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Rollover and Drop Tests — The Influence of Roof Strength on Injury Mechanics Using Belted Dummies

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ABSTRACT

This report presents the test methods and results of a study involving lap/shoulder belted dummies in dynamic dolly rollover tests and inverted vehicle drop tests. Data are presented showing dummy neck loadings resulting from head impacts to the vehicle interior as the vehicle contacts the ground. Comparison of the number and magnitude of axial neckloads are presented for rollcaged and production vehicles, as well as an analysis of the factors which influence neckloads under these conditions.

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BACKGROUND

The purpose of this background review is to present some of the past research which has addressed seat belted occupants in rollovers. Please see Reference 1 for a review of the literature regarding rollovers with unrestrained occupants.

To evaluate whether seatbelts are hazardous for persons in convertible car rollovers, Campbell[2] analyzed ACIR data in 1962. He found that unrestrained, contained (non-ejected) occupants in convertibles were no more seriously injured than unrestrained, contained occupants in other body style cars but that convertibles had a significantly higher ejection rate. He hypothesized that seatbelts would not be hazardous to occupants in convertible rollovers.

During the 1970's, field accident investigations were used to study the effects of seatbelts in rollovers. Mackay[3] investigated 89 rollover accidents in which 20 occupants were using lap/shoulder belts. One of his findings was that seatbelts did not appear to reduce head injuries in rollovers. Hight[4] investigated 139 vehicle rollovers involving 114 contained, unrestrained and 39 contained, restrained people. There was one fatality among the 39 restrained. He also found that the unrestrained, contained occupants had a slightly greater chance of severe injury than the restrained occupants.

Huelke[5] studied the CPIR data from 377 front seat occupants in rollovers, including 62 who were restrained. He found that 6 percent of the restrained suffered critical to fatal injuries compared with 20 percent of the unrestrained (including ejectees). A later study by Huelke[6], using CPIR data of 757 unbelted and 59 lap/shoulder belted occupants, concluded that the use of restraints reduced fatalities by 91 percent in rollovers, primarily by preventing ejection. He also compared injuries to restrained contained and unrestrained contained people and found that the benefits of belts were significant, with fewer AIS 3-5 and fatalities to all body regions except the head. Huelke and Lawson[7] concluded that for contained occupants, those belted had fewer severe injuries and fewer fatalities. The restrained contained suffered 4 percent fatalities compared with 10 percent for the unrestrained contained.

Several authors have attempted to use the NCSS data to evaluate the benefits of seatbelts in rollovers. Partyka[8] found there was too sparse data to draw conclusions. McGuigan and Bondy[9] noted that fewer than 3 percent of the weighted NCSS rollover occupants were restrained. They observed a slightly higher severe injury rate for those restrained, but, due to the sparsity of data, noted it would not be correct to conclude that restrained occupants are worse off. It is unclear whether the unrestrained included ejectees in their figures. Strother[10] found in the NCSS data that the seatbelt usage rate in rollover accidents was about one-half the usage rate in all accidents. He also found the NCSS rollover/restrained data sparse but noted that the existing data showed no restrained rollovers with an AIS over 4. Evans[11] used FARS data to show lap/shoulder belts are 82 percent effective in fatality reduction in rollovers, with 64 percent due to ejection prevention.

How roof crush affects belted people has been considered by several authors. Huelke[12] observed that, even in those accidents where there was 13-24 inches of roof crush, the average injury to lapbelted occupants was moderate. He concluded that no significant statistical relationship exists between AIS and roof crush for restrained occupants in rollovers. Huelke[5] presented data showing that, for less than 6 inches of roof crush, seatbelts apparently prevented injurious contact with the roof, but for more than 7 inches, a greater percentage of belted occupants contacted the roof than unbelted. He suggested that this result may be because unbelted people are less apt to be upright and more likely to strike other objects within the vehicle or be ejected. Anderson[13] studied the effects of intrusion using the Calspan data and found that roof crush did not affect unrestrained people but opined that a restrained person would remain upright and could not avoid contact with the intruding top. He suggested that a restraint study is needed before the hazard of intrusion can be evaluated. Moffat[14] compared rollovers to side impacts, where the seatbelt is of little benefit to the person adjacent to the point of impact but may benefit the remote side occupant. Almusallam[15] modeled an idealized representation of a rollover as a mass on a spring in a deformable box.

Partyka[8] found the NCSS data showed that the average roof deformation in rollover accidents is 3.7 inches. Najjar[16] found the NCSS data to show the typical roof crush to be two-thirds of the side window height. In contrast, McGuigan[17] used NCSS data and found that 83 percent of the roof crush is less than two-thirds of the side window height.

