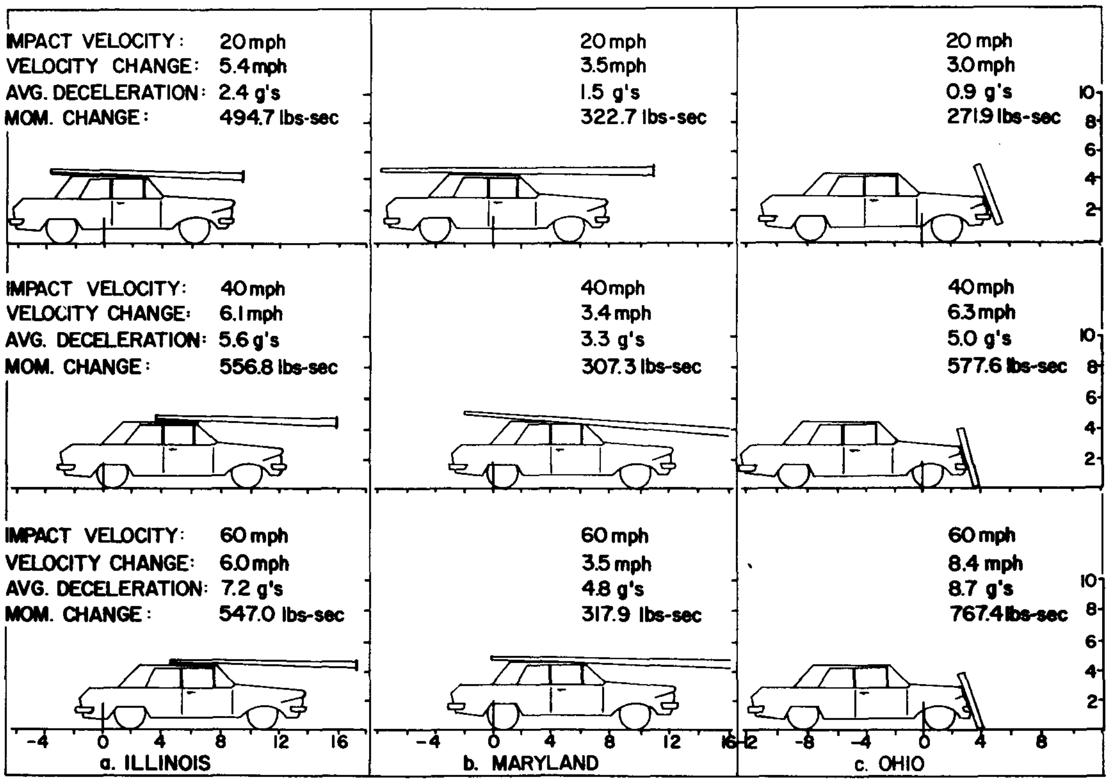


FIGURE 8. *Parameter study results for 2000 lb vehicle (after Martinez)*

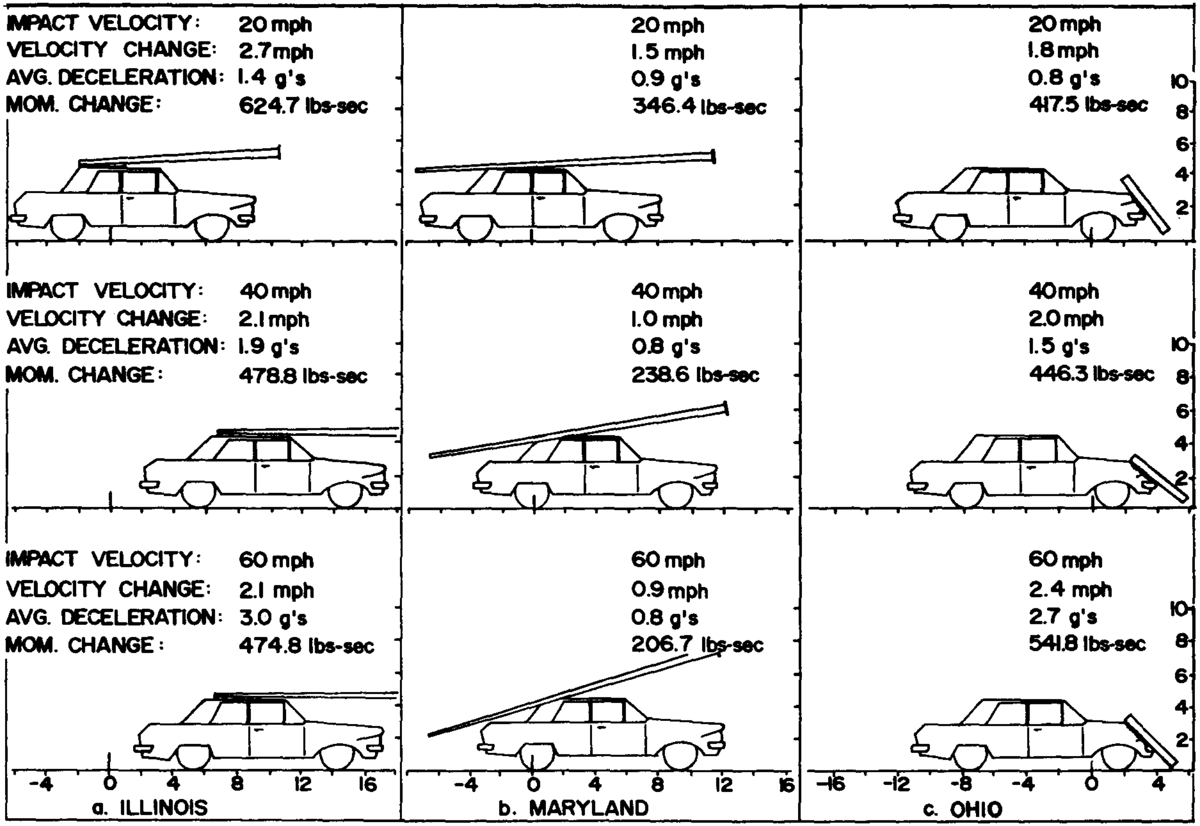


FIGURE 9. *Parameter study results for 5000 lb vehicle*

front end, rotates slightly toward the vehicle, then drops to the ground in front of the vehicle. The system that contains the effects of the mass of the call-box shows a stronger tendency to rotate toward the vehicle; however, due to the geometric and inertial properties of the assembly, it does not appear that the trajectory would be appreciably changed under actual field conditions. Thus, based on the parameter study and observation of the crash tests, it appears that a hazardous situation is not created unless component parts of this assembly become detached during the collision and strike the windshield area of the vehicle.

Mathematical Model of an Automobile

To facilitate in the evaluation and design of a roadway and its environment, it is important to understand what effects various roadway geometric features have on the dynamic behavior of an automobile and its occupants.

The mathematical model described herein was used to investigate the dynamic behavior of an automobile traversing embankments of various height and slope. In general, the model can be utilized to investigate a variety of problems associated with the roadway environment, such as highway traffic barrier collisions, rapid lane change maneuvers, handling response on horizontal curves, drainage ditch cross sections, and others.

The mathematical model was developed by Cornell Aeronautical Laboratory (CAL) (McHenry and Segal, 1967: and McHenry and Deleys, 1968) and later modified for specific problem studies by the Texas Transportation Institute (TTI) (Young, et al., 1969). A conceptual idealization of the model is shown in Figure A-1. The model is idealized as four rigid masses, which include: (a) the sprung mass (M_S) of the body supported by the springs, (b) the unsprung masses (M_1 and M_2) of the left and right independent suspension system of the front wheels, and (c) the unsprung mass (M_3) representing the rear axle assembly.

