Computer Simulation of the Crash Victim—A Validation Study

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Abstract

A program of research was conducted to examine the validity of a digital computer simulation of an automobile occupant during a frontal, head-on collision. The simulation is designed to permit a detailed study of the effects of several types of restraint systems on occupant responses in a confined compartment, where injury producing contact forces occur. The effects on occupant responses produced by the positions, orientations, and load-deflection properties of contacted interior surfaces are also simulated. This progress report covers one phase of a CAL long-range program of development of simulation techniques for study of occupant/vehicle and vehicle/obstacle collision responses.

Detailed comparisons are presented of responses from instrumented sled tests and corresponding computed responses from the simulation. The comparisons include forces in restraint belts and on contacted surfaces, accelerations of the dummy, and the detailed kinematics of the dummy itself. The results of repeat experimental runs of several of the test conditions are also displayed.

It is concluded that the comparisons between simulated and experimental time-histories show good agreement in the timing of events, occupant kinematics, general levels of peak values, and waveforms of responses, in view of recognized shortcomings in some of the parameter data and recognized limitations imposed by simplified analytical representations.

THE RESEARCH PROGRAM described in this paper is related to the development of an analytical tool for use in the exploration of performance requirements for crash injury countermeasures in automobiles. Since development is still in progress, this paper may be viewed as a progress report.

The overall problem of improving the crashworthiness of automobiles is sufficiently complex that various aspects have been isolated for concentrated study. For example, controlled collisions of actual automobiles are essential to define the acceleration environment within the passenger compartment and to investigate the various modes of structural collapse. However, the development of human tolerance data, improved interiors, and restraint system designs by this means alone is not feasible. Rather, human responses and tolerance limits for the type of impact forces and accelerations that occur in automobile collisions are investigated with cadavers and anthropomorphic dummies in a variety of sled tests. Also, mild impacts are sometimes investigated with living subjects to permit comparison with the responses of cadavers and dummies.

Although much excellent experimental work has been done on the dynamics of automobile crash victims, a particular difficulty in this research stems from the system complexities and nonlinearities which preclude extrapolations and cloud interpretations of test results. Variations in equipment and procedures (for example, stopping distance, deceleration waveform, size and weight of subject) prevent a direct correlation of the results obtained by different investigators. Also, there is a lack of agreement on the procedures and equipment that are required for a realistic and repeatable physical simulation.

In analytical approaches to the automobile crash injury problem, the human body has been represented by a wide range of mathematical models. At one extreme, a linearized equation for a single rigid mass has been used. At the other extreme, the presently reported mathematical model includes nonlinear equations for an articulated assembly of rigid mass segments with 10 deg of freedom within a confined compartment.

Each technique of automobile collision simulation, whether physical or analytical, has its own limitations and difficulties. In view of the overall complexity of crash victim responses, both experimental and analytical simulation techniques are required in a comprehensive research program.

The CAL mathematical model of the frontal collision case (the most frequent test condition) was developed for the purpose of providing a unifying, theoretical frame of reference for correlating applicable experimental results that have been obtained with diverse test procedures. It constitutes a research tool that can be manipulated quickly, easily, and at low cost to extrapolate experimental results to other impact conditions, system configurations, passenger sizes and weights, and conditions of occupant muscular tension that may arise from anticipation of a crash. It also can be applied in the performance of parameter studies with repeated, identical impact conditions. The advantages of this approach over others are considered to be following:

1. The capability of establishing optimum characteristics for crash injury countermeasures through the relatively rapid and inexpensive exploratory variation of idealized parameters.

2. The ability to repeat identical impact conditions while changing a single system parameter.

3. The comprehensive output information which clarifies the dynamic interactions that occur within the complex, nonlinear system and thereby provides insight for developing system improvements.

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Background

The research described in this paper involves mathematical modeling of the human body in a manner that is significantly different from related aerospace research. It therefore seems important, prior to further detailed discussion, to point out differences between the two applications.

Relationship to Aerospace Research—Results obtained from the extensive related aerospace research have only a limited application to the automobile case, because of several basic differences in the problems. For this reason, the aerospace work has not appreciably diminished the need for research related specifically to the automobile case.

For example, a highly restrictive restraint system and protective headgear can be specified in an aerospace vehicle, and the directions and speeds of impact are controlled within specified limits. Also, in aerospace vehicles the ranges of passenger size, weight, and physical condition are limited.

In the case of automobiles, the voluntary use of crash helmets and highly restrictive restraint systems is not, of course, a widespread practice at the present time. Standardization of the design of compartment interiors is not seen as an early development, and the ranges of passenger size, weight, and physical condition encompass those of the entire population. The variety of possible impact conditions is almost limitless, although certain statistics are available regarding the relative rates of incidence and the relative severities for the various directions of impact and contact regions around the periphery of the vehicle.

Therefore, in comparison with aerospace vehicles, the automobile is seen to constitute a much more complicated problem for attenuation of crash injuries. Whereas much of the related aerospace research has been concerned with the response of viscera within a tightly restrained or even "encapsulated" torso, and aerospace mathematical models have therefore dealt with very limited visceral, spinal, and torso deformation considerations, the corresponding automobile research must be primarily concerned with large and highly variable changes in the position and orientation of the occupant, even with the use of existing restraints. For this reason, contacts with the vehicle interior, particularly those of the unprotected head, must receive concentrated attention, as well as the various kinds of restraint devices and the conditions associated with crashes.

Earlier CAL Simulations—During 1962-1963, a relatively brief (six months) analytical study of automobile restraint systems was performed by the Cornell Aeronautical Laboratory (Ref. 1), supported by funds from the U.S. Public Health Service, Grant AC 00101-01, Division of Accident Prevention, Bureau of State Services, and the Automobile Manufacturers Association, Inc. In that study, a seven degree of freedom nonlinear mathematical model of a restrained, articulated body on a test cart, for the case of a frontal collision, was formulated and programmed for an IBM 704 computer.

In view of the overall system complexity, the objectives of that initial analysis were:

1. Develop a simple mathematical model capable of producing correlation of major responses with the results of experimental, frontal, head-on collisions in which anthropometric dummies were used.
2. Apply such a "first approximation" mathematical model in an investigation of fundamental points of controversy (for example, load elongation of webbing, stopping distance for cart tests, waveform of cart deceleration, and so on).
3. Determine both the feasibility and the utility of a more sophisticated model.
4. Develop methodology and parameter data that might be useful in related studies.

The responses of the earlier simulation, using some estimated parameters, were compared with experimental responses in the literature and were found to be in good agreement. However, a lack of both comprehensive parameter data and comprehensive experimental responses in available test results precluded a validation of the simulation.

Present CAL Simulation—The results of the earlier simulation were sufficiently encouraging to warrant an extension of the mathematical model, with additions aimed at the simulation of body responses in a confined compartment, where injury producing contact forces occur. The revised simulation (Fig. 1) is the subject of the reported validation study.

Objectives

The ultimate objective of the reported research is a valid analytical simulation of the responses of a living subject in an actual automobile. However, in view of the overall system complexity, it appears that this objective can best be accomplished through the mechanism of specialized simulation programs for particular areas of interest. That is, programs in which analytical detail and sophistication would be incorporated only in relation to a particular aspect of occupant-interior interaction (for example, head impact on instrument panel). The remainder of the analytical representation would be left in the simplest form that is found to be adequate. This general approach toward achieving the ultimate objective is based on a consideration of both the economics of obtaining the time-history solutions and the requirements for parameter data. For example, it would appear to be both unnecessary and inefficient to incorporate a sophisticated and detailed treatment of foot-floor interactions in a parameter study that is concerned with steering wheel/column-chest interactions.

This initial validation study may therefore be viewed as an examination of the adequacy of a variety of analytical representations that were deliberately simplified. The existing simplifications reflect both the exploratory nature of this initial attempt at simulating contact forces and the associated uncertainty, while the equations were being derived, of the economic feasibility of time-history solutions. The extent and the magnitudes of discontinuities in the nonlinear differential equations, even in the simplified case, made the machine time for time-history solutions uncertain.

The computer time requirement of initial runs of the existing simulation...
program was found to be approximately four to five times that of the simulation described in Ref. 1. While not exorbitant (approximately $35$-$40$ for a 200 msec time-history), the running costs made it desirable to seek a basic validation within the limitations imposed by the existing, relatively simple analytic geometry and solution logic, following which more detailed and sophisticated treatments could be developed and validated in specialized programs for areas of particular interest.

The General Motors sled facility at Wayne State University was found to be ideally suited for the initial, basic validation study, since it had instrumented, padded, simple “targets” representing the contacted regions of the automobile interior (Fig. 2 and Ref. 2). Note, however, that it was necessary to modify the facility to incorporate additional instrumentation and anchorages for restraints (Figs. 3 and 4). The availability of the G. M. facility reaffirmed the decision to retain simplicity in the initial simulation of contact forces.

The specific objective of the reported research program has therefore been to obtain detailed parameter and response data from fully instrumented
sled tests in order to examine the basic validity of the developed mathematical model, with analytical refinements incorporated only as required to achieve an adequate degree of correlation. The selected test subject was an anthropometric dummy, since it is not feasible to use living subjects to validate the simulation of injury producing contact forces. Also, some of the detailed body parameters of living subjects and cadavers are rather difficult to measure, and it was considered to be desirable to avoid the use of estimates of “typical” parameter data in this initial validation study.

Method

A series of 15 instrumented sled tests was performed with an anthropometric dummy unrestrained, restrained by a lap belt, and restrained by a lap belt and an isolated shoulder strap, each at two levels of severity. The series included repeat runs of all but one of the experimental responses. Dynamic load-deflection properties of system components (that is, target padding and restraint belts) were measured in a separate series of component tests. Note that the sled test series and the component tests were reported at this Conference by Patrick, Mertz, and Kroell. Also, detailed measurements were made of properties of the anthropometric dummy, as reported at this Conference by Naab.

It was originally planned to separately schedule the tests associated with each condition of restraint, so that comparisons of analytical and experimental responses could be completed prior to proceeding with tests of another restraint condition. In this manner, it would have been convenient to perform runs of experiments as required and to incorporate analytical refinements, as required for the particular case, before proceeding with the test program. However, a prolonged series of delays in the original test schedule, combined with limitations on the overall schedule and budget available for this research, resulted in the use of “first shot” measurements of component characteristics and results from sled tests for all conditions of restraint. In fact, the final reduced test data became available only in the final weeks of the program. For this reason, many of the discrepancies found between theory and experiment are of a sort that would normally have been corrected either in

1. Repeated runs of experiments (for example, target positions adjusted to achieve contact on the appropriate regions of the dummy, sled speed reduced to avoid “bottoming out” of target pads, and so on).
2. Improved measurements of component characteristics (for example, target properties under conditions of oblique impact, dummy padding under belts at higher load levels, and so on).
3. Analytical refinements (for example, improvements in the simulation of torso and neck bending resistances).

Results

In the interest of brevity, only three of the detailed comparisons are presented. However, a brief discussion of the findings in other comparisons is included.

Before proceeding with detailed discussions of the individual comparisons, it should be explained that the rather eye-catching discrepancies in the kinematics of the arms were produced by a regrettable but explainable set of circumstances.

The decision was made during the sled tests to physically lock the elbows in four of the six test conditions in order to provide a better view of the knee and upper leg. This modification of the system effectively reduced each arm to a single degree of freedom as opposed to the simulated two degrees of freedom. On first thought, it would appear that the simulated arms could be readily reduced to single degrees of freedom with friction at the elbow point. However, excessively large values of the simulated joint friction in relation to the time increment size used in the digital computer calculation can produce extraneous, self-excited oscillations. For this reason, the simulated elbow joints are not locked. It is noteworthy that in other comparisons that have been made with tests, where the elbow joints have not been locked, the kinematics of the simulated arms have consistently been remarkably close to those in the experiments.

Response Comparison for Unrestrained Dummy at 10 MPH Sled Velocity (Figs. 5-8)—In Fig. 5, the kinematics of the simulated dummy are seen to be in close agreement with those of the test dummy. It should be noted that small differences in dummy position exist at t = 0 sec. The position of the test dummy appears to have been shifted slightly from the measured static position by the sled acceleration. Also, although the difference in arm kinematics is small in this particular test, it is pointed out that the elbows of the test dummy were locked. Delayed access to the test films prevented the correction of these two sources of discrepancies.

In Fig. 6, the generally lower calculated forces normal to the target surfaces may have been produced by the neglect of shear effects on the simulated target properties. Measurements of the target properties were made under conditions of perpendicular impact. It is hypothesized that the relatively small diameter (6 in.); 4 in. thick cardboard honeycomb targets tend to yield in shear at a relatively low tangential force level, thereby reducing the resistance to perpendicular loading.

The assumption of proportionality between tangential and normal forces on the small diameter honeycomb targets appears to be unrealistic from a comparison of the two upper plots of Fig. 6. Instrumentation for the tangential force on the chest target did not function properly during this test. The tangential forces on the knee targets were not recorded.

Recognition of the above difficulties with simulated target properties occurred too late in the research program to permit corrective action. Note, however, that the small diameter cardboard honeycomb targets constitute a unique form of contact surface that appeared to be well-suited for this basic validation study, but is not representative of the interior surface of real automobiles.

In Fig. 6 it is seen that the times of occurrence of the calculated contact forces are in generally good agreement with the experiment.

The calculated peak value of knee forces in Fig. 6 is approximately 10%
Fig. 5—Dummy kinematic comparison: no restraint at 10 mph cart velocity.

Note that the assumption of proportionality between normal and tangential target forces appears unrealistic for the small-diameter cardboard honeycomb targets.

The dynamic impact simulation shows that the deformation at impact begins at the head and affects the chest. The position of the head and chest changes accordingly.

Fig. 6—No restraint at 10 mph cart velocity.

- Head force norm. to target - LBS.
- Head force tang. to target - LBS.
- Chest force norm. to target - LBS.
- Total knee force norm. to target - LBS.

Simulated target properties correspond to measurements made under conditions of perpendicular impact.
high for the first peak and 42% low for the second peak as compared with the experimental mean values. The delayed and reduced second calculated peak value could have been produced by the analytical retention of permanent deformation from the first contact (that is, the analytical treatment assumes that the second impact takes place at the identical location on the target of the first impact).

In Fig. 7, the calculated peak head acceleration in the A-P direction is approximately 27% lower than the mean experimental value. This direction of error was unexpected in view of the larger calculated force normal to the target in Fig. 6. The fact that the approximate "effective" head mass appears to be more reasonable in the calculation (that is, the corresponding "effective" head weights at the time of occurrence of peak acceleration are approximately 8 lb from the experiment and 16 lb from the calculation) casts some doubt on the experimental results. Note, however, that the existence of a chest force at the time of occurrence of peak load acceleration could conceivably make the comparison of "effective" head weights invalid.

The chest acceleration was expected to produce the worst agreement in view of the simulation of a rigid chest segment. The actual dummy construction includes steel ribs, and other parts which would be expected to produce large discrepancies between calculation and experiment. In view of this fact, the time-histories of the chest acceleration components in Fig. 7 are considered to be quite good.

In Fig. 8, the experimental measurements of hip acceleration were made at a position on the upper leg close to the hip. Corrections were necessary to transfer the measured accelerations to the position of the hip pivot. Therefore, only one of the test records was selected for comparison. It is the test that appears in the photographs in Fig. 5. Horizontal and vertical displacements of the hip were obtained from the film records. In general, Fig. 8 is considered to show good correlation.

**RESPONSE COMPARISON FOR LAP BELT RESTRAINT AT 20 MPH SLED VELOCITY (Figs. 9-13)**—In Fig. 9, the kinematics of the simulated dummy are seen to be in fairly good agreement with those of the test dummy up to \( t = 0.120 \) sec. Beyond that time, the excessive aft motion of the hip distorts the kinematics of upper torso rebound from the targets. The absence of an analytical representation of the lower seat back in the simulation is immediately apparent from inspection of Fig. 9, in which the lower torso penetrates the seat back position. However, a comparison of the experimental and calculated time-histories of horizontal hip acceleration (Fig. 13) indicates an improper simulation of seat cushion friction (that is, horizontal friction force too small during the initial aft motion of the hip), and no evidence on the experimental record of hip acceleration that a contact force was produced by the lower seat back. In these tests, as in others of the series, the elbows of the test dummy were locked, whereas the elbows of the simulated dummy could not be locked. As a result, there are significant differences between the experimental and calculated arm kinematics.

In Fig. 10, it is seen that the simulated head target was bottomed out in
The dummy elbows were locked in this test. Since the simulation does not permit complete locking of joints, there are significant differences in arm kinematics.

Lower seat back not simulated. Note, however, that the horizontal hip acceleration indicates an improper simulation of seat cushion friction as the primary cause of the discrepancy.

Fig. 9—Dummy kinematic comparison: lap belt restraint at 20 mph cart velocity
Fig. 10—Lap belt restraint at 20 mph cart velocity

Fig. 11—Lap belt restraint at 20 mph cart velocity
the calculation. A bottomed out condition is not indicated in the experimental record. The "chest force normal to target" and "lap belt loop force" comparisons in Fig. 10 show very good correlation.

The acceleration comparisons in Fig. 11 are considered to be very good. In Fig. 12, the measured forces tangential to the targets indicate a probable yielding of the small diameter targets in shear. The S-I chest acceleration comparison is only fair.

Fig. 13 indicates two probable shortcomings in the analytical treatment of the seat cushion. The vertical hip acceleration comparison indicates that the simulated seat cushion stiffness (based on static measurements) is too low. The horizontal hip acceleration comparison indicates that the simulated seat cushion "friction" is too small during the initial aft motion of the hip. It should be noted that the simulated seat cushion "friction" assumes proportionality between the horizontal and vertical forces generated by the seat cushion. Fig. 9 indicates that a "digging in" or "plowing" effect may exist at the time of initial aft motion of the hip.

**Response Comparison for Lap Belt and Shoulder Strap at 10 MPH Sled Velocity (Figs. 14-17)**—The simulation program includes two options in the treatment of the shoulder strap. In the first option, the webbing tension is equalized throughout the strap. In the second option, the two ends of the strap are treated separately (that is, they are completely isolated from each other). It is hypothesized that the behavior of the actual physical system lies somewhere between these two extremes. In this response comparison and in the one that follows it, both options are applied for purposes of comparison. The display of computed kinematics in Fig. 14 corresponds to the equalized tension option.

In Fig. 14, the kinematics of the simulated dummy are seen to be in excellent agreement with those of the test dummy. In this test, the dummy elbows were not locked. It is interesting to note that the simulated dummy arms appear to "average" the kinematics of the experimental arms. The unsymmetrical shoulder strap produced differences in the experimental responses of the individual arms which, of course, are not simulated in the present plane motion analysis.

In Fig. 15, the comparison of calculated and measured lap belt forces shows a discrepancy similar to that found in the 10 mph lap belt tests. A reasonable explanation is that discussed in the section following the present comparison, regarding the analytical treatment of dummy padding. The other plots in Fig. 15 are considered to show a fairly good correlation. The equalized tension option in the shoulder strap appears to be the better approximation.

In Fig. 16, the comparison of calculated and experimental head accelerations shows a poor correlation. The difficulty in this case is believed to lie in the approximate analytical representation of the neck bending resistance. The use of constant friction and limit stops appears to provide a poor simulation in cases such as the present one where large neck deflections occur. The calculated "spikes" on the chest acceleration plot are also believed to be produced by the simulation of excessively abrupt limit stops in the spinal "joints"
Fig. 13—Lap belt restraint at 20 mph cart velocity
Duodenal padding under belt may have reduced effective belt stiffness to a greater extent than that simulated.

Approximate analytical representation of neck bending resistance.

Fig. 15—Lap and torso restraint at 10 mph cart velocity.

Fig. 16—Lap and torso restraint at 10 mph cart velocity.
and the neck. The present representations of bending resistances are first approximations. Unfortunately, the presented comparison of responses is the first one that has been available upon which a second approximation could be based.

In Fig. 17, the erratic behavior of the calculated hip accelerations is believed to have been produced by the discussed difficulties with spinal and neck bending resistances.

Also, in Fig. 17, the recovery of horizontal hip position is seen to deviate further for the case of equalized tension in the shoulder strap. However, the single experimental response that is plotted gives no indication of the repeatability of the experimental recovery of hip position.

Findings in Other Comparisons—In comparisons that are not presented in this paper (all of the comparisons appear in Ref. 3), the following shortcomings and/or difficulties were encountered,

Unrestrained Dummy at 20 Mph—The time-history comparisons demonstrated another form of difficulty with the simulation of target properties that could have been corrected if recognized earlier in the program. The difficulty was that of exceeding the range of measured target properties in both the calculated and the experimental sled runs.

In the present simulation of contact forces, the effects of local deformations of the articulated body (the dummy) are assumed to be included in the load-deflection relationships that are entered for each individual target. The fitted load-deflection polynomials for the targets therefore represent composite load-deflection relationships. In keeping with this analytical simplification, the corresponding dynamic properties of the targets were measured in a series of component tests in which the actual contact regions of the dummy were impacted against sample targets in the direction perpendicular to the target surface. Since it was not known how large the velocities of target impact and the energy inputs to the various targets might be, the component tests were run at several different speeds. In the case of the chest target, the dynamic properties were measured in the range of “bottoming,” for one target sample only, up to a force level of 2700 lb at 4.6 in. deflection. The fitted polynomial load-deflection characteristic, which is valid only in the measured range, extrapolates the measured data for inadvertent deflection greater than 4.6 in. In the extrapolated range, it essentially simulates a level of target stiffness that is based on an extension of the slope measured in the final 9% of the range of deflection for which actual load-deflection measurements were obtained.

In the present comparison, the calculated chest force was found to reach a value of 10,240 lb, which is 8.8 times as large as the highest measured load in the determination of the composite load-deflection characteristics of the chest target. This inadvertent extrapolation of the component test data by means of the fitted polynomial therefore led to a force level which probably would correspond to appreciable deflections of both the dummy chest and the target support structure.

Lap Belt Restraint at 10 Mph—The three experimental runs of this test
condition were performed without detection of the fact that the dummy chest was not hitting the chest target. This defect in the experimental responses was not recognized prior to viewing of the films after completion of the test series. In view of the objective of the test series, the target positions should, of course, have been adjusted to achieve chest contact with the chest target. In the present version of the computer simulation, the contact regions on the dummy effectively always achieve contact with the appropriate targets.

In each of the three test runs, the chest target was struck by the neck of the dummy and the measured "chest force normal to target" actually was applied to the dummy chin and upper chest region.

Also, in these three tests, the comparison of calculated and measured lap belt forces indicated that the simulated belt stiffness was slightly higher than actual. Since the 20 mph comparison presented in Figs. 9-13 shows excellent agreement in the belt force, it is hypothesized that the dummy padding is more nearly bottomed out at the 3600 lb of force level that occurs at 20 mph, but that the padding acted to reduce the effective belt stiffness in the present test condition.

The dynamic belt characteristics were measured on a rigid body block, and a correction was incorporated to approximate the effects of the series compliance of the dummy padding. However, the load-deflection of the dummy padding was measured statically over a range of only 200 lb of load.

Conclusions and Recommendations

Conclusions—

1. The comparisons between simulated and experimental time-histories show good agreement in the timing of events, occupant kinematics, general levels of peak values, and waveforms of responses, in view of recognized shortcomings in some of the parameter data and recognized limitations imposed by simplified analytical representations.

2. The present combination of (a) analytical treatment of torso and neck bending, and (b) associated parameter data, does not produce an adequate degree of correlation of the waveforms of calculated acceleration time-histories with those of moderate-to-high severity experiments to permit direct application of available information on human tolerances.

3. The "first approximation" parameters used in the analytical representations of spinal and neck bending resistances are excessively nonlinear.

The experimental responses for chest and head accelerations indicate a greater degree of linearity in bending resistances of the dummy torso and neck (that is, proportionality between resistance and deflection) than that simulated. On the basis of preliminary static measurements on the Alderson F-50-AU dummy, it was concluded that the torso and neck were essentially inelastic (that is, there was no appreciable recovery from deflections). Measurements were made of the maximum bending deflections, and limit stops were adjusted in the computer simulation to prevent excessive deflections. In the initial selection of related parameters, the bending resistances were simulated essentially with constant friction and rather abrupt inelastic travel limits. From a review of head and chest accelerations in the calculated-experimental response comparisons, it appears that the simulated limit stops should be less abrupt and should be brought into play at smaller angular deflections.

With the availability of detailed responses from the reported test series for guidance, it is anticipated that the described discrepancies in responses can be remedied quite readily. Actually, such analytical developments were planned as a part of the present research program, in the original schedule of events. Unfortunately, there was no opportunity to fully explore modifications in this aspect of the simulation.

4. The assumption of proportionality between tangential and normal forces on the 6 in. diameter, 4 in. thick honeycomb cardboard targets used in the reported test series is not valid. Note, however, that this assumption may be a reasonable first approximation for surfaces less susceptible to shear failure.

The selection of the relatively thick honeycomb padding was based on a desire to avoid "bottoming out" the contact surface padding in the reported test series. In prior tests on the G. M. sled facility, bottoming out of padding was known to have produced appreciable deflections in the "target" support structures. Also, it was recognized that the peak loads that would be generated in a bottomed out condition would be difficult to both measure and predict.

Actually, the goal of avoidance of bottoming out of padding was not achieved. Also, a review of the recorded normal and tangential loads suggests that shear displacement of the honeycomb pads may have both limited the tangential forces and reduced the resistances to perpendicular loading. The simulated target properties were based on dynamic tests under the condition of perpendicular loading.
5. The analytical simulation of seat cushion friction is not adequate for conditions of large vertical deflection of the cushion.

On the basis of the 20 mph test condition with the lap belt restraint, it appears that some "plowing" or "digging in" effects exist under conditions of large vertical deflection of the seat cushion. The assumption of proportionality between horizontal and vertical forces on the seat cushion is a poor approximation under these conditions. Note that the effects of this shortcoming in the simulation might be partially alleviated by means of increasing the hysteresis of the simulated belts beyond that measured in the separate, dynamic tests performed on the belts.

6. The actual dynamic vertical stiffness of the seat cushion is somewhat higher than that simulated.

It is unfortunate that the attempted development of instrumentation for measurement of vertical loading of the seat cushion was unsuccessful. That measurement plus a time-history of the vertical position of the hip (from film) would have provided a direct measure of the dynamic load-deflection properties of the seat cushion. The simulated properties correspond to static measurements, with a viscous damper added to simulate dynamic stiffening effects. A review of the two response comparisons for the case with lap belt restraint indicates that the actual seat cushion offered a greater resistance to vertical hip movement than that simulated.

7. The measurement, in this validation study, of load-deflection properties of padding on the dummy structure, under the lap belt, did not include a sufficiently large range of loading.

The dummy padding in the pelvic region constitutes a compliance in series with the lap belt. Effects of the padding, as measured up to a loop load of only 200 lb, were included in the simulated lap belt load elongation. However, a review of the comparisons between calculated and experimental time-histories of load belt loading indicates that the agreement improves as the range of the load belt load is increased. In the tests with lower measured lap belt loads, the calculated time-histories indicate that the simulated lap belt is too stiff. A logical explanation is that the padding is not yet "bottomed out" in the cases of tests with lower ranges of lap belt loading.

RECOMMENDATIONS—As previously discussed, difficulties in scheduling tests and in obtaining reduced test data in a timely fashion have restricted the present validation study essentially to a "first shot" comparison of responses. For this reason, the objectives of the reported research have not been fully achieved. However, the presented comparisons are considered to be sufficiently good to justify certain applications to current related problem areas. Also, by working backward from the reported comparisons with exploratory adjustments, it seems entirely possible that some of the recognized shortcomings in the present analytical representations and parameter data can be at least partially remedied (for example, Conclusions No. 3-7). Exploratory adjustment of parameters would not have been appropriate, of course, in the reported validation study. However, it seems a reasonable course of action prior to applications.

The following recommendations include applications of the computer simulation in essentially its present form; further developments aimed at special applications; and further developments aimed at general improvement of the simulation.

Applications in Present Form—
1. Generation of response information for design guidance. The recently increased attention being focused on performance specifications for crash injury countermeasures has revealed a dearth of applicable information on occupant responses. For example, relationships between head velocity, normal to a specific contact surface, and vehicle speed immediately prior to impact, in a frontal collision, are not known to be defined. Similarly, the corresponding inertial loading of the head during contact with an interior surface of the vehicle is not known to be defined (for example, the "effective head mass" during impact on the instrument panel).

Factors that determine the ranges of head velocities and the inertial loading of head contacts in a given collision, include the impact type (that is, time-history of compartment deceleration), compartment dimensions, occupant size, condition of restraint, position of seat adjustment, muscular tension, and so on. Definitions of the above two aspects of occupant response, among others, would appear to be essential for the development of design improvements and related performance specifications. The present version of the computer simulation is ideally suited for the generation of applicable response information.

2. Specification of dynamic test procedures for acceptance testing of restraint belts. There is an extensive current interest in dynamic acceptance testing of restraint belts. The development of specifications for an acceptable test procedure involves the resolution of many controversial issues. The present version of the computer simulation could constitute a means for resolving existing differences of opinion regarding the extent of sophistication that is required in components of a test facility (for example, the test dummy, the seat, and so on). It could also be applied to the problem of tolerance specifications in a dynamic test procedure. For example, the sensitivities of the peak belt loading and the time-history of belt elongation to specific types and magnitudes of variations in the waveform of sled deceleration, to errors in the sled speed, and so forth, could be evaluated analytically.

Further Developments Aided at Special Applications—In the existing CAL mathematical model, both the analytic geometry and the solution logic associated with contact forces were deliberately simplified, in view of the exploratory nature of this initial attempt at simulation. The analysis philosophy employed in the development of the simulation was aimed at initial simplicity and a relatively flexible form of programming. For particular areas of interest, which will require more detailed treatment of specific aspects of the simulation, the form of programming will permit relatively easy modifications in the analytic geometry and the logic associated with force generation.

Several areas of particular interest, related to contact forces, can be anticipated. They are briefly described in the following paragraphs.

1. Steering wheel/collar program. Refinements should be incorporated.
in the existing mathematical simulation of the "chest target" to more closely simulate contact between a steering wheel and column and the human chest. The simulation could also be modified to permit column motions relative to the vehicle interior prior to contact (that is, column "penetration"). Important aspects of this application will be the development of adequate analytical treatments of the inertia of the steering wheel and shaft, and interactions between the chest and the deforming steering wheel.

2. Instrument panel program. The development of logic and programming to permit the simulation of a curved instrument panel shape (that is, in the vertical plane) is recommended. Refinements could also be developed in the analytical treatment of tangential components of contact forces (for example, by simulating a tangential force that varies with the depth of indentation), and in the detailed treatment of recurrent loading.

3. Windshield impact program. A valid simulation of head impacts on windshield glass will require the development of a special subroutine to generate the dynamic load-deflection characteristics of the glass. Inertial effects and the discontinuities associated with penetration are foreseen as areas that will require special attention.

Further Developments Aimed at General Improvement of Simulation—The ultimate objective of the present research is validation of the simulation for the case of a living subject in a real automobile interior. The described special applications are, of course, primarily concerned with analytical representation of the automobile interior and the localized contact properties of the occupant. In the following, further research related to general improvement of the simulation of the occupant, and to criteria for evaluating the injury potential of responses, is recommended.

1. Correlation of simulated responses with those of cadavers and living subjects. Exploratory variations of the present parameter values associated with torso and neck bending, and of the analytical representations of those bending modes, should be performed in conjunction with a program of detailed comparisons of computed responses with those of dummies, cadavers, and living subjects. The analytical approach to human simulation has a unique potential for incorporation of adjustable, time-varying muscular restraints by means of tabular entries in the computer input. It may, therefore, permit a close approximation of the responses of living subjects. The feasibility of adaptation of the results of aerospace research to a complex simulation of the torso, including visceral and spinal details, should be explored.

2. Criteria for evaluation of injury. After improvements are achieved in the degree of correlation of waveforms of acceleration time-histories, it may become feasible to develop processing logic and criteria for evaluation of probable injuries within the simulation program. These criteria would be based on a comprehensive review of existing tolerance data. Ideally, the end product would be an automated scanning and analysis of the time-histories of forces and accelerations at various regions of the body. On the basis of the analysis, an output statement would be made regarding the probable occurrence and extent of injuries. The injury criteria should, of course, be programmed for relatively easy adjustment as new tolerance information is obtained.

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References


APPENDIX

CAL Mathematical Simulation

A preliminary CAL mathematical model of a vehicle occupant, restrained by a lap belt or by a combination of lap belt and shoulder restraint in a frontal collision, is described in Ref. 1. The present CAL simulation (Fig. 1) is an extension of that model, with additions that are aimed at exploration of body responses in a confined compartment and injury producing contact forces. The additions to the earlier model are described below.

Extension of Earlier CAL Simulation—

1. Four additional degrees of freedom. Additional head and torso degrees of freedom have been incorporated to permit first approximations of the inertial loading of skull, chest, and knee contacts on portions of the vehicle interior; and whiplash effects that may be produced by shoulder restraints.

The torso deflection in the revised model also permits a direct comparison
of the calculated components of chest acceleration with unidirectional accelerometer measurements in the literature that have been taken at the chest.

2. Nonlinear contact forces on head, upper torso, knees, and feet. To achieve simplicity in this initial attempt at simulation, the positions and directions of the contact forces have been made determinate by approximating the contact surfaces on the torso with circular arcs and representing the interior surfaces of the vehicle with plane surfaces (Fig. 18). It should be noted that the seat cushion forces, \( F_s, F'_s \), and \( f \) are treated in a different manner, as depicted in Fig. 19.

The component of each contact force that is perpendicular to the contacted interior surface is treated as a nonlinear function of the deflection and the
velocity of deflection, measured perpendicular to the contacted surface. A general nonlinear force-deflection subroutine is used to generate the contact, belt, and cart stopping forces from individual sets of polynomial coefficients for the loading curves (increasing load) and individual sets of coefficients for dissipated energy and residual deformation that are used to determine the unloading curves (decreasing load).

The general form of the simulated load-deflection relationships is illustrated in Fig. 20. The load-deflection relationship for increasing loads is represented by a general polynomial function of deflection and the velocity of deflection. For decreasing loads, the load-deflection relationship is represented by a parabolic function of deflection, which is determined from the specified (input data) ratios of conserved energy to maximum absorbed energy, and residual deflection to maximum deflection. When recurrent loading takes place, the residual deformation for each cycle is incorporated, in the form of added slack or initial surface displacement, for subsequent cycles. If the unloading between cycles is incomplete, a value of residual deformation is determined such that the new loading curve will pass through the final point on the preceding unloading curve (Fig. 21). The objective in the development of this subroutine has been to incorporate sufficient generality to permit the use of both detailed experimental and idealized load-deflection characteristics.

The component of each contact force that is tangential to the contacted surface (sliding friction force) is assumed to be proportional to the normal force, and the output of the calculation program has been expanded to include the magnitudes, directions, and positions on the torso of the resultant contact forces (vector summations of the normal and tangential components).

3. Friction in all body pivots, including the simulated torso pivots. Constant restoring couples were used in the hip and knee joints of the earlier simulation, on the basis of an early form of anthropometric dummy. With that form of joint restraint, the “muscle tone” of the simulated crash victim acted to restore initial joint angularities. However, in all currently available anthropometric dummies, muscle tone is simulated with an adjustable level of constant friction. Since correlation was to be first attempted with data from an instrumented dummy, the simulation of joint restraints was modified accordingly. In future revisions of the model, it is planned to attempt a simulation of time varying joint restraints, in order to permit a more realistic representation of the muscular responses in a living subject.

4. Spinal elasticity. Linear torsion springs are simulated in the torso “pivots” to permit a first approximation representation of torso (spinal) elasticity.

5. Joint stops. One-way friction stops are included in the elbow, neck, and spinal “joints,” as well as in the knee. This feature has been found necessary to prevent reverse bending of knee and elbow joints and to limit maximum bending deflections of the neck and torso. The general form of the stops is illustrated in Fig. 22.

6. Gravity effects. The potential energy changes that are produced by gravity have been incorporated. The earlier simulation did not include seatback and floor forces and, therefore, the simulated occupant could not be balanced statically. While the effects of gravity on the overall response are considered to be of a secondary nature, the present extension of the simulation permitted their incorporation by means of trivial additions.

7. Lap belt force. The analytical treatment of the lap belt elongation and force have been revised to improve the simulation under conditions of extreme jackknifing of the torso.

In the previous simulation, a simplifying assumption was made that the

![Fig. 20 - General form of contact, belt, and cart stopping forces](image)

![Fig. 21 - Assumed form of load-deflection for recurrent loading](image)
intersection of the line-of-action of the lap belt with the torso centerline remained fixed on the torso as the torso rotated (Fig. 23a). It was recognized that this was a crude representation and that a region of potential difficulty existed, under conditions of extreme jackknifing, for the case of a simultaneous occurrence of a belt load and an overcenter moment arm about the hip. However, the potential difficulties were minimized by the fact that a rigid torso was simulated.

In the present case, the additional degrees of freedom in the simulated torso made necessary an improved representation for the lap belt. In Fig. 23b, the present revision is shown in which the line-of-action of the lap belt is assumed to remain tangent to a circle with center at the hip pivot. With this assumption, vertical movements of the hip can alter the point of tangency without necessarily producing elongation. Therefore, the lap belt elongation is defined as the change in length between the anchor point and the intersection point between the belt and torso centerlines, with the appropriate portion of this length measured along the circumference of the assumed circle.

8. Expanded output calculations. The output calculations were expanded to provide comprehensive response information, including the added degrees of freedom and the contact forces that are described above. Velocities of torso components normal to corresponding interior "contact" surfaces have been added to the output. Also, a time-history of the detailed distribution of system energy is included.

It should be noted that the output calculations have no effect on responses. They are merely auxiliary calculations which combine individual responses or convert units to provide a more useful form of output.

The energy calculations, in the case of the 11 degree of freedom form of solution (that is, where a sled stopping force is generated by the sled velocity and displacement), can provide additional evidence that the computer program is functioning properly. That is, the total system energy must remain constant within the range of error attributable to digital solution of the equations of motion. In computer runs of the appropriate type, performed as a part of the present research program, the total system energy has been found to remain constant within 0.5% over a 200 msec time-history. The calculations...
presented in this paper have all made use of a tabular input of sled (or vehicle) deceleration, in which case the bypass of interactions between the occupant and the sled effectively creates an "open" rather than "closed" system (that is, work done on the sled by the occupant does not alter the sled motion and is therefore external to the calculated energy distribution).

Form of Computer Solutions—The form of computer solutions and the associated options are essentially the same as those of the earlier simulation. A brief description is given in the following paragraphs.

Time-history solutions of the equations of motion have been programmed to permit the use of either a general polynomial form of sled stopping force, which is a function of both displacement and velocity of the test sled, or a direct tabular input of vehicle (or test sled) deceleration as a function of time. Since occupant-to-vehicle interaction is simulated in the former, the adequacy of a test sled and its stopping mechanism, for simulation of actual vehicle collisions, can be evaluated. The latter permits application of experimental data and idealized waveforms for vehicle (or test sled) decelerations.

The following input information is required for the present CAL simulation:

1. Mass, dimensional, and moment of inertia data for the articulated body.
2. Muscular restraint in body joints as approximated by adjustable values of constant friction.
3. Spinal elasticity as approximated by torsional springs in the simulated spinal "joints."
4. Travel limits in body joints (for example, knee and elbow stops to prevent reverse bending).
5. Dynamic load-deflection characteristics of restraints, seat cushion, and contacted surfaces in the vehicle interior.
6. Initial forces on seat cushion, seat back, and toe board.
7. Initial position of articulated body as defined by angular coordinates of the body segments.
8. Initial forward velocity of the vehicle.
9. Either the measured time-history of vehicle deceleration for the specific vehicle collision (or sled test) or the mass of the vehicle and the dynamic load-deflection characteristics of the vehicle stopping mechanism (for example, front structure of an automobile or sled stopping device).

Because the system is nonlinear, the computer solutions are in the form of time-histories. Output information from the simulation includes time-histories of the following:

1. Vehicle (or sled) displacement, velocity, and acceleration. Vehicle stopping force if that form of solution is used.
2. Restraint belt forces, elongations, rates of elongation, and angularities.
3. Vertical and horizontal components of displacement, velocity, and acceleration of hip.
4. Directions and magnitudes of resultant chest and head accelerations.
5. Position and orientation of articulated body as defined by hip position and angularities of body segments.
6. Normal and tangential components of contact forces on vehicle interior surfaces. Positions and angularities of resultant contact forces on articulated body, Seat cushion friction force.
7. Normal deflections, velocities of normal deflections, and tangential velocities at contacted surfaces.
8. Joint restraining couples produced by the combination of simulated muscle tone and joint stops, and also by the seat cushion.
9. Kinetic energy in articulated body segments and vehicle.
10. Energy absorbed (conserved and dissipated listed separately) by contacted surfaces, restraining belts, body joints, seat cushion, cart stopping device (if used in solution), and vertical movements of body segments (gravitational potential).