McGuigan and Bondy[9] stated that the NCSS data was too sparse to draw any conclusions regarding the probability of severe injuries for unrestrained versus restrained people with respect to roof crush. They suggested that, due to the slightly higher frequency of severe injuries to restrained people in rollovers, there remains the possibility that restrained occupants would be at a greater risk of injury due to roof crush. Strother[10] also studied NCSS data and presented the injury rate for 28 restrained occupants versus roof deformation. He concluded that, because there were only seven restrained occupants with roof crush more than 12 inches, nothing could be concluded about roof crush and injury.

The study of seatbelted occupant kinematics in rollovers was begun in 1959 by Shoemaker[18], who placed dummies in various vehicle simulators and restrained them using aircraft-type lapbelts. These vehicles were then rotated on a spit-type platform and the motion of the dummies was documented. The author recognized the potential value of lapbelts but noted that, even wearing the belt, the dummies could still hit their head on the roof. In 1974, Stone[19] reported a rollover crash test using belted dummies. His test showed that the lap shoulder-belted dummy could have considerable lateral motion of the head and upper torso which can result in severe head and shoulder impacts with the roof side rails and upper B-pillar. One of their most severe head impacts was the belted dummy head striking the shoulder of the other dummy. He noted that seatbelts cause a change in injury pattern, from partial ejection of limbs to head impacts with the interior of the car. He qualified these results by stating that his were severe lateral rollover tests, whereas actual field rollovers often involved frontal collisions where the belt would be helpful.

Several computer-generated simulations of occupant motion in rollovers have been presented. Johnson[20] presented the simulation of belted dummy movements during a staged guardrail and rollover collision in which an actual dummy was filmed. Obergefell[21,22] and Kaleps[23] furthered Johnson's simulation and found that the vehicle rotation keeps the mannequin high in the seat and against the side door until the test concludes when it settles back into the seat. Their model gave belt forces with peaks typically in the range of 250-600 lb. Their model did not have the mannequin striking the roof except above the side door. In all seven of their simulations, the occupant fell to the side, sliding out of the shoulder belt. Robbins[24,25] used occupant motion simulators to study various parameters of ejection based upon vehicle kinematics from a crash test.

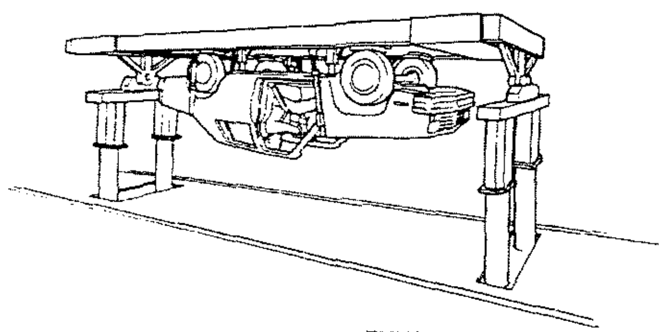

Fig. 1 Occupant Position Tests on FMVSS 301 Vehicle Inversion Device

INTRODUCTION

At the 1985 Stapp Conference, General Motors[1] reported the results of eight rollover crash tests using unrestrained dummies. The following study considers the effects of roof strength on belted occupants in rollovers. This paper presents the results of three test programs:

1. Human volunteers statically inverted in a 1983 Chevrolet Malibu to measure head excursion while wearing the lap/shoulder belt.
2. Eight dolly rollover tests with lap/shoulder belted dummies. Four cars had rollcages and four had production roofs.
3. Five inverted vehicle drop tests using rollcaged and production roof vehicles in combination with belted and unbelted dummies.

OCCUPANT POSITION TESTS WITH AN INVERTED VEHICLE

Three human volunteers were belted in a 1983 Malibu and then the vehicle was rotated 180 degrees in order to measure their position while suspended upside down with the safety belt. Each volunteer closely represented a 50th percentile male in stature and weight. Each was asked to wear the safety belt as he normally would. Their usage of the belts was verified to be consistent with Owner's Manual instructions. The car was inverted using the FMVSS 301 inversion device illustrated in Figure 1. The 1983 Malibu used for this test was equipped with production belts and a manually adjusted production bench seat located in the mid position. The safety belts in the outboard front positions were continuous loop three-point restraints with an inertia locking torso belt retractor with tension reliever and cinching latch plate. The roof panel was cut out above the front seat area so that the head of the suspended person was free to hang without contacting the inside of the roof panel.

