SIMULATION OF OCCUPANT KINEMATICS IN ROLLOVERS USING THE MVMA 2-D MODEL


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This report describes the results of the first phase of a study entitled "Simulation of Occupant Kinematics in Rollovers." What little information is available on the kinematics of vehicle occupants during rollovers has been obtained either after the fact by accident reconstruction or by expensive experimentally-staged accidents. The report describes the use of less expensive analytical techniques to graphically illustrate the applicability of occupant motion simulation computer models to this problem. It also provides guidelines and tutorial information for future users of the software in this application.
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1.0 INTRODUCTION AND SUMMARY

The report which follows describes the results of the first phase of a study at the University of Michigan Transportation Research Institute entitled "Simulation of Occupant Kinematics in Rollovers." What little information is available on the kinematics of vehicle occupants during rollovers has been obtained either after the fact by accident reconstruction or by expensive experimentally-staged accidents. The remainder of the report describes the use of less expensive analytical techniques to graphically illustrate the applicability of occupant motion simulation computer models to this problem. It also provides guidelines and tutorial information for future General Motors users of the software for this application. The first phase report deals with the development of two-dimensional rollover simulations using the MVMA two-dimensional occupant motion model.

The report is divided into two parts. The first is an introduction and summary. Included are review sections on the analytical tools used, the data required for operation of the models, the output generated by the example rollover simulation, and conclusions. The second part of the report contains sections detailing the preparation of data for use in simulating rollovers using the MVMA 2-D occupant model. Additional results are included which address the problem of occupant ejection. An appendix to the report contains a complete sample exercise.

1.1. Analytical Tool Used. The MVMA 2-D Occupant Motion Simulation.

The analytical tool chosen for the two-dimensional simulation of a pure rollover is the MVMA 2-D Occupant motion simulation computer program. Figure 1 is a schematic of the vehicle occupant configured for the most traditional simulation using the software. Among the features available for use of the software are:

- Occupant or pedestrian with a nine segment body linkage
- Generation of forces on the occupant due to interaction with vehicle structures and restraint systems
- Capability for inclusion of vertical, horizontal, and rotational vehicle crash pulses
- Prediction of occupant motions and responses such as HIC, femur loads, and neck forces
- Capability to model intrusion of vehicle regions such as roof and side door structures
- Graphical display of results in the form of acceleration and force plots as a function of time
- Computer-generated animation of occupant motions during the time period of the impact event

1.2. Data Required for Operation of the Model

A schematic of the side view of a typical seated occupant is shown in Figure 2. From the rear, this occupant would appear as shown in Figure 3. These geometric view concepts were developed during a project conducted for MVMA entitled "Baseline Data for Describing Occupant Side Impacts and Pedestrian Front Impacts in Two Dimensions" (Reference 1). The occupant/vehicle configuration shown in Figure 4 is based on the MVMA baseline and represents the configuration of an anthropomorphic test device in the driver position of a 1973 Buick prior to a dolly rollover test conducted at the General Motors Proving Grounds. Any vehicle geometry, occupant size, or occupant position could have been used in developing a configuration with the overall features of Figure 4.

Definition of the rollover event can be presented in terms of known vehicle motions. In cases where test data are available, these can be derived either from accelerometers mounted in the test vehicle or from high speed motion pictures of the event. In the case of a real crash event, a reconstruction of the vehicle trajectory would be required based on the estimates of initial velocity, vehicle contact points with the ground, final resting location, and extent of damage to the vehicle.

In the example case of the 1973 Buick test rollover, both vehicle accelerometer data and movies of the event were available. Use of the movies was selected as the simplest procedure to determine vehicle position and rotation angle as a function of time. Plots of vehicle position and angle as derived from the movies are shown in Figures 5, 6, and 7.
MVMA 2-D MODEL

FIG. 1. SCHEMATIC OF MVMA TWO-DIMENSIONAL OCCUPANT MOTION SIMULATOR
FIG. 2. OCCUPANT FOR SIDE IMPACT SIMULATION (SIDE VIEW).
FIG. 3. OCCUPANT FOR SIDE IMPACT SIMULATION (REAR VIEW).
FIG. 4. INITIAL CONFIGURATION OF OCCUPANT IN VEHICLE FOR SIMULATION OF DOLLY DROP ROLLOVER.
FIG. 5. VEHICLE POSITION ALONG GROUND AS A FUNCTION OF TIME.

CAMERA SHIFT (13 INCHES)
FIG. 6. VEHICLE VERTICAL POSITION AS A FUNCTION OF TIME.
FIG. 7. VEHICLE ROTATION (ROLL) ANGLE AS A FUNCTION OF TIME.
1.3. Output Generated by the Model

Output from the model is generated in the form of tables and graphical displays. Standard output is in the form of tables of a large number of physical variables such as:

- vehicle motions
- body segment motion, velocity, and accelerations
- forces generated by body contacts with the vehicle as a function of time
- forces, torques, and relative motions at all joint structures
- post-processed quantities such as HIC (for 1000 time steps), resultant accelerations at specified locations in the head and chest, and femur loads.

Graphical displays are available as plots of the physical variables versus either time or other variables. Occupant motions can be presented in an animated display or movie of the occupant moving within the vehicle during the impact event. Example plots of forces generated by the head and hip regions of the occupant as a function of time are shown in Figures 8 and 9. Figure 10 illustrates the vehicle and occupant kinematics from the moment the vehicle is released from the dolly at a velocity of 29.6 mph until the vehicle is nearing its final rest point after about 2000 milliseconds.

The most striking feature shown by these three figures is the large number of individual dynamic interactions which take place. The head interacts with doors and the roof on both sides of the vehicle. The torso and legs also interact with structures on both sides of the vehicle. Body segment accelerations are moderate throughout the event. The individual head contacts do not appear to be of a level which would lead to fatal injuries.

The first in a sequence of major contact events takes place at about 200 milliseconds. The vehicle begins to drop toward the ground after release from the dolly. During this period the vehicle/occupant combination is in freefall. The seat cushion exerts just enough force to cause the occupant to move toward the roof.
FIG. 9. CONTACTS OF TORSO AND LEGS WITH VEHICLE INTERIOR (BASELINE ROLLOVER).
BASELINE

FIGURE 10. BASELINE OCCUPANT MOTIONS.
The contact of the vehicle tires with the ground at about 300 milliseconds initiates the rollover sequence. The vehicle has passed 90 degrees of roll by 480 milliseconds which is about the same time the occupant has dropped, largely through freefall, toward the passenger door. Between 400 and 600 milliseconds there are several contacts of the torso and head with the door and roof structures. In addition, there is restraining action of the knees and feet by the instrument panel as was observed in the impact test movies.

The test movies show production of roof crush during the period between about 700 and 800 milliseconds. Figure 10 shows the head of the occupant well away from the roof during this period. Movies taken with a vehicle-mounted camera also do not show evidence of dummy/vehicle contact during this period.

After the roof contacts the ground while the vehicle is 180 degrees inverted, the vehicle again becomes airborne with the occupant compartment rotating through 270 degrees at about 1200 milliseconds. The driver door restrains the occupant from ejection at this point and redirects his motion toward the opposite side of the vehicle.

Final contacts with the passenger door occur near the end of the simulation when the vehicle wheels again contact the ground essentially stopping the horizontal motion of the vehicle. The driver once again moves across the vehicle to contact the passenger side structure. Seat cushion forces are large during this last interaction.

Figure 11 shows vehicle and occupant kinematics for a second computer exercise where over 7 inches of roof crush are added between 700 and 800 milliseconds. Note that the location of the head of the occupant at 720 and 840 milliseconds is not near the roof. It is not until after 900 milliseconds that head contact with the vehicle is again observed. Even though there are more contacts of the head with the roof in the case of roof crush, their level of force is no larger than those contacts observed when the roof remained intact.

1.4. Conclusions

The basic conclusion reached during Phase I activity on this project is that simulation is a useful technique for the study of
ROOF CRUSH

FIGURE 11. OCCUPANT MOTIONS IN CASE WITH ROOF CRUSH.
rollovers. Although two-dimensional techniques are limited to "pure" rolls, it is anticipated that three-dimensional techniques will be applicable to the general problem.

In addition, it has been found that computer graphics is an exceptionally valuable tool for study of occupant and vehicle motions in the mind-boggling geometry of a rollover. Animation of the rollover event, similar to high speed impact test movies, is valuable. These can be supplemented with individual frames from the dynamic event to study contact interactions at specific time points in detail.

Finally, in order to utilize simulation effectively, particular attention must be paid to the following items in preparing input data:

- quality detailed accident definition or reconstruction
- correlation of observed occupant/vehicle contact points with injuries
- vehicle interior geometry and material property definition

Although these items are important and critical to the success of any simulation exercise, it should be noted that model use is inexpensive compared with full-scale tests. As a result, it is possible to estimate a range of values for parameters which are not well-defined. This can be followed by multiple exercises in order to see how changing parameter values affects occupant dynamics.
2.0 TECHNIQUES FOR USE OF MVMA 2-D OCCUPANT MOTION MODEL IN SIMULATION OF ROLLOVERS

2.1. Description of Impact Event

2.1.1. Data Required

In order to simulate a rollover or other crash event using the MVMA 2-D occupant motion model, it is necessary to define the initial location and velocity of the vehicle as well as a time history of its motions. The specification of location and velocity requires:

- definition of a planar two-dimensional coordinate system in which the vehicle roll motion takes place
- the x- and z-location of the vehicle origin within the coordinate system
- the initial pitch (or roll) of the vehicle ($\Theta$),
- the initial velocity of the vehicle in the two translational and one rotational directions

Several input data options are available for the specification of the motion time history. These are:

- Data from vehicle-mounted x- and z-accelerometers
- Acceleration data for the vehicle origin
- Position of the origin as a function of time
- A combination of one translational acceleration with the other translational position
- Data from an x-accelerometer reading and a measured point about which the vehicle rotates

These position data must be supplemented by angular position or acceleration as a function of time.

2.1.2. Example Case

As an example, an instrumented test of a vehicle dropped from a moving dolly was selected for simulation. This test involved a 1973 Buick which was released from the dolly at an initial velocity of 29.6 mph. High speed cameras were positioned along the course of the roll to
record gross vehicle motions. A camera was also mounted within the vehicle to monitor the motions of the two unbelted anthropomorphic test devices in the front bench seat. Triaxial accelerometer packs were located on the left and right rocker pans.

The movies were reviewed to ascertain whether the event qualified as a roll in which the motion was predominantly in a plane. Although some vehicle pitching was noted (less than 10 degrees) during the roll, it was concluded that the event fairly well approximated the case of a pure rollover. It was also necessary to review the anthropomorphic test device motions. The driver dummy appeared to move with a predominantly planar motion when viewed from the rear. Basically, it slid across the seat from door to door. It also rose to contact the roof. The torso rotated sideways down toward the seat in addition to its back-and-forth translational motion. The feet appeared to move from side to side but were somewhat restrained in their motions by interactions with the floor and lower instrument panel.

Two of the alternative techniques mentioned previously were reviewed for use in specifying vehicle position. The first of these techniques used accelerometer data from the test. Triaxial accelerometer packs mounted in the right and left rocker pans were observed to record lateral and vertical accelerations which were significantly larger than the longitudinal values. This reflected the predominantly roll quality of the event. The accelerometer data traces were hand-digitized for the simulation. Estimates of accelerometer locations were obtained relative to the vehicle coordinate system. In order to supplement the accelerometer data with the necessary vehicle angular (roll) data, the test films were analyzed. The cameras were positioned to view the front of the vehicle as the roll event progressed. Roll angle was estimated as the angle a line drawn between the vehicle head lamps made with a ground line.

These accelerometer and angle data were then used as input to the simulation. The resulting vehicle motion, based on integration of the accelerometer data, showed the vehicle rising several hundred inches in addition to its motion along the ground. In order to test the quality of the input data for isolation of the problem, angular motion and
acceleration data values were varied. There was no significant change in the results. Finally, it was observed that a 1 G acceleration applied to a mass will cause it to fall approximately the same amount observed in the simulation results which covered a time duration of 2000 milliseconds. Review of the accelerometer traces revealed that a 1 G signal was in the noise range of the recorded signal and probably was zeroed out prior to test initiation. Thus the conclusions were reached that the test data were reasonable, the simulation worked properly, and another vehicle motion input data technique should be explored.

The second technique supplemented the angular roll data with vehicle position data measured directly from the test movies. The position along the direction of roll (both horizontal and vertical) of the center of a line constructed between the headlamps was chosen as the vehicle point. The location of this point in a coordinate system attached to the H-point was estimated to specify occupant compartment position as a function of time. The resulting data are shown in Figures 5, 6, and 7. These curves were represented by a subset of points for use in the input data set. Some inaccuracies are inherent in these data due to the lack of a correction for non-planar vehicle rocking (pitch) motions. It was not possible to measure this correction without additional three-dimensional camera coverage. It was found that the distance along the ground over which the roll took place was similar for both the integrated accelerometer data and the measurements from the movies. This lends some credibility to the conclusions both about the need for a gravity correction and the integrated and digitized vehicle resting position at 2000 milliseconds.

2.1.3. Conclusions and Recommendations for the User

Three key conclusions and recommendations have been extracted from the previous two sections.

1. In specifying the vehicle response, the user should develop position data using film coverage whenever possible.

2. If accelerometer data are to be used, the 1 G vertical acceleration should be removed from the resultant signal by removing the
appropriate fraction from the components based on vehicle angular orientation as a function of time.

3. Before a simulation using the MVMA 2-D occupant motion model is attempted, a decision must be made, based on review of accident investigation or test data, on whether the event can be represented by a two-dimensional simulation.

2.2. Description of Baseline Occupant

The starting point for developing a description of the occupant was the baseline developed for side impact simulations under an MVMA project entitled "Baseline Data for Describing Occupant Side Impacts and Pedestrian Front Impacts in Two Dimensions" (See Reference 1). This was based on an earlier three-dimensional occupant linkage developed for use with the Calspan 3-D CVS (Reference 2). Figure 2 shows a side view of the original three-dimensional occupant while Figure 3 shows a rear view with the linkage projected into the vertical-lateral vehicle plane. Figure 4 shows the occupant, configured for MVMA 2-D use, in the vehicle prior to initiation of the rollover event. The occupant outline and linkage are very similar to the three-dimensional case. The primary differences are lack of a right arm and lumping together of the left and right leg masses.

The numerical values for quantities such as segment mass, moment of inertia, position in space, ellipse axes, link angles, and joint properties are given in Table I which is a listing of the baseline rollover data set. The Part 572 data set, developed at Calspan and supplied with the Calspan CVS Version 20, was used as the initial basis for the occupant used in the rollover simulations.

The two types of changes to the occupant data, which were made in the process of developing simulations which yielded results qualitatively similar to those observed in full scale rollover tests, involved modifications to:

- the number of occupant/vehicle contacts allowed
- the joint stiffness properties
### TABLE 1. BASELINE ROLLOVER DATA SET (PAGE 1 OF 4).

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### Notes:
- The table includes various measurements and dimensions for different body parts and areas, such as head, torso, and legs, with specified coordinates and values.
- The data is presented in a structured format, with rows and columns indicating different measurements and their corresponding values.
- The measurements likely pertain to anthropometric or biomechanical data relevant to vehicle safety and occupant protection, possibly for automotive research or regulatory compliance.
### TABLE 1. BASELINE ROLLOVER DATA SET (PAGE 2 OF 4).

| LEFT UPPER ARM | LEFT UPPER ARM | 7. | 1. | 219 |
| LEFT UPPER ARM | 0. | 0. | 6.88 | 1.64 | 220 |
| LEFT LOWER ARM | 8. | 1. | 220 |
| LEFT LOWER ARM | 0. | 0. | 8.17523 | 1.11 | 220 |
| RIGHT LOWER LEG | 6. | 1. | 219 |
| RIGHT LOWER LEG | -36406 | -4.45 | 7.37778 | 2.23 | 220 |
| 0. | 8.80333 | 4.63511 | 4.89074 | 4.24 | 10.7 | 1.56504 | -7.6 | 201 |
| 3.22789 | 2.15193 | 2.24974 | 2.44537 | 2.1982 | 6.05145 | 5.25 | 0.573486 | 0.76 | 202 |
| 0.025 | 0.095 | 0.031 | 0.098 | 0.09 | 0.05 | 0.012 | 0.012 | 0.0047 | 203 |
| 0.297 | 2.17 | 0.31 | 1.78 | 0.77 | 1. | 0.137 | 0.27 | 204 |
| 31.2 | 5. | 0. | 0. | 2000. | 3000. | 0. | -30. | 1. | 205 |
| 31.2 | 5. | 0. | 0. | 2000. | 3000. | 0. | -30. | 1. | 206 |
| 31.2 | 5. | 0. | 0. | 2000. | 3000. | 0. | -30. | 1. | 206 |
| 0.50 | 5. | 0. | 0. | 2000. | 3000. | 15. | -15. | 1. | 207 |
| 50. | 5. | 0. | 0. | 2000. | 3000. | 15. | -15. | 1. | 208 |
| 0.16 | 5. | 0. | 0. | 2000. | 3000. | 0. | -165. | -195. | 1. | 209 |
| 0.16 | 5. | 0. | 0. | 2000. | 3000. | 195. | 165. | 1. | 210 |
| 0.16 | 5. | 0. | 0. | 2000. | 3000. | 0. | -10. | 1. | 211 |
| 0.16 | 5. | 0. | 0. | 2000. | 3000. | 0. | -30. | 1. | 212 |
| 751. | 0. | 757. | 1.98 | 213 |
| 1000. | 0. | 800. | 2.5 | 0. | 1. | 214 |
| 31.2 | 5. | 0. | 0. | 2000. | 3000. | 30. | 0. | 1. | 215 |
| 31.2 | 5. | 0. | 0. | 2000. | 3000. | 30. | 0. | 1. | 216 |
| 751. | 0. | 757. | 1.98 | 212 |
| 0. | 0. | 0. | -180. | 180. | 0. | 0. | 217 |
| 3.188 | 2.125 | 0. | 218 |
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| THORAX MATERIAL | 1. | THORAX ZERO | GRRATIO | 222 |
| THORAX | -1. | 4080. | 225 |
| 90. | 90. | 90. | 90. | 90. | -90. | -90. | -90. | 90. | 301 |
| 90. | 90. | 90. | 90. | 90. | -90. | -90. | -90. | 90. | 301 |
| 0. | 0. | -29. | 0. | 4.89074 | 0. | 303 |
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| HEADER | PANEL MATERIAL | 0. | 1. | 1. | 1. | 401 |
| DOOR SILL | PANEL MATERIAL | 0. | 1. | 1. | 1. | 401 |
| 100 | B-PILLAR | PILLAR MATERIAL | 0. | 1. | 1. | 1. | 401 |
| HIP PANEL | PANEL MATERIAL | 0. | 1. | 1. | 1. | 401 |
| WINDOW | GLASS MATERIAL | 0. | 1. | 1. | 1. | 401 |
| DOOR | DOOR MATERIAL | 0. | 1. | 1. | 1. | 401 |
| P.ROOF | FLOOR MATERIAL | 0. | 1. | 1. | 1. | 401 |
| P.HEADER | PANEL MATERIAL | 0. | 1. | 1. | 1. | 401 |
| P.DOOR SILL | PANEL MATERIAL | 0. | 1. | 1. | 1. | 401 |
| LOW DASH | PANEL MATERIAL | 0. | 1. | 1. | 1. | 401 |
| T.ROOF | FLOOR MATERIAL | 0. | 1. | 1. | 1. | 401 |
| P.DOOR SILL | PANEL MATERIAL | 0. | 1. | 1. | 1. | 401 |
| SEAT CUSHION | SEAT MATERIAL | 0. | 1. | 1. | 401 |
| 11 | ROOF | 2. | 1. | 1. | 0. | 1. | 401 |
| 115 | 11 | HEADER | 1. | 1. | 1. | 0. | 1. | 401 |
| 116 | DOOR SILL | 1. | 1. | 1. | 0. | 1. | 402 |
| 117 | B-PILLAR | 1. | 1. | 1. | 0. | 1. | 402 |
| 118 | HIP PANEL | 1. | 1. | 1. | 0. | 1. | 402 |
| 119 | WINDOW | 1. | 1. | 1. | 0. | 1. | 402 |
| 120 | DOOR | 1. | 1. | 1. | 0. | 1. | 402 |
| 121 | P.ROOF | 2. | 1. | 1. | 0. | 1. | 402 |
| 122 | P.HEADER | 1. | 1. | 1. | 0. | 1. | 402 |
| 123 | P.DOOR SILL | 1. | 1. | 1. | 0. | 1. | 402 |
| 124 | LOW DASH | 1. | 1. | 1. | 0. | 1. | 402 |
| 125 | P.B-PILLAR | 1. | 1. | 1. | 0. | 1. | 402 |
| 126 | P.HIP PANEL | 1. | 1. | 1. | 0. | 1. | 402 |
| 127 | P.WINDOW | 1. | 1. | 1. | 0. | 1. | 402 |
| 128 | P.DOOR | 1. | 1. | 1. | 0. | 1. | 402 |
| 129 | FLOOR | 1. | 1. | 1. | 0. | 1. | 402 |
| 130 | SEAT CUSHION | 1. | 1. | 1. | 0. | 1. | 402 |
| 131 | PANNEL MATERIAL | 0. | 0. | 50. | 100. | 101. | 0. | 0. | 0. | 403 |
| 132 | PILLAR MATERIAL | 0. | 0. | 50. | 100. | 101. | 0. | 0. | 0. | 403 |
## TABLE 1. BASELINE ROLLOVER DATA SET (PAGE 3 OF 4).

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**成绩**: 403
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</table>
The primary additions to vehicle components were roof structures, contact surfaces on the passenger side of the vehicle, and a lower instrument panel. In order to contain the occupant within the vehicle, it was necessary to allow most body segments to contact most vehicle components. The contacts which were added to the baseline side impact data set include:

- head (passenger window, passenger header, passenger door, roof, passenger roof)
- upper torso (roof, passenger door, seat cushion, passenger roof)
- lower torso (roof, passenger roof, passenger hip panel)
- left upper leg (door replaces hip panel)
- right upper leg (passenger door)
- left foot (door replaces sill, lower instrument panel)
- right foot (passenger door, roof, passenger roof, lower instrument panel)

It should also be noted that B-pillar and door sill contacts have been deleted.

One of the new contacts is specified to be between the feet and the lower instrument panel. The reason for this contact is based on comparisons between the results of early attempts at rollover simulation and the dolly rollover test discussed earlier. In the tests the legs and feet were observed to remain under the instrument panel, perhaps being trapped. In the early simulations the occupant literally did cartwheels within the vehicle while bouncing from contact to contact. The foot/lower instrument panel contact was inserted to limit motion of the lower extremities to the lower portion of the vehicle. This resulted in dramatic improvements in simulated occupant motion when compared with the rollover test movies.

Based on results generated in early rollover exercises, it became clear that work was required on the joint properties. Early results showed considerable oscillation between adjacent body segments demonstrating that energy absorption was lacking. Also, due to the large motions which took place between segments, well-defined joint
stops were required. Changes to the data cards numbered 205-216 included:

- addition of non-zero linear spring characteristics to knee, shoulder, and elbow joints
- addition of quadratic joint stop characteristics to all body joints
- addition of frictional resistance to all joints

These additions and changes ensured model operation. In order to tailor the occupant kinematics to mimic impact tests or accident results, it is expected that considerable additional work will be required in each individual rollover case to assure reasonable and realistic results.

2.3. Description of Baseline Vehicle

In the original baseline data set which was developed for use in side impact simulations, the following contact surfaces were anticipated to be involved:

- seat cushion
- front door sill region (foot/lower leg contact)
- door panel lower region (hip and upper leg contact)
- door panel upper region (head contact)
- window panel (head contact)
- door header (head contact)
- floor (foot contact)
- B-pillar (head contact)

As discussed in Section 2.2 the number of contact surfaces was expanded to the complete set used for rollover simulation shown in Figure 12. Measurements of vehicle interior height and width were used to develop locations for the roof and passenger side contact surfaces.

The force-deflection characteristic curves governing interactions between the occupant and the vehicle have been derived from a variety of sources as discussed in Reference 1. Some are based on idealized vehicle component tests. Others are hypothetical estimates chosen to
*THE LETTER "P" REFERS TO PASSENGER SIDE OF VEHICLE.

FIGURE 12. VEHICLE INTERIOR CONTACT SURFACES (VIEW FROM FRONT).
fill voids in the available data. All are intended to be treated as baseline data which should be replaced when measured data are available for use in actual rollover studies. The only curve which was modified for this study was the force-deflection property of the seat cushion (Card 407 in the input). The original baseline for side impact was not defined suitably for the larger deflections generated by the occupant during the rollover. The new curve provides for considerable seat cushion stiffening when the seat deflection exceeds 4 inches.

The 411 cards included in the Table 1 baseline data set are set up to show the format for including roof crush. In many cases (roof edge line, for example), four time points are included (0., 1271., 1600., 1800. ms) for specification of the location of the contact surface endpoints. As the location of these endpoints does not change from one time to the next, no intrusion is included for this baseline example. More time points can be inserted if a complex motion is desired, or, in this case of no intrusion, one time point card would have been sufficient as in the case with contact surfaces such as door sill, hip panel, window, door, etc.

The only other change to the baseline developed for side impact was the addition of contact friction between body segments and interior components. It was observed that friction can have a major effect on occupant kinematics and energy absorption during the rollover events. The effect involves the time phasing of contacts. In other words a contact where an ellipse slides into a surface with friction will slide off more slowly than would be the case in a contact with a frictionless surface.

2.4. Model Operation and Results

Up to this point in the report, the discussion has been concentrated primarily on the physical problem and the generation of an input data set describing the rollover crash event, the vehicle, and the occupant. It remains to discuss model operation and the variety of results which are and can be generated.
2.4.1. Integration Time Steps

In the initial phases of this project, a time step of 5 milliseconds was chosen because of the relatively long duration of the event (2000 milliseconds or more) and the relatively low G's experienced by the vehicle in a rollover. In actual fact however, as noted in Section 1.3, the occupant experiences a series of dynamic interactions with the vehicle, each of which may be as severe as the single interaction of an occupant with the interior structures in a frontal barrier crash. Because of this, it was necessary to reduce step size to 0.5 milliseconds, which is a typical value used for most simulations.

As the result of the small integration time step, some problems with MVMA 2-D Version 3 information storage capabilities were observed. Affected are storage of head and chest resultant acceleration data which is limited to 2000 time points. Computations of HIC and severity index are not possible without increasing dimension sizes in the OUT processor to allow for these computations. This change is simple to make but will increase MVMA 2-D run cost.

2.4.2. Tabular Output

The tabular output which is available from the MVMA 2-D model includes most useful physical variables describing both the occupant and vehicle as functions of time. Computed results are stored by the GO processor at user option by means of variable categories defined on input data cards 107-113. These categories may be printed by their inclusion in a list contained on Cards 1001 and 1002 which are used by the OUT processor. Printer plots of stick figure graphics as a function of time are included in this specification.

Table 2 is a list of the variable categories which were actually included in the output tabulations for the baseline rollover simulations. This list is an index to the page in the output printer where each variable is located. The quantities include:

- body joint coordinates and velocities
- link angles, velocities, and accelerations
- forces and moments on body segments
## Table 2. Variable Categories Printed Out During Example Exercise (Page 1 of 2)

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<tr>
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<th>Description</th>
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</table>
- head and chest center of gravity motion
- contact forces between occupant and vehicle
- joint relative angles and torques
- energies
- forces at neck and shoulder
- vehicle response
- accelerations
- stick figures

A printout for an entire rollover run is included as the Appendix to this report.

2.4.3. Sample Results Derived from Baseline Rollover Output

A sample of results from the baseline rollover exercise is presented in this section. These include quantities of interest such as contact interactions of various body segments with the vehicle interior, head accelerations, and forces on the neck at the head. Many other quantities are available for similar presentation and analysis.

Figures 8, 9, 13, and 14 show the forces predicted for many of the occupant interactions with the vehicle interior. These plots were assembled from several of the contact force tables contained in the printout. Overlay capabilities would be required in a computer graphics system to construct the same plots. The first interaction takes place at about 200 milliseconds with the vehicle and occupant in freefall. The occupant is forced toward the roof by the release of the compression force caused by the driver sitting on the seat cushion. During the period of 400-600 milliseconds, the vehicle is into its first roll. There are a variety of interactions of the driver with the passenger door and roof structures. Restraining action of the lower instrument panel is also evident. The vehicle is airborne at about 1200 milliseconds with the driver's door toward the ground (one 360° roll almost complete). The vehicle center of gravity has risen to its maximum point as the result of the ground interaction leaving the driver in contact with the door structures on the driver's side of the vehicle.
Due to the force of this interaction, most of the remaining interactions are with the passenger's side as the vehicle enters the end of the one- and one-quarter roll event. Figure 15 shows the resultant acceleration at the head center of gravity. As expected, the peaks correspond with the peaks in contact force. The one exception is the peak shortly before 1200 milliseconds which is transmitted to the head as the result of the interaction of the torso with the driver door.

Figure 16, 17, and 18 show the shear and compressive forces on the neck at the head as well as the moment exerted in the region of this junction. It should be noted that there is more of a correlation between shear force and moment than between either of these quantities and compressive force. This implies (as can be validated by reviewing occupant kinematics displays such as Figure 10) that the forces shown in Figure 8 are applied more toward the side of the head. In these cases the occupant is positioned more or less upright as he interacts with door and roof structures near the side of the vehicle. The effect of a vertex contact is shown in Figure 17 for the roof contact at about 200 milliseconds which results as the occupant rises nearly straight up from the seat cushion. There is virtually no shear force or moment on the neck during this contact. Although the quality of the actual predicted numerical values for the neck variables depends very strongly on the quality of data which describes the occupant, the availability of these predictions can be very useful in assessing direction of impact and the nature of the combined stresses which are applied to the neck. This applies whether the forces are transmitted to the neck as the result either of a blow to the head or to the torso.

The location of the occupant within the vehicle is most graphically illustrated by ellipse man computer-generated displays such as those illustrated by Figures 10 and 11. Figure 10 shows the sequence or flow of motions as an overlay but can be difficult to use for analysis of occupant position at a particular point in time. More useful for details is the single frame plot such as Figure 12 which can be obtained either in vehicle coordinates or in inertial coordinates with the vehicle oriented properly with respect to the ground.
FIG. 15. RESULTANT ACCELERATION AT HEAD CENTER OF GRAVITY (BASELINE ROLLOVER).
FIG. 16. SHEAR FORCE ON NECK AT HEAD (BASELINE ROLLOVER).

P = PASSENGER SIDE
D = DRIVER SIDE
Fig. 17. Compressive force on neck at head (baseline rollover).
Fig. 18. Moment on neck at head (baseline rollover).

- Roof (P)
- Roof/Header (P)
- Roof (D)
- Window/Door (P)
- Door (P)
- Door (D)

P = Passenger Side
D = Door Side

MOMENT - INCH POUNDS

TIME - MILLISECONDS
This sample of results has been selected to demonstrate the flexibility available for viewing and analysis of results. Occupant motions, while available as tabular data or plots of variables as a function of time, are more readily viewed using the ellipse man displays. Forces of interaction and all the other dynamic quantities are most usefully viewed as computer-generated plots, in many cases using overlays.

2.4.4. Parameter Variations

Four additional exercises were conducted to examine aspects of roof crush and ejection. All used the baseline data set given in Table 1 as a starting point. The first variation involved inclusion of roof crush. Table 3 contains this data set. Timing and duration of the roof crush were based on that period of time during the baseline run when the vehicle was inverted and in contact with the ground as estimated from the test movies. An arbitrary deflection of roof structures downward into the vehicle was initiated at 700 milliseconds. By 800 milliseconds the roof structures intruded into the occupant compartment by more than 7 inches. After 800 milliseconds, the roof structures held the deformed position. The following contact surfaces were involved in the intrusion:

- roof edge line
- roof line
- passenger roof edge line
- passenger roof line

Others could have been included or the surfaces could have been skewed to represent crush on one side only. The technique for implementing these data is illustrated on the 411 Cards in Table 3.

Figure 11 shows the ellipse man occupant motion display for this case while Figures 19 and 20 show forces generated during occupant/vehicle interactions. It has been noted previously that the location of the head of the occupant (from a review of ellipse man plots) is not near the roof during the period roof crush is occurring. It is not until after 900 milliseconds that head contact with the vehicle is again
<table>
<thead>
<tr>
<th>TABLE 3. ROLLOVER DATA SET INCLUDING ROOF CRUSH (PAGE 1 OF 4).</th>
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| 3. | 600. | 500. | 30. | 0.05 | 10. | 1. | 1. |
| 4. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1. | 0. |
| 5. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1. | 0. |
| 6. | 1. | 1. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1. | 0. |
| 7. | 1. | 1. | 0. | 0. | 1. | 1. | 1. | 1. |
| 8. | 0. | 0. | 1. | 0. | 0. | 0. | 0. | 0. | 0. | 1. | 1. |
| 9. | 0. | 0. | 1. | 0. | 0. | 0. | 0. | 0. | 0. | 1. | 1. |

| 10. | 4.4897 | 3.1 |
| 11. | 4.83205 | 6.78 |
| 12. | 6.87638 | 6.35 |
| 13. | 7.4339 | 6.94 |
| 14. | 7.81836 | -4.45 |
| 15. | 7.3 | 4.45 |
| 16. | 7.3 | -4.45 | 2. | 1.8 |

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| HEAD | 106 |
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| CENTER TORSO | THORAX MATERIAL | 3. | 1. |
| CENTER TORSO | -1.9563 | 0. |
| LOWER TORSO | 4. | 1. |
| LOWER TORSO | 0. | 0. |
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| LEFT UPPER LEG | .781836 | -4.45 |
| LEFT LOWER LEG | 1. |
| LEFT LOWER LEG | .36406 | 4.45 |
| LEFT FOOT | 6. | 1. |
| LEFT FOOT | 7.3 | 4.45 |
| RIGHT UPPER LEG | 5. | 1. |
| RIGHT UPPER LEG | .781836 | 4.45 |
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TABLE 3. ROLLOVER DATA SET INCLUDING ROOF CRUSH (PAGE 3 OF 4).

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| 134 | FLOOR MATERIAL | 0. | 0. | 50. | 100. | 101. | 0. | 0. | 403 |
| 135 | SEAT MATERIAL | 0. | 0. | 50. | 100. | 101. | 1500. | 2500. | 403 |
| 136 | GLASS MATERIAL | 0. | 0. | 0.001 | 5 | 0. | 0. | 403 |
| 137 | PANEL MATERIAL | 1. | PANEL ZERO | GRRATIO | 404 |
| 138 | PILLAR MATERIAL | 1. | PILLAR ZERO | GRRATIO | 404 |
| 139 | DOOR MATERIAL | 1. | DOOR ZERO | GRRATIO | 404 |
| 140 | FLOOR MATERIAL | 1. | FLOOR ZERO | GRRATIO | 404 |
| 141 | SEAT MATERIAL | 1. | SEAT ZERO | GRRATIO | 404 |
| 142 | GLASS MATERIAL | 1. | GLASS ZERO | GRRATIO | 404 |
| 143 | GRRATIO -1. | 0. | 405 |
| 144 | GRRATIO -1. | 1. | 406 |
| 145 | PANEL 0. | 0. | 407 |
| 146 | PANEL 3. | 3000. | 407 |
| 147 | PANEL 4. | 13000. | 407 |
| 148 | PILLAR -1. | 4000. | 407 |
| 149 | DOOR -1. | 1000. | -562.5 | 1031.25 | -562.5 | 93.75 | 407 |
| 150 | FLOOR -1. | 860. | 407 |
| 151 | SEAT 0. | 0. | 407 |
| 152 | SEAT 2.58 | 103. | 407 |
| 153 | SEAT 4. | 400. | 407 |
| 154 | SEAT 5. | 1000. | 407 |
| 155 | SEAT 5.5 | 2000. | 407 |
| 156 | GLASS -1. | 10000. | 407 |
| 157 | ZERO -1. | 0. | 408 |
| 158 | ROOF EDGE LINE | ROOF | 5. | .5 | 1. | 1. | 409 |
| 159 | ROOF LINE | ROOF | 5. | .203 | 1. | 2. | 409 |
| 160 | HEADERLINE | HEADER | 4.5 | .5 | 1. | 1. | 409 |
| 161 | DOOR SILL LINE | DOOR SILL | 7. | 0. | 1. | 1. | 409 |
| 162 | B-PILLAR LINE | B-PILLAR | 7. | .284 | 1. | 1. | 409 |
| 163 | HIP PANEL LINE | HIP PANEL | 7.5 | 0. | 1. | 1. | 409 |
| 164 | WINDOW LINE | WINDOW | 4.5 | 0. | 1. | 1. | 409 |
| 165 | DOORLINE | DOOR | 6.8 | 0. | 1. | 1. | 409 |
| 166 | P.ROOF EDGE LINEP.ROOF | 5. | .5 | 1. | 1. | 409 |
| 167 | P.ROOF LINE P.ROOF | 5. | .203 | 1. | 2. | 409 |
| 168 | P.HEADERLINE P.HEADER | 4.5 | .5 | 1. | 1. | 409 |
| 169 | P.DOOR SILL LINEP.DOOR SILL | 7. | 0. | 1. | 1. | 409 |
| 170 | LOW DASH | LOW DASH | 5. | .5 | 1. | 1. | 409 |
| 171 | P.B-PILLAR LINE P.B-PILLAR | 7. | .284 | 1. | 1. | 409 |
| 172 | P.HIP PANEL LINEP.HIP PANEL | 7.5 | 0. | 1. | 1. | 409 |
| 173 | P.WINDOW LINE P.WINDOW | 4.5 | 0. | 1. | 1. | 409 |
| 174 | P.DOORLINE P.DOOR | 6.8 | 0. | 1. | 1. | 409 |
| 175 | FLOORLINE | FLOOR | 4. | 0. | 1. | 1. | 409 |
| 176 | SEAT CUSHION LN. | SEAT CUSHION | 7.5 | 0. | 1. | 1. | 409 |
| 177 | ROOF EDGE LINE | 4. | 410 |
| 178 | ROOF LINE | 4. | 410 |
| 179 | HEADERLINE | 4. | 410 |
| 180 | DOOR SILL LINE | 1. | 410 |
| 181 | B-PILLAR LINE | 4. | 410 |
| 182 | HIP PANEL LINE | 1. | 410 |
| 183 | WINDOW LINE | 1. | 410 |
| 184 | DOORLINE | 1. | 410 |
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| 189 | LOW DASH | 1. | 410 |
| 190 | P.B-PILLAR LINE | 4. | 410 |
| 191 | P.HIP PANEL LINE1. | 4. | 410 |
| 192 | P.WINDOW LINE | 1. | 410 |
| 193 | P.DOORLINE | 1. | 410 |
| 194 | FLOORLINE | 1. | 410 |
| 195 | SEAT CUSHION LN. | 1. | 410 |
| 196 | ROOF EDGE LINE | 0. | -8.854 | -42.881 | -6.549 | -45.515 | 411 |
| 197 | ROOF EDGE LINE 700. | -8.854 | -42.881 | -6.549 | -45.515 | 411 |
| 198 | ROOF EDGE LINE 800. | -8.854 | -35. | -6.549 | -38. | 411 |
### Table 3: Rollover Data Set Including Roof Crush (Page 4 of 4)

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noted. Even though there are more contacts of the head with the roof in the case of roof crush, their level of force is no larger than those contacts observed when the roof remained intact.

The appendix to this report contains the bulk of printout from the roof crush simulation based on the data set contained in Table 3. Although printout is at 10 millisecond intervals in the printout, actual values were computed at 0.5 millisecond intervals. These last values would be the most appropriate for use in a computer-generated display of the results. In fact, because of the bulk of the output, graphical displays are the only practical method for handling most of the variables.

Figure 21 shows the second parameter variation where the passenger door is to be presumed to be forced open near the end of the exercise. This was accomplished in the data set (411 cards) by moving the passenger door and window contact surfaces away from the vehicle when the vehicle finishes its roll to land upright during a forcible lateral interaction between the vehicle tires and the ground (1700 milliseconds). The occupant is shown being ejected at the end of the simulation while still moving at close to 15 mph. It should be noted that all interactions with the passenger door and window structures were the same as in the baseline case until 1700 milliseconds.

Figure 22 shows the third parameter variation which simulated the case where there was no passenger door at anytime during the simulation. Ejection occurred shortly after 500 milliseconds while the vehicle was in a primarily rotational mode. The result was that the occupant was flipped up into the air as the result of head and shoulder contacts with the roof structures near the passenger door. By 2000 milliseconds the duration of the simulation, the occupant is beginning to fall toward the ground.

Figure 23 shows yet another case of ejection by eliminating the driver door. In this case the driver is ejected at 1200 milliseconds. This occurs as the vehicle becomes airborne after roof and driver side contact with the ground. The driver is literally dumped out onto the ground and could be trapped under the vehicle as both entities continue their simulated movement.
FIG. 19. CONTACTS OF HEAD WITH VEHICLE INTERIOR (ROLLOVER WITH ROOF CRUSH).

P = PASSENGER SIDE
D = DRIVER SIDE
FIG. 20. CONTACTS OF TORSO AND LEGS WITH VEHICLE INTERIOR (ROLLOVER WITH ROOF CRUSH).
PASSENGER DOOR OPENS AT END

FIGURE 21. OCCUPANT MOTIONS WITH PASSENGER DOOR OPEN AT END.
NO PASSENGER DOOR

FIGURE 22. OCCUPANT MOTIONS WITH NO PASSENGER DOOR.
3.0 REFERENCES


APPENDIX

EXAMPLE OF TABULAR OUTPUT.
ROLLOVER WITH ROOF CRUSH.