ANALYTICAL AID FOR EVALUATING HIGHWAY AND ROADSIDE GEOMETRICS

Raymond R. McHenry and Norman J. DeLeys,
Transportation Research Department, Cornell Aeronautical Laboratory, Inc.; and John P. Eicher, Office of Research, Federal Highway Administration

A mathematical model is described that represents the dynamic motions of a motor vehicle in contact with a variety of roadway and roadside geometric design features including fixed obstacles. The model has 15 degrees of freedom, and all major nonlinearities are included in the motion equations that have been programmed for time-history solutions on a digital computer. The task of interpreting the extensive output information from the model is eased by a computer-graphics display technique that produces detailed perspective drawings of the vehicle and terrain at selected intervals of time during a simulated maneuver. Sample comparisons are presented of analytically predicted vehicle responses and full-scale test results. A description of the validation approach followed in this research effort is included. A series of sample applications is described, and the capabilities of the model to aid in the establishment of improved design specifications for highway and roadside safety are emphasized.

• RESEARCH during the past several years at the Cornell Aeronautical Laboratory (CAL) has led to the development of a computer model representing the dynamics of a motor vehicle in contact with a variety of roadway and roadside terrain features and certain classes of obstacles (1, 2). This research has been sponsored by the Federal Highway Administration as part of an overall research program aimed at the development of improved roadside protective systems to enhance occupant survivability in single motor vehicle collisions.

Rigorous comparisons of simulated responses with full-scale test responses under a variety of maneuvers have substantiated the validity of the model in situations where all major external forces acting on the vehicle are introduced through the tires (1, 3). Preliminary comparisons of collision predictions with experimental results for certain classes of fixed objects also exhibit generally close agreement (4, 5, 6).

The existing capabilities of the computer model can be and are being exploited to converge on improved roadway and roadside geometrics and protective devices. The present version of the model represents, with confidence, the motions and responses of a motor vehicle on the roadway or in contact with the terrain irregularities of the roadside. All major vehicle nonlinearities, detailed braking dynamics, and driver control inputs have been included.

The CAL effort, at full fruition, will provide analytic procedures for evaluating the performance of a variety of roadside structural concepts in their ability to "protect" the vehicle and its occupants in the collision environment.

As a supplement to the conventional time-history form of simulation outputs, an auxiliary computer-graphics program has also been developed within the CAL research program to produce perspective drawings of the simulated vehicle as seen from selected viewing positions and at selected times during a predicted event (7, 8). Figure 1

Sponsored by Committee on Operational Effects of Geometrics.