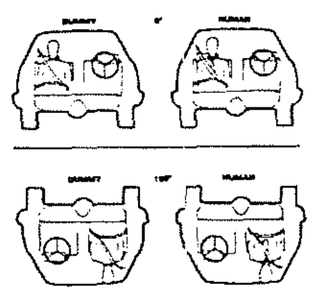

Fig. 2 Comparison of Dummy and Human Volunteers During Inversion Test

The results of the human tests identified the positions of each of the volunteer's heads while the car was slowly rotated 360 degrees. The average head position when upside down was displaced 3.9 inches toward the roof relative to the head position when seated right side up. This resulted in the head extending to the roof line of the vehicle. The relative displacement of the head resulted from the torso rotating more erect, torso elongation, changes in the belt geometry and compression of body tissue from belt pressure. The Hybrid III dummy was then tested in the same manner. The safety belt was adjusted on the dummy to duplicate the average head excursion of the three volunteers. The head position of the inverted dummy compared with the volunteers, is shown in Figure 2.

The lapbelt adjustment which produced an inverted dummy head position that matched the volunteers was subsequently used in the dolly rollover tests and the inverted vehicle drop tests.

DOLLY ROLLOVER TESTS

Test Methodology

Eight dolly rollover tests were conducted per FMVSS 208 criteria using 1983 Chevrolet Malibu vehicles at a nominal speed of 32 mph. The Chevrolet Malibu is a front engine, rear drive car weighing 3,179 lb. with a 108-in. wheelbase. For these tests, the production cars were four-door sedans with bench seats and the head restraints removed to enhance photo coverage. The doors were locked and the windows closed prior to the test. The rear seat was removed to accommodate camera equipment. Each vehicle was launched from the dolly fixture into a lateral roll with the right side leading (see Figure 3). The dolly moved along the track up to the assigned test speed and then came to an abrupt stop, at which time the vehicle was 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.

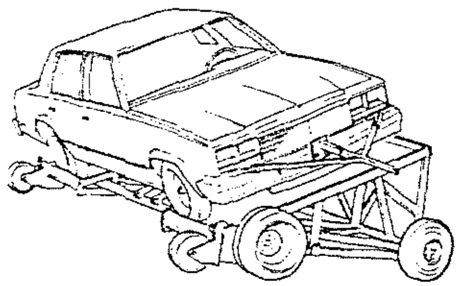

Fig. 3 Vehicle on Dolly Rollover Fixture

Four of the test vehicles utilized the standard production roof. The other four incorporated a rollcage, as illustrated in Figure 4.

Film analysis of two tests incorporating a rollcage indicated that the section of the rollcage along the roof side rails may have affected dummy head position. To determine if this observation was correct, the rollcage was modified by removing that section of the rollcage as shown by the dotted line in Figure 4. Two subsequent tests incorporating the modified rollcage demonstrated no significant increase in dummy neck loads.

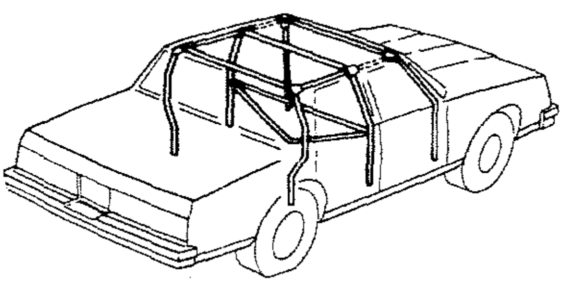

Fig. 4 Vehicle Equipped With Rollcage Structure

This rollcage configuration incorporated approximately 49 ft. of two and three inch diameter tubing weighing 164 lb. A FMVSS 216 roof crush test was performed on the Malibu with the rollcage which demonstrated a strength of 24,000 lbs. which is approximately 2-1/2 times that of the production vehicle. No attempt was made to design the rollcage for practical vehicle application or determine its production feasibility.

Each vehicle was instrumented with accelerometers located on the B-pillars at its intersection with the rocker panels and with deflection transducers on each seat cushion. The GM Hybrid III 50th percentile male dummies were placed in the left front and right front seated position. The production safety belt was used, with the lapbelt adjusted as described in the Human Inversion Tests. Again, the safety belts in the outboard front positions were the production continuous loop, three-point restraints with an inertial locking belt retractor with a tension reliever and a cinching adjustable latch plate. The tension reliever on the torso belt was engaged with approximately one inch of slack. The dummies were instrumented with triaxial head accelerometers and the Hybrid III neck transducer, which measures axial compression and tension, anterior-posterior shear and bending moment, and lateral shear and bending moment.

Four on-board movie cameras documented the dummy movements. A wide angle, high-speed camera recorded the full area of the front seat. Two high-speed cameras recorded the left and right sides of the occupant front seat area. One additional camera photographed the region of the buttocks-to-cushion contact through openings cut in the lower front seatbacks. Off-board high-speed cameras photographed the front and rear of the vehicle. A side view of the 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 5 illustrates the camera positions.

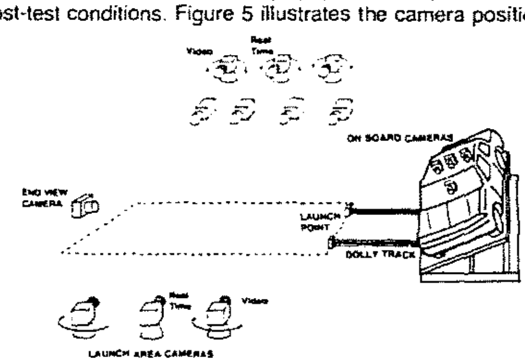

Fig. 5 Dolly Rollover Typical Camera Positions

DOLLY TEST RESULTS – VEHICLE KINEMATICS

The data from the eight dolly rollover tests are summarized in Figure 6. The vehicles were rolled laterally off the dolly with the passenger side leading at approximately 32 mph. The passenger side of the roof was exposed to ground contact first, followed by the driver side. The eight cars rolled between three and four complete rolls over a distance which ranged from 22.6 to 31.1m (74 to 102 ft.) The typical test lasted approximately 4 s, with peak roll velocities slightly greater than 1 revolution per second. Generally, the rollover kinematics were as follows:

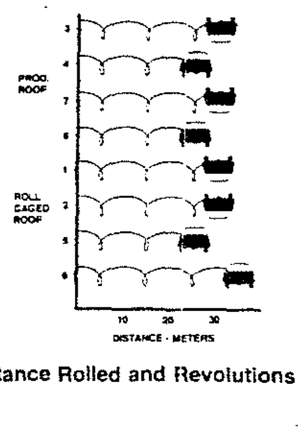

Fig. 6 Distance Rolled and Revolutions

The vehicle left the dolly with a slight roll velocity of about 75 degrees per second and with little speed loss. The initial contact between the right side wheels and the ground increased the roll velocity so that when the roof first approached the ground, it was rotating at approximately 300 degrees per second. The first ground contact with the roof accelerated the rolling further so that the vehicle began to roll smoothly in a "cylinder-type" roll. Subsequently when tire and additional car corner contacts occurred, the motion became irregular. Each continuing ground contact resulted in an energy loss, so that the translational and rotational velocities were reduced as the vehicle came to rest.

The rollover characteristics of the eight rollcaged cars and eight production cars used in this and the previous study described in Reference 1 have been compared. The average distance rolled for eight production cars was 25.6m (84 ft.), compared with 27.1m (89 ft.) for the eight rollcaged cars. The production cars rolled an average of 3.2 rolls, compared with 3.5 for the rollcaged cars. Differences in roof stiffness appeared to have little effect on the distance rolled and the number of rolls.

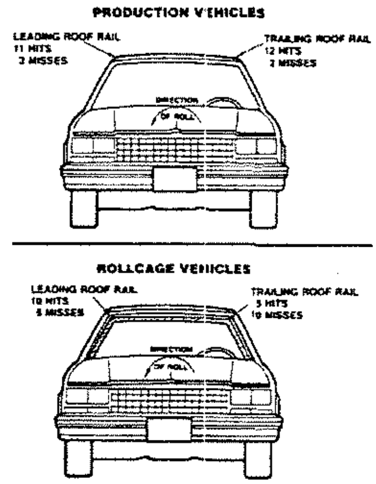

Fig. 7 Comparison of Roof-to-Ground Impacts For Production vs. Rollcage Vehicles

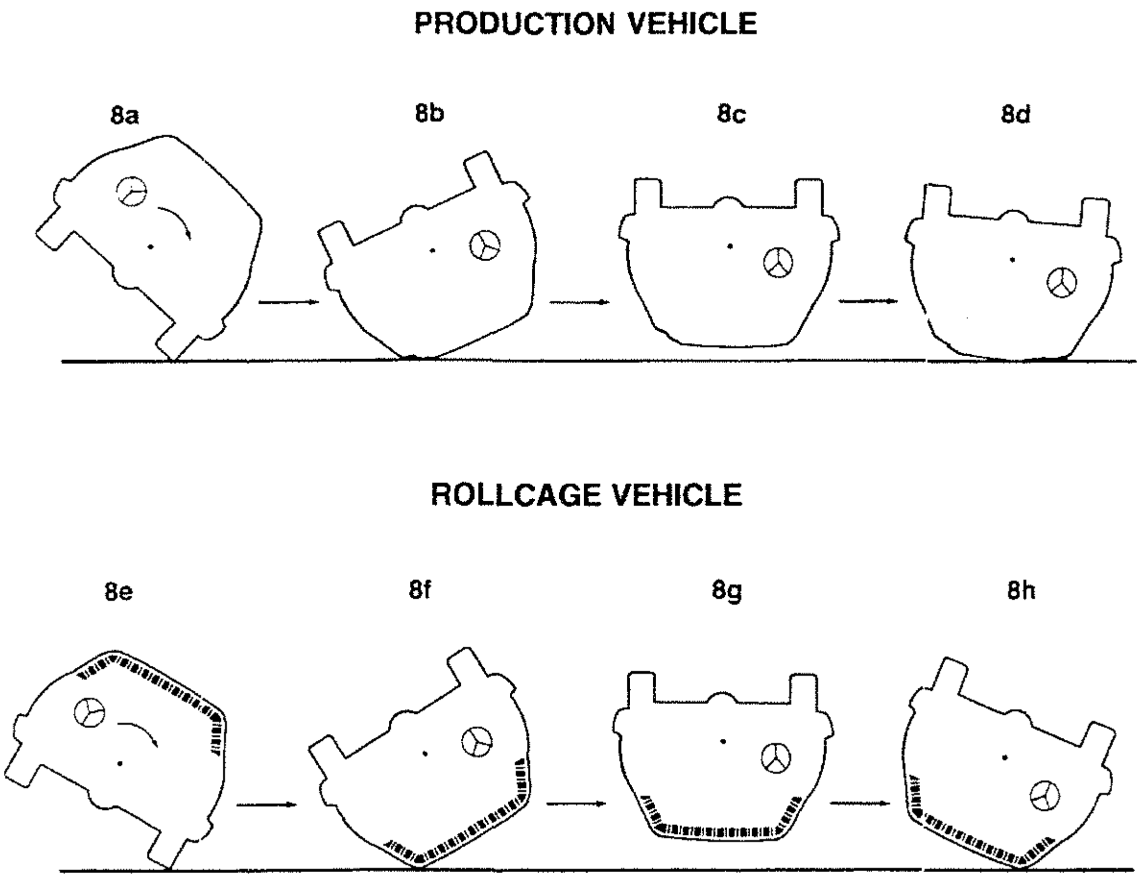

Fig. 8 Kinematic Comparison of Roll Dynamics - Production vs. Rollcage Vehicle

Although the basic rollover kinematics of the rollcaged and production vehicles were similar, the difference in roof stiffness led to significant differences in the number of roof impacts and their severity. The terms "leading" and "trailing" were used to describe the sides of the roof which have first and second exposure to ground contact as the vehicle rolls. The passenger side of the roof was the "leading" roofrail, and the driver side was the "trailing" roofrail because the passenger side approached the ground first and the driver side followed.

In these eight rollover tests, the trailing roofrail struck the ground more than twice as often for the production cars than the rollcaged cars, illustrated in Figure 7. The reason for the significantly higher number of trailing roofrail ground impacts of the production cars is illustrated in the vehicle kinematics of roof crush, as shown in Figure 8. As the typical roll began, for both type vehicles, the leading rail contacted the ground. For the production cars, Figure 8b, this caused more deformation to the leading rail than in the rollcaged cars. The difference in leading rail deformation between the production and rollcaged roofs resulted in the rollcaged car rolling higher above the ground. (Figure 8c and 8g). As its trailing rail approached the ground, this change in elevation, combined with the vehicle geometry, usually resulted in the trailing rail lightly striking or missing the ground in the rollcaged car (Figure 8h), whereas, for the production car, it usually struck the ground with greater severity (Figure 8d). This slight change in elevation of the inverted vehicle resulted in a substantial increase in the velocity and duration of the roof-to-ground impact of the trailing roofrail of the production vehicle as compared to the rollcaged vehicle.

Figure 9 shows how roll height affects the orientation of the roof at ground impact. In the case of the rollcaged vehicle, this orientation results in a reduced resultant velocity at impact or possibly no ground contact at all. In these tests, slight differences in the vehicle height above ground resulted in major differences in the frequency and severity of the trailing roofrail impacts.

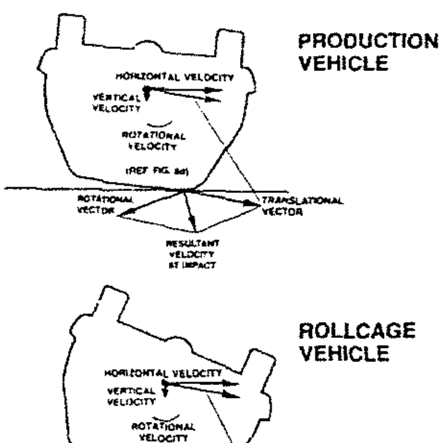

Fig. 9 Roof Rail Impact Velocity as a Result of Vehicle Orientation at Impact

Differences in ground surface, terrain, vehicle geometry, and rollover mechanics in field collisions cannot be directly represented in these test results. Accordingly, the correlation of this trailing roofrail phenomenon to actual field collisions may be limited.

DOLLY TEST RESULTS – DUMMY KINEMATICS

The movement of the dummies was documented by four on-board cameras. Three covered the area above the seatbacks, and one showed the interaction of the dummy buttocks with the seat cushion. Each seat cushion was equipped with a string potentiometer that measured its vertical deflection as a result of dummy buttocks contact.

During the airborne phase of the rollovers, centrifugal force nearly always dictated the position of the dummy. Rotational velocities on the order of one revolution per second were consistently observed by the end of the first revolution. As a result of this rotational velocity, dummies moved upward and outward to the extent which the lapbelt and vehicle side interior would allow. They tended to remain with their heads adjacent to the outboard roof siderail while constrained by the lapbelt and door and moved away from that point only by vehicle-to-ground impacts. In the majority of near side roof-to-ground impacts, the dummy remained in essentially its same orientation and struck the roof with its head as the roof struck the ground. For impacts where the occupant was opposite the impact point, the occupant movement was towards the impacted side of the car. For right wheel impacts, the driver dummy pelvis moved laterally inboard to the extent which the lap belt allowed and the torso leaned laterally out of the shoulder belt. The passenger leaned against the adjacent right door with little additional restraint from the safety belt.

The on-board camera documenting the relative position of the dummy buttocks to the seat cushion and the seat displacement measurements showed that the dummys' buttocks lifted off the seat cushion early in each test and never returned to the original depressed seat position until the test was completed. The dummy kinematics were controlled primarily by the tension of the lapbelt across the pelvis and the interaction of the dummy with the sides of the vehicle interior. The seat cushion and seatback had little, if any, effect on the overall dummy kinematics.

DOLLY TESTS RESULTS – DUMMY MEASUREMENTS

The Hybrid III dummies measured head accelerations and neck loads. In each test, there were repeated head impacts, but there were no significant impacts observed to any other parts of the belted dummies. No significant HIC numbers were measured in any of the eight tests, so the only test-to-test comparison was based upon the neck loads. In order to evaluate the relative performance of the two roof configurations, neck axial compression was selected as the common measurement. The performance of the two vehicles was studied by comparing the number of "potentially injurious impacts" (PII) measured by the dummies. A PII was defined as any impact causing an axial neck load of 2,000 N or higher. This level of impact was used as a criterion of potential injury to compare the performance of the two roof configurations. It is not the intent of this report to state that these impact levels would result in a particular injury.

Figure 10 illustrates the location and frequency of the potentially injurious impacts measured in rollovers in the two types of cars. The four production cars had 22 PII's averaging 5,168 N. The four rollcaged cars had 18 PII's averaging 3,388 N. Figure 11 shows neck axial loads for the passenger and driver in all eight tests.

As seen in Figure 10, there were many more PII's to the trailing roofrail of the production car than the rollcaged car. This was because the four production cars had the trailing roofrail strike the ground 12 times while the four rollcaged cars had the trailing roofrail strike the ground only five times as shown in

Figure 7 (with three of those very light contacts). When PII's from other impacts (interior vehicle impacts where the dummy head is not in the area of ground impact) are added, there are 15 driver PII's for the production vehicle averaging 5880 N and four driver PII's averaging 3663 N for the rollcaged vehicles. This higher frequency and severity of neck loads to the driver dummy in the production vehicles was the result of the increased number and severity of trailing rail-to-ground impacts, as explained previously in the vehicle kinematics section.

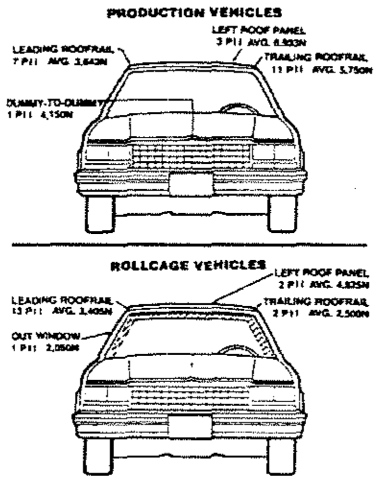

Fig. 10 Location & Frequency of the Potentially Injurious Impacts PII = Neck Axial Load 2,000 N. or Higher

The passenger dummy in the production vehicles had half as many PII's (7) averaging 3643 N as the passenger in the rollcaged vehicle (14) averaging 3309 N.

To analyze the effect of roof strength on neck loading, comparable driver dummy impacts were identified. The last one-half roll of Test 2 (rollcaged) and Test 3 (production) showed very similar roof-to-ground impacts, with the production car having significant roof crush. In the rollcaged car, which had no roof deformation, the driver dummy had an axial neck load of 5,600 N (impact 2L1)*. In the production roof vehicle, which had approximately 280mm of roof crush, the driver dummy had an axial neck load of 4,700 N (3L5). In both instances, the dummies were in very similar positions, the roof-to-ground impacts were of similar severity, with ground impact velocities of 10km/h (6.2mph) for the rollcaged car and 11km/h (6.8mph) for the production car. The neck loads were also similar despite the roof crush. Photo analysis of this impact reveals that the neck load measured by the dummy occurred when the roof hit the ground and the dummy head was on the inside of the roof panel. The roof crush which is seen in the films is actually the vehicle body moving closer to the roof, which occurred after the peak force on the neck; consequently, this deformation had no effect on the severity of the head-to-roof impact. Figure 12 illustrates that the dummy neck loads occurred prior to vehicle roof crush.

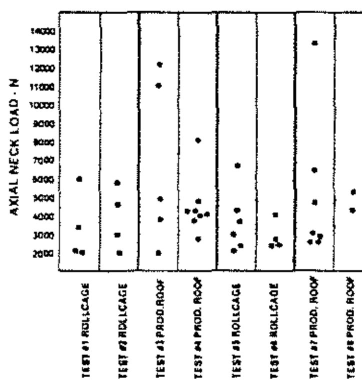

Fig. 11 Passenger and Driver Neck Loads for the Eight Rollover Tests

The PII's with relatively high loads in the production roof tests were studied using film analysis in conjunction with instrumentation data to determine when the loading was experienced by the dummy. This analysis confirmed that the peak load occurred at the roof-to-ground impact prior to the roof deformation. There was no evidence in any of the tests of the dummy having higher neck force due to being compressed between the seat and the roof.

The highest neck load measured in any test was 13,200 N (7L4) in a production roof car which had a ground impact causing extensive roof crush. Figure 13 illustrates two important facts of the dummy-to-roof collision as seen in this impact. First, the load on the dummy neck is the result of the dummy head stopping against the roof when the roof is against the ground. When the dummy head stops, the dummy torso continues to move toward the head, causing high axial forces in the neck. The neck measurements indicate that the peak of the force pulse occurred approximately 10 ms after the adjacent roof panel struck the ground, which was before any significant roof crush occurred. The overall roof crush took approximately 150 ms and had no effect on the neck load. Second, the only effect which roof crush had was to reduce the volume of the occupant compartment and allow the seat cushion to get closer to the ground. There was no compression of the dummy between the seat and the roof as evidenced by the fact that the dummy buttocks were off the seat during the entire event.

DOLLY TEST RESULTS – EFFECT OF SAFETY BELTS

In each of these rollover tests, the safety belt on the dummy was adjusted to duplicate the inverted head position which was measured on human volunteers. The on-board cameras documented the effect of the three-point safety belts on the dummies. The general kinematics were such that centrifugal force moved the dummies upward and outward in the vehicle until the lapbelt restrained the pelvis, but after it had lifted off the seat. This allowed the dummy head to be adjacent to the outboard roofrail.

Comparison of the previous eight tests in the unbelted dummy series (Ref. 1) with the belted series of this study demonstrates the benefits of belt usage. First, ejection was eliminated. Second, the projected impact where the dummy is thrown from one side of the car to the other was eliminated, except for one instance where the driver dummy head hit the shoulder of the right front dummy. Overall, the eight belted rollover tests in this series had a reduction of the number of PII's but an increase in their average severity compared with the eight tests in the unbelted series. The unbelted dummies measured 54 PII's averaging 3,496 N compared with 40 PII's averaging 4,367 N for the belted dummies. One reason that this reduction in the number of PII's was not greater was that the combination of vehicle rotation and pelvic restraint by the lap belt maintained the dummy in an upright position so when a ground impact on the adjacent roofrail occurred, there was an increased likelihood of measurable head and neck load. This positioning of the lapbelted dummy, in conjunction with the trailing rail phenomenon contributed to a higher number of dummy head and neck loads. In contrast, the unbelted dummies reported earlier (Ref. 1) were constantly changing

*For this study, a code was used to designate each dummy impact. In "2L1", the "2" refers to Test 2, "L" means the driver dummy, and "1" refers to the first potentially injurious impact to the left dummy.

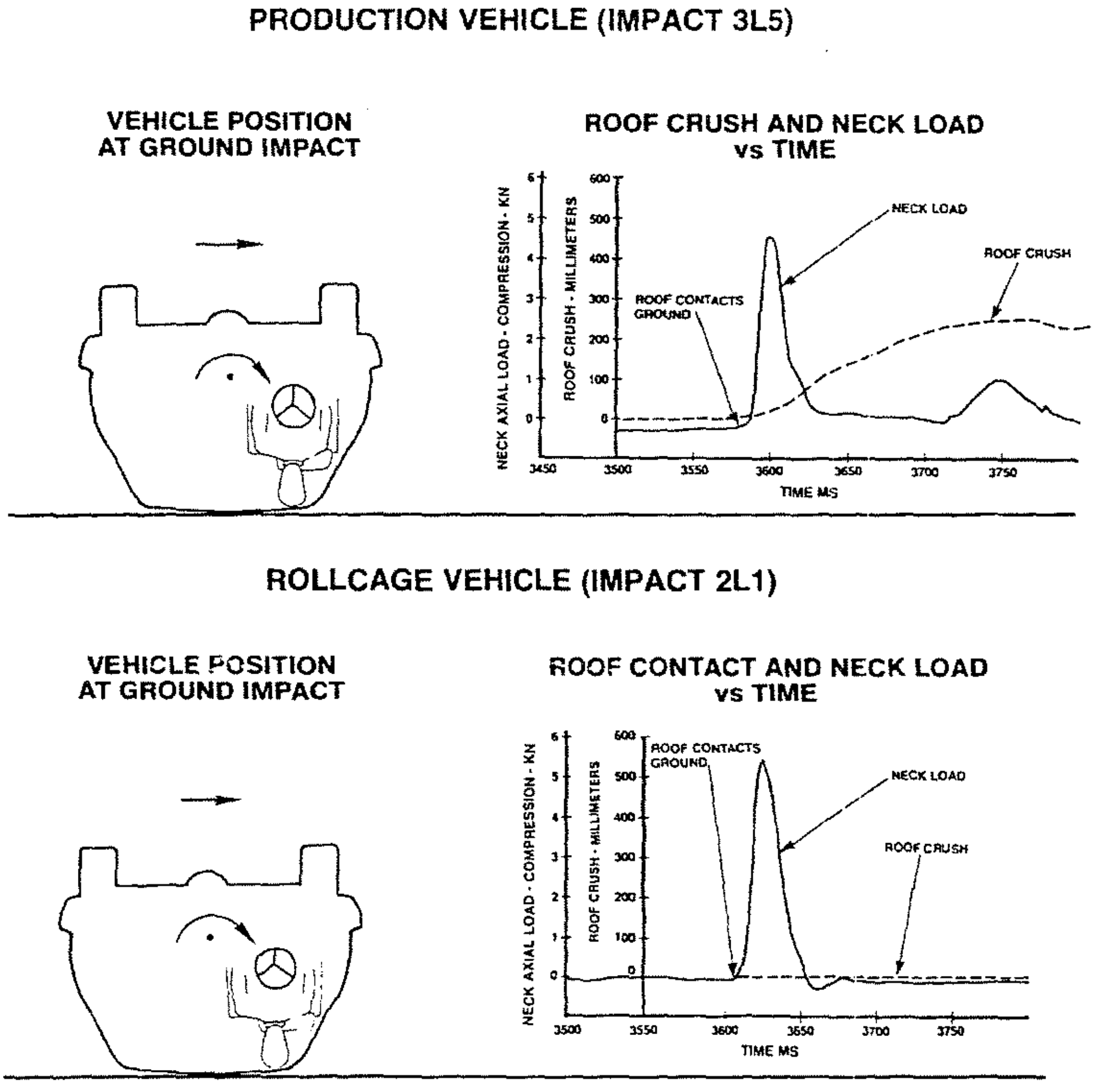

Fig. 12 Roof Crush and Neck Loads vs Time

their positions relative to the vehicle interior. As a result, when a roof impact occurred, the unbelted dummies were often oriented in a position other than with their heads in line with their torsos toward the roof, so no PII occurred. Although one might expect the belted series to have lower neck loads due to restriction of dummy movement by the lapbelt, there is a counteracting effect of the safety belt which maintains the dummy in a more upright orientation relative to the vehicle. As a result, ground impacts to the roofrail are more likely to result in more frequent axial neck loads than would occur to the differently oriented dummies in the unbelted series.

The outboard portions of the lapbelts were equipped with force transducers. The lapbelt loop load ("loop load" estimated as twice the outboard belt load) averaged 1,399 N during roof-to-ground impacts. The highest load measured was 4,240 N in impact 4L4 when the right wheels impacted the ground and the driver dummy was projected into the passenger dummy. In most cases, high neck loads and high belt loads were unrelated. Also, when both occurred in the same time frame, the peak neck load typically preceded the peak belt load indicating that the pelvis and lower torso were being restrained later and independently without significant effect in reducing neck load. