SIMULATION OF VEHICLE IMPACT WITH THE
TEXAS CONCRETE MEDIAN BARRIER
VOLUME I: TEST COMPARISONS AND PARAMETER STUDY

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Evaluation of the Roadway Environment by
Dynamic Analysis of the Interaction Between
the Vehicle, Passenger, and Roadway

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FOREWORD

The information contained herein was developed on Research Project 2-5-69-140 entitled "Evaluation of the Roadside Environment by Dynamic Analysis of the Interaction Between the Vehicle, Passenger, and Roadway" which is a cooperative research study sponsored jointly by the Texas Highway Department and the U. S. Department of Transportation, Federal Highway Administration.

Basically, the objectives of the study are to apply mathematical simulation techniques in determining the dynamic behavior of automobiles and their occupants when in collision with various roadside objects or when traversing curves in the road, shoulders, or other situations. It is a continuing study, having been initiated in September 1968.

As part of the first year's work, the computer program HVOSM (formerly known as CALSVA) was obtained from Cornell Aeronautical Laboratory and made operational on the IBM 360 computer facilities at Texas A&M University. In adapting the program, additions and modifications were made which increased its flexibility and usefulness. These changes and the input requirements of the program are documented in Research Report 140-1.

The primary emphasis of the second year's work was the development of an analytical model which predicts the dynamic response of an automobile's occupant in three-dimensional space. Research Report 140-2 presents the derivation of the occupant model, a validation study, and a description of computer input data for determining the occupant's response.
In the 1970-71 year the emphasis was on application of HVOSM to specific roadway design problems. Research Report 140-3 describes an investigation of the traffic-safe characteristics of different sloping culvert grate configurations. Criteria are presented for designing a traffic-safe sloping grate. Research Report 140-4 describes the development of criteria from which the need and location of guardrail on embankments can be determined.

Volume I of this report describes a comparison of full-scale test results of the Texas Concrete Median Barrier with simulated results as computed by a modified version of HVOSM. Also contained in Volume I is a parametric study of the performance characteristics of the CMB for various vehicle encroachment or impact conditions. Volume II contains the computer input for all runs made and some sample output.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.
ABSTRACT

Key Words: Accidents, Automobile, Barrier Impact, Computer Simulation, Concrete Median Barrier, Injury Level, Math Modeling, Safety, Severity Index, Vehicle Redirection, Vehicle Simulation

The Highway-Vehicle-Object Simulation Model (HVOSM), a computer program developed at Cornell Aeronautical Lab. (CAL), has been modified with generous help from CAL and used to successfully simulate a vehicle impacting the Texas Concrete Median Barrier (CMB) at speeds ranging from 50 to 80 m.p.h. and angles ranging from 5 to 25 degrees.

The Texas CMB (a New Jersey type design) was impacted by a 4000 lb. sedan at angles of 7, 15 and 25 degrees at 60 m.p.h. The results of these full scale tests were closely approximated by the modified HVOSM.

Comparison of simulation and test results are presented both visually and quantitatively in the form of computer generated drawings of the vehicle during impact alongside corresponding frames from the high speed film and plots relating predicted and measured accelerometer readings.

Following the successful simulation of the full scale tests, a parameter study on impact conditions was conducted. Using the modified HVOSM, a 4780 lb. vehicle impacting the CMB was simulated for speeds of 50, 70 and 80 m.p.h. at angles of 5, 10 and 15 degrees for each of those speeds.

For speeds less than 70 m.p.h., the results were in line with
findings of other researchers in testing similar barriers. However, it was concluded that for impact speeds of 70 m.p.h. and greater in conjunction with impact angles of 15 degrees and greater, automobile rollover can be expected.

The results of all simulated impacts with the Texas CMB are presented graphically with regard to a severity index which quantifies the severity of each crash. This index is based on vehicle accelerations.
SUMMARY

In this study, the performance of the Texas Concrete Median Barrier (CMB) was evaluated from the standpoint of severity of impact, vehicle exit angle, maximum roll angle, and maximum pitch angle for a wide range of vehicle encroachment conditions. A modified version of the Highway-Vehicle-Object Simulation Model (HVOSM) was used to simulate a 4780 lb. automobile impacting the CMB at speeds of 50, 70, and 80 m.p.h. at angles of 5, 10 and 15 degrees for each of those speeds. These parameter studies were preceded by a validation phase where full-scale tests on the CMB were successfully simulated with the HVOSM.

In summary the major findings are:

1. that the Texas CMB performs well with respect to exit angle and maximum roll and pitch angles at least up to 80 m.p.h. (highest speed considered) for impact angles of less than 10 degrees.

2. that serious injuries could occur at 70 m.p.h. for impact angles greater than 7.5 degrees (see Figure 25).

3. that rollover can be expected for speeds greater than 70 m.p.h. at angles greater than 15 degrees. Although these encroachment conditions would probably result in serious or fatal injury even without the rollover, this creates a hazard for other motorists as well.
IMPLEMENTATION STATEMENT

There is very little disagreement (if any) among Highway Engineers on the superior attributes of the Concrete Median Barrier (New Jersey or Texas type) for use in narrow medians of roadways carrying high traffic volume such as in urban areas. Tests have shown that impacting the CMB at low angles is safe and that maintenance is virtually non existant.

The results of this study provide additional detailed information which will aid the highway designer in evaluating an existing roadway for possible installation of a CMB or designing a new roadway to accomodate a CMB. For an automobile colliding with the Texas CMB, Figure 25 of this report gives combinations of speed and impact angles for which serious injury to the occupant is unlikely.
ACKNOWLEDGEMENTS

This research was sponsored by the Texas Highway Department (THD) in cooperation with the U.S. Department of Transportation, Federal Highway Administration (FHWA).

The authors sincerely thank Messrs. Norman J. Deleys and Raymond R. McHenry of Cornell Aeronautical Laboratories for providing generous professional assistance in the form of copies of their previous work on modifying their model, the Highway-Vehicle-Object Simulation Model (HVOSM), to include the effect of vehicle structural hard points in simulating automobile-barrier crashes.

Thanks are also extended to Messrs. John F. Nixon and David Hustace (THD) and Mr. Edward V. Kristaponis (FHWA) for their cooperation in meeting the uncertainties of this particular research effort and their patience in awaiting the reported results.
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I. INTRODUCTION

Evaluation of barrier systems usually include full-scale vehicle crash tests. These tests are often quite expensive and many man-hours are required for all phases of the test program. A more ideal method of studying the performance of barriers is by computer simulation.

The original version of the Highway-Vehicle-Object-Simulation Model (HVOSM)* (1,2) was capable of predicting automobile behavior for impact with certain types of barriers, provided the automobile crush was moderate (12 to 18 inches). The types of barrier systems which can be studied with the HVOSM are those whose lateral resistance to vehicle penetration is independent of the longitudinal position of the vehicle contact. The Texas Highway Department (THD) concrete median barrier (CMB), being a rigid barrier, falls within this category.

To study barrier impacts in which large automobile crush occurs, the HVOSM was modified to include hard points within the automobile structure. These hard points simulate the effects caused when very stiff automobile members are encountered, such as the engine, a frame member, or a wheel assembly. Basic details of HVOSM are summarized in Appendix A and a description of the hard point modifications is given in Appendix B.

In Chapter II, comparisons are made between experimental data from full-scale crash tests of the Texas CMB and simulated results from TTI's modified version of HVOSM (including hard points). The

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*Formerly known as CALSVA.
crash test data were obtained from another THD sponsored research program (3). In general, good correlation exists between simulated and experimental results.

A parametric study of the Texas concrete median barrier was conducted using HVOSM and the results are described in Chapter III. The parametric study was used to determine the barrier's performance characteristics for a range of vehicle encroachment conditions. Factors used in measuring the performance were the vehicle's exit angle, maximum pitch and roll angle, and a severity index which quantified the impact severity.
II. COMPARISON OF EXPERIMENTAL DATA WITH PREDICTIONS BY HVOSM

General

It was felt by sponsors and researchers alike that a good correlation between simulation and testing was a prerequisite to conducting parametric studies of the Texas CMB with the HVOSM. The crash test data used in the comparisons were obtained from another THD sponsored research program (3) and the results were available to this study at no extra cost.

The three tests used in the comparisons consisted of passenger cars (roughly 4000 lbs. in weight) being towed into a full scale model of the CMB, model I-70 (designated CMBI-70), at approximately 60 mph for impact angles of 7, 15, and 25 degrees. The CMBI-70 designation is used when illumination poles are placed atop the barrier. The exterior dimensions of the barrier are the same however, whether illumination is used or not. Reference to the barrier will henceforth be the CMB. Accelerometers were mounted to the structural framework of the vehicles, at the locations described in APPENDIX C (Figures C1 and C2). They were oriented to measure the lateral and the longitudinal components of vehicle acceleration. Vehicle motion was recorded on high speed film from rear, side, and overhead views. These films were used to determine the automobile's speed and angle at impact and to provide a comparison of the vehicle's simulated and actual motion.

The computer simulation used was a modified version of the HVOSM, as discussed in Appendix B. The modification made was the addition of
NOTE: Dotted Outline Shows the Actual Shape of the CMBI-70 and Solid Lines Show the Shape Used for Simulation.

FIGURE 1. IDEALIZATION OF THE CMBI-70 FOR COMPUTER SIMULATION.
vehicle structural hard points to the existing sheet metal crushing capability, to account for stiffer portions of the vehicle (frame members, wheels, etc.) impacting the barrier.

Due to limitations within HVOSM, it was necessary to describe the CMB by a combination (or superposition) of the program's "curb impact" and "barrier impact" capabilities. As shown in Figure 1, the sloping face of the barrier was simulated as a curb (line 1-2) and the upright face was simulated as a vertical rigid barrier (line 2-3). In the simulation tire-curb interaction is accounted for but tire-rigid barrier interaction is not. However, since good comparisons between simulations and tests were obtained (for both kinematics and accelerations), it would appear that tire contact with the upright face is of secondary importance. For the same reason, the omission of slope 4-5 was apparently not detrimental to the simulation. This is not surprising in view of the relative dimensions of the tires to the length of line 4-5 and the high impact speeds. Likewise, idealizing the upright face as vertical rather than sloped a few degrees proved to be an adequate representation. For the shallow angle impact of 7°, the whole concrete median barrier could have been defined as one high curb (1), but for the sake of uniformity all cases were defined as described above.

Data corresponding to the CMB and the test vehicles, such as vehicle weight, barrier and vehicle dimensions, impact speed and angle, etc., were read into the HVOSM program. All computer input data are described in Volume II of this report (4).

Plots of the predicted and measured acceleration components at
points corresponding to the locations of accelerometers in the actual vehicle were made. Drawings of the simulated impacts were generated using a computer program (5). The program produces a perspective drawing of the vehicle and barrier at selected times, utilizing vehicle position as determined from the HVOSM. These line drawings were then compared with corresponding photographs taken from the high speed photography of the test.

Results of the Comparisons

The results of the comparisons are given both pictorially and graphically in Figures 2 through 23. It should be noted that the test results are for a vehicle impacting on the left (driver) side of the vehicle, while the simulation impacts the car on the opposite side (passenger side). For this reason, the results are expressed in terms of "impact side" and "free side" of the vehicle, the free side being the side of the vehicle away from the wall. Time of initial impact was taken as zero and the times shown on the figures are with respect to impact time. Comparisons were stopped when the vehicle lost contact with the barrier.

The comparison of test photographs to computer drawings in Figures 2 through 11 is very good for all three tests. Comparing the wheel positions, height of climb, and relative position of vehicle body to the ground shows that the simulation accurately computed the motions of the test vehicle. The small differences observable
FIGURE 2.- COMPARISON OF COMPUTER SIMULATION WITH TEST RESULTS FOR 4000 LB. VEHICLE IMPACTING CONCRETE MEDIAN BARRIER AT 63 MPH AT 25 DEGREES; TIME = 0.000 SEC. TO 0.085 SEC.
FIGURE 3. - COMPARISON OF COMPUTER SIMULATION WITH TEST RESULTS FOR 4000 LB. VEHICLE IMPACTING CONCRETE MEDIAN BARRIER AT 63 MPH AT 25 DEGREES; TIME = 0.156 SEC. TO 0.321 SEC.
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FIGURE 7.—COMPARISON OF COMPUTER SIMULATION WITH TEST RESULTS FOR 4210 LB. VEHICLE IMPACTING CONCRETE MEDIAN BARRIER AT 59.6 MPH AT 15 DEGREES; TIME = 0.285 SEC. TO 0.335 SEC.
FIGURE 8. - COMPARISON OF COMPUTER SIMULATION WITH TEST RESULTS FOR 4210 LB. VEHICLE IMPACTING CONCRETE MEDIAN BARRIER AT 61.9 MPH AT 7 DEGREE; TIME = 0.000 SEC. TO 0.050 SEC.
FIGURE 9. - COMPARISON OF COMPUTER SIMULATION WITH TEST RESULTS FOR 4210 LB. VEHICLE IMPACTING CONCRETE MEDIAN BARRIER AT 61.9 MPH AT 7 DEGREES; TIME = 0.075 SEC. TO 0.125 SEC.
FIGURE 10—COMPARISON OF COMPUTER SIMULATION WITH TEST RESULTS FOR 4210 LB. VEHICLE IMPACTING CONCRETE MEDIAN BARRIER AT 61.9 MPH AT 7 DEGREES; TIME = 0.150 SEC. TO 0.200 SEC.
FIGURE 11.- COMPARISON OF COMPUTER SIMULATION WITH TEST RESULTS FOR 4210 LB. VEHICLE IMPACTING CONCRETE MEDIAN BARRIER AT 61.9 MPH AT 7 DEGREES; TIME = 0.225 SEC. TO 0.275 SEC.
between the positions of simulated and actual vehicles is largely attributable to a standard automobile used for all the computer drawings, which was not necessarily of the same dimensions as the actual test vehicles. A second noticeable discrepancy is the appearance of the simulated vehicle to penetrate the barrier in a few instances. The program which produces the computer drawing cannot show sheet metal crushing, although it is accounted for in the HVOSM.

The comparisons of simulated and measured acceleration components are given in Figures 12 through 15 for the 63 mph and 25 degree impact and in Figure 16 through 19 for the 59.6 mph and 15 degree impact. Taken at face value, these two comparisons could be considered good, whereas the comparison of accelerations for the 61.9 mph and 7 degree impact (Figures 20 through 23) could only be considered poor. Fortunately, the discrepancies occurring in all three cases, whether slight or major, can be explained in terms of two basic differences between the actual and simulated vehicles:

1. The actual vehicle structure is comprised of structural subassemblies each possessing its own vibrational characteristics (natural frequencies and damping). However, the simulated vehicle structure (wheels and suspension systems excluded) is a rigid mass which is undamped and free of natural frequencies of vibration. Therefore, the actual accelerometers will respond to those structural vibrations which do not contribute to vehicle redirection and accordingly, which
FIGURE 12. - LATERAL ACCELERATION ON IMPACT SIDE OF 4000 LB. VEHICLE IMPACTING CONCRETE MEDIAN BARRIER AT 63 MPH AT 25 DEGREES.
FIGURE 13. **LONGITUDINAL ACCELERATION ON IMPACT SIDE OF 4000 LB. VEHICLE IMPACTING CONCRETE MEDIAN BARRIER AT 63 MPH AT 25 DEGREES.**
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FIGURE 15. - LONGITUDINAL ACCELERATION ON FREE SIDE OF 4000 LB. VEHICLE IMPACTING CONCRETE MEDIAN BARRIER AT 63 MPH AT 25 DEGREES.
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FIGURE 23 - LONGITUDINAL ACCELERATION ON FREE SIDE OF 4210 LB. VEHICLE IMPACTING CONCRETE MEDIAN BARRIER AT 61.9 MPH AT 7 DEGREES.
would not be felt by an occupant. Correspondingly, the simulated accelerometers respond only to those actions which cause vehicle redirection or rigid body motion since the simulation is devoid of structural vibrations except those stemming from the wheels and suspension systems.

2. In the actual case the effect of a force applied to the vehicle structure is diminished or damped before reaching an accelerometer located some distance away from the point of application. In some cases if the distance is large enough and the force is of short duration, the effect may be damped out completely and hence, undetected by the accelerometer. However, in the simulated case all forces applied to the vehicle structure are transferred to the center of gravity of the rigid body as an equivalent force-couple system such that all simulated accelerometers respond instantaneously regardless of their location on the structure.

The simulated accelerometer traces in Figures 12 and 14 exhibit an oscillation of \( \pm 11 \) G's between 30 and 50 milliseconds which was not recorded by the test accelerometers. This is caused by the front wheel violently engaging the suspension bumper stops as it first hits the barrier at the large impact angle of 25 degrees. The same probably occurred in the test, but since the accelerometers were located about 6.5 ft behind the front wheel (just ahead of the rear wheel mounted to the frame member), the effects of these short duration forces were largely
damped out before reaching the accelerometers.

The test accelerometer traces in Figures 12, 16 and 18 reveal oscillations between 175 and 200 milliseconds which were not predicted by the simulation. These represent structural vibrations of the frame member, to which the accelerometers were mounted (just ahead of the rear wheel), induced by oscillations of the rear axle assembly when the rear wheel encountered the barrier. All of the differences in accelerations explained thus far were vibrational in nature and produced negligible net changes in velocity and hence, did not contribute to vehicle redirection. This is upheld by the fact that the comparisons of vehicle position are excellent (Figures 2 through 7).

The huge spike appearing in Figures 20 through 23 has 2 possible explanations. First, it is highly probable that this spike is also the result of a structural vibration caused by the rear wheel impacting the barrier. The vibration could have been critically damped explaining the existence of only 1 spike. Furthermore, the reason that higher G levels were recorded for this test, although it was less severe (only slight sheet metal damage), could be a result of the accelerometers being more directly aligned with the blow because of the small pitch and roll motions of the vehicle. If this explanation is accepted, the spike can be disregarded as not contributing to redirection of the vehicle, and the accelerometer comparison can be considered good.

However, as a second explanation, it is conceivable that initial tire contact caused the vehicle to rotate (yaw) parallel to the barrier
without appreciably changing the vehicle's velocity vector (magnitude
nor direction). The vehicle would then have impacted the barrier in
this position, causing an abrupt change in lateral velocity. In fact,
for 60 mph at 7 degrees, the component of velocity normal to the
barrier is 10.7 ft per second which corresponds to the area under the
spike in question. This comparison is justifiable in this case since
the car was parallel to the barrier when the spike occurred. If this
explanation is accepted, the question remains as to whether this is a
reproducible phenomenon or an abnormality. Until this question is
answered, the HVOSM accelerometer results cannot be discounted, especially
since good accelerometer comparisons were achieved for the 2 higher
angles of impact, and good vehicle position comparisons were attained
for all 3 tests.

Considering all facets of the comparison, it can be concluded
that the HVOSM (with added structural hard points) provides a good
simulation of an automobile impacting a rigid barrier of the Texas
CMB type. Hence, it follows that the results of the parameter study
(Chapter III) can be treated with added confidence.
III. PARAMETER STUDY

General

The modified version of the HVOSM computer program (including hard points, as described in Appendix B) was used to study the dynamic behavior of an automobile impacting the Texas CMB. The objective of the parametric study was to determine the performance characteristics of the CMB for a range of vehicle encroachment conditions. Factors used to measure barrier performance consisted of the vehicle's exit angle, maximum pitch and roll angle, and a severity index to quantify the event severity. The index is an interaction formula involving vehicle acceleration components and tolerable vehicle accelerations. It is discussed in Appendix D.

Nine different automobile impacts with the CMB were simulated. The impact speeds were 50, 70, and 80 mph and for each speed there were three impact angles; 5, 10, and 15 degrees. The simulated automobile had the properties of a 1963 Ford Galaxie weighing 4,780 pounds. Also included in this phase of the study were the three impacts simulated in the validation study (Chapter II), consisting of impact angles of 7, 15, and 25 degrees at an impact speed of approximately 60 mph. These twelve different impact conditions are representative of the majority of accidents involving traffic barriers. The results of the twelve runs are presented in Table 1.

All impact data for the computer runs, including vehicle and barrier information, are given in Volume II of this report. Some of the significant parameters were as follows:
## TABLE 1

RESULTS OF CMB BARRIER SIMULATIONS

<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>AUTO WEIGHT</th>
<th>IMPACT CONDITIONS</th>
<th>AUTOMOBILE KINEMATICS</th>
<th>AVERAGE ACCELERATIONS DURING PRIMARY IMPACT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S.I.***</td>
</tr>
<tr>
<td></td>
<td>(LBS)</td>
<td>SPEED (MPH)</td>
<td>ANGLE, ( \theta_1 ) (DEG)</td>
<td>MAX. ROLL (DEG)</td>
</tr>
<tr>
<td>1</td>
<td>4780</td>
<td>50.0</td>
<td>5.0</td>
<td>1.3</td>
</tr>
<tr>
<td>2</td>
<td>4780</td>
<td>70.0</td>
<td>5.0</td>
<td>2.2</td>
</tr>
<tr>
<td>3</td>
<td>4780</td>
<td>80.0</td>
<td>5.0</td>
<td>3.3</td>
</tr>
<tr>
<td>4</td>
<td>4780</td>
<td>50.0</td>
<td>10.0</td>
<td>4.2</td>
</tr>
<tr>
<td>5</td>
<td>4780</td>
<td>70.0</td>
<td>10.0</td>
<td>19.5*</td>
</tr>
<tr>
<td>6</td>
<td>4780</td>
<td>80.0</td>
<td>10.0</td>
<td>34.6*</td>
</tr>
<tr>
<td>7</td>
<td>4780</td>
<td>50.0</td>
<td>15.0</td>
<td>15.0*</td>
</tr>
<tr>
<td>8</td>
<td>4780</td>
<td>70.0</td>
<td>15.0</td>
<td>RO</td>
</tr>
<tr>
<td>9</td>
<td>4780</td>
<td>80.0</td>
<td>15.0</td>
<td>RO</td>
</tr>
<tr>
<td>10</td>
<td>4210</td>
<td>61.9</td>
<td>7.0</td>
<td>4.7</td>
</tr>
<tr>
<td>11</td>
<td>4210</td>
<td>59.6</td>
<td>15.0</td>
<td>21.0*</td>
</tr>
<tr>
<td>12</td>
<td>4000</td>
<td>63.0</td>
<td>25.0</td>
<td>37.0</td>
</tr>
</tbody>
</table>

*Estimated roll obtained by energy expression using initial conditions from computer simulation at the time it was terminated. (See Appendix E)

**When vehicle loses contact with barrier.

***From Equation D1.

RO=Rollover
NA=Not available
Hardpoint Stiffness = 2500 LB/IN
Sheet Metal Crushing Coefficient = 2 LB/IN$^3$
Auto-Barrier Coefficient of Friction = 0.3
Tire-Curb Coefficient of Friction = 0.50

In some instances, the roll angle of the vehicle was still increasing at the termination of the computer run. Rather than re-run those cases (which would have been uneconomical) a formula was developed to estimate the roll angle beyond the termination point. This relationship was used to determine the maximum roll angle. Its derivation is given in Appendix E.

**Barrier Performance**

Model simulation indicates that the vehicle will roll over during a collision with a CMB at impact speeds of 70 and 80 mph and an impact angle of 15 degrees. The roll angle reported in Table 1 is the maximum roll angle of the automobile and may or may not occur when the automobile is in contact with the barrier.

As shown in Table 1, the maximum pitch angle of the automobile appears more sensitive to impact angle than to impact speed. In any event, the pitch angle remains small for any angle of impact and appears to be insignificant when considering the motion of the automobile.

Height of climb of the front tire on the face of the CMB is given in Table 1. During a 5 degree collision, the front tire of the automobile climbs roughly 5 to 7 inches on the lower inclined CMB surface; and, during
a 10 degree collision the tire climbs roughly 9 to 12 inches on the lower surface. As indicated, the climb height was not available in some cases because tire-rigid barrier interaction is not accounted for in HVOSM (see discussion in Chapter II). However, based on an analysis of the output, it is doubtful that the tire climb would have exceeded the height of the barrier in those cases.

A desirable characteristic of a traffic barrier is that a colliding automobile be redirected at a shallow exit angle in order to minimize the danger to traffic. The exit angles shown in Table 1 were determined at the time the vehicle lost contact with the barrier. The exit angle appears to be more sensitive to impact angle than to impact speed. In all cases, however, the exit angles were shallow.

Another criterion used to determine barrier performance was the relative severity of the impact as measured by automobile accelerations. A severity index, which quantifies the severity, was computed and listed in Table 1 for each of the twelve runs studied. A discussion of the index is given in Appendix D.

Figure 24 shows the severity index versus impact angle for four different impact speeds. The apparent inconsistency of the 60 mph case is attributable to the differences in vehicle weight and dimensions. For vehicle speeds of 50, 70, and 80 mph the vehicle weighed 4,780 pounds, whereas, in the 60 mph case the vehicle weighed 4,210 pounds. The hardpoint stiffness, sheet metal crushing coefficient, auto-barrier coefficient of friction, and tire-curb coefficient of friction were the same for all four speeds. The results therefore suggest that the severity of a lighter
FIGURE 24. - SEVERITY INDEX OF CMB AS RELATED TO VEHICLE ENCROACHMENT CONDITIONS

NOTE: FOR VEHICLE SPEEDS OF 50, 70, AND 80 MPH, THE VEHICLE WEIGHT WAS 4,780 LB. FOR THE 60 MPH SPEED THE VEHICLE WEIGHED 4,210 LB.
vehicle impacting the barrier is higher than for a heavier vehicle, all
other factors being the same.

Figure 25 shows impact speed versus impact angle for a severity
index of one (1.0). The four points on the curve in Figure 25 were
obtained from the intersection of the $SI = 1.0$ line with the four respec-
tive speed curves of Figure 24. The data as presented in Figure 25 may
be useful in selecting roadway locations where the CMB can be safely used.
For a given roadway, an upper limit on impact angle can be estimated as a
function of the roadway's design speed and surface conditions and the
distance from the roadway to the barrier.(6) If the combination of design
(or impact) speed and impact angle falls above the curve it may be advisable
to select a more flexible barrier.
SERIOUS OR FATAL INJURIES
PROBABLE FOR UNRESTRAINED
OCCUPANTS

SEVERITY INDEX = 1.0,
FROM FIGURE 24

JUDGEMENT

SERIOUS INJURY
UNLIKELY

FIGURE 25. - RELATION BETWEEN ENCROACHMENT CONDITIONS AT A SEVERITY INDEX NEAR
UNITY FOR CMB
IV. CONCLUSIONS

1. The impact subroutines of HVOSM were modified by TTI to account for the effects of hardpoint contacts (frame members, motor block, etc.) which occur when large vehicle deformations occur.

2. The modified HVOSM computer program (with hardpoints) can accurately predict automobile accelerations, motions, and external forces due to an impact with the Texas Concrete Median Barrier. This conclusion is based on a good correlation that was obtained between full-scale test results and simulations by HVOSM.

3. As a result of a parametric study with HVOSM, the following conclusions are made with regard to the Texas Concrete Median Barrier's performance:

   (a) For impact speeds of 70 mph and greater in conjunction with impact angles of 15 degrees and greater, automobile rollover can be expected. This is a redundant finding in one respect since the severity indices indicate that serious or fatal injuries can be expected for these encroachment conditions. However, it is indeed an important consideration in view of the hazard that a rollover creates for other motorists.

   (b) For impact speeds of 80 mph and less at impact angles of 15 degrees and less there was no tendency for the automobile to vault or climb over the barrier.

   (c) In each of the ten impact conditions studied, where rollover did not occur, the automobile's exit angle was shallow after impact with the barrier (less than 6 degrees).

   (d) A graphical presentation of the impact angles and speeds for which
the barrier can redirect an automobile without serious injuries to the occupants is given in Figure 25. This graph will aid the highway designer in deciding whether to install a CMB or a more flexible barrier. For instance, if the design speed is 70 mph, the width of roadway should be sufficiently narrow that an errant vehicle would impact the CMB at no greater than 10 degrees. (An estimate of maximum roadway width for a desired impact angle can be made using an equation suggested by Deleys (6)).
V. RECOMMENDATIONS

In view of the research findings the authors recommend the following:

1. further application of HVOSM in studying alternate shapes for the CMB in an effort to find one which will restrict the threat of rollover to much higher speeds and impact angles;

2. refinement of the severity index by taking a closer look at the relationship between accelerations experienced by the vehicle and the corresponding injury to the occupant. The current state-of-the-art requires one to assume that occupant accelerations equal those encountered by the vehicle. The validity of this assumption is questionable (especially for the unrestrained occupant) and as such it reduces the confidence level of the computed severity index. TTI is currently extending the development of a vehicle-victim model (on a separate study) that was initiated in Project 140 (7). This model will provide a means to determine the relationship between vehicle and occupant accelerations. This would enable a refinement of Figure 25 making it more objective and hopefully broadening its design application. For example, Figure 25 would require a safe impact angle of 7.5° maximum at 70 mph which is highly restrictive; and

3. parameter studies aimed at the performance of the CMB for a range of vehicle sizes, weights, and suspension properties.
APPENDIX A

A DESCRIPTION OF THE HIGHWAY-VEHICLE-OBJECT SIMULATION MODEL
APPENDIX A

A Description of the Highway-Vehicle-Object Simulation Model

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

The mathematical model described herein is known as The Highway-Vehicle-Object Simulation Model (HVOSM). In general, this model can be utilized to investigate various 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 HVOSM was developed by Cornell Aeronautical Laboratory (CAL) (1, 2) and later modified for specific problem studies by the Texas Transportation Institute (TTI) (3). A conceptual idealization of the model is shown in Figure A1. 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 coordinate of the automobile; independent displacement of each front wheel suspension
system; suspension displacement and rotation of the rear axle assembly; and steer 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.
APPENDIX B

THE ADDITION OF STRUCTURAL HARDPOINTS TO THE ORIGINAL HVOSM
APPENDIX B

The Addition of Structural Hard Points
to the Original HVOSM

During TTI's initial attempts at simulating automobile collisions with a rigid type barrier, it became obvious that for large angles of attack (characterized by heavy sheet metal crushing), the HVOSM needed modification to account for the high impact forces resulting from stiff automobile structural components (hard points) slamming into the barrier.

According to McHenry et al.'s description of their mathematical model (2, pp. 126-129), the collision properties of the vehicle structure stem from an idealized layer of isotropic, homogenous, plastic material which surrounds the vehicle. They never intended this representation for anything more than simulating sheet metal crush of moderate penetration (i.e., 12 to 18 inches). In fact, McHenry and Deleys were the first to realize the need to account for structural hard points as they had formulated the problem (including preliminary computer programming) prior to TTI's request for assistance in the matter. They generously provided TTI with copies of their work which
proved to be a momentous contribution toward modifying the HVOSM and ultimately led to a successful simulation of an automobile impacting the Texas CMB.

Conceptually the idea of hard points was quite simple as it merely required defining (as input to HVOSM) the location of the desired points on the vehicle and the stiffness of each. The difficulty arose in trying to weave that concept into the existing fabric of sophisticated logic comprising the sprung-mass impact subroutines of the HVOSM. This is where CAL's assistance proved invaluable.

The new input variables required to define the hardpoints are as follows:

- XSTIO (J) - Coordinates of original position of hard point no. J in vehicle-fixed coordinate system
- YSTIO (J) - Stiffness (lbs./in.) of hard point no. J, assumed to be omnidirectional
- ZSTIO (J)
- AKST (J)

A listing of subroutine "SFORCE" is provided in this appendix. It shows the computation and use of the following quantities:

- YSTIPO (J) - the Y position of undeformed hardpoint no. J in space-fixed coordinates
- XSTIP (J)
- YSTIP (J)
- ZSTIP (J) - the coordinates of the present position (deformed state) of hard point no. J in space-fixed coordinates
- FNSTI (J) - force (lbs.) on deformed hard point no. J
$\text{SFNST} \quad - \quad \text{the sum of forces on all hard points for an assumed barrier deflection during iteration for equilibrium}$

$\text{FNXl} \quad - \quad \text{force due to sheet metal crushing for an assumed barrier detection}$

$\text{FNX} \quad = \quad \text{FNXl} + \text{SFNST}, \text{i.e., total force derived from barrier impact for an assumed barrier deflection}$

$\text{FN} \quad - \quad \text{force due to sheet metal crushing the barrier in its equilibrium position}$

$\text{FNI} \quad = \quad \text{FN} + \text{SFNST}, \text{i.e., total force derived from barrier contact for barrier in equilibrium position}$

$\{\text{XSTI (J)}, \text{YSTI (J)}, \text{ZSTI (J)}\} \quad - \quad \text{coordinates of hard point no. J (deformed state) in vehicle-fixed coordinates}$

A listing of subroutine "RESFRC" is also included in this appendix to show the manner in which the forces derived from sheet metal crushing and various hard point impacts are resolved into forces and couples at the vehicle's center of gravity.
XMTX(2, 3) = PGB
XMTX(2, 4) = PPRB
XMTX(3, 1) = 0
XMTX(3, 2) = 0
XMTX(3, 3) = 1
XMTX(3, 4) = PSZR

CALL SIMSIL(XMTX, 3, 3)
X01 = XMTX(1, 4)
YH1 = XMTX(2, 4)
ZB1 = XMTX(3, 4)

IF (XVR.LE.XH1.AND.XH1.LE.XVF.AND.ABS(YB1).LT.YV.AND.ZVI.LE.ZB1) THEN
1.AND.(ZB1.LE.ZVH) \# NAXIS = 1
TPMP = CGH*PCHR-CAB*PCGB
TMPD = CAn*PCGB-CHB*PCAB
TMPAP = TMPB*PCHR-TMPA*PCAB
THCP = TMPH*PCAB-CAB*PCHR
TMPD = SNR(TMPAP**2+TMPB**2+TMPC**2)
CHB1 = TMPAP/TMPD
CGH1 = TMPB/TMPD

RBI = Xb1*CAb1+YB1*CB1+ZB1*CGH1
YB1VF = 1.0E6

IF (CGH1.NE.0.) YB1VF = (RBI-XVF*CAH1)/CGH1
78 DO 79 1=12, 17
AA21(1) = CAB1
BB21(1) = CB1
CC21(1) = CGH1
RR21(1) = R1
79 CONTINUE

97 CONTINUE
C PRESENT LOCATION OF HARDPOINTS IN SPACE FIXED COORDINATES
DO 81 1=1, 3
XSTP1(I) = XCP+AMTX(I,1)*XST1(I)+AMTX(I,2)*YST1(I)+AMTX(I,3)*ZST1(I)
YSTP1(I) = YCP+AMTX(2,1)*XST1(I)+AMTX(2,2)*YST1(I)+AMTX(2,3)*ZST1(I)
ZSTP1(I) = ZCP+AMTX(3,1)*XST1(I)+AMTX(3,2)*YST1(I)+AMTX(3,3)*ZST1(I)
81 CONTINUE

XR1 = 0.
YR1 = 0.
ZR1 = 0.
AIN1 = 0.
SXR = 0.
SYR = 0.
SZR = 0.
SDEN = 0.
FNX = 0.
FNX1 = 0.
FH = 0.
FBNST = 0.
NSEG = (YPMP-YBP)/DLYBP+1.0
IPLN = NSEG
YPB = YBP+IPLN*DLYBP
NSGII = NSEG*1
I111 = 1
9 DO 38 I=111, NSGII
IPLNP = IPLN
PYBP = YBP
PUDELBd = DELBB
PPSX = SXR
PPSY = SYR
PPSZ = SZR
PSDEN = SDEN
PFN = FXN
PFN1 = FXN1
PF = FH
PFBN = FB
PSFNST = SFNST
SFNST = 0.
IPLN = NSL E-1 + 1
YBP = YBP + 1
IPLN * DELYBP
DO 91 IJ = 1, 3

CONTINUE
IF(YSTI[P(IJ, GE) = YBP] = AKST(IJ) * (YSTIPO(IJ) - YBP)
SFNST = SFNST + FNST(IJ)

based on undeformed position

IPT = 0
10 DO 15 J = 1, 17
IDPT(J) = 0
IF(PSIT.LT.0.0) AND J.LE.2) GO TO 15
IF(INDO.LT.2) AND J.GT.11) GO TO 15
IF(ICA + EQ.0.0) AND (J EQ.4.0) OR J.EQ.5.0) OR J.EQ.10.0) OR J.EQ.11.0) GO TO 15
IF(ICCG + EQ.0.0) AND (J EQ.2.0) OR J.EQ.3.0) OR J.EQ.4.0) OR J.EQ.9.0) GO TO 15
IF(ICAB1 + EQ.0.0) AND (J EQ.12.0) OR J.EQ.13.0) GO TO 15
IF(IBC1 + EQ.1) OR J.EQ.14.0 OR J.EQ.15.0) GO TO 15
IF(IBCB1 + EQ.0.0) AND (J EQ.16.0) OR J.GE.16.0) GO TO 15
IF(NAXIS + EQ.0.0) AND J.GT.11) GO TO 15
IF(NAXIS + EQ.0.0) AND J.GT.11) GO TO 15
IF(NAXIS + EQ.0.0) AND J.GT.11) GO TO 15
IF(NAXIS + EQ.0.0) AND J.GT.11) GO TO 15
IF(NAXIS + EQ.0.0) AND J.GT.11) GO TO 15
11 XMTX(I, 1) = CAB
XMTX(I, 2) = CB
XMTX(I, 3) = CB
XMTX(I, 4) = RAB
12 XMTX(I, 1) = AAJ(J)
XMTX(I, 2) = B(J)
XMTX(I, 3) = CJ(J)
XMTX(I, 4) = RJ(J)
13 XMTX(I, 1) = AAJ(J)
XMTX(I, 2) = B(J)
XMTX(I, 3) = CJ(J)
XMTX(I, 4) = RJ(J)
14 CALL SIMSOL(XMTX(3, 3, 2))
XN(J) = XMTX(I, 1)
YNN(J) = XMTX(I, 2)
ZN(J) = XMTX(I, 3)

IF(XNN(J), LT, XVF OR XNN(J), GT, XVF) GO TO 15
IF((YNN(J), LT, YV OR YNN(J), GT, YV) GO TO 15
IF(ZNN(J), LT, ZVF OR ZNN(J), GT, ZVF) GO TO 15
IDPT(J) = 1
IPT = IPT + 1

55
<table>
<thead>
<tr>
<th>Line</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>IPPT = J</td>
</tr>
<tr>
<td>15</td>
<td>CONTINUE</td>
</tr>
<tr>
<td>15</td>
<td>IF (IPPT.EQ.11.AND.((NAXS.EQ.1.AND.Y1VF.GT.YV.AND.ININD.EQ.2)))</td>
</tr>
<tr>
<td>15</td>
<td>GO TO 38</td>
</tr>
<tr>
<td>15</td>
<td>IF (MOD(NOB,2).EQ.1) GO TO 23</td>
</tr>
<tr>
<td>15</td>
<td>IF (CGB.EQ.0.0.AND.CGBT.EQ.0.0) GO TO 23</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(1) = RBT</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(2) = RBB</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(4) = RBT</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(5) = RBB</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(7) = RBT</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(8) = RBB</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(10) = RBT</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(11) = RBB</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(12) = RBT</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(13) = RBB</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(14) = RBT</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(15) = RBB</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(16) = RBT</td>
</tr>
<tr>
<td>15</td>
<td>RR2P(17) = RBB</td>
</tr>
<tr>
<td>16</td>
<td>DU 22 J=1,17</td>
</tr>
<tr>
<td>16</td>
<td>IF (PSIT.EQ.0.0.AND.J.EQ.2) GO TO 22</td>
</tr>
<tr>
<td>16</td>
<td>IF (J.EQ.0.0) GO TO 22</td>
</tr>
<tr>
<td>16</td>
<td>IF (CAB.EQ.0.0) GO TO 22</td>
</tr>
<tr>
<td>16</td>
<td>IF (LG.EQ.0.0) GO TO 22</td>
</tr>
<tr>
<td>16</td>
<td>IF (CGB.EQ.0.0) GO TO 22</td>
</tr>
<tr>
<td>16</td>
<td>IF (CGBT.EQ.0.0) GO TO 22</td>
</tr>
<tr>
<td>16</td>
<td>XMTX(1,1) = CAB</td>
</tr>
<tr>
<td>16</td>
<td>XMTX(1,2) = CBB</td>
</tr>
<tr>
<td>16</td>
<td>XMTX(1,3) = CGB</td>
</tr>
<tr>
<td>16</td>
<td>XMTX(1,4) = RBT</td>
</tr>
<tr>
<td>17</td>
<td>XMTX(2,2) = BBI(J)</td>
</tr>
<tr>
<td>17</td>
<td>XMTX(2,3) = CC2(J)</td>
</tr>
<tr>
<td>17</td>
<td>XMTX(2,4) = RR2(J)</td>
</tr>
<tr>
<td>17</td>
<td>GO TO 18</td>
</tr>
<tr>
<td>17</td>
<td>XMTX(2,1) = AA2(J)</td>
</tr>
<tr>
<td>18</td>
<td>XMTX(3,2) = CBT</td>
</tr>
<tr>
<td>18</td>
<td>XMTX(3,3) = CGB</td>
</tr>
<tr>
<td>18</td>
<td>IF (10PT(1).EQ.1.AND.J.EQ.14) OR (10PT(4).EQ.1.AND.J.EQ.16))</td>
</tr>
<tr>
<td>18</td>
<td>GO TO 171</td>
</tr>
<tr>
<td>18</td>
<td>IF (10PT(8).EQ.1.AND.J.EQ.15) OR (10PT(11).EQ.1.AND.J.EQ.17))</td>
</tr>
<tr>
<td>18</td>
<td>GO TO 172</td>
</tr>
<tr>
<td>18</td>
<td>XMTX(3,4) = RR2P(J)</td>
</tr>
<tr>
<td>18</td>
<td>GO TO 19</td>
</tr>
<tr>
<td>171</td>
<td>XMTX(3,4) = RBB</td>
</tr>
<tr>
<td>171</td>
<td>GO TO 19</td>
</tr>
</tbody>
</table>

56
CALL SIMSOL(XMTX,3,3,3)
IF(XMTX(1,4).LT.XVK.UK.XMTX(1,4).GT.XVF) GO TO 22
IF(ABS(XMTX(2,4)).GT.YV) GO TO 22
IF(XMTX(3,4).LT.ZVT.OK.XMTX(3,4).GT.ZVB) GO TO 22
IF(IDPT(J).NE.0) GO TO 20
IDPT(J) = 1
GO TO 21
IFABS(XMTX(3,4)) .GE. ABS(ZNN(J))) GO TO 22
20 IF(XMTX(2,4).LT.YV) GO TO 22
21 XNN(J) = XMTX(1,4)
YNN(J) = XMTX(2,4)
ZNN(J) = XMTX(3,4)
GO TO 22
173 IDPT(J) = 0
1PT = 1PT - 1
22 CONTINUE
23 IF(1PT.LT.3) GO TO 38
24 DO 25 J=1,17
25 CONTINUE
26 DO 27 J=1,4
VMAX(J) = -1.0E30
INDXP(J) = 0
27 CONTINUE
28 DO 34 J=1,17
29 IF(VNP(J).LT.VMAX(K)) GO TO 33
30 DO 31 L=K+1
31 CONTINUE
32 VMAX(K) = VNP(J)
INDXP(K) = J
GO TO 34
33 CONTINUE
34 IF (1PT.LT.3) GO TO 38
35 (J3 = 13
J1 = 11
J2 = 12
J4 = 14
CALL AREA
IF(IB.EQ.1) GO TO 38
FNXI=AKV*DELYBP*SDEN
FNX=FNXI+SFNST
IF(NSLC.EQ.1) GO TO 38
40 DEL08 = AMAX1(YHP+YHPO,EPSL*SET*DELP)
CALL NLDf-RC

IF(EPSB.LT.FBFN)GOTO105
IF(FFN.GE.0.)GOTO105
IF(AABS(FBN).LT.ABS(FPN))GOTO105
PRINT 1001,Y,YN,YBP,PFN,PFN


IPLN=IPLN+1
YP=YP+N
DELBP=DELBP+N
SX=PSXR+N
SY=PSYR+N
SDEN=PSDEN+N
FN=FN+N
FN1=N

IF(NLDCTR.EQ.31)CALL NLOFL
NUNLD2=0
IF(NUNLD.EQ.0)GOTO38
CONTINUE

38  DO 110 1J=1,3
   IF(YSTIP(IJ).GT.YBPT)YSTIP(IJ)=YBPT
   AA=XSTIP(IJ)-XCP
   BB=YSTIP(IJ)-YCP
   CC=ZSTIP(IJ)-ZCP
   XST(IJ)=AMT(I,I)*AA+AMT(2,1)*BB+AMT(3,1)*CC
   YST(IJ)=AMT(I,2)*AA+AMT(2,2)*BB+AMT(3,2)*CC
   ZST(IJ)=AMT(I,3)*AA+AMT(2,3)*BB+AMT(3,3)*CC
   CONTINUE

110  IF(NUNLD2.NE.0)GOTO103
       IF(NUNLD.NE.0)GO TO 100
       IF( IB .NE. 1 ) GO TO 50
       CONTINUE

45  NEGR=0
   DO 46  J=1, IPT
   IF( VMAX(J) .LT. 0.0 ) NEGR=NEGR+1
   CONTINUE

46  IF( NEGR.GE. IPT ) GO TO 41

50  FN =AKV*DELYBP*SDEN
   NUNLD2=0
   IF(ININD.EQ.0) ININD = 1
   IF(FN1.NE.0.0.AND.NUNLD.EQ.0) CALL RESFRC
   IF(NSCL.EQ.0.AND.IB.EQ.1) GO TO 103
   IF(NSLCE.EQ.0) GO TO 100

103  TMP =YBPT-YCP

       XBPP =-AMT(I,1)*XCP+AMT(2,1)*TMP-AMT(3,1)*ZCP
       YBPP =-AMT(I,2)*XCP+AMT(2,2)*TMP-AMT(3,2)*ZCP
       ZBPP =-AMT(I,3)*XCP+AMT(2,3)*TMP-AMT(3,3)*ZCP
       RB = XBPP*GAB + YBPP*GAB + ZBPP*GAB
       GO TO 39
<table>
<thead>
<tr>
<th>Line</th>
<th>Code</th>
<th>SFRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>NUNLD = NUNLD+1</td>
<td>393</td>
</tr>
<tr>
<td></td>
<td>NSG111 = NSG111+1</td>
<td>394</td>
</tr>
<tr>
<td></td>
<td>1111 = NSG111</td>
<td>395</td>
</tr>
<tr>
<td></td>
<td>GO TO 9</td>
<td>396</td>
</tr>
<tr>
<td>39</td>
<td>NUNLD = 0</td>
<td>397</td>
</tr>
<tr>
<td>41</td>
<td>IF(NLDCTR.EQ.3.AND.IPT.GE.3) THEN</td>
<td>398</td>
</tr>
<tr>
<td></td>
<td>WRITE(*,1000)i, XG1, YB1, IPT, J1, J2, J3,</td>
<td>399</td>
</tr>
<tr>
<td></td>
<td>J4, XNN(J1), YNN(J1), ZNN(J1), XNN(J2), YNN(J2), ZNN(J2),</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>XNN(J3), YNN(J3), ZNN(J3), XNN(J4), YNN(J4), ZNN(J4)</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>FORMAT(F7.4,2F7.1,5I3,12F8.1)</td>
<td>401</td>
</tr>
<tr>
<td></td>
<td>NLDCTR = NLDCTR+1</td>
<td>402</td>
</tr>
<tr>
<td></td>
<td>RETURN</td>
<td>403</td>
</tr>
<tr>
<td></td>
<td>END</td>
<td>404</td>
</tr>
</tbody>
</table>
SUBROUTINE RESFRC

COMMON/INPT/PHIO,THETAO,PSIO,PO,QO,RO,XCOP,YCOP,UCOP,UO,VO,WO,G,RO

COMMON/INPT1/YC1P,YC2P,ZC2P,UELTC,PHIC1,PHIC2,AMUC,CPSP,OMGPS,AKPS,EPSPS,XPS,RWHJB,RWHEJ,INDCR8

COMMON/OIMV/ASI41,BS141,CSI41,CAS(41),CBSI41,CGSI41,BETP(41),BETBRI41,FSXU(41),FSYU(41),FSZU(41),FSYUF,FSYUF,FSYUF

COMMON/ADTNL/U1,U2,U3,U4,V1,V2,V3,V4,W1,W2,W3,W4,XTRAI301

DIMENSION XP(4),YP(4),ZP(4),PHI(4),PSI(4),U(4),V(4),W(4)

EQUIVALENCE (U,VAR(1)),(V,VAR(2)),(W,VAR(3)),(U,VAR(4)),(V,VAR(5)),(W,VAR(6))

COMMON/COMP/DTM21,FRTSP(4),FRCP(4),UOEGT,ICBHIT,JCBHIT

COMMON/ATN1/UT1,UT2,UT3,UT4,VT1,VT2,VT3,VT4,WT1,WT2,WT3,WT4

DIMENSION XP(4),YP(4),ZP(4),PHI(4),PSI(4),U(4),V(4),W(4)

EQUIVALENCE (XP,VAR(1)),(YP,VAR(2)),(ZP,VAR(3))
VTAN=SQRTR(URP*URP+WRP*WRP)
TEMP1=0.
TEMP2=0.
IF(VTAN.LT.EPSVIGOT06
AA=AMUB*FN
FRICT=AA
AA=AA/VTAN
TEMP1=-AA*URP
TEMP2=-AA*WRP
CONTINUE
DO5 J=1,4
FX=AMTX(1,1)*TEMP1-AMTX(2,1)*F(J)+AMTX(3,1)*TEMP2
FY=AMTX(1,2)*TEMP1-AMTX(2,2)*F(J)+AMTX(3,2)*TEMP2
FZ=AMTX(1,3)*TEMP1-AMTX(2,3)*F(J)+AMTX(3,3)*TEMP2
TEMP1=0.
TEMP2=0.
SFXS=SFXS+FX
SFYS=SFYS+FY
SFZS=SFZS+FZ
SNPS=SNPS+FZ*Y(J)-FY*Z(J)
SNTS=SNTS+FX*Z(J)-FZ*X(J)
SNPSS=SNPSS+FY*X(J)-FX*Y(J)
RETURN
END
APPENDIX C

ACCELEROMETER LOCATIONS
Vehicle Dimensions - 1963 Plymouth

Weight - 4000 lb
Length - 16'11" = 203"
Width - 6'2" = 74"
Wheel base - 9'8" = 116"
Track width - 5' = 60"
Bumper to front wheel center - 2'-8" = 32"
Front bumper to center of gravity - 7'-7 1/2" = 91 1/2"

Location of accelerometers on frame members (symmetrical about vehicle centerline)

FIGURE C1- Vehicle data for test impacting concrete median barrier at 63 mph at 25 deg.
Vehicle Dimensions - 1963 Chevrolet

Weight - 4210 lb
Length - 17'-3" = 207"
Width - 6'-6" = 78"
Wheel base - 9'-11" = 119"
Track width - 4'-11" = 59"
Bumper to front wheel center - 2'-8" = 32"
Bumper to center of gravity - 7'-2" = 86"

Location of accelerometers on frame members (symmetrical about vehicle centerline)

FIGURE C2- Vehicle data for tests impacting concrete median barrier at 61.9 mph at 7 deg, and at 59.6 mph at 15 deg.
APPENDIX D

SEVERITY INDEX
SEVERITY INDEX

An automobile acceleration severity-index was used in this study to quantify the relative severity an automobile impacting a traffic barrier. The severity-index takes into consideration the combined effects of the longitudinal, lateral, and vertical accelerations of the automobile at its center-of-mass. The severity-index (SI) is computed by Eq. D1.

\[
SI = \sqrt{\left(\frac{G_{\text{LONG}}}{G_{XL}}\right)^2 + \left(\frac{G_{\text{LAT}}}{G_{YL}}\right)^2 + \left(\frac{G_{\text{VERT}}}{G_{ZL}}\right)^2} \quad (D1)
\]

The terms in the numerator of Eq. D1 are the computed or measured accelerations of the automobile; whereas, the terms in the denominator are automobile accelerations which represent a "limiting condition" for the occupant.

An indepth discussion of the background and development of Eq. D1 was given in TTI Research Report 140-4 (7). Information relating tolerable accelerations to degree of occupant restraint, rate of onset or rise time, and time duration of accelerations was included in the discussion. In the study presented herein, the tolerable accelerations were for an unrestrained occupant, rise times greater than 0.03 seconds, and for a time duration of 0.050 seconds. The limit or tolerable accelerations for these conditions are (10):

\[
\begin{align*}
G_{XL} &= 7 \, G's \\
G_{YL} &= 5 \, G's \\
G_{ZL} &= 6 \, G's
\end{align*} \quad (D2)
\]
There has been much discussion as to the relationship of the severity-index to the probable level of occupant injury. The writers have interpreted an SI of unity to imply that occupants will sustain injuries which border on the "serious" type. Until more data are available on limit accelerations and the interaction relationship itself, there appears to be no other logical way to interpret the index.

In addition, vehicle accelerations have never been translated into expected g-levels on the occupant, and until such a correlation becomes available the possible applications of the severity-index must be qualified. The index in its present form is intended for comparing the severity of one event to another and can also serve as an aide in making decisions concerning highway modifications which should effect a reduction in occupant injury and loss of life. However, it must be emphasized that the index, as defined by TTI researchers (here and elsewhere), has never been intended for direct assessment of human injury and therefore should not be used in that regard.
APPENDIX E

FORMULAS FOR MAXIMUM ROLL ANGLE
VALUES OBTAINED FROM PROGRAM AT TIME OF ITS TERMINATION

\[ Z' (\text{IN}), \ \phi \ (\text{DEG}), \ \dot{\phi} \ (\text{DEG/SEC}) \]

\[
\alpha = \tan^{-1} \left( \frac{Z}{B} \right)
\]

\[ R = \frac{Z}{\sin \alpha} \]

\[ H = R \sin (\alpha + \phi) \]

\[ S = Z' - H \]

ASSUMPTIONS

1. NEGLECT PITCH ANGLE AND PITCH RATE
2. NO VERTICAL VELOCITY (\(Z' = \text{MAX}\))

\[
\phi = \phi + \sqrt{\frac{2S}{g}} \dot{\phi}
\]

\[ \Theta = \phi + \alpha \]

\[ L = R \left( \sin \gamma - \sin \Theta \right) \]

\[ I_0 = I_{cm} + \frac{W}{g} R^2 \]

FIGURE BIA. AUTO AIRBORNE

FIGURE BIB. MAXIMUM ROLL

KINETIC ENERGY = WORK DONE BY AUTO WEIGHT

\[
\frac{1}{2} I_0 (\dot{\phi})^2 = WL = WR (\sin \gamma - \sin \Theta)
\]

\[ \gamma = \sin^{-1} \left[ \frac{1}{2} \frac{I_0 \dot{\phi}^2}{WR} + \sin \Theta \right] \]

MAX ROLL = \( \phi + \Delta \phi \)

MAX ROLL = \( \Theta + \gamma - \Theta \)

IF: \( \gamma > 90^\circ \) ROLLOVER WILL OCCUR

IF: \( \phi > 90^\circ - \tan^{-1} \left( \frac{Z}{B} \right) \) ROLLOVER WILL OCCUR

FIGURE BII. PROCEDURE TO ESTIMATE MAXIMUM ROLL ANGLE
APPENDIX F

REFERENCES
APPENDIX F

References