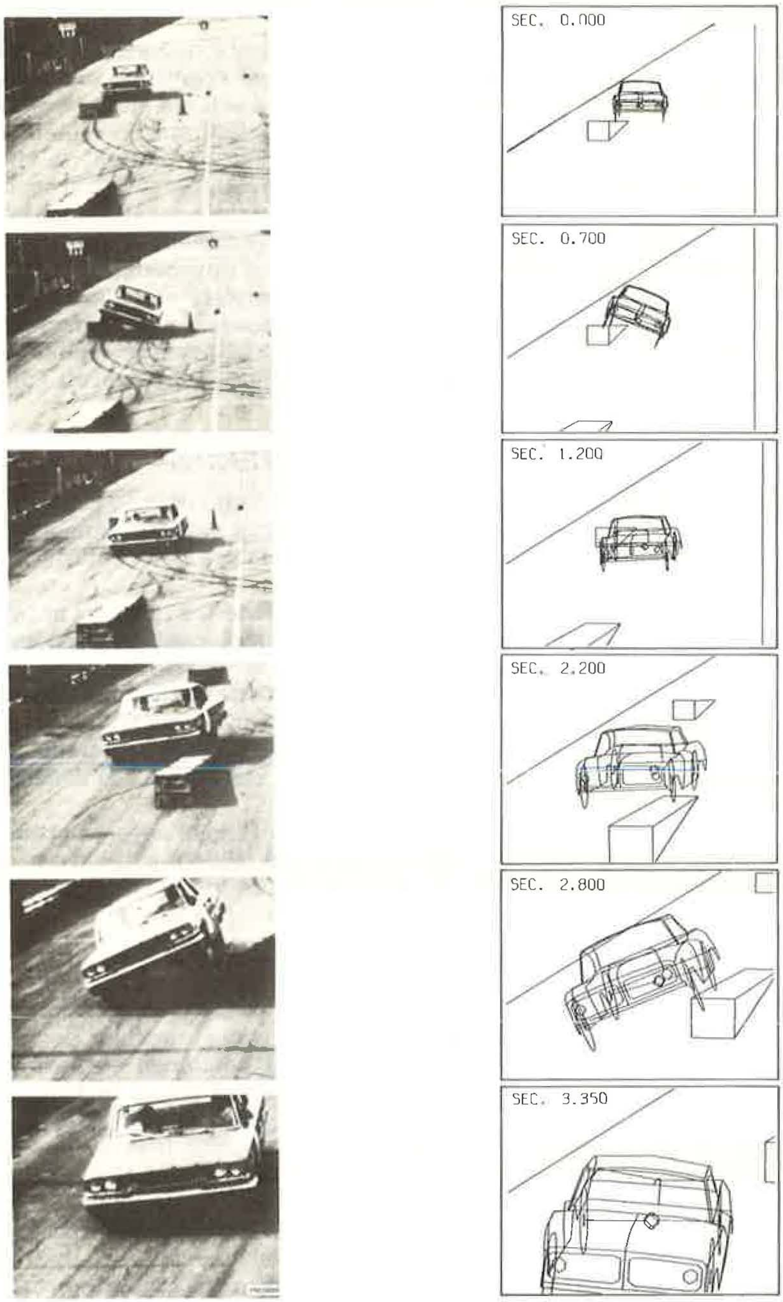

Figure 1. Alternate ramp traversal at 30 mph.

shows the graphics display for a ramp traversal; a series of photographs taken during one of the validation experiments is shown on the left while the corresponding model prediction is shown on the right. Ongoing and future model extensions include improvement in the treatment of collision mechanics, i.e., the representation of the vehicle structural interaction with fixed objects along the roadside and the vehicular responses resulting therefrom.

Evaluation of existing and proposed highway geometrics and protective features by experimental means requires a selection of specific test conditions and procedures to represent the wide distributions of the variables (e.g., vehicle sizes, speeds, angles of approach, and evasive control inputs) that exist in actual single-vehicle collisions. The total number of tests of a given highway feature must be limited, in view of the costs associated with full-scale testing, and the interpretation and extrapolation of test results are made difficult, if not impossible, by the overall complexity of the terrain-obstacle-vehicle-occupant system and by the prevalence of system nonlinearities. An exclusively experimental approach to the problem of improving the performance of a complex physical system is neither scientifically complete nor efficient.

Mathematical modeling of physical systems is, of course, the fundamental methodology of engineering analysis and physical research. The present application is unique in the number and extent of the nonlinearities treated and in the overall complexity of the system.

SIGNIFICANCE OF THE RESEARCH

The model in its present status of development and validation is capable of addressing a host of questions that are of interest to the highway safety community and has implications for new highway construction projects as well as safety improvement programs such as TOPICS.

Typical applications that can now be addressed include the efficacy of (a) roadside terrain details such as the degree of side slope flattening, configuration and placement of drainage channels, and geometric and surface characteristics of curbing; (b) protective structures such as geometric and surface characteristics of rigid redirective barriers (e.g., the New Jersey median barrier design and the GM bridge parapet) and limited classes of guardrail structures; and (c) highway design practices such as geometric and surface interactive elements of horizontal curvature and superelevation and consideration of transition and spiral connections.

It is anticipated that by mid-1971 the development of those aspects of the model associated with interaction between the vehicle and fixed objects will have progressed to the point where greater generality can be accommodated in the treatment of roadside structures.

VALIDATION APPROACH

A high degree of correlation has been achieved between the responses of the vehicle predicted by the computer model and those measured experimentally in a rigorous investigation of validity that included both separate and combined cornering and ride motions (1). A sampling of these response comparisons is shown in Figures 2 and 3.

One of the objectives in this research program has been to apply each item of the vehicle parameters in a directly measurable form. Because it is a common practice in mathematical modeling to define "equivalent" parameters and to adjust the values to achieve correlation with experimental data, it is well to distinguish the approach taken by CAL. A subcontract was let to the Ford Motor Company for measurement of the vehicle parameters, and the results of these measurements have been used directly. The tire properties were measured by the General Motors engineering staff and were also applied directly. Because of the direct use of parameters as measured by disinterested individuals, it should be very clear that the correlation with experimental responses is genuine, involving no "tune-up" of the simulated vehicle properties.

Within the CAL validation program, repeated runs of all but 1 of the 10 test conditions were performed. It is unfortunate that most other experimental efforts that have been performed in relation to vehicle dynamics and to automobile collisions have not

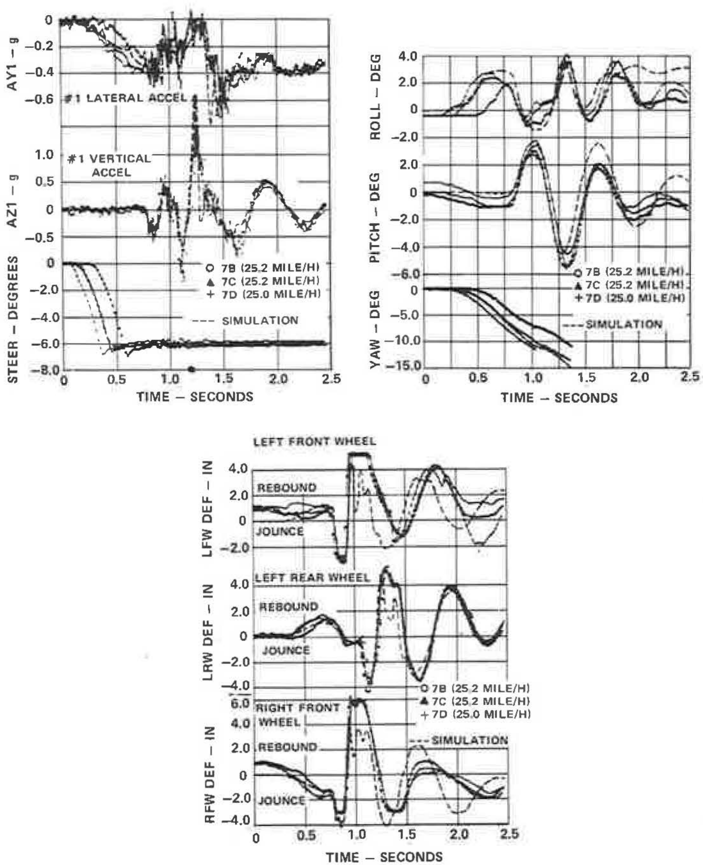

Figure 2. Measured and simulated responses of vehicle traversing 7.1-deg, 6.75-in. high ramp while cornering at 0.4 g.

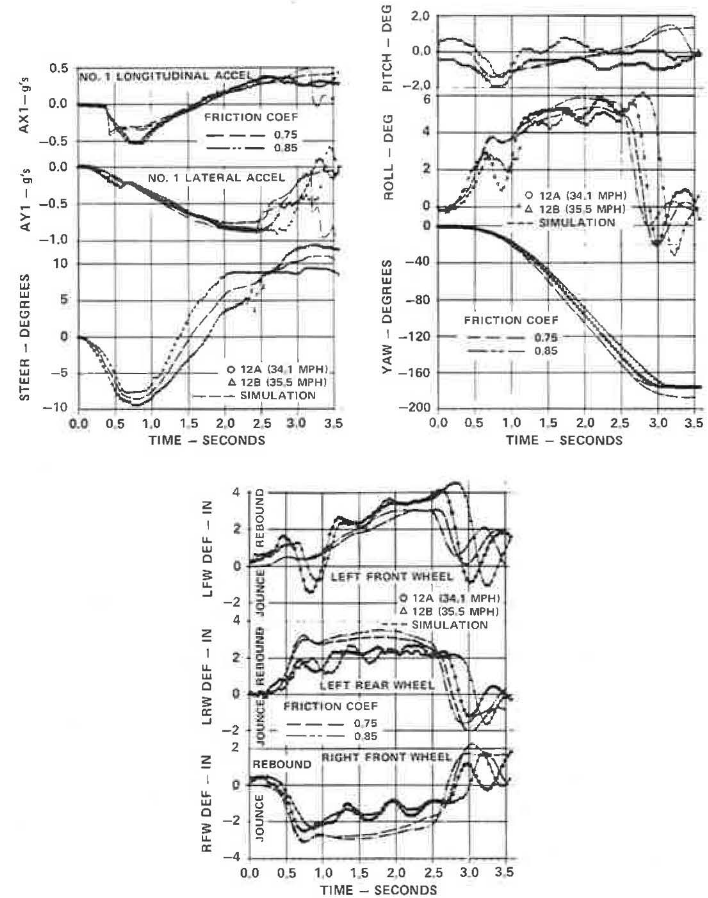

Figure 3. Measured and predicted responses of vehicle in forward skid on dry pavement.

included measures of the variability of the experimental responses. Without such measures, the accuracy of analytical predictions cannot be properly evaluated.

The high degree of repeatability of the experimental responses, shown in Figures 2 and 3, reflects the use of closely controlled experimental procedures. The performance of repeated experiments enables the quantification of statistical reliability and comparison of mean test results with analytic predictions.

The required extent of the total validation effort is determined by the nature of specific intended applications. For example, a primary interest in kinematics (i.e., the trajectory of the vehicle), as opposed to the detailed time history of acceleration, could be satisfied with a less extensive validation effort, in view of the direct measurements that can be made (i.e., no instrumentation response problems) and the "smoothing" or "filtering" effect of double integration of the simulated acceleration. On the other hand, a primary interest in acceleration waveform and peak accelerations requires a greater validation effort.

MODEL DESCRIPTION

The vehicle is treated as an assembly of 4 rigid masses, as shown in Figure 4, with a total of 15 degrees of freedom. These consist of the 6 degrees of freedom associated with 3-dimensional, rigid-body motions of the sprung mass; 5 degrees of freedom associated with motions of the unsprung masses (wheel assemblies) relative to the sprung mass (i.e., suspension deflections and front wheel steer); and 4 rotational degrees of freedom of the wheels. The steer mode degree of freedom, for which any inertial coupling effects are neglected, is introduced at the front wheels when rigid obstacles (e.g., curbs) are encountered by either or both of those wheels. The rotational degrees of freedom of the 4 wheels have been incorporated in order that the effects on tire forces of rotational wheel slip, in braking or traction, can be approximated.

Inertial properties, suspension and tire characteristics, and the detailed brake system are represented. The geometric and surface details of the terrain profile are introduced as an input to the model. Likewise, open-loop control parameters in the form of the steer angle at the front wheels, the throttle setting, the hydraulic pressure

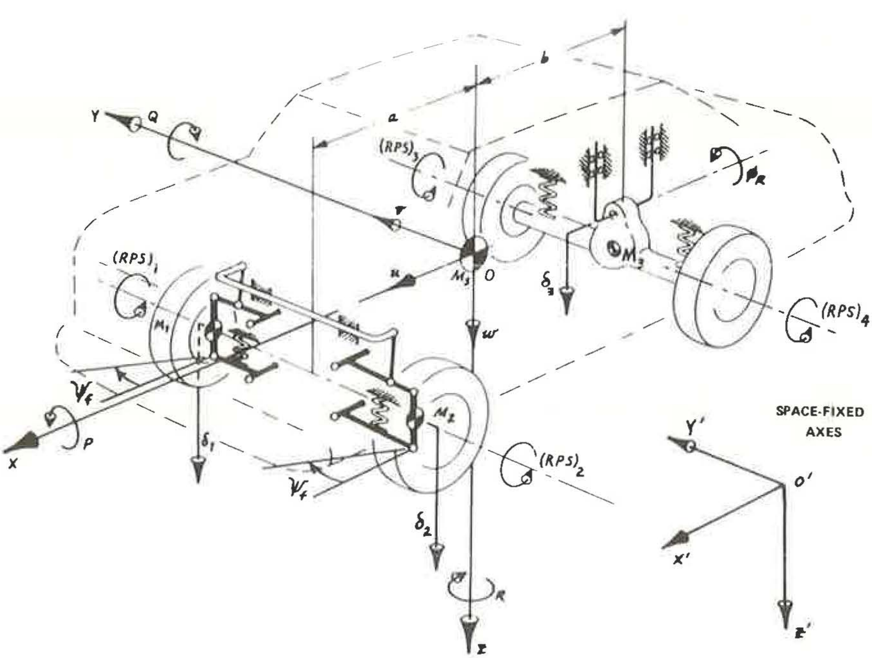

Figure 4. Analytical representation of vehicle.

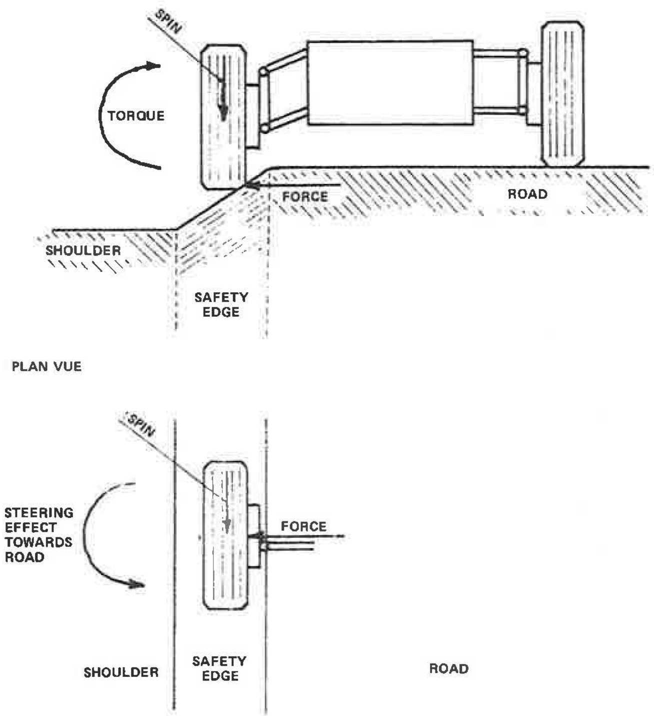

Figure 5. BRIG Road Safety Edge.

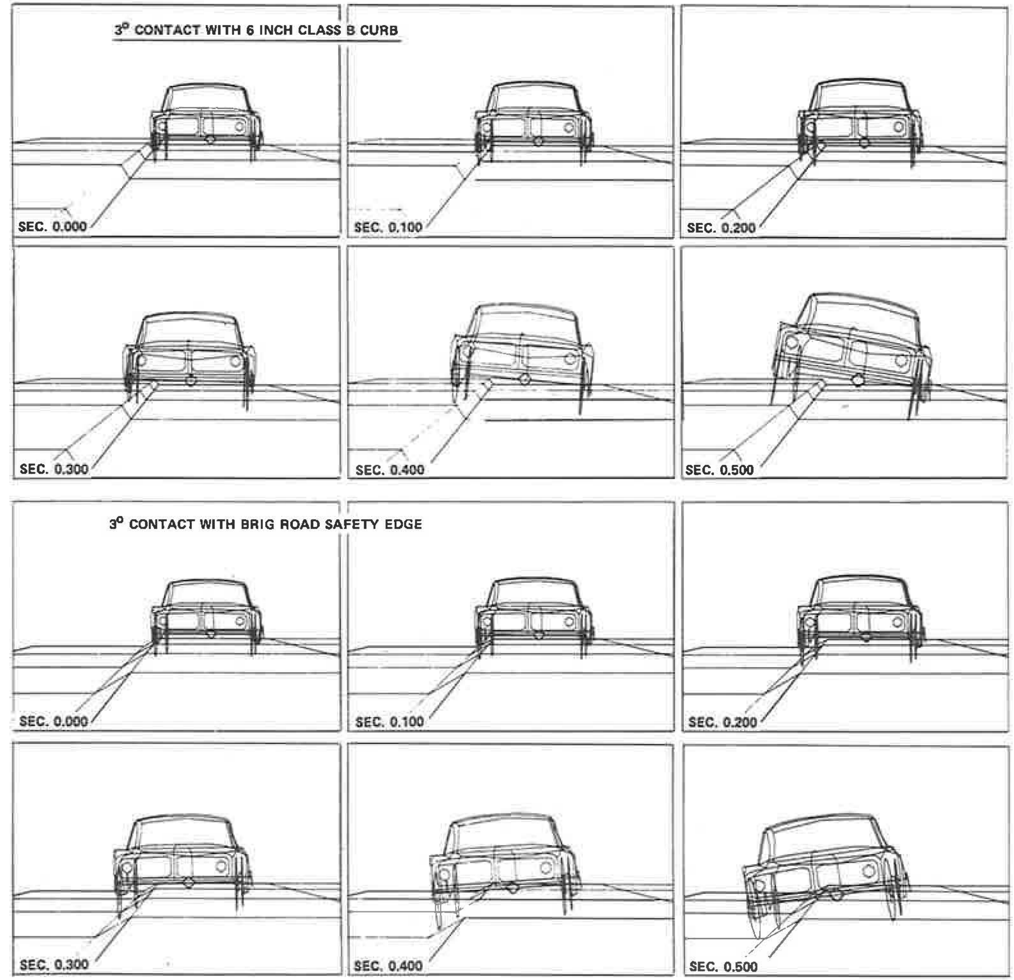

Figure 6. Computer-graphics display of simulated 60 mph.

in the brake system, and the transmission ratio are entered as tabular functions of time. There is also a provision within the model to simulate closed-loop (driver) control in the form of inputs.

SAMPLE APPLICATIONS

The following sample applications are presented to demonstrate the versatility of the described analytical aid.

BRIG Road Safety Edge Concept

The BRIG Road Safety Edge concept (9), shown in Figure 5, consists of a depressed edge between the pavement and the roadside shoulder. It is claimed that this device produces corrective steer effects through the mechanism of gyroscopic precession in the steered wheels of an automobile departing from the pavement.

The BPR-CAL computer simulation program was applied in a preliminary evaluation of the BRIG concept (Fig. 6). It was concluded that the proposed road edge will produce corrective steer effects only under extremely limited conditions of departure from the pavement and that the mechanism through which the effects are produced differs substantially from that described in the related U. S. patent and in an earlier analysis supporting the patent claims. In particular, it was concluded that the role of gyroscopic precession in influencing automobile steering responses during contacts with either conventional curbs or the BRIG Road Safety Edge is a secondary role that can be neglected in first-approximation calculations and that the redirective properties of the BRIG Road Safety Edge are effective only under conditions of extremely gradual departures from the roadway.

Torsion-Post Bridge Rail

The capability of the BPR-CAL computer model for simulating vehicle impacts with roadside structures was used in a recent application of the simulation in a research program to evaluate a new type of bridge railing conceived by the District of Columbia Department of Highways and Traffic (6). A primary feature of the concept was the use of torsion posts for supporting the rails to provide flexibility of the structure and to absorb and subsequently release energy transferred from an impacting vehicle by operating within the elastic range of the post material. It was hypothesized that good redirection characteristics might result from a configuration having a larger inertia that would effectively delay release of the energy stored in the torsion posts until the vehicle had already departed from the impacted area.

The computer simulation was used to predict the dynamic responses of the vehicle and bridge railing under various impact conditions and to provide guidance in the selection and design of prototype torsion-post bridge railing configurations for subsequent full-scale experimental testing.

Sequence photos of a test of one of the experimental bridge railings are shown in Figure 7. Figure 8 shows a comparison of the predicted and measured responses of the vehicle and bridge rail for the test impact conditions of 52 mph and 25-deg angle of approach.

Bridge Parapet Investigation

The computer simulation was applied in a brief investigation to determine how the response of a vehicle impacting a rigid, redirecting barrier such as the General Motors bridge parapet or the New Jersey median barrier would be affected by variations of the friction coefficient of the sloped face (10). Simulation runs of vehicles impacting at 30 mph and 5-deg angle of approach and 50 mph and 12 deg for values of friction coefficient between 0.25 and 0.7 were made. A representative graphic display of the predicted response of a vehicle for comparison with photos made during a test performed by General Motors (11) is shown in Figure 9. The results of the study substantiated the conclusion previously reported by Lundstrom et al. (11) that the value of the friction coefficient of

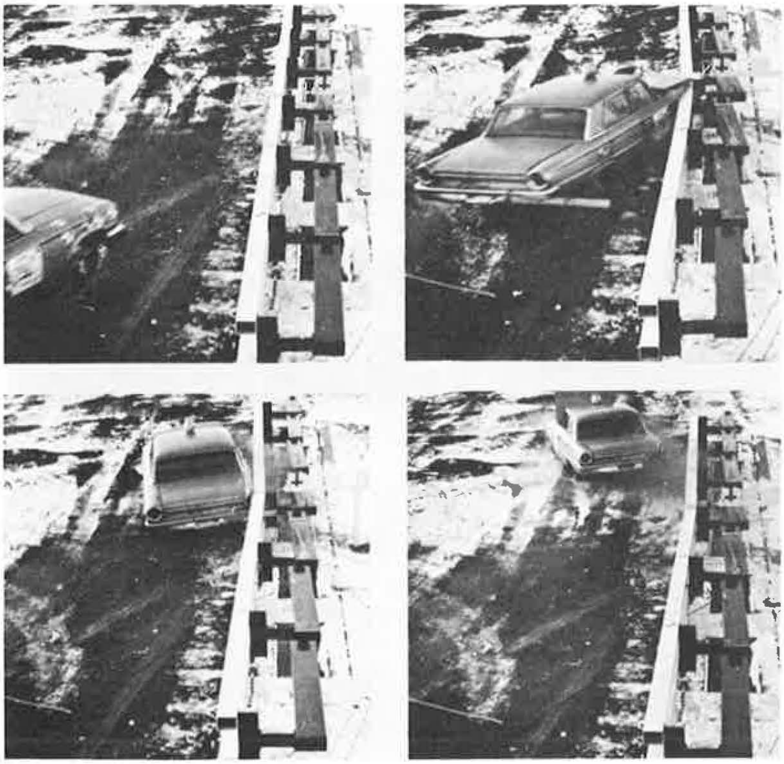

Figure 7. Sequence of test 1 impact.

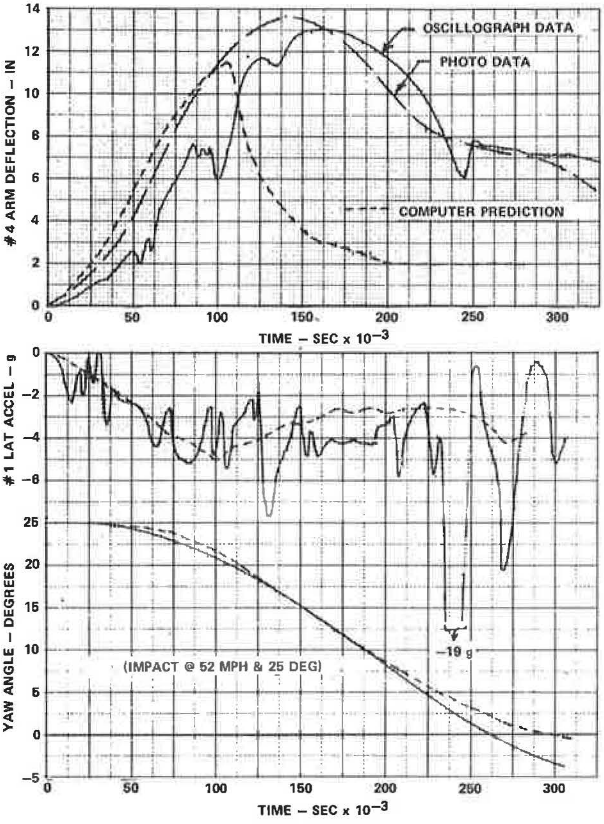

Figure 8. Vehicle and bridge railing responses in test 1.

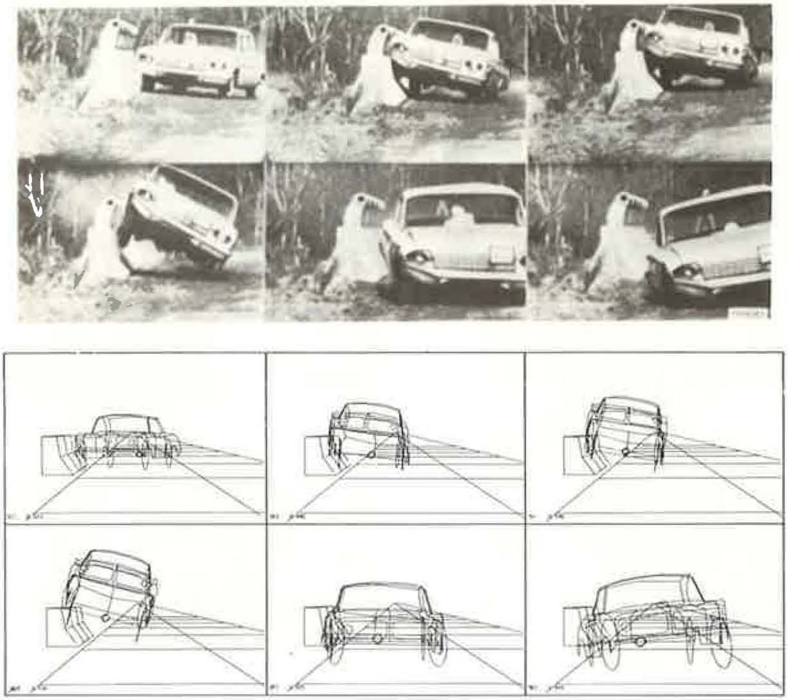

Figure 9. Experimental and predicted vehicle responses for 50-mph, 12-deg collision with General Motors bridge parapet.

the surface does not significantly affect the response of the vehicle or the height of climb up the wall.

Railroad Grade-Crossing Topography

An exploratory analytical investigation was conducted to determine speed-topography combinations for which vehicle responses when traversing railroad grade crossings may be sufficiently violent to induce loss of control (12).

It was found that neither steer effects from tire contacts with rails protruding above the highway surface nor "wheel hop" excitations from protruding rails or other terrain irregularities constitute a significant control problem at grade crossings. Crossings situated on crest vertical curves were concluded to be potentially prone to loss of vehicle control, contingent, of course, on the specifics of the cross section. The exploratory analysis demonstrated most importantly that dimensional tolerances for highway-railroad grade crossings may be objectively defined on the basis of dynamic vehicular responses assessed through the BPR-CAL model for a representative family of highway vehicles.

Figure 10 shows a computer-graphics display of a simulation run for an actual railroad crossing with a crest vertical curve in the Buffalo, New York, area where loss of vehicle control resulted in a ran-off-roadway fatal accident. Potential loss of control effects were exaggerated by the selection of a speed of 70 mph, and a steer input of 3 deg (at the front wheels) was entered while the front wheels were off the ground.

In the drawings shown in Figure 10, the simulated event is viewed from a constant distance ahead of the vehicle and along the centerline of the road. The simulated vehicle went up on its 2 right wheels and then departed from the opposite side of the roadway. Such a driver maneuver conceivably could have been made in an attempt to avoid encroaching on the ditch on the right side of the roadway, with an excessive steer input applied while the front wheels are off the ground.

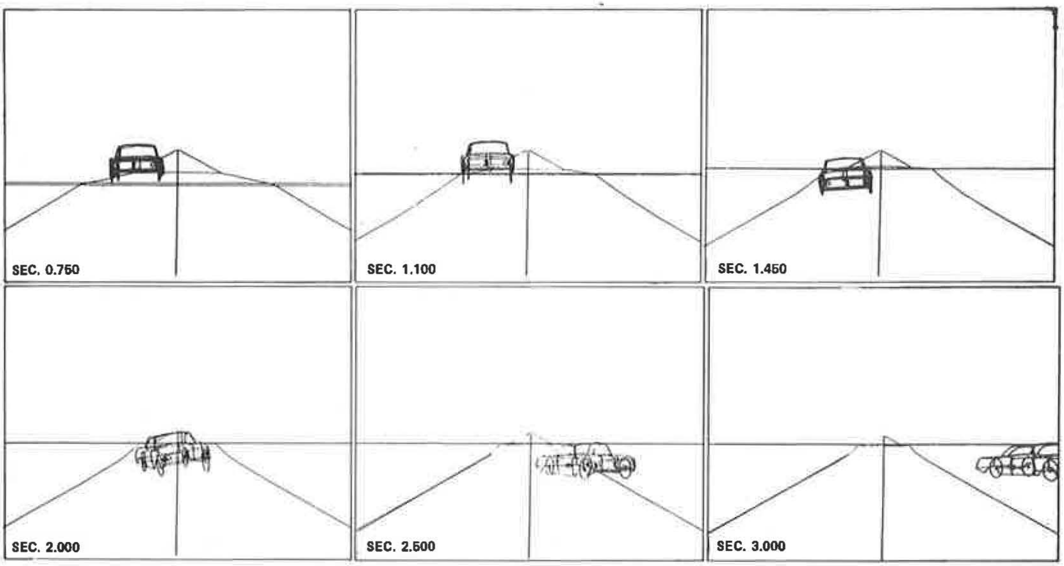

Figure 10. Simulated traversal of railroad crossing.

CONCLUDING REMARKS

This paper has presented a brief review of the status and capabilities of the BPR-CAL computer simulation of single vehicle accidents. The selected approach in computer implementation for this analytical aid (i.e., digital in the Fortran IV language) has been aimed at ease of transfer of the computer program to other research facilities. The objective of FHWA in this selection has been to contribute to a general elevation of the state of the art of highway vehicle dynamics by making the computer program readily available. To date, copies of the computer program have been distributed to 25 research organizations.

The potential of the model as an aid for objective evaluation of highway design practices and for rational development of warrants and specifications for roadside safety is virtually untapped. The capability to represent a cross section of vehicle and driver evasive maneuvers affords a unique opportunity for definitive analyses.

The model also has provisions for the generation of realistic closed-loop driver control inputs (13) and for detailed treatment of antilock braking systems (2). It also has an important potential as an aid in the analytical reconstruction of highway accidents.

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