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851734

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Reprinted from P-167—
Twenty-Ninth Stapp Car Crash
Conference Proceedings

Twenty-Ninth Stapp
Car Crash Conference
Hyatt Regency
Crystal City
Washington, DC
October 9—11, 1985

ISSN 0148-7191

Printed in U.S.A.

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ABSTRACT

Eight lateral dolly rollover tests were conducted on 1983 Chevrolet Malibus at a nominal speed of 51.5 km/h (32 mi/h). Four of the vehicles had rollcages and four had standard production roofs. Unrestrained outboard front GM Hybrid III dummies with head and neck transducers were used. Numerous cameras documented the vehicle and dummy movements. Detailed vehicle kinematics data allowed quantitative analysis of the conditions for head and neck loads. For both roof structures, the dummies moved upward and outward from their seats due to rotation and acceleration of the vehicle. High head/neck loads were measured when the head contacted a part of the car experiencing a large change in velocity, often that part of the car which struck the ground. The results of this work indicate that roof strength is not an important factor in the mechanics of head/neck injuries in rollover collisions for unrestrained occupants. There was no significant difference in the occupant kinematics resulting from rollcaged and standard roof vehicles. There was no reduction in the incidence or severity of head/neck injuries in the rollcaged cars compared with the standard roof vehicles. The rollcaged vehicles incurred less glass breakage.

BACKGROUND

The literature regarding the effect of roof strength on rollover protection has evolved from the early assumption in the 1950's that stronger is necessarily better to the current consensus which questions whether there is a relationship between increased roof strength and increased safety.

The experimental safety cars developed in the 1950's and 1960's all incorporated some roof strengthening device under the assumption that stronger is safer. McHenry (1)* noted that studies of occupant behavior in rollover accidents are quite limited, but concluded that "the desirability of minimizing collapse of the roof structure is obvious." This assumption was supported by an early rollover study by Mackay (2), who investigated 57 rollover accidents. He observed that roof "penetration" in rollovers was closely associated with injury severity. Subsequent to Mackay's early study, numerous other accident investigators have made the same observation: vehicles with more roof deformation tended to have more injured occupants — Huelke (3, 4, 5), Mackay (6), and Fan (7).

During the same period, however, other authors did not find a correlation between roof crush and injury. Hight (8), in his investigation of 139 rollover accidents, observed that injury severity was not a function of roof crush. Wilson (9) also found no correlation between increased roof crush and increased head injury or overall injury. More recently, based upon NCSS data, McGuigan (10) found that there was an increased likelihood of severe injury with increased roof crush but also that there was a higher percentage of high injuries for minor roof crush than moderate roof crush. He concluded that the data is too sparse to draw any reliable conclusions concerning probabilities of severe injuries with respect to roof crush. Huelke (5) and Strother (11) found that severe roof deformation was not necessarily associated with severe injury. Provensal (12) noted that APR accidentological data does not find any clear relation between "maximum roof crushing" and severity of lesions.

The initial observation that roof crush and injury are related was followed by questioning whether they are causally related. Mackay (6) first questioned this relationship from their investigation of 89 rollover vehicles. They, too, found that there were more injuries associated with severe roof crush. However, they stated that "this does not necessarily mean that the roof collapse was the immediate cause of the increased injury; it may be that large amounts of roof collapse are an indication of large collision forces which would have led to serious injury anyway." Anderson (13) studied 63 rollover accidents and concluded that unrestrained occupants "are often thrown from the seat and are not affected by the intrusion of the top structure." Subsequently, numerous authors have observed that roof crush and injury are not necessarily causally related — Huelke (3), Mackay (14), Melvin (15), Provensal (12), Versace (16), Wilson (17), and Strother (11).

The lack of a causal relationship between roof crush and injury was discussed by Moffatt (18) He suggested that confusion arises when accident investigators such as Huelke (3) refer to the "downward crush" of the roof in a rollover accident. Moffatt illustrates that roof crush occurs only when the vehicle is upside down, so it is not the roof which moves down to the car but the car which moves down closer to the roof. Strother (11) offered a velocity-time analysis of a falling dummy in a vehicle being dropped on its top which further illustrated that it is the occupant who moves down relative to the roof and not vice versa. He concluded that even if there is roof crush, the occupant will strike the roof before any significant crushing occurs. Melvin (15) also suggested that, in many instances, an unrestrained occupant may contact the roof early in the roof-to-ground impact and not during the final stages of intrusion.

Mackay (14) suggested that to demonstrate that roof crush relates to injury severity, one must necessarily examine the accident data from a sample of cars with markedly different roof strength characteristics Plastiras (19) has attempted just that, with a very limited study comparing the rollover injuries with FMVSS 216 performance of small cars. She found that the stiffer roof vehicles did not have a lower injury rate in rollovers.

The test series which is the basis for this paper involves the rolling over of four cars with production roofs and four with rollcages added to the roof structure. There was a similar study by Stone (20), in which he rolled a variety of British Ford vehicles with strengthened and weakened roof structures. He found that the vehicle with the strengthened roof rolled further and opined that increased roof strength is not necessarily beneficial. The following study is similar to Stone's but involves more nearly identical cars under more controlled conditions, with more extensive photo and instrumentation coverage. This increased number of tests and the test methodology reduced the effect of randomness in this study.

TEST METHODOLOGY

Eight dolly rollover tests were conducted using 1983 Chevrolet Malibu vehicles at a nominal speed of 51.5 km/h (32 mi/h). The Chevrolet Malibu is a front engine rear wheel drive car weighing 1445 kg (3179 lb), with a 2743 mm (108 in) wheelbase. For these tests, the standard equipped cars were four door sedans with bench seats and the head restraints removed. The doors were locked and the windows closed prior to the tests. The rear seat was removed to accommodate camera equipment. Each vehicle was launched into a lateral roll with the right side leading from the dolly fixture, as described in FMVSS 208 and shown in Figure 1. This dolly fixture inclines the car at an angle of 23 deg. The dolly moves along the track up to the assigned test speed and then comes to an abrupt stop, at which time the vehicle is launched. This test method was selected because it is the most repeatable type of rollover test. All tests were conducted on flat asphaltic concrete in dry conditions.

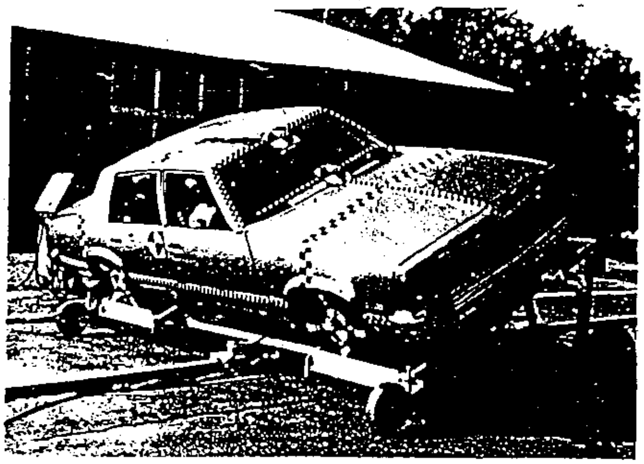

Figure 1

The intent of these tests was to investigate the effects of added roof structure on the safety of unrestrained occupants during rollover collisions. Consequently, the test methodology and speed were selected to subject the vehicles to extremely severe rollover conditions so that any differences in protection would become apparent. Compared with commonly observed field accidents, these tests were very severe. Mackay (6) in his investigations of 89 vehicles found that nearly 50 percent of the vehicles rolled one-half revolution or less and that almost 90 percent of the vehicles rolled one complete revolution or less. In these tests, all of the vehicles rolled over at least twice and many rolled 3 to 3-1/2 times.

Four of the test vehicles utilized the standard production roof. The other four incorporated a rollcage, as illustrated in Figure 2. This rollcage configuration incorporated 8.5 m (28 ft) of 50.8 mm (2 in) steel tubing and 6.4 m (21 ft) of 76.2 mm (3 in) tubing and weighed 74.3 kg (164 lbs). This rollcage is not a feasible alternative design for production vehicles; rather, it provides an extremely strong and nearly rigid configuration. A FMVSS 216 roof crush test was conducted on one of the vehicles after the rollover test, and the rollcage demonstrated a strength of approximately 2-1/2 times that of the production vehicle.

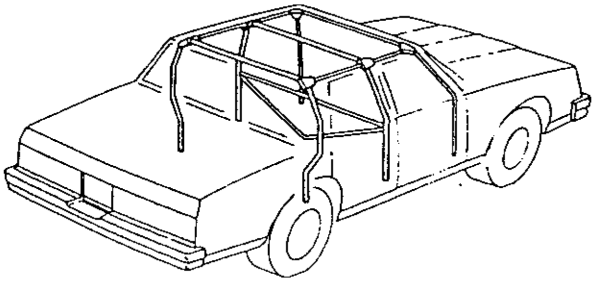

Figure 2

Figure 1 1983 Chevrolet Malibu with rollcage used in Tests 2, 3, 6 & 7

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*Numbers in parentheses designate references at end of paper

Each vehicle was instrumented with accelerometers on the B-pillars, a roll velocity gyro, and deflection transducers on each seat cushion.

Unrestrained GM Hybrid III 50th percentile male dummies were placed in the left front and right front seated positions for each test. These dummies were instrumented with triaxial head accelerometers and the Hybrid III neck transducer, which measures axial compression and tension, anterior-posterior shear, and anterior-posterior bending moments. Four of the tests were conducted using dummies with a pedestrian pelvis and four used a seated form pelvis. Each dummy type was used in two standard roof and two rollcaged vehicles.

Five onboard movie cameras documented the dummy movements. A wide-angle, real-time camera recorded the full area of the front seat. Two high speed cameras recorded the left and right sides of the occupant compartment. Two additional cameras photographed the excursions of the dummies in the region of the buttock-to-cushion contact through openings cut into the lower seatbacks. Offboard high-speed cameras photographed the front and rear of the vehicle. A side view of the lateral rolling vehicle was obtained from a camera placed at the end of the test area. Real-time video and still photography recorded pre- and post-test conditions. Figure 3 illustrates the camera positions.

DOLLY ROLLOVER
TYPICAL CAMERA POSITIONS

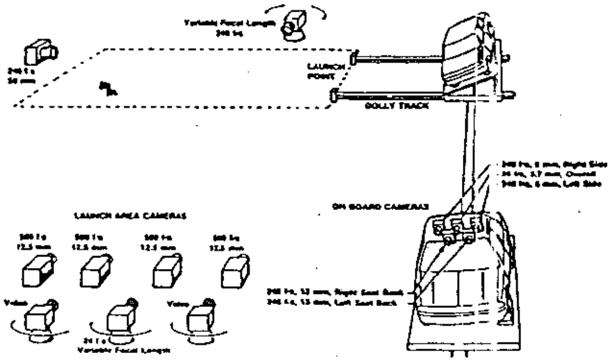


Figure 3

TEST RESULTS

Figure 4 shows the launch speed, length of roll, and number of revolutions for each test. The standard roof cars rolled 2-1/2 to 3-1/2 revolutions over a distance of 20.1 to 27.4 m (66 to 89 ft). They averaged 3-1/8 revolutions over 25.3 m (83 ft). The rollcaged vehicles rolled 2 to 3-1/2 revolutions over a distance of 19.8 to 22.6 m (65 to 74 ft), with an average of 2-3/4 revolutions in 21.6 m (71 ft). The differences in the average number of revolutions and distance rolled between the two types of vehicles was not significant. For both vehicle types, there was a good correlation between the number of revolutions and the distance traveled. Although Figure 4 depicts the vehicles rolling purely laterally, in reality, most of the vehicles developed some degree of yaw and end-to-end contact during the rollovers. The average deceleration for the rolling vehicles was .43 g between dolly launch and point of rest.

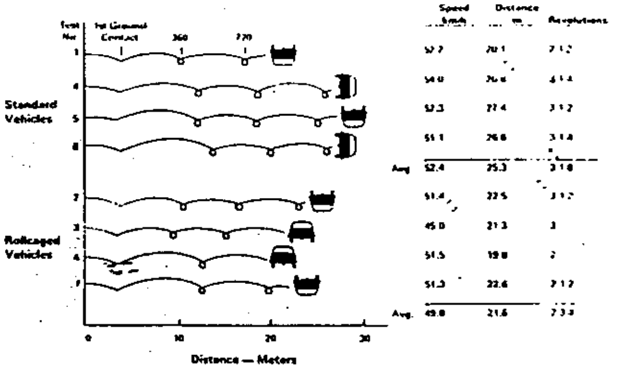


Figure 4 Launch Speed, Distance Rolled and Revolutions

Figure 5 is a sequence of still photographs taken from Test 6. This sequence depicts the angular position of the vehicle during the rollover. The position of the vehicle is not linearly to scale across the figure, however, in order to avoid overlapping photographs in instances where the vehicle has a high roll rate and a low translational velocity. Below the vehicle sequence are photographs of the interior showing the occupant positions and impacts. These impacts will be described in more detail in a later section of this paper. Data summaries and photo sequences similar to Figure 5 are provided for the other seven tests in Figure 14 and the Appendix of this paper.

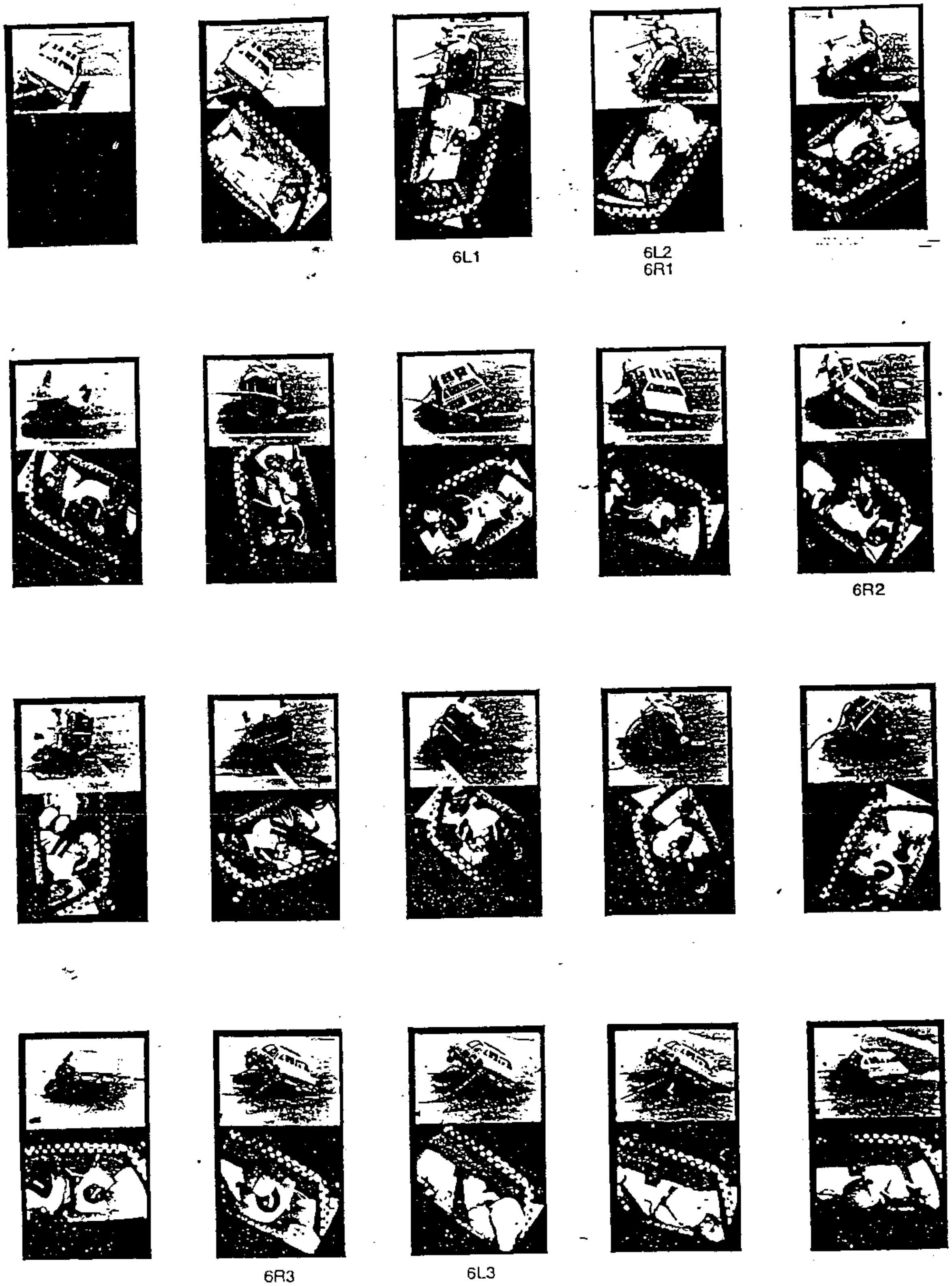


FIGURE 5 TEST 6

VEHICLE KINEMATICS

The primary purpose of this study is to investigate the conditions leading to injuries in rollover collisions and the effect of roof strength on preventing injuries. To understand the mechanics of injuries, the vehicle kinematics must be determined. In these tests, the kinematics of each vehicle were documented through the use of onboard instrumentation and offboard high-speed photography. The following section presents the kinematic analysis of Test 5 (standard roof vehicle) and Test 6 (rollcaged vehicle).

Accelerometers were mounted on the B-pillars at C.G. height and aligned in the vertical and lateral directions to provide continuous records throughout the test sequence. Output from the roll velocity transducer was integrated to provide a continuous record of roll angle. Knowledge of the roll angle allowed a transformation of the acceleration records from the vehicle axis to the earth reference system. The time duration and intensity of the vehicle-to-ground impacts were clearly indicated from the horizontal and vertical accelerometer traces. The traces for Tests 5 and 6 are presented in Figures 6 and 7, respectively. Each figure is marked with the letter R, T, or B to indicate whether the ground contact with the vehicle was to the roof (R), tire (T), or vehicle body (B). For the purpose of this paper, roof contact is defined as when the primary impact between the vehicle and ground occurs anywhere on the vehicle above the door windows.

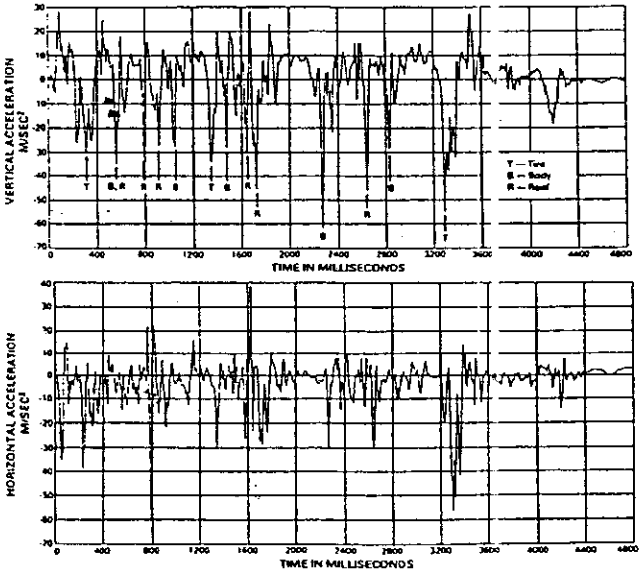


Figure 6 Test 5 Acceleration Responses (Standard Vehicle)

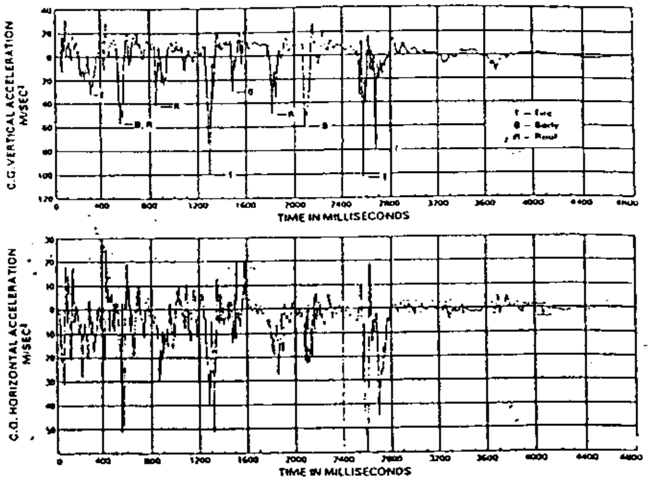


Figure 7 Test 6 Acceleration Responses (Rollcaged Vehicles)

The accelerations presented in Figures 6 and 7 were integrated to obtain horizontal and vertical velocity histories for Tests 5 and 6. There are inherent difficulties in such analysis, but it was possible to obtain good assessments of vehicle velocity and energy loss during each impact. The horizontal velocity plots are presented for Tests 5 and 6 in Figures 7 and 8.

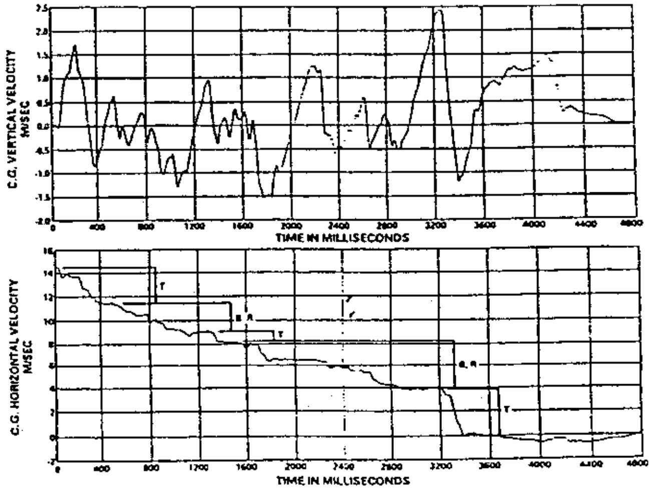


Figure 8 Test 5 Velocity Responses (Standard Vehicles)

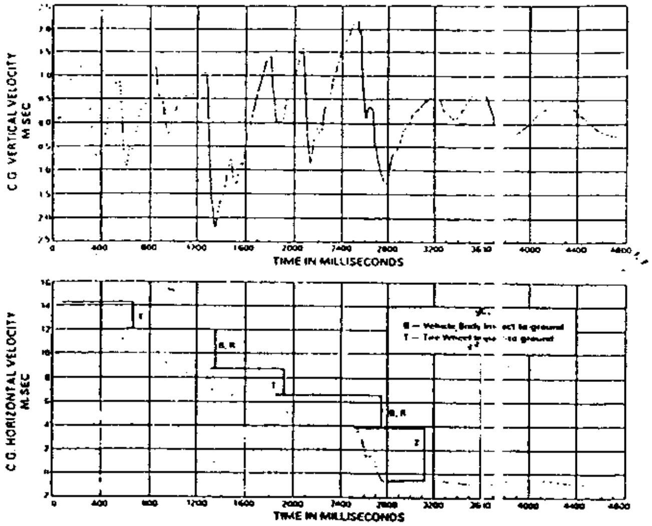


Figure 9 Test 6 Velocity Responses (Rollcaged Vehicle)

Figures 10 and 11 present the energy loss for the vehicles during Tests 5 and 6. Energy is computed as the sum of the kinetic energy from the vertical and horizontal velocities, rotational velocity, and potential energy. Virtually all of the energy is in horizontal velocity so the form of these plots is similar to the horizontal velocity plots.

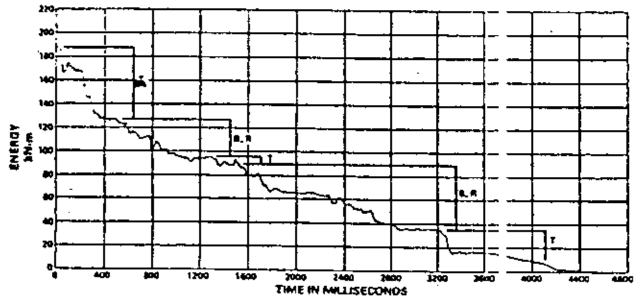


Figure 10 Test 5 Energy Loss (Standard Vehicle)

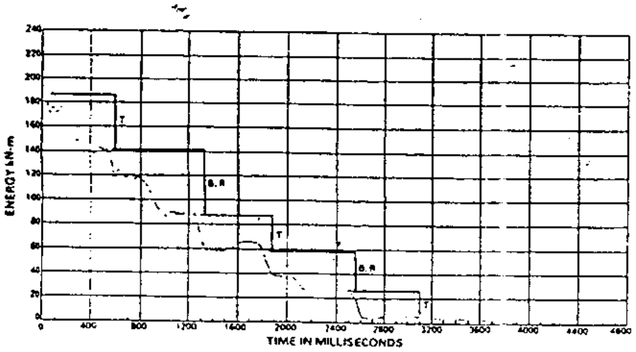


Figure 11 Test 6 Energy Loss (Rollcaged Vehicle)

Rotational velocity data obtained from the roll velocity gyro are shown in Figures 12 and 13. As noted above, these plots were integrated to provide roll angle data. These plots were also used to assess impact velocities of various local points on the vehicle.

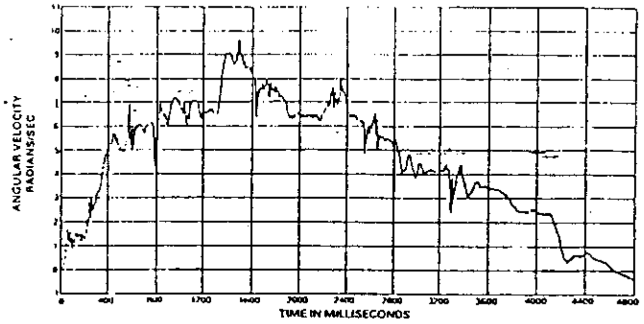


Figure 12 Test 5 Roll Velocity Response (Standard Vehicle)

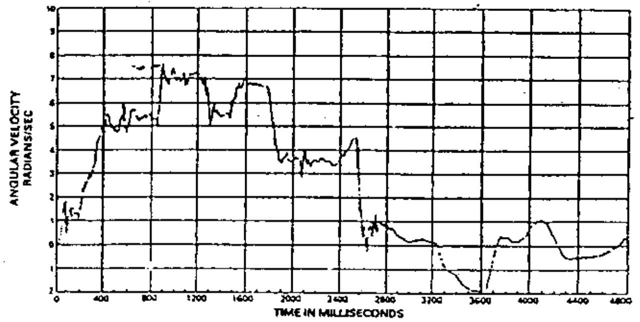
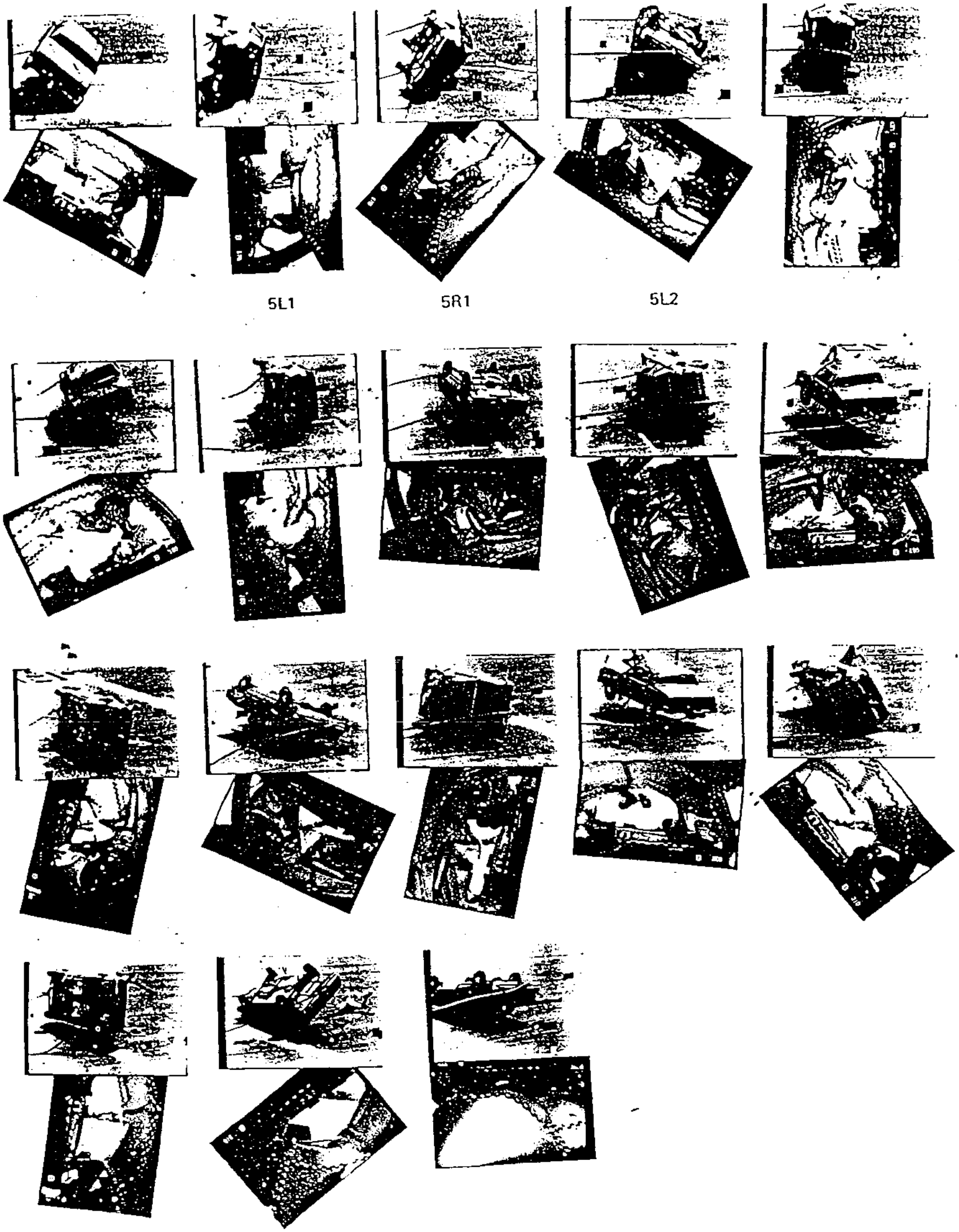


Figure 13 Test 6 Roll Velocity Response (Rollcaged Vehicle)

Test 6 was typical of all tests in that the vehicle began to roll as it left the dolly. A slight tripping force was generated between the dolly and the tires of the vehicle such that a roll velocity of approximately 75 deg/s, and a slight decrease in translational velocity were incurred as the vehicle became airborne leaving the dolly. Referring back to the still photo sequence of Test 6 (Figure 5), the vehicle was airborne until it struck the ground on its right side wheels at a roll angle of approximately 40 degrees. Immediately prior to the wheels striking the ground, the vehicle was translating at approximately 13.8 m/s (45 ft/s) and rotating at a comparatively low rate of 75 deg/s. Consequently, this first ground impact involved a lengthy sliding contact, adding significant rotational velocity at the expense of translational velocity. During this first ground impact, the roll velocity increased to 310 deg/s, and the translational velocity decreased to 12 m/s (39 ft/s).

The next two ground contacts in Test 6 were to the upper vehicle body and roof. They further increased the roll velocity to approximately 400 deg/s. The horizontal velocity, was reduced during the first revolution to 8.8 m/s (29 ft/s). As a result, the vehicle expended more



5L1 5R1 5L2

5R2 5R3

FIGURE 14 TEST 5

than a third of its translational velocity and more than half of its kinetic energy in the first revolution.

At the start of the second revolution, there was a severe tire and wheel impact with the ground which abruptly reduced the roll velocity to 315 deg/s. There followed three more vehicle body and roof impacts with the ground. Upon the first of these vehicle body impacts, the roll velocity momentarily increased to nearly 400 deg/s and then rapidly decreased on further impacts. The second revolution ended with another very severe tire/wheel impact to the ground, which essentially stopped the vehicle. This impact abruptly reduced the horizontal velocity by approximately 4.0 m/s (13 ft/s) and the roll velocity by 230 deg/s. The significance of these velocity changes upon the dummy motion will be discussed in a later section.

The occupant and vehicle kinematics from Test 5 are shown photographically in the sequence of still photographs in Figure 14. The exit from the dolly and the first ground impact were similar to Test 6. The vehicle developed roll velocity rapidly to a level of 370 deg/s at the end of the first revolution. Also similar to Test 6, vehicle body-to-ground impacts occurred, causing an increase in rotational velocity and a reduction in translational velocity. At the end of the first roll of Test 5, the translational velocity had decreased to approximately 9 m/s (29 ft/s).

Early in the second revolution of Test 5, there was a moderately severe tire/wheel-to-ground impact which increased the roll velocity to 520 deg/s with a minimal reduction in translational velocity. Subsequently, several vehicle body and roof contacts occurred, and the second revolution ended with a translational velocity of 6.5 m/s (21 ft/s) and a roll velocity of 370 deg/s.

The subsequent movement of the vehicle in Test 5 was unlike that of Test 6 because there was no tire/wheel-to-ground impact at the end of the second revolution. Consequently, the vehicle continued to roll for another 1-1/2 revolution. At the end of the third revolution, a significant tire/wheel-to-ground impact occurred which sharply reduced the translational velocity to 3.8 m/s (12 ft/s). This final tire/wheel-to-ground impact resulted in only a slight reduction in the roll velocity, however, and the vehicle continued to roll another 1/2 revolution.

In comparing Tests 5 and 6, one finds a difference in the severity and duration of the ground impulses for the standard and rollcaged cars. These parameters relate to the severity of the impacts, since high acceleration indicates high forces on the vehicle, and long duration causes high velocity changes. The magnitude of the vertical accelerations was consistently higher with the rollcaged vehicle. The standard roof vehicle impulses were more numerous and were sometimes clustered, which indicated less severe but more frequent impacts. It appeared that upon roof contact with the ground, the rollcaged vehicle generally rebounded higher, possibly due to better retention of its "hard-cornered" profile and/or storage of energy in its less yielding framework which was released in rebound.

Approximately one-half of the kinetic energy loss for the vehicles in these tests resulted from tire/wheel-to-ground impacts. The remainder of the energy loss was distributed among the vehicle body and roof impacts. The individual impacts which consistently produced the greatest energy loss were the first ground contact by the tires and wheels after leaving the dolly. Inspection of the energy plots in the areas of roof contact indicates that the energy expended by the rollcaged vehicle was approximately the same as that for the standard roof vehicle. The primary difference was that the rollcaged vehicle expended its kinetic energy in two very abrupt roof contacts, whereas the standard roof vehicle had more numerous, less severe roof-to-ground contacts.

OCCUPANT KINEMATICS

The movements of the dummies in these rollover tests are best considered in two phases: (1) while the vehicle is airborne and (2) when the vehicle hits the ground.

VEHICLE AIRBORNE — In the airborne phase, centrifugal force nearly always dictated the position of the dummy. Rotational velocity on the order of one revolution per second was consistently observed by the end of the first revolution. The distance from the roof side rail of the vehicle to the vehicle center of gravity is approximately 1 m (3 ft), so this rotational velocity resulted in a centripetal acceleration of 3 g to 4 g at the perimeter of the vehicle while the vehicle was in the air. As this rotational velocity developed, the dummies left their seated position and moved toward the perimeter of the vehicle. They tended to remain against the vehicle perimeter, constrained by the upper door and roof areas, and moved away from that point only upon vehicle-to-ground impact.

In all eight tests, none of the dummies ever remained seated on their seat cushions (where "cushion" means the portion of the seat upon which the buttocks sit) after the rollover began. In order to document the relationship of the buttocks of the dummy with the seat cushion, openings were cut in the lower seat backs so that onboard cameras could record the dummy movement in that area. Figure 15 is a photograph of the seat back openings. String potentiometers were used to

Figure 15 Openings cut in seat back to photo dummy buttocks to seat cushion contact

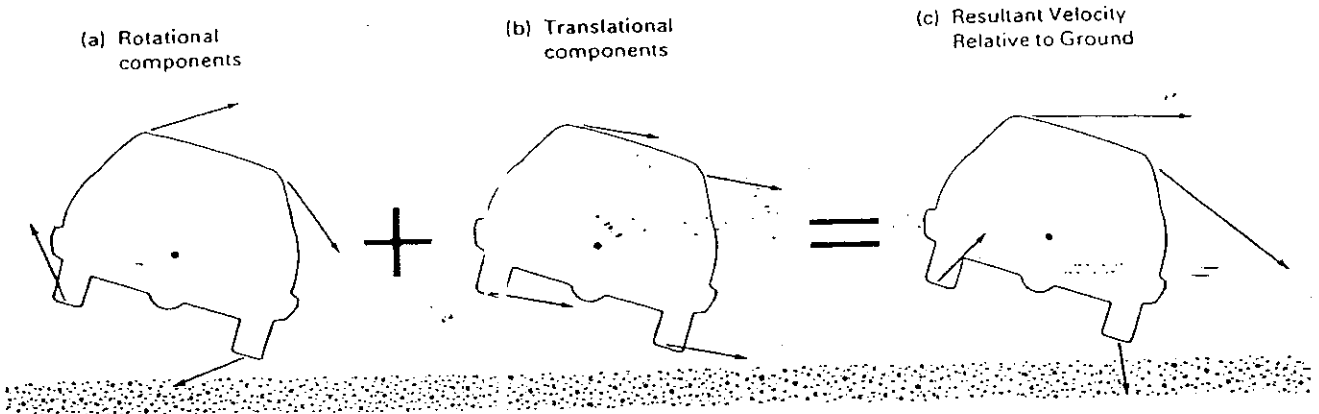


Figure 16 Velocity of Various Points on a Rolling Vehicle

measure the deflection of the cushions during the test. These measurements and the films demonstrated that the dummies lifted off their seat cushions at the beginning of the test and seldom touched the cushions again. There were no instances where the subsequent touching of the seat cushion affected the injury mechanics.

During the vehicle airborne phases, the dummy was usually in synchronous motion with the perimeter of the vehicle, moving at the same velocity and direction as that portion of the vehicle. Therefore, if the roll velocity and translational velocity of that point of the vehicle prior to the ground impact can be determined, then the velocity of the occupants at that point also are determined.

VEHICLE-TO-GROUND IMPACTS — Ground impacts occur between the airborne phases of the rollover. When the vehicle strikes the ground, the occupant compartment rotational and translational velocities change, leading to movement of the dummies within the compartment. In the majority of the ground impacts, the dummy essentially remained in contact with the same part of the vehicle perimeter and simply pressed harder against it as the vehicle struck the ground. Consequently, the change in velocity of that portion of the vehicle against which the dummy was touching determined the change in velocity of the dummy through that impact. It was the change in velocity rather than acceleration of the dummy which was the critical measure of the impact severity in these tests. This is because the majority of these dummy impacts involve potential neck injuries rather than head injuries. Head injury is greatly dependent on acceleration, whereas neck loading depends on relative displacement of the torso to the head, which is more sensitive to velocity change than acceleration.

The change in velocity during an impact is the difference between the velocity before and after the impact. The velocity before the impact of any point on the vehicle in a lateral rollover may be derived from three velocity components: (1) horizontal velocity of the vehicle center of gravity, (2) vertical velocity of the vehicle center of gravity, and (3) roll velocity. The individual and combined effects of each velocity component are shown in Figure 16 for various positions on the vehicle.

The rotational velocity components are shown in Figure 16A. These velocities are normal to a line to the center of gravity of the vehicle and have a magnitude in proportion to the length of that line and the rotational velocity. All the velocities in Figure 16A have different magnitudes and directions because they are at different places on the rotating vehicle.

Figure 16B shows the translational velocity component of the vehicle center of gravity and all points on the vehicle, due to the combined horizontal and vertical velocities.

Figure 16C is a superpositioning of these rotational and translational component vectors. As shown in this vector diagram and as clearly seen in the films of the rollovers, the effects of adding the rotational and translational velocity vectors is that that portion of the vehicle furthest from the ground is moving the fastest and the portion of the vehicle closest to the ground is moving the slowest. It is even possible that the point closest to the ground can be moving in the direction opposite to the vehicle translation if there is high roll velocity.

An analysis was made of impact 6R1 to define the change in velocity experienced by the dummy. Figure 5 illustrates the dummy orientation in impact 6R1. (For this paper, a code was used to designate each dummy impact. In "6R1," the 6 refers to Test 6, R means right dummy, and 1 refers to the first potentially injurious impact to the right dummy.) The impact to the right dummy occurred when the right side roof rail hit the ground and the dummy head remained in contact with the right side roof rail. Force was generated in the dummy neck because its head remained in contact with the underside of the roof rail as the roof rail went through a velocity change of approximately 4 m/s (13.1 ft/s). Also, the head struck the window, which was simultaneously striking the ground. Impact 6R1 was typical of many impacts where the dummy was held against the perimeter of the vehicle until that part of the vehicle struck the ground. This was the most common type of potentially injurious loading to the dummies in these tests. In viewing the on-board film, however, such impacts are not easily seen, because there is little motion between the dummy head and vehicle interior.

Figure 17A illustrates impact 6R1, showing the various components of velocity immediately prior to impact with the ground. Figure 17B shows the velocity vectors of the vehicle just after the ground impact. During this impact, the roll angle changed from approximately 110 to 135 degrees. The vertical velocity at the center of gravity of the vehicle changed from 1 m/s (3 ft/s) downward to 1 m/s (3 ft/s) upward. The horizontal velocity changed from 12.2 m/s (40 ft/s) to 11.0 m/s (36 ft/s). The rotational velocity changed from 270 deg/s to 290 deg/s. When these velocity changes were transformed to the point of contact with the ground, the change in horizontal velocity was 2.1 m/s (6.9 ft/s), but the vertical change in velocity was 3.4 m/s (11.2 ft/s). These velocity changes resulted in an overall change in velocity of approximately 4 m/s (13.1 ft/s) for that part of the car which struck the ground. This was a significant velocity change for the passenger dummy, both in magnitude and direction, because the force was aligned with the dummy neck. The time duration for this local change in velocity was approximately 80 ms.

A similar analysis was made of 6L2, which occurred simultaneously with 6R1 but at a location near the center of the roof. The change in velocity at the center of the roof was 3.7 m/s, compared with 4.0 m/s for the right roof rail. The neck loads were lower due to the lower velocity change and the relative dummy movement. The driver dummy had struck the roof approximately 100 ms earlier and was rebounding from it when the vehicle impact occurred.

PROJECTED IMPACTS — Most of the dummy impacts in this study occurred when the head of the dummy remained in contact with a portion of the vehicle as the vehicle impacted the ground (as in 6R1 above). There was another less frequent type of dummy impact, however, where the dummy moved from one part of the vehicle to strike another part. This occurred when the vehicle struck the ground with the dummy remote from the point of contact but somewhat in line with the imposed force. Figure 18 illustrates impact 6L3. In the left figure, the dummy on the left side of the vehicle was stationary relative to the vehicle just before ground impact. At this point the horizontal velocity of the dummy head (calculated from the kinematics data for this location) was 6.5 m/s (21.3 ft/s). Approximately 180 ms later, the vehicle was essentially stopped by the ground impact, but the unrestrained dummy continued to move at its original velocity, traversed the occupant compartment and impacted the roll bar with a relative velocity of about 6 m/s (19.7 ft/s). There was a resultant HIC number of 1450 but no significant neck load because of the lateral orientation of the head and neck to the roll bar. This was an example of the importance of dummy head/neck orientation in determining whether neck loading occurred in a potentially injurious environment.

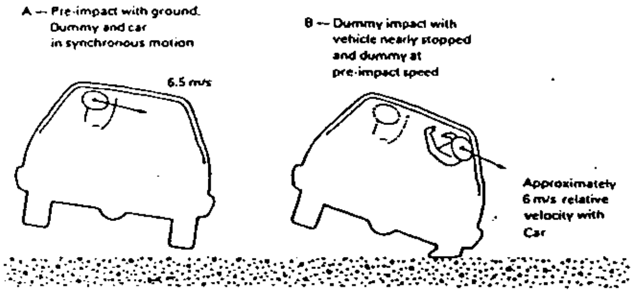


Figure 18 Projection of dummy across car due to right wheel impact — impact 6L3

The significant projected impacts in these tests occurred when the left side dummy projected across the vehicle to impact the right side of the car. The right side dummies rarely moved very far from the right side of the vehicle. The tire/wheel impacts are capable of causing a higher and more sustained deceleration of the vehicle than the roof structure would for a comparable impact. The wheel-to-ground impact related to 6L3 resulted in a peak horizontal deceleration of the vehicle center of gravity of 60 m/sec^2 with an impulse extending over 200 ms. A severe rollcaged roof impact, such as 6R1, caused a 50 m/sec^2 horizontal deceleration of the vehicle center of gravity over a period of only 80 ms. As a result, tire/wheel impacts cause a higher change in velocity and are more apt to cause a projected impact of the left dummy into the right side of the vehicle. There were no projected impacts of the right dummy into the left side of the vehicle as a result of roof impacts.

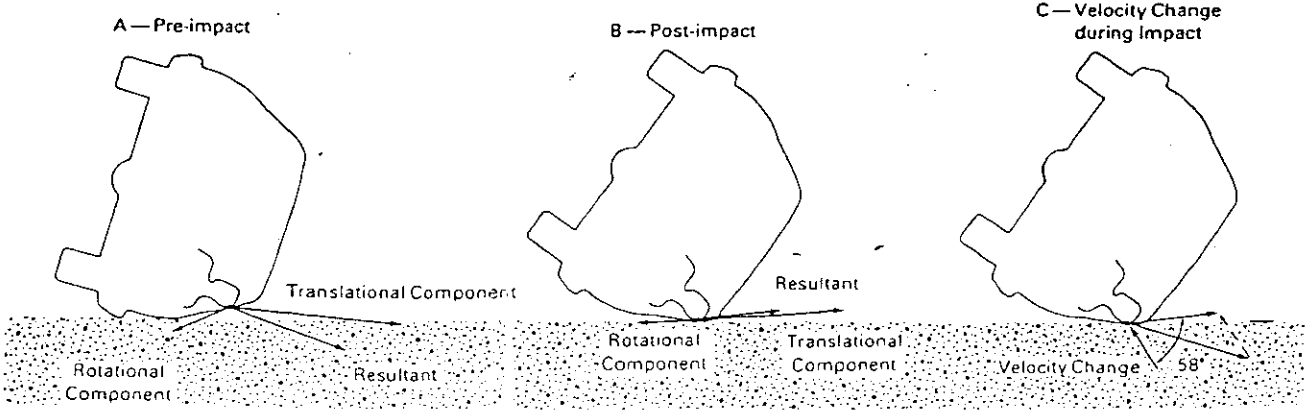


Figure 17 Velocity Change on Dummy When Positioned at Point of Impact (Impact 6R1)

INJURY MECHANICS

One of the purposes of these dolly rollover tests was to develop a better understanding regarding the general pattern of occupant movement and injury mechanics in rollover crashes. Even though rollover crash testing is characterized by some variability of vehicle motion and randomness of injury mechanism, certain patterns of injury mechanics and occupant motion became apparent.

The injury mechanics in rollovers are similar to all collisions in that the injury severity is related to how fast the occupant is moving and how quickly he stops. Rollovers are different from other types of collisions, however, due to the many impacts and the randomness in occupant position. The two most significant factors related to potential injury events are: (1) the orientation of the body at impact and (2) the proximity of the occupant to that part of the car which experiences the high change in velocity.

The orientation of the occupant at impact is important because the human body has varying degrees of tolerance to impact depending upon which part of the body is struck or loaded. For example, the buttocks have a much higher tolerance to impact than the head. Consequently, occupants who land on their heads will probably be more injured than those who impact their buttocks.

The second factor is the proximity of the occupant to the portion of the vehicle which experiences the high velocity change. In these tests, the dummy closest to the area of roof-to-ground contact nearly always experienced a higher change in velocity than the occupant remote from the point of impact. For tire-to-ground impacts, the proximity to the point of impact was not important.

The Hybrid III dummies used in these tests were equipped with head accelerometers and neck transducers. In each test, the dummies were subjected to repeated impacts to the head varying from insignificant to severe. In order to compare the injury mechanics in the rollcaged vehicles with those in the standard roof vehicles, it was necessary to make a judgment as to which were the significant impacts to the head and neck. It is not always possible to state whether a particular measured dummy impact would be injurious to a human being. For the purposes of this rollover study, that judgment was not necessary. A consistent method of analysis was established to compare the potential injuries in the standard roof vehicles to those in the rollcaged vehicles. The performance of the two types of vehicles was studied by comparing the number of "potentially injurious impacts" measured by the dummies. A "potentially injurious impact" was defined as any impact to the head causing a neck axial compression load exceeding 2000 N or a HIC number exceeding 1000. It is not the intent of this paper to state that these levels of impact would cause a particular injury to a person. The intent is to use these criteria as a level of potential injury by which to compare the performance of the two types of vehicles.

The location of the ground impacts on the vehicle which led to injury were determined. There were 54 potentially injurious impacts for those dummies who remained within the vehicles or were partially ejected. Figure 19 shows the locations on the vehicle of the ground impacts. This figure indicates that a majority of the potentially injurious ground impacts occurred to the right side (passenger side) of the car. Note that although most of the injurious impacts came from the right side of the car impacting the ground, this does not necessarily mean that it was the right dummy that measured the potential injury.

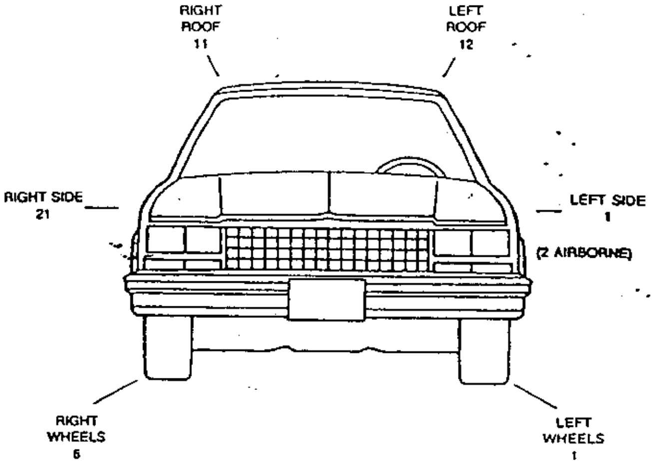


Figure 19 Locations on the vehicle of the 54 ground impacts which caused potentially injurious impacts to the dummy.

The locations within the vehicle of the 54 potentially injurious dummy impacts are shown in Figure 20. Seventy percent of these impacts were to the inside of the roof, with the majority on the right side. Approximately 20% of the impacts were from the dummy head striking the ground through the right door window opening.

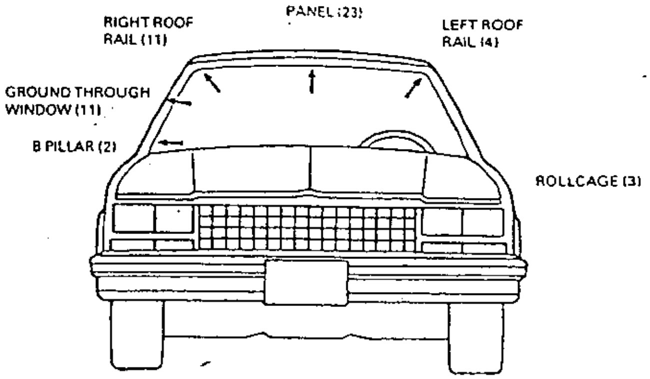


Figure 20 Locations of the head contacts for the 54 potentially injurious impacts.

EFFECT OF ROOF STRENGTH

The distribution and magnitude of the injury numbers for the rollcaged and standard roof vehicles indicate that there was no significant difference in the level of protection offered by either vehicle in these tests. The rollcaged vehicles had 28 potentially injurious impacts compared with 26 in the standard vehicles. The average neck loads in the rollcaged cars was 3318 N compared with 3688 N for the standard vehicles. Figure 21 is a graphical summary of the neck loads measured in all eight tests. Table 1 in the Appendix presents a summary of all the tests.

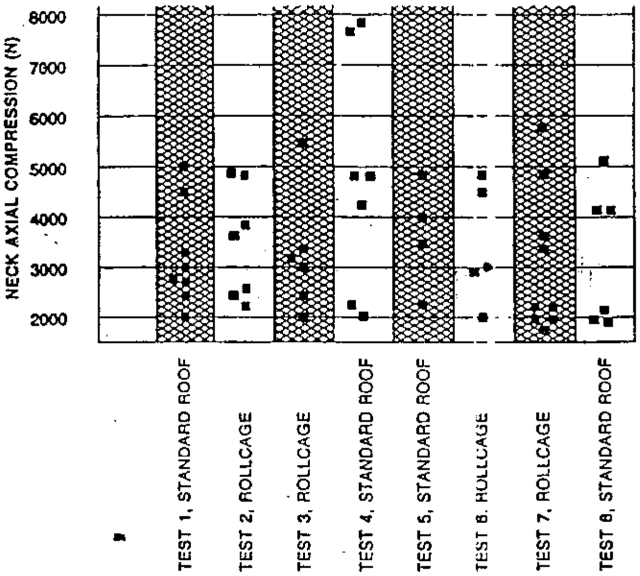


Figure 21 Summary of all neck loads above 2000 N.

There were 54 potentially injurious head/neck impacts. In 32 of the impacts, the dummy struck the roof, but there was no significant roof deformation. In 13 of the 54, the dummy did not strike the roof. In the 10 cases where there was roof deformation of approximately 75 mm (3 in) or more, eight of the dummies were clearly not affected by the crush of the roof. In two of the 54 impacts the increased area of roof contact with the ground potentially related to the injury mechanics. Figure 22 is a graphic illustration of the 54 head/neck impacts and their relation to roof crush.

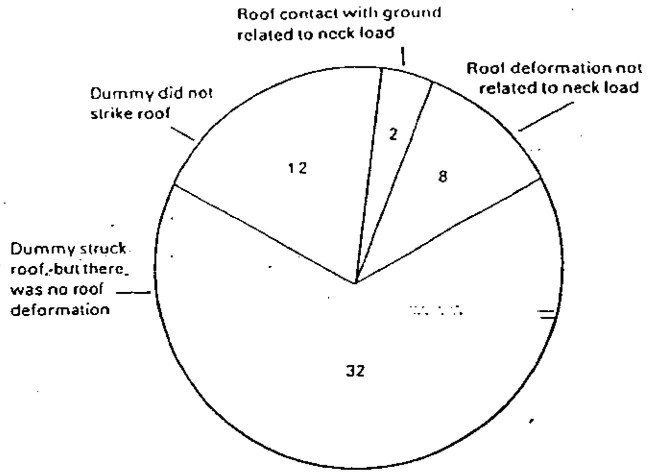


Figure 22 The 54 head/neck impacts and their relation with roof deformation

NO ROOF DEFORMATION — Thirty-two of the potentially injurious impacts measured in these eight tests occurred from the dummy striking the interior of the vehicle roof when there was no roof crush. Typical of these impacts was impact 6R1, described previously. In that impact, the head of the dummy was tucked under the right roof rail when the right roof rail and window struck the ground. There was no significant roof deformation, yet the dummy neck transducer measured an axial load of 4500 N.

DUMMY DID NOT STRIKE ROOF — In 13 of the 54 potentially injurious impacts, the dummy did not impact the roof. Examples of these included projected impacts across the vehicle, partial ejection impacts where the dummy head struck the ground, and impacts of dummies against the vertical portions of the rollcage or B-pillar. Roof strength had no effect on the mechanics of these injuries.

ROOF DEFORMATION NOT RELATED TO NECK LOAD — In eight of the ten head impacts, where there was roof deformation of approximately 75 mm (3 in) or more, the roof crush had no effect on the injuries. Examples where there is significant roof crush and significant head impacts but where the two are not causally related are shown in impacts 5R1 and 8L2. In 5R1, the right dummy head was in contact with the inside of the right side roof rail when the outside of the roof struck the ground. A high neck load (3800 N) was measured at the beginning of the collision before any significant roof deformation had occurred. After the head struck the roof, there was significant displacement of the roof relative to the car, but the peak neck load had already occurred.

While the roof was deforming, the neck load was actually decreasing because the impact between the dummy head and the roof side rail had already reached its maximum force level. Comparison of the injury mechanism in 5R1 with that of 6R1 described previously demonstrates the lack of causal relationship between the crush and injury. In both cases, the dummy head struck the right side roof rail, but in 5R1 there was roof crush and in 6R1 there was not. Both dummies measured similar neck loads (4500 N for 6R1 and 3800 N for 5R1). Analysis of these impacts indicates that both vehicles struck the ground at approximately the same angle with approximately the same velocity change at the dummy's head location (3.2 m/s aligned at 54 degrees from horizontal for 5R1 and 4.0 m/s aligned at 58 degrees for 6R1).

In some of these eight roof crush instances, the dummy measured high neck loads but was not near the area of the roof which deformed. In 8L2, the roof crushed and the dummy measured a neck load of 2400 N but the dummy head struck the roof panel, remote from the area of deformation on the right side roof rail. Therefore, the only effect of the roof crush was on the deceleration of the roof panel. Comparison of impact 6L2 (a rollcaged car) with impact 8L2 shows a similar impact and similar neck loads (3000 N for 6L2 and 2400 N for 8L2).

ROOF CONTACT WITH GROUND POTENTIALLY RELATED TO NECK INJURY — In impacts 4L4 and 1L3, the left dummy head was against the roof panel in an area which struck the ground. In each instance, the deformation of the roof had begun on the right side of the roof and spread as a "contact patch" to the left side of the roof. It was not the displacement of the roof relative to the seat but, rather, the increased area of contact between the roof panel and the ground which defined this specific injury mechanism.

Although a stronger roof will have a smaller contact patch with the ground, it will not necessarily prevent the injury. The absence of deformation does not eliminate the impact, because the lack of deformation may result in the ground contact skipping from the right to left side roof rails. As a result, this skipping from one side roof rail to the other might be beneficial to an occupant in the center of the vehicle but more harmful to one located at the left side roof rail. For example, in rollcage impact 2L4, the contact patch did not progress across from the right side roof rail. Instead, after the right side roof rail struck the ground, the vehicle bounced over the center of the roof panel and landed again on the left side roof rail. The left dummy in 2L4 measured a 4800 N neck load from vertical impact to the left side roof rail. There was no significant roof displacement, yet the dummy neck load was very high.

DISCUSSION

The purpose of these tests was to better understand the mechanics of injuries in rollover collisions, with particular emphasis on the effect of roof strength. These tests were designed to evaluate the principle of the stronger roof and not a particular roof design. Consequently, the rollcage was selected because it represented an extreme case. Likewise, the rollover tests themselves were designed to be extremely severe. They involved high speed and numerous rolls. It was felt that by testing to the extreme case, any differences in the level of protection afforded by an extremely strong roof would be more apparent.

The results showed that there was no significant difference in the injury frequency or severity for the two types of roofs. The explanation for this lack of difference lies in the occupant kinematics and injury mechanics in rollovers. The unrestrained dummies lifted off their seats and remained in the roof or upper door window areas as the vehicles rolled and repeatedly contacted the ground. If the dummy head happened to be next to a part of the car which sustained a high change in velocity, then the dummy had a high injury number. Roof strength had no effect on this mechanism of injury, because it had no effect on the change in velocity of the part of the roof against which the dummy's head was placed.

Occasionally accident investigators report that the roof "came down" into the occupant compartment during a rollover collision. These tests demonstrate that this is a misconception. When the vehicle is inspected upright, the crushed roof is down relative to the seat. When the damage occurred, however, it was the seat which

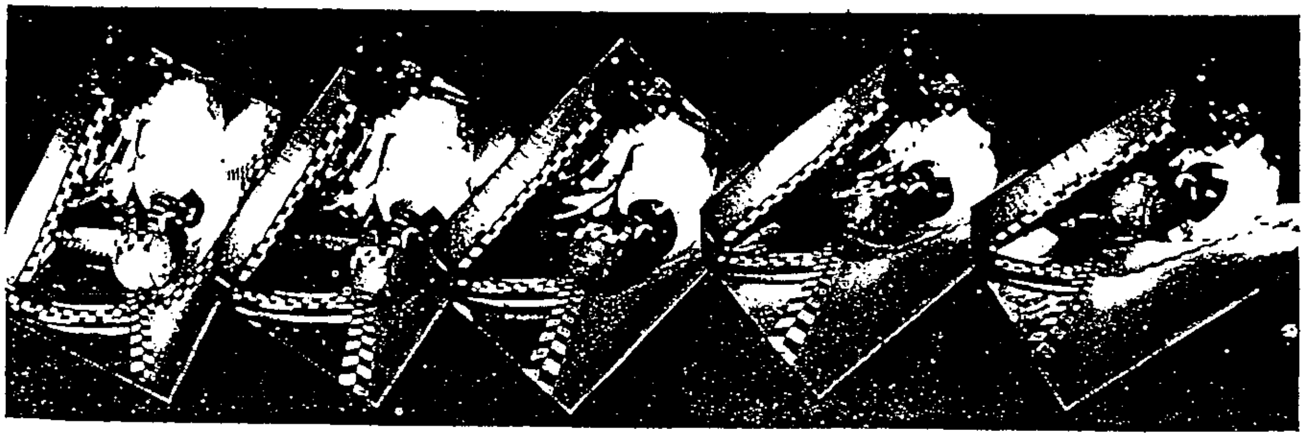


Figure 23 Sequence of photographs from Test 4 showing the roof against the ground and the seat moving closer to the side rail

moved towards the roof and not vice versa. Figure 23 is a sequence of still photographs taken from the onboard film of impact 4R3, which is typical of roof crush impacts. It shows that the crush occurred when the right side roof rail struck the ground and the seat subsequently moved closer to the side roof rail.

Another misconception is that when the roof "came down," it pushed the occupant into the seat, implying that the seat played a role in the mechanics of the head or neck injury. In these tests, the dummies left the seat cushions and had no significant contact with them again. Even in those tests where the deformed roof nearly touched the seat back (1L3 and 4R3), the seat had no effect on the dummy forces. The effect of the major roof displacements in these tests was to make the occupant compartment smaller. The injury numbers resulted from the dummies striking the roof early in the collision, and subsequently the seat moved closer to the roof. These tests do not support the theory that roof crush drives an occupant into the seat, thereby causing an injury which would not have occurred otherwise.

EJECTION — These tests were conducted to investigate the effect of roof strength on contained occupants in rollovers. However, five of the dummies were either ejected or partially ejected. The average neck load measured by the partially ejected dummies was approximately 4000 N compared with an average neck load for non-ejected dummy impacts of approximately 3400 N, and the average head acceleration was significantly higher for the partial ejectees than for the non-ejectees. Although one cannot draw conclusions regarding the hazards of ejection based upon these few ejections, these injury levels in conjunction with the observed injury mechanics, support the conclusion that it is generally more desirable to remain contained in the car than to be ejected in a rollover collision.

All of the partial ejections were through side window openings as a result of glass breakage. The only total ejection was through a windshield opening. None of the doors opened in these tests. The rollcaged vehicles had less glass breakage than the standard roof vehicles. In the standard vehicles, 18 of the 20 side and rear windows were broken, and all were broken due to roof deformation as a result of ground contact. For the rollcaged vehicles, only five of the 20 side and rear windows were broken, and one of the side windows was broken by occupant loading.

CONCLUSIONS

(1) The rollcaged vehicles rolled an average of 2-3/4 revolutions over an average distance of 21.6 m (71 ft). The standard roof vehicles rolled an average of 3-1/8 revolutions over an average distance of 25.3 m (83 ft). The rollcaged vehicles tended to maintain a more "hard-cornered" profile, which, with their greater rigidity resulted in a slightly different impulse pattern from the roof-to-ground impacts. There was no correlation between these different impulses, the number of revolutions or rollover distance with the injury mechanics in these tests.

(2) The dummies moved outward from the center of gravity of the rotating vehicle, causing them to lift off the seat and to come in contact with the occupant compartment perimeter in the roof and upper door areas. With a roll rate of approximately one revolution per second, the dummies were pinned on the perimeter of the vehicle with a centripetal acceleration of approximately 3 g to 4 g. They remained in these positions until the vehicle struck the ground.

(3) Upon ground impact, the chance of neck injury was primarily dependent upon two factors: (1) The orientation of the dummy and (2) the change in velocity of that portion of the vehicle against which the head of the dummy was touching.

(4) Roof deformation relative to the seat had no effect on the injury mechanics in these tests. The theory that head and neck injuries in rollover accidents are from the roof "coming down" and pinning the occupant into his seat is not supported. That sequence of injury did not occur.

(5) The rollcaged vehicles did not have any increased level of protection over the standard roof vehicles in these tests. The number of potentially injurious impacts for the rollcage vehicles was 28 compared with 26 for the standard roof vehicles. The average neck load measured in the rollcaged vehicles was 3318 N compared with 3688 N in the standard roof vehicles.

ACKNOWLEDGEMENT

The authors wish to express their appreciation to the personnel of the Safety Research and Development Laboratory at the General Motors Proving Ground in Milford, Michigan who skillfully conducted these tests.

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APPENDIX

ROOF TYPE	DUMMY IMPACT NUMBER	NECK AXIAL COMPRES-SION (N)	HIC	APPROX— ROOF DISPLACE-MENT (MM)	LOCATION OF HEAD IMPACT	PART OF CAR STRIKING GROUND
STD	1L1	5200		0	LEFT ROOF PANEL	RIGHT SIDE
	1R1	3400		0	RIGHT ROOF RAIL	RIGHT SIDE
	1R2	2800		0	RIGHT ROOF RAIL AND GROUND	RIGHT WINDOW & ROOF RAIL
	1L2	3200		100	LEFT ROOF RAIL	LEFT ROOF PANEL
	1R3	2400		0	RIGHT ROOF RAIL	LEFT ROOF RAIL
	1R4	4600		150	GROUND	RIGHT ROOF RAIL
	1L3	2000	2820	330	LEFT ROOF PANEL	LEFT ROOF
	1R5	2800		0	GROUND	RIGHT SIDE
ROLLCAGE	2R1	2700		0	RIGHT ROOF PANEL	RIGHT WHEELS
	2L1	4900		0	LEFT ROOF RAIL	RIGHT SIDE
	2R2	3600		0	RIGHT ROOF RAIL AND GROUND	RIGHT ROOF RAIL
	2L2	2400		0	LEFT ROOF PANEL	RIGHT ROOF RAIL
	2L3	2200		0	LEFT ROOF RAIL	CAR AIRBORNE & UPRIGHT
	2L4	4800		50	LEFT ROOF RAIL	LEFT ROOF RAIL
	2L5	3600		0	CENTER ROOF PANEL	RIGHT SIDE
ROLLCAGE	3L1	5500		0	CENTER ROOF PANEL	RIGHT SIDE
	3R1	3200		0	RIGHT ROOF RAIL AND GROUND	RIGHT ROOF RAIL
	3L2	2000		0	CENTER ROOF PANEL	LEFT ROOF RAIL
	2R2	3000		0	RIGHT ROOF RAIL	LEFT ROOF RAIL
	3R3	2400		0	GROUND	UPPER RIGHT SIDE
	3R4	3400		0	GROUND	RIGHT ROOF RAIL
STD	4L1	4500		0	CENTER ROOF PANEL	LOWER RIGHT SIDE
	4L2	2100		0	CENTER ROOF PANEL	RIGHT ROOF RAIL
	4R1	4000		75	RIGHT ROOF RAIL AND GROUND	UPPER RIGHT SIDE
	4R2	7700		0	GROUND	RIGHT SIDE
	4L3	4500		75	LEFT ROOF PANEL	LEFT ROOF PANEL
	4R3	2400		175	RIGHT ROOF RAIL	RIGHT ROOF RAIL
	4L4	7800		175	LEFT ROOF PANEL	LEFT ROOF

ROOF TYPE	DUMMY IMPACT NUMBER	NECK AXIAL COMPRESSION (N)	HIC	APPROX— ROOF DISPLACEMENT (MM)	LOCATION OF HEAD IMPACT	PART OF CAR STRIKING GROUND
STD	5L1	4500		10	CENTER ROOF PANEL	RIGHT SIDE
	5R1	3800		75	RIGHT ROOF RAIL	RIGHT ROOF RAIL
	5L2	2400		125	CENTER ROOF PANEL	LEFT ROOF
	5R2	-2200		—	GROUND-PARTIAL EJECTION	RIGHT WHEELS
	5R3	3500		—	GROUND-PARTIAL EJECTION	ROOF ROLLS ONTO DUMMY
ROLLCAGE	6L1	4800		0	CENTER ROOF PANEL	RIGHT SIDE
	6L2	3000		0	CENTER ROOF PANEL	UPPER RIGHT SIDE
	6R1	4500		0	RIGHT SIDE RAIL AND GROUND	UPPER RIGHT SIDE
	6R2	2900		0	B PILLAR	RIGHT REAR WHEEL
	6R3	2000		0	B PILLAR	RIGHT WHEELS
	6L3		14[illegible]0	0	ROLLCAGE AT RIGHT B PILLAR	RIGHT WHEELS
ROLLCAGE	7L1	5700		0	CENTER ROOF PANEL	RIGHT SIDE
	7L2	3300		0	CENTER ROOF PANEL	UPPER RIGHT SIDE
	7R1	3600		0	RIGHT ROOF RAIL AND WINDOW	UPPER RIGHT SIDE
	7R2	2200		0	RIGHT ROOF RAIL	LEFT ROOF RAIL
	7R3	4800		0	RIGHT ROOF PANEL	LEFT REAR WHEEL
	7L3	2400		0	CENTER ROLLBAR	RIGHT SIDE
	7L4	2100		0	CENTER ROLLBAR	LEFT FENDER & A PILLAR
	7R4	2200		0	GROUND OR B PILLAR	UPPER RIGHT SIDE
	7R5	2400		0	RIGHT ROOF RAIL	LEFT ROOF
STD	8L1	4200		0	CENTER ROOF PANEL	RIGHT SIDE
	8L2	2400		75	RIGHT ROOF PANEL	RIGHT ROOF RAIL
	8R1	2200		0	RIGHT ROOF PANEL	LEFT ROOF RAIL
	8R2	2100		0	RIGHT ROOF PANEL	CAR AIRBORNE & UPRIGHT
	8L3	4100		0	CENTER ROOF PANEL	RIGHT SIDE
	8L4	5100		0	CENTER ROOF RAIL	RIGHT WHEELS

1L2 1R2 1L1 1R1

1L3 1R4 1R3

1R5

TEST NO. 1

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2L1

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2R2

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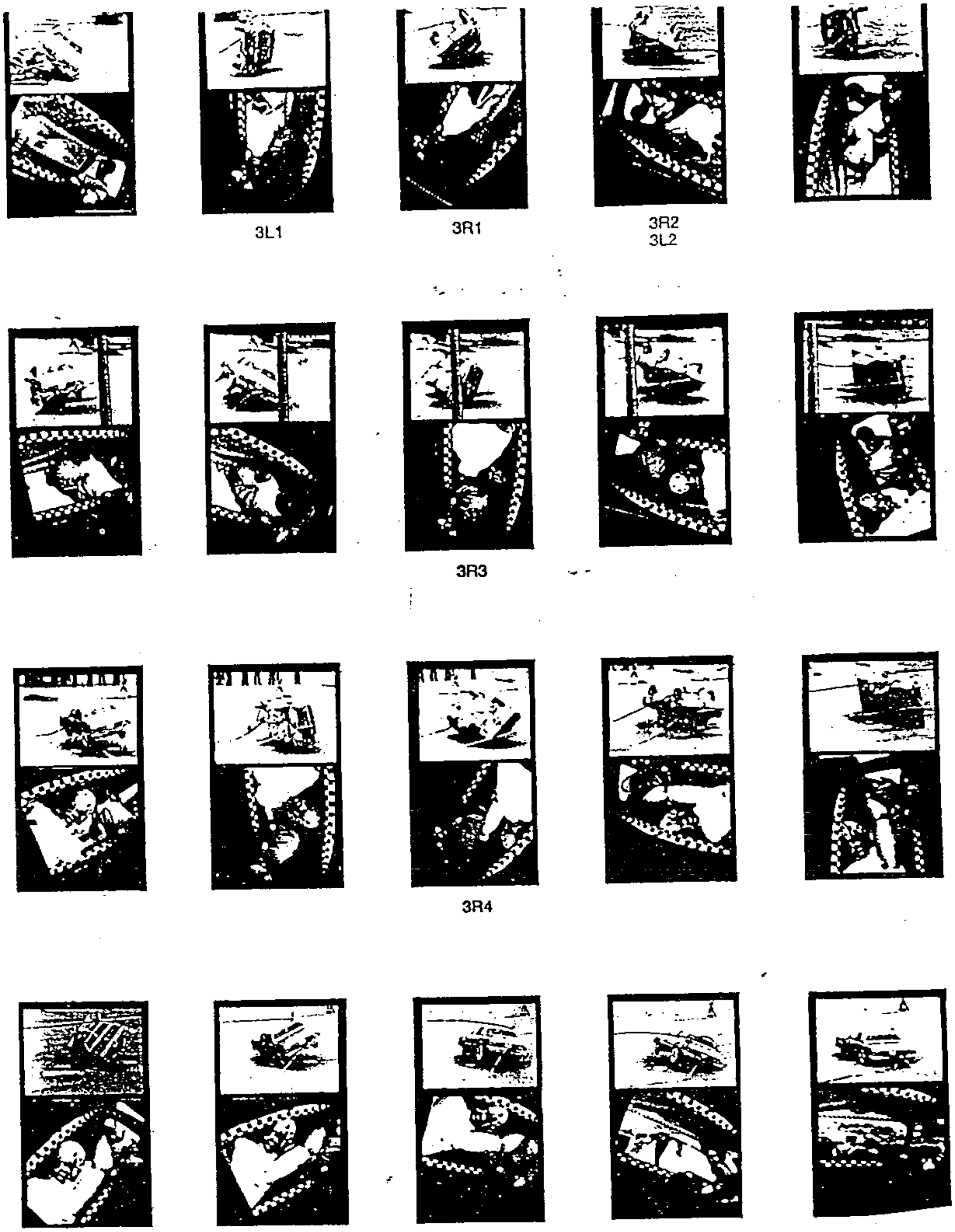

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3R1

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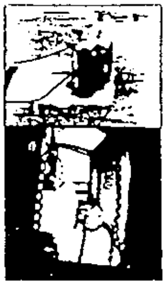
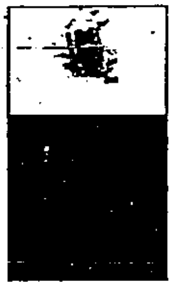


4L1

4R1

4L2



4R2

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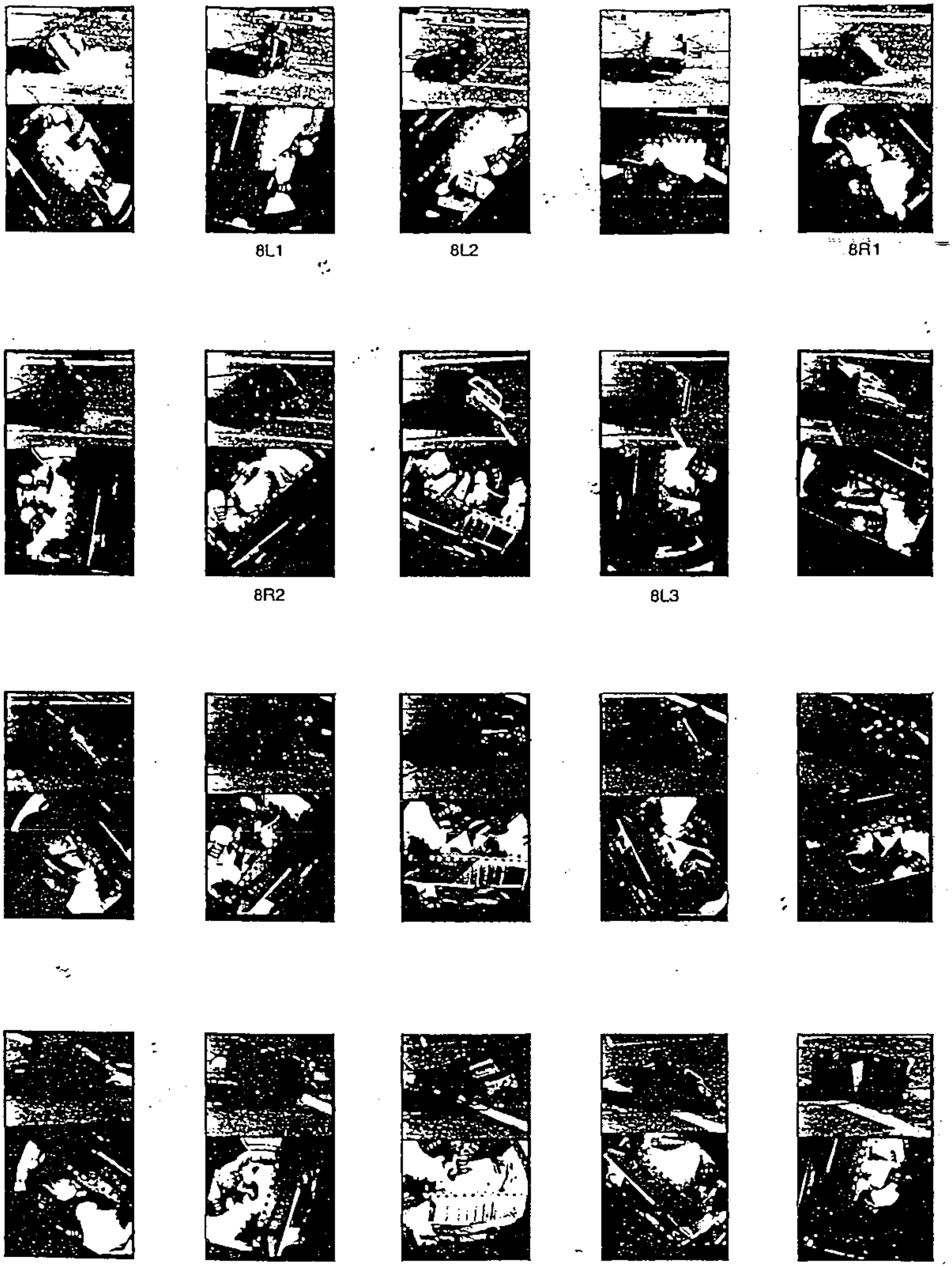

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