The eleven degrees of freedom of the model include translation of the automobile in three directions measured relative to some fixed coordinate axes system; rotation about the three coordinates of the automobile; indendent displacement of each front wheel suspension

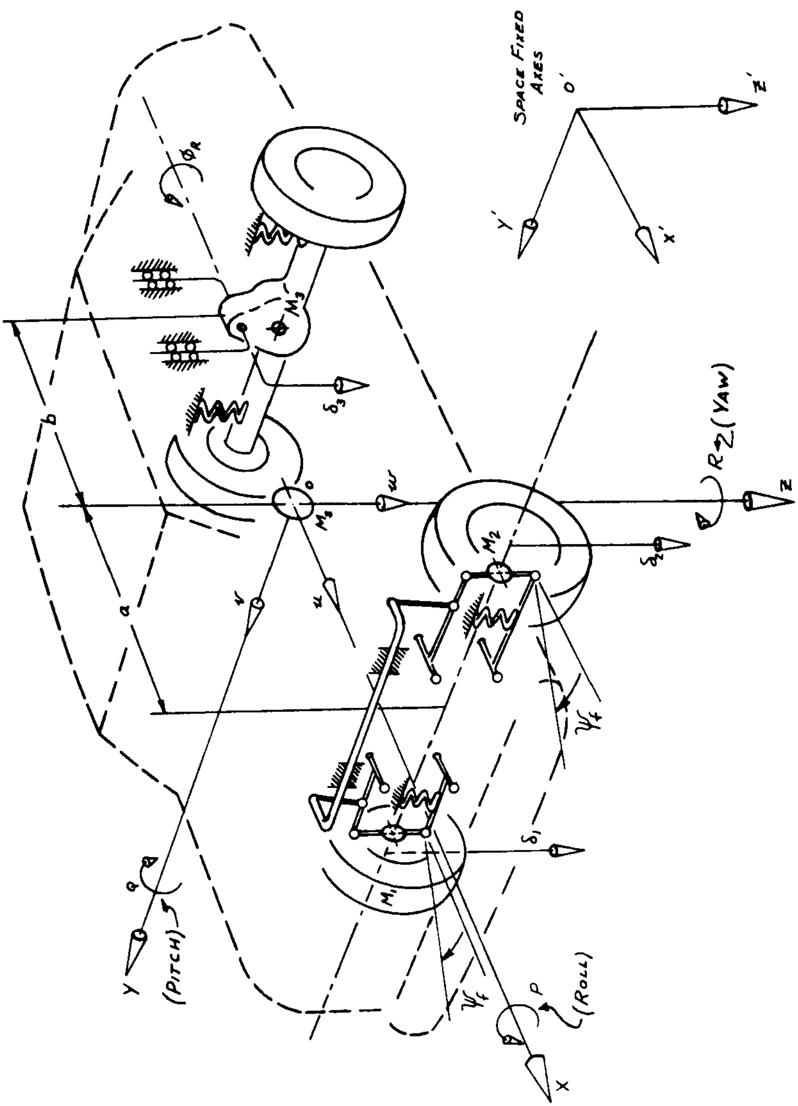


FIGURE 10. *Idealization of automobile*

system; suspension displacement and rotation of the rear axle assembly; and steerage of the front wheels. If interested, the reader is referred to the references quoted earlier for a more in-depth discussion of the mathematical model.

The validity of the model is dependent to a large extent on the accuracy of the input parameters pertaining to the automobile selected. In this study, a 1963 Ford Galaxie four-door sedan was selected for the following reasons: (a) the availability of data on the automobile input parameters; (b) the excellent comparisons obtained by CAL (McHenry and Segal, 1967: and McHenry and Deleys, 1968) between full-scale tests and mathematical simulation during a variety of maneuvers; and (c) the similarity to a large population of automobiles from a size and weight standpoint.

Mathematical simulation provides a rapid and economical method of investigating the many parameters involved as an automobile traverses some defined roadway configuration. Once the limiting parameters are identified, it may be desirable to conduct a limited number of full-scale tests prior to final selection of a particular design. This approach, in contrast to a full-scale, trial-and-error approach, will yield more meaningful results with considerably less resource expenditure.

Embankment Study

The basic geometry of each embankment investigated consisted of a 10-ft shoulder adjoining a side slope of b:a and height H, with a flat bottom ditch, as shown in Figure 10. Slopes (b:a) of 2:1, 3:1 and 6:1 in combination with heights (H) of 10 ft, 20 ft, 30 ft and 50 ft were studied. In addition, a 3.25:1 slope with a height of 20 ft and a 4:1 slope with a height of 20 ft were studied.

In the 14 embankment combinations studied, the simulated automobile was placed on the roadway with an initial velocity and encroachment angle, θ_1. Throughout the maneuvers the automobile was assumed to be out of control; that is, no attempt was made to steer the automobile. A summary of the 14 runs and the results are shown in Table 1.

In most cases, as can be seen in Table 1, the encroachment angle and speed of the automobile increase as the vehicle traverses the

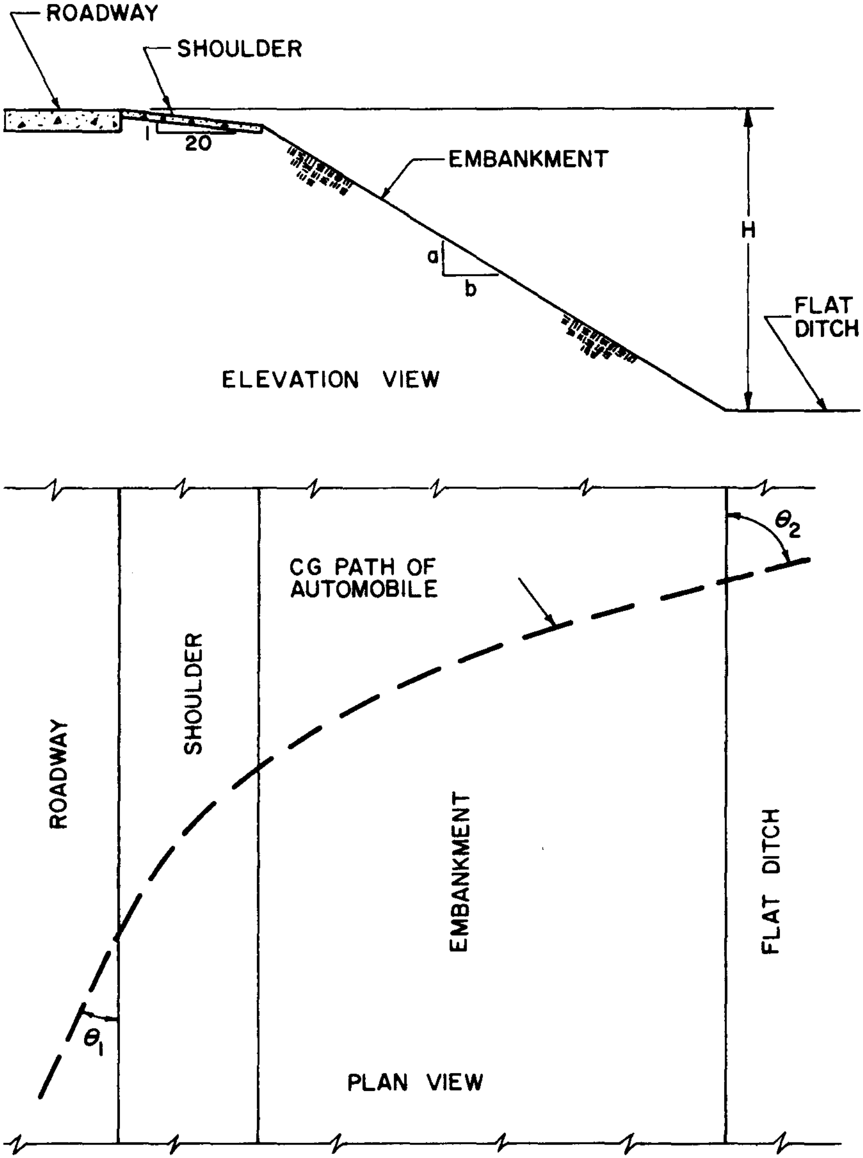


FIGURE 11. *Embankment geometry and CG path of automobile*

TABLE 1. *Simulation results on embankments of various heights and slopes*

ENCROACHMENT SPEED = 60 MPH SHOULDER WIDTH = 10 FT.
ENCROACHMENT ANGLE (θ_1) = 25 DEG SHOULDER SLOPE = 20:1

RUN NUMBER	TERRAIN		AUTOMOBILE							
							AVERAGE DECELERATIONS OVER 50 MILLISECONDS			
	EMBANKMENT HEIGHT (H) (FT)	EMBANKMENT SLOPE (b:a)	MAXIMUM ROLL ANGLE (DEG)	MAXIMUM PITCH ANGLE (DEG)	ANGLE (DEG) AUTOMOBILE CONTACTS FLAT DITCH (θ_2)	SPEED (MPH) AUTOMOBILE CONTACTS FLAT DITCH	$G_{LONG.}$	$G_{LAT.}$	$G_{VERT.}$	SEVERITY INDEX (EQ. B1)
1	10	2:1	33	RO[a]	24	60	2.6	3.4	4.7	1.1[b]
2	10	3:1	29	10	25	61	0.2	0.6	5.3	0.9
3	10	6:1	11	5	29	62	0.1	0.3	2.2	0.4
4	20	2:1	48	15	24	62	2.6	4.9	6.3	1.5
5	20	3:1	30	12	40	62	1.3	0.8	7.6	1.3
6	20	6:1	11	5	34	65	0.1	0.4	2.8	0.5
7	20	3.25:1	27	10	37	64	1.3	0.7	4.5	0.8
8	20	4:1	20	9	30	64	—	0.5	3.7	0.6
9	30	2:1	47	23	32	58	0.3	1.3	6.8	1.2
10	30	3:1	29	13	36	66	0.4	0.9	4.9	0.8
11	30	6:1	11	5	33	67	0.0	0.6	3.5	0.6
12	50	2:1	47	26	66	55	7.6	3.4	9.7	2.1
13	50	3:1	29	13	43	68	1.2	1.3	6.4	1.1
14	50	6:1	11	6	43	70	0.2	0.5	3.7	0.6

a. Automobile rolled over about its front-end as it contacts flat ditch after being airborne
b. Severity-Index when contact with flat ditch occurs (just prior to roll-over)

embankment slope. In all but the 6:1 slope combinations, the automobile became completely airborne (all tires off ground) for a period of time after leaving the shoulder. In traversing a 2:1 slope with a height of 10 ft, the automobile landed on the ditch bottom and then pitched over about its front end. For all other height and slope combinations, the automobile landed on the embankment slope after being airborne with no tendency to roll or pitch over.

Also shown in Table 1 are the maximum average decelerations for a 50-millisecond period. These values were obtained by studying the computer output for those times when the larger decelerations occurred and then, by trial and error, selecting the 50-millisecond period with the highest average deceleration. The severity index was computed from Equation B-1 of Appendix A and data from Table B-1.

Comparison of Relative Severity

The severity indices of embankment traversals, from Table 1, are shown plotted in Figure 11. Superimposed on the figure is the range of severity indices for impacts with the guardrail from Table 2. The range of severity indices shown on Table 2 for guardrail are based on accelerations averaged over the longer time duration.

It was anticipated that the severity index would increase as the embankment height increased for a given slope. However, this was not always the case, as the plots in Figure 11 show.

Equal severity curves based on the upper and lower bounds of guardrail severities are shown in Figure 12. The coordinates of the 4 points from which each curve was drawn were taken from data in Tables 1 and 2.

As shown in Figure 12, a line through a slope equal to 3:1 appears to be an average equal severity curve. Therefore, an embankment with a slope steeper than a 3:1 should be protected and, conversely, slopes flatter than 3:1 do not need guardrail protection.

Embankment heights less than 10 ft were not investigated, and the data must be extrapolated for these heights. Nevertheless, it seems reasonable to assume that a 3:1 slope can also be used as the equal severity curve for heights up to 10 ft. Implementation of the criteria would thus be simplified, by doing this.

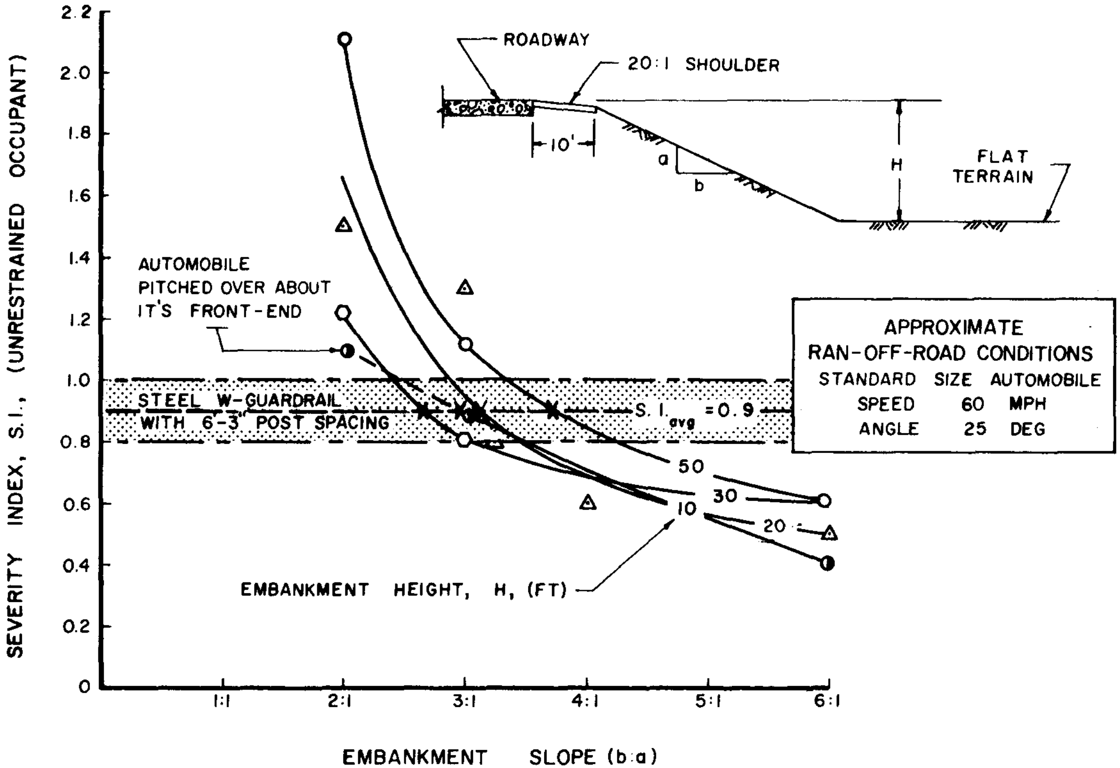


FIGURE 12. *Severity comparison of automobile traversing an embankment versus guardrail redirection*

W-BEAM
27″
BLOCKOUT
POST

TABLE 2. *Guardrail full-scale crash tests by SwRI*

RAIL HEIGHT = 27 IN.
POST SPACING = 6 FT. – 3 IN.

	GUARDRAIL					AUTOMOBILE								
									DECELERATIONS (G's)					
									50 M.S.			325-450 M.S.		
SwRI TEST NUMBER	TYPE RAIL MEMBER	TYPE POST	BLOCK-OUT	POST EMBEDMENT, L (IN.)	DYNAMIC DISPLACEMENT (FT.)	WEIGHT (LBS)	IMPACT SPEED (MPH)	IMPACT ANGLE (DEG)	$G_{LONG.}$	$G_{LAT.}$	SEVERITY INDEX a.	$G_{LONG.}$	$G_{LAT.}$	SEVERITY INDEX (EQ. B1) b.
101	STEEL W-BEAM	8x8 IN. WOOD	8 IN. WOOD	36	4.25	4042	55	31	4.6	4.5	1.1	2.9	3.1	0.9
103	STEEL W-BEAM	8x8 IN. WOOD	8 IN. WOOD	36	2.84	4123	60	22	3.1	6.1	1.3	2.2	3.3	0.9
119	STEEL W-BEAM	6B8.5	NONE	42	2.74	4169	53	30	4.5	4.4	1.1	2.3	2.7	0.8
120	STEEL W-BEAM	6B8.5	1-6B8.5	42	4.05	3813	57	28	3.9	6.6	1.4	2.9	3.5	1.0
121	STEEL W-BEAM	6B8.5	2-6B8.5	42	3.10	4478	56	27	3.6	6.7	1.5	1.9	3.3	0.9
122	STEEL W-BEAM	6B8.5	2-6B8.5	42	4.95	4570	63	25	3.9	7.6	1.6	2.3	3.9	1.0

TOLERABLE ACCELERATION LIMITS (SEE APPENDIX B FOR DISCUSSION)

a. $G_{XL} = 7$ and $G_{YL} = 5$

b. $G_{XL} = 6$ and $G_{YL} = 4$

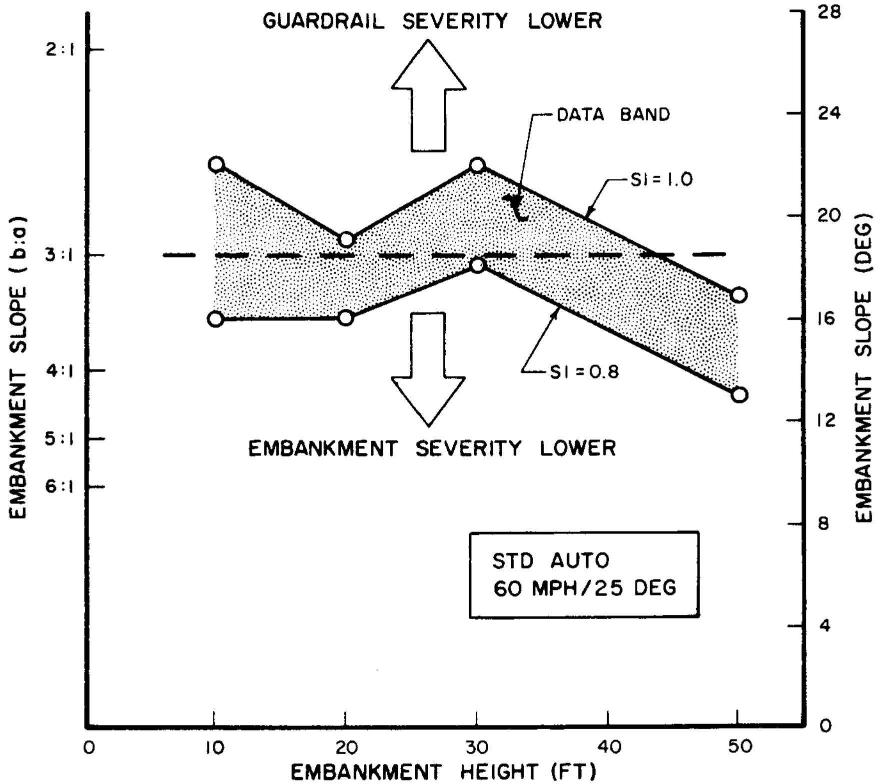


FIGURE 13. *Warrant for guardrail on embankments*

For comparison with this study, other equal severity curves are shown in Figure 13. The relationship established by Glennon and Tamburri (1967) was based on statistical analysis of accident information compiled on the California highways during the years of 1963 and 1964. Their work is currently used by many highway engineers.

As evident in Figure 13, the relationship established by Glennon and Tamburri generally agrees with the relationship established in this study. The differences existing between these two independently established curves are attributed to the following: (a) The conditions of encroachment of 60 mph and 25 degrees investigated in this study are probably more severe than those conditions occurring in the majority of the accidents statistically analyzed, and (b) the Texas guardrail system is stiffer than that used at the time of the accidents because of a smaller post spacing. Where a hazardous condition exists along or at the bottom of the embankment, guardrail may be warranted in the immediate vicinity of the hazard.

Simulation of Vehicles Traversing Sloping Culvert Grates

Some highway drainage structures have a geometrical configuration that can cause an errant automobile to come to an abrupt stop or veer out of control. One such structure is the end culvert inlet with or without headwalls. In recent years, highway engineers have used sloping inlet and outlet grates which allow an automobile to traverse the culvert opening rather than come to an abrupt stop. Sloping grates are currently designed on judgment and experience because objective criteria are practically nonexistent. Figure 14 illustrates such grates.

Using a mathematical simulation technique, this study investigated the dynamic behavior of a selected standard size automobile traversing a median containing a crossover and a sloping culvert inlet grate as shown in Figure 15. Twenty-three computer simulations were made. Some of the computer simulation results are illustrated by Figures 16, 17, and 18. Figures 16 and 18 are drawn by the computer. It was determined that 8:1 ditch side slopes and 10:1 culvert grate slopes produced tolerable automobile accelerations to an unrestrained occupant. Steeper combinations of side and grate slopes were found to produce severe accelerations and/or rollover and should be avoided wherever possible.

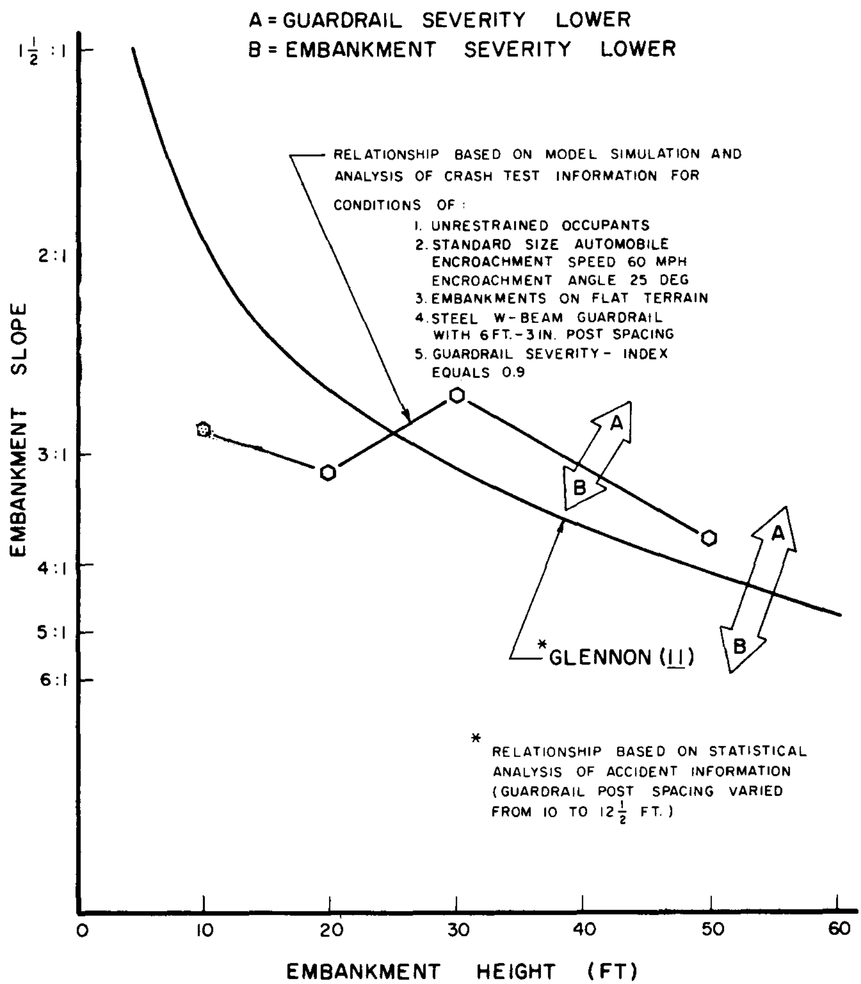
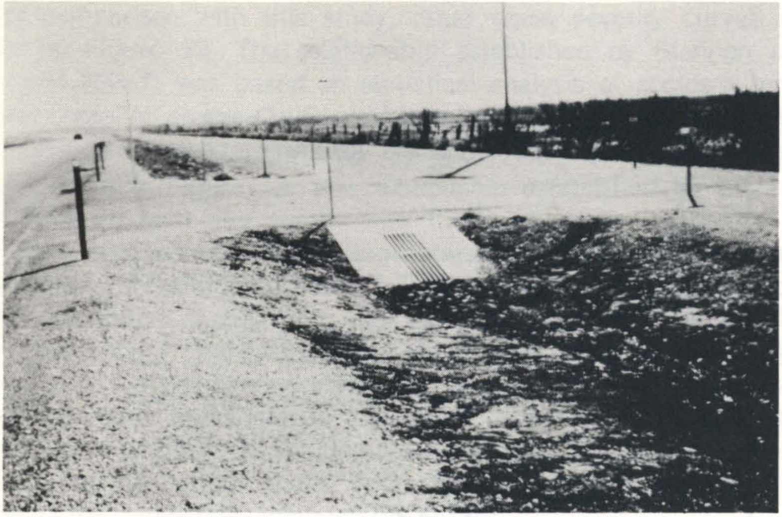
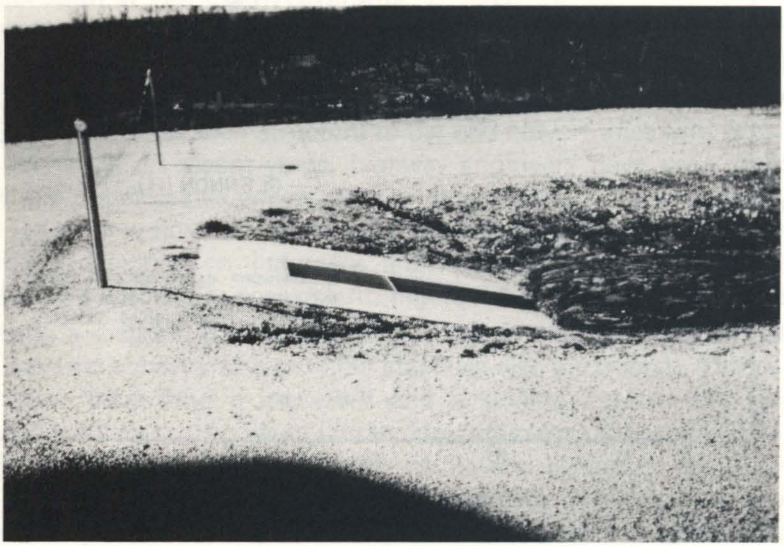


FIGURE 14. *Comparison of warrants for guardrail on embankments*



(a) APPROACH TO A SLOPING GRATE



(b) SIDE VIEW OF A SLOPING GRATE

FIGURE 15. *A typical sloping culvert grate*

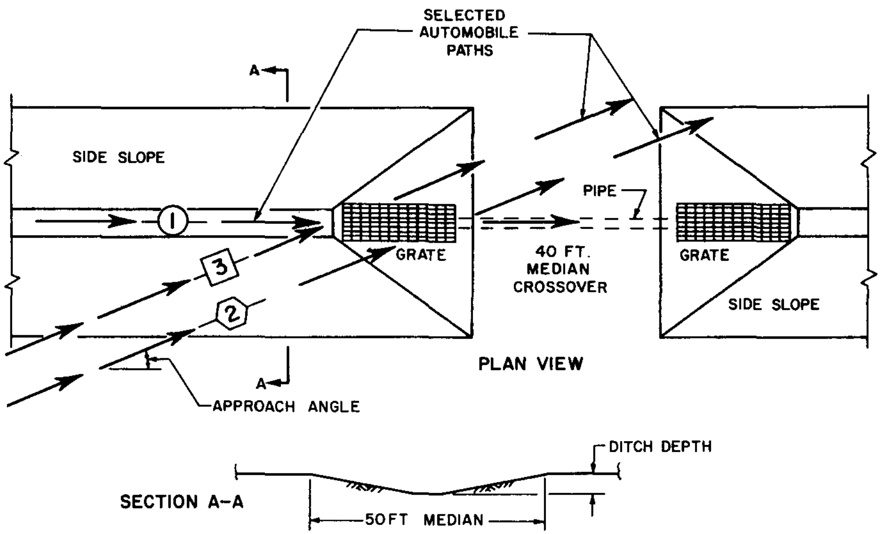


FIGURE 16. *Simulated median terrain configuration and selected ran-off-road automobile paths*

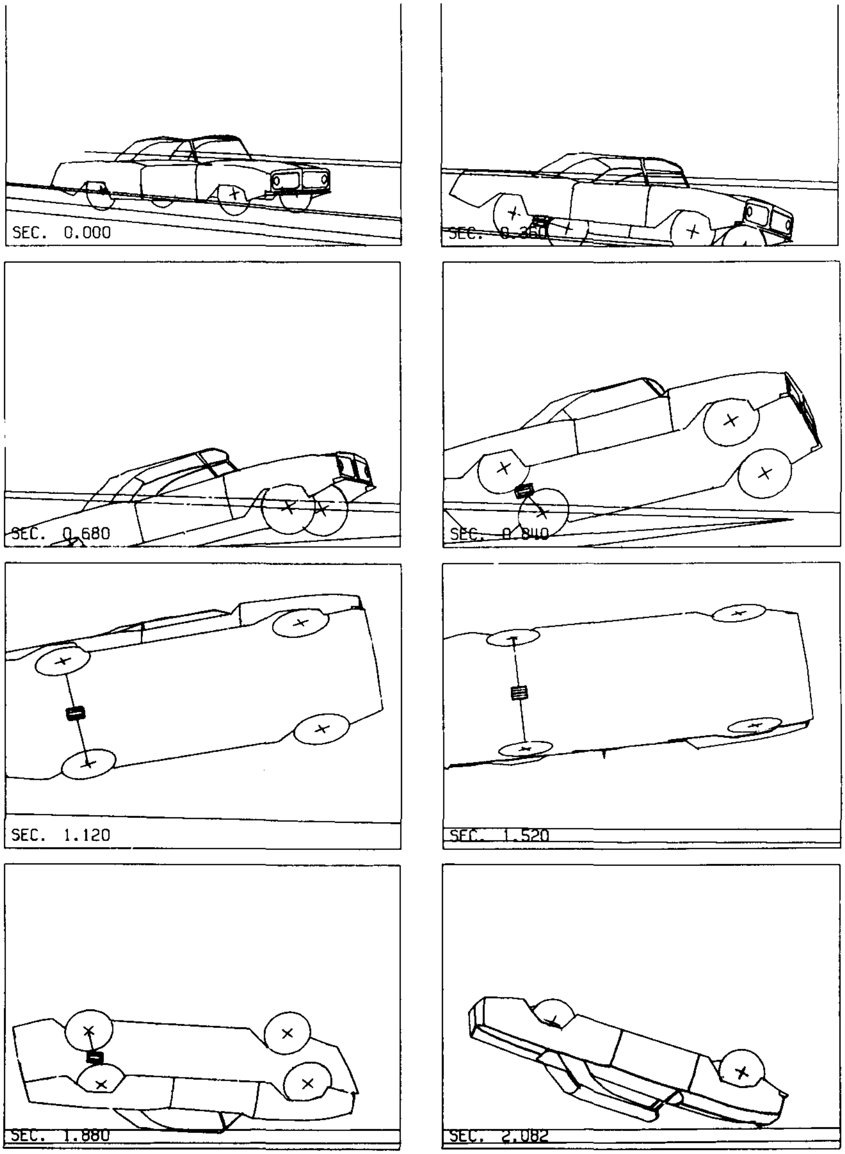


FIGURE 17. *60 mph/25 deg simulation of automobile negotiating 6:1 side slope and 6:1 culvert grate slope*

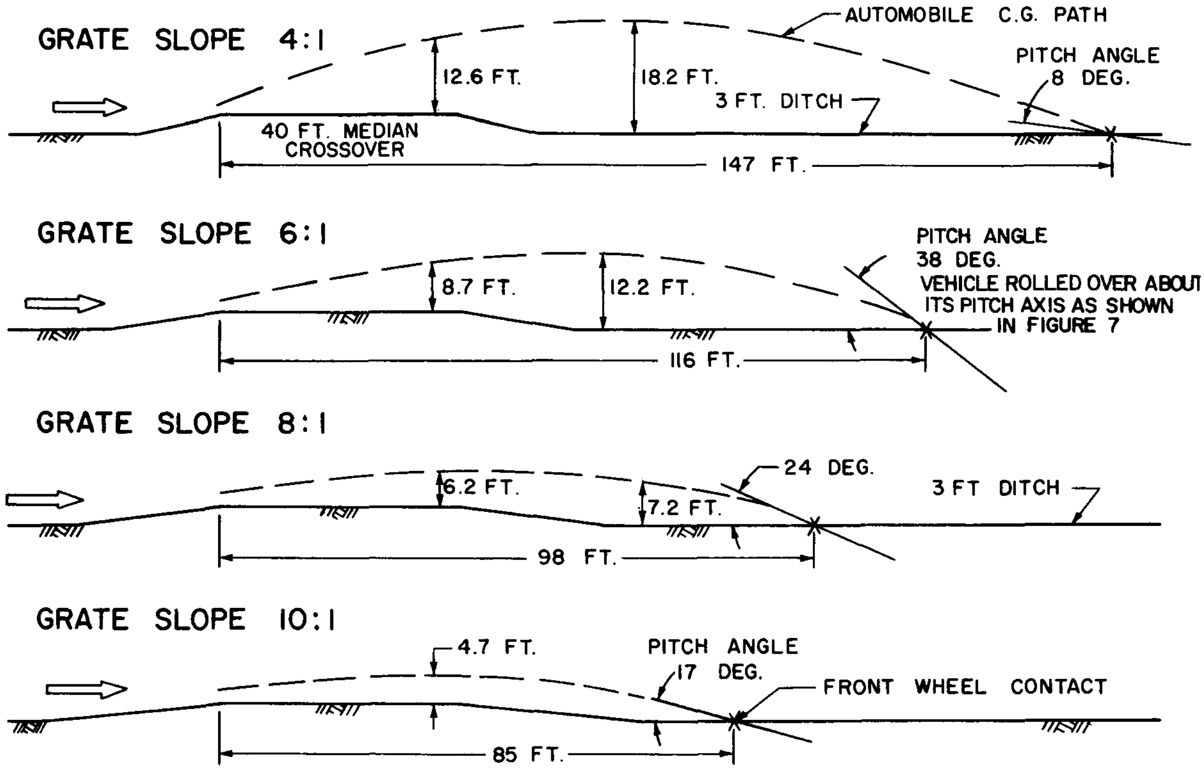


FIGURE 18. *Head-on 60 mph simulations of automobile traversing a 6:1 culvert grate slope*

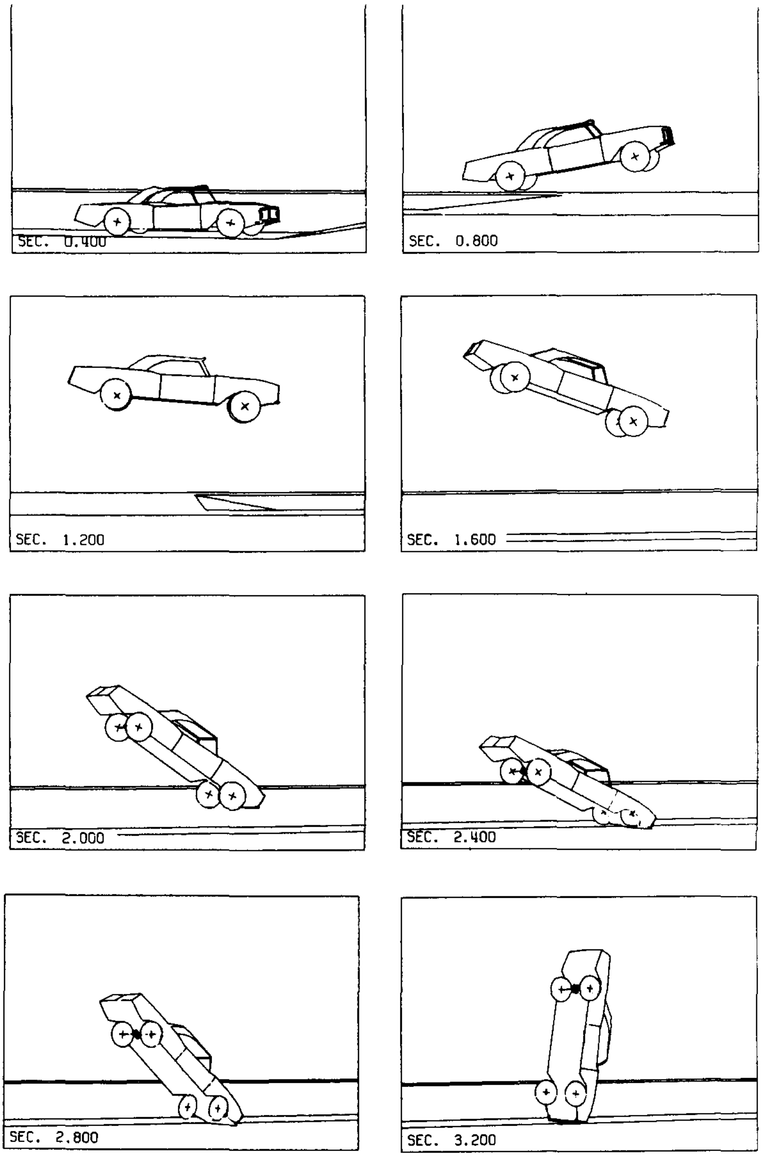


FIGURE 19. *Head-on 60 mph simulation of automobile negotiating a 6:1 culvert grate slope*

For purposes of the grates' structural design, it was found that a dynamic tire load on grate slopes of 8:1 and flatter was about five times the automobile curb weight. And, for 6:1 and steeper grate slopes, the dynamic tire load reached values of about 10 times the automobile curb weight.

Simulation of Vehicles Impacting Guardrail, Bridge Rails, and Median Barriers

The Cornell vehicle simulation program is also useful in analyzing and designing safer curbs and various type traffic rails. Early in this paper (see Figure 3) it was shown how a relatively simple mathematical simulation could be used to analyze various traffic rails. The simple simulation has obvious limitations indicated by the simplifying assumptions made. The more sophisticated Cornell vehicle simulation is a more complete description of the behavior of a vehicle colliding with such barriers. Figure 20 illustrates the three dimensional behavior of a vehicle impacting a median barrier with a parallel curb in front. Certain curb configurations can cause the vehicle to vault over the traffic rail.

Summary and Conclusions

This paper has attempted to summarize some of the significant mathematical simulations (or models) which researchers are using to aid highway engineers in developing safter highways. In general, the simplified simulations are easier to understand and, therefore, easier to use for design purposes. Conversely, the more complex and sophisticated mathematical simulations are quite difficult to understand and use. Complex simulations are required, however, for some of the more complex problems.

One should remember that a mathematical simulation itself does not solve a problem. It is merely a "tool" which imaginative researchers or engineers can use to investigate a particular problem in an attempt to develop safer or more effective designs or alternatives.

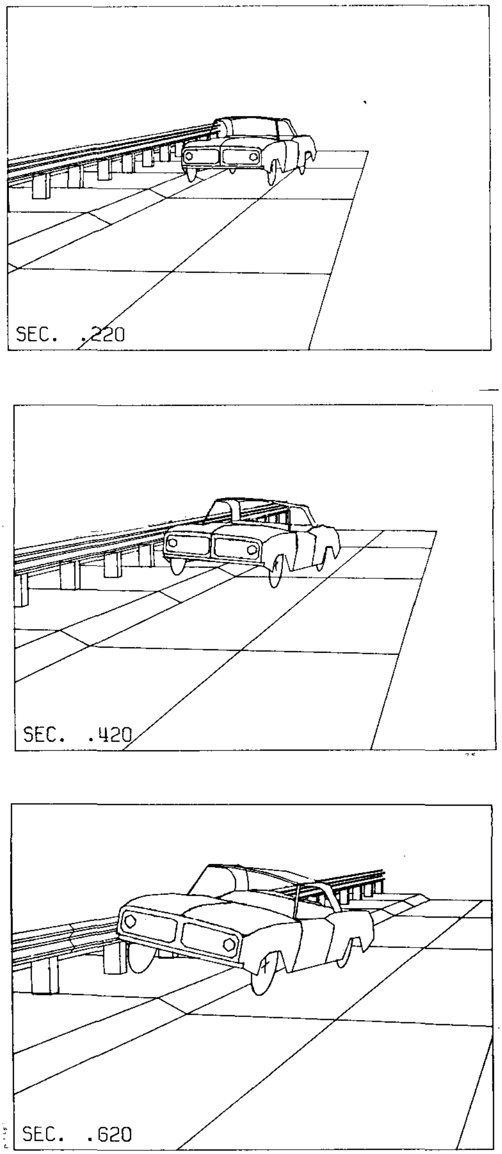


FIGURE 20. *Simulation of vehicle impacting median barrier with parallel curb in front*

APPENDIX A

Evaluation Criteria

An acceleration severity index was used to evaluate the relative hazard of an automobile: (a) being redirected by a 12 Ga. W-Beam guardrail with posts spaced 6 ft.-3 in. on centers, and (b) traversing various height and slope embankments constructed on level terrain.

A discussion of the acceleration severity index was given in an earlier report (Ross and Post, 1972). For completeness, that discussion is repeated here in more detail. The index takes into consideration the combined effects of the longitudinal, lateral, and vertical accelerations of the automobile at its center-of-mass. A severity index of unity and less indicates that an unrestrained occupant will not be seriously injured. The equation used to compute the severity index was similar to an equation presented in a recent publication by Hyde (1968) of Wyle Laboratories. The severity index equation is:

$$SI = \sqrt{\left(\frac{G_{LONG.}}{G_{XL}}\right)^2 + \left(\frac{G_{LAT.}}{G_{YL}}\right)^2 + \left(\frac{G_{VERT.}}{G_{ZL}}\right)^2} \qquad (B1)$$

The acceleration terms in the numerator of the severity index equation are the measured or computed values of the automobile; whereas, the acceleration terms in the denominator of the severity index are the "limit" accelerations of the automobile that an unrestrained occupant can sustain without serious or fatal injury.

Human body peak acceleration limits for various rise times, time durations, and directions were presented by Hyde (1968) as shown in Figure B-1. A technique for constructing the trapezoidal acceleration-time diagram shown in Figure B-1 from accelerometer recordings of a ninety-fifth percentile point mass representing an occupant was discussed by Hyde. The acceleration limits shown in Figure B-1 define the axes of an ellipsoidal envelope as shown in Figure B-2. Hyde indicates that the limits of acceleration are *not* nominal limits for "no injury" but rather are maximum limits beyond which disabling injury or death may be expected. Therefore, the resultant acceleration of the components in the X, Y, and Z directions should not exceed the ellipsoidal envelope shown in Figure B-2 to prevent disabling injury

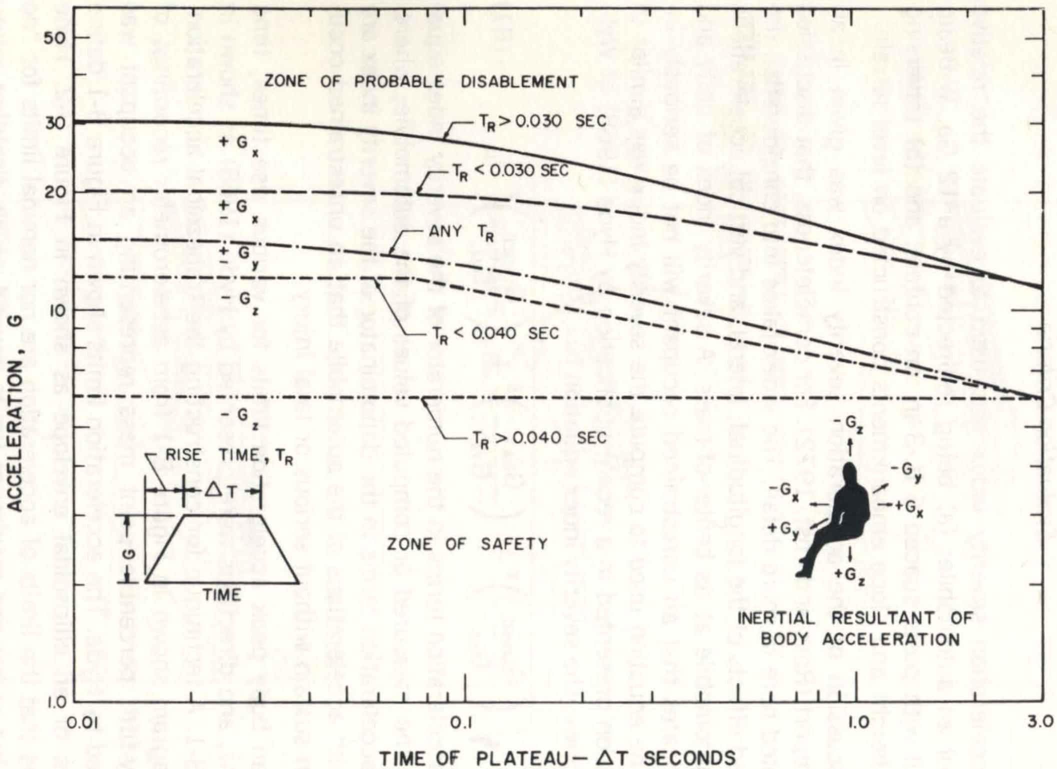


FIGURE B1. *Human body peak acceleration limits for various rise times, time durations, and directions (4)*

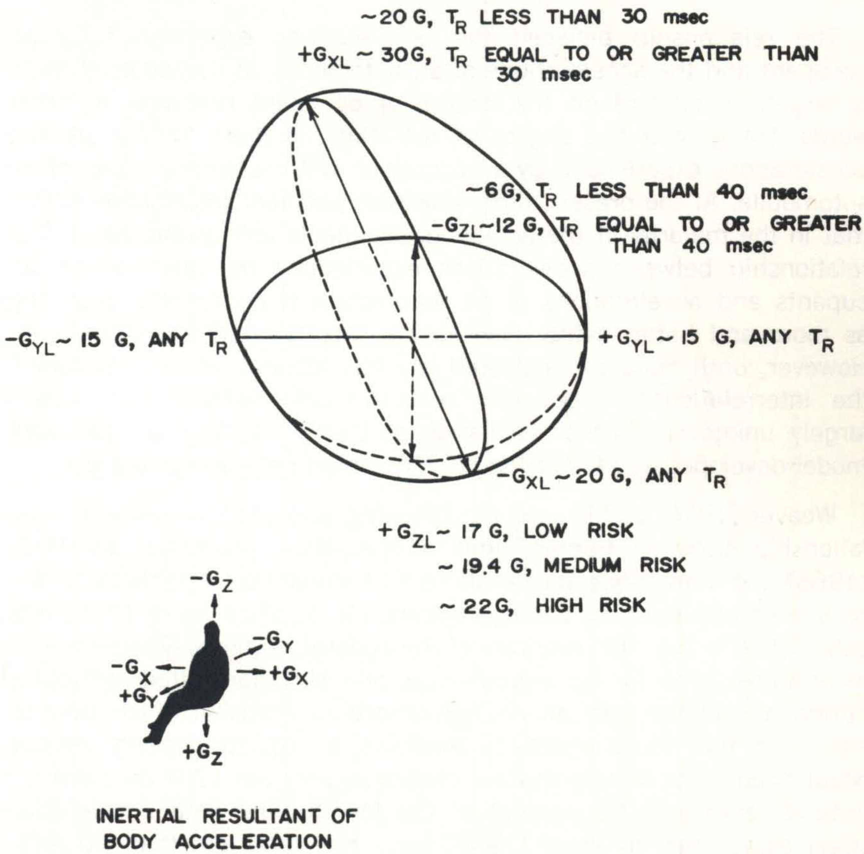


FIGURE B2. *Ellipsoidal envelope for defining the multiaxial acceleration limits* or death. It is to be noted that the "limit" accelerations established by Hyde are those experienced by a human occupant. The research engineers of this study were unable to determine from the report of Hyde what the degree of occupant restraint was on which the limit accelerations shown in Figures B-1 and B-2 were established.

The relationship between the accelerations experienced by an occupant and the accelerations of an automobile at its center-of-mass is largely dependent on the degree of occupant restraint. In other words, the greater the degree of restraint the more similar are the accelerations experienced by an occupant and the accelerations of an automobile. At the present time, however, accident information shows that in the majority of the accidents occupants are unrestrained. The relationship between accelerations experienced by unrestrained occupants and accelerations of an automobile is continually changing as more and better safety devices are incorporated in automobiles. However, until more sophisticated analysis techniques are developed, the interrelationships between occupant and vehicle will remain largely unknown. Further validation and refinement of an occupant model developed at TTI (Young, 1970) should help bridge the gap.

Weaver (1970) of TTI used the following approach to establish a relationship between human limit accelerations presented by Hyde (1968) and automobile accelerations that would be tolerable to an unrestrained occupant. An average automobile deceleration of 12 G's was established in the "4S" program of the Federal Highway Administration as an upper limit for lap belted or lap and shoulder belted occupants during a collision with an energy absorbing roadside crash barrier. Assuming that most accidents involving energy-attenuating devices occur head-on or at very shallow impact angles, the 12 G deceleration criteria represents 60 percent of the longitudinal limit acceleration (G_{XL}) established by Hyde (1968) for a rise time less than 30 milliseconds. The lateral and vertical automobile accelerations for a lap belt restrained occupant were similarly selected as 60 percent of the values established by Hyde. In turn, Weaver assumed that the maximum automobile accelerations for an unrestrained occupant was 60 percent of the limit automobile accelerations for a lap belt restrained occupant. The limit acceleration limits used in this study were selected in a manner similar to the procedure used by Weaver.

TABLE B-1 *Limit accelerations (G's)*

DIRECTION	HUMAN ACCELERATION LIMITS PRESENTED BY HYDE (4)		LIMIT AUTOMOBILE ACCELERATIONS FOR AN UNRESTRAINED OCCUPANT*	
	50 MS (Figure 2)	275-450 MS (Figure 2)	50 MS	225-450 MS
G_{XL}	20	17	7	6
G_{YL}	15	11	5	4
G_{ZL}	17 (LOW RISK)	Not Needed	6	Not Needed

* Limits selected in a manner similar to the procedure used by Weaver.

As shown in Figure B-1, acceleration limits are a function of both direction and time duration. Two time durations were used in the analysis. On embankments a time duration of 50 milliseconds was used; whereas, on guardrail collisions time durations of both 50 milliseconds and 225 to 450 milliseconds were used. The limit automobile acceleration values used for these two time durations are shown in Table B-1.

It is well known that the accelerations of an automobile may reach very high values over some very small time duration ranging from roughly 2 to 10 milliseconds. Such accelerations are commonly referred to as "spikes." There is much discussion among highway and research engineers as to the significance of "spikes." In a recent publication, Nordlin (1970) concluded from an investigation of available literature that the accelerations of an automobile at its center-of-mass should be measured over a time duration of 50 milliseconds. This time duration appears reasonable for automobile embankment traversals because in most of the instances investigated the highest acceleration time duration upon contacting the ditch was less than 80 to 100 milliseconds.

In guardrail impacts, sustained accelerations occur over a longer period of time and it is difficult to select the "appropriate" 50 millisecond period. Since the "limit" accelerations take the duration effects into account, it simplifies the analysis procedure to average the accelerations over the major portion of the event. The longer acceleration time duration used for guardrail collisions was also necessitated by the restrictions imposed by the mathematical model of the vehicle-guardrail collision. It was possible, however, to show that the severity indices computed from accelerations measured in full-scale crash tests over 50 milliseconds agreed closely with severity indices computed and measured from accelerations over the longer 225 to 450 millisecond time duration.

ACKNOWLEDGMENTS

This paper was prepared using research results and papers from many of my associates at the Texas Transportation Institute. The reference list will indicate the specific papers used.

Dr. Hayes E. Ross, Dr. Ronald D. Young, Dr. R. M. Olson, Dr. Jose E. Martinez, Dr. T. C. Edwards (deceased), and Mr. Edward R. Post are acknowledged further for their contributions to the goal of safer highway transportation.

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Section IV

Simulation and Simulators: A Selected Biblography

Neville L. Grow, Jr.

The bibliography of simulation is enormous. Simulation is used in many fields and has been, in a general sense, practiced at least since the time of Aristotle. The literature scope has considerable breadth as well as depth. The objective of this bibliography has been to identify literature, primarily research, which is relatively recently written and which has some application to the study of highway safety.

An important trait of simulation is that of "spin-off" or transference. It is not uncommon for a simulation technique which has been developed in one field to be used, albeit in modified form, in another field. Through the approach of bibliographic studies, related materials from numerous fields can be brought together in a relatively efficient and useful form, thus aiding the spin-off phenomenon. The research behind this bibliography involved an examination of the literature of the following fields: mechanical engineering; automotive engineering; aerospace engineering; mathematics; medicine; psychology; education; physics; computer technology; and information science.

Nearly three hundred references were selected. From these references, the reader will not only gain access to specific works but should also be able to gather important indications of individuals and institutions involved in simulation and simulator activities. Further access to simulation literature may be had from the references contained within the literature cited here. The contents of this bibliography also indicate the development of trends and possibilities in simulation, particularly those in the area of the development of computer generated graphic displays and computer driven simulators.

The material in the bibliography has been divided into categories of related simulation activities as they pertain to areas of highway safety: collision; driver; driver/occupant; roadway; vehicle. These subdivisions are intended to be an aid by drawing topically related materials together. They should not be allowed to become an impediment. Because of the spin-off phenomenon, material contained in one class will inevitably be found to have an important bearing on material contained within another. Further, variance of natural language used in different fields has resulted in some lack of uniformity of the category contents.

As an aid to further study and research, the items cited here have been verified and, whenever necessary, clarified to facilitate obtaining the materials from library resources. Wherever useful, order or document numbers have been included at the end of the citations.

It has been suggested elsewhere that the process of research begins and ends in the library. This bibliography, or any other carefully researched and compiled reference list, can stand as evidence of that.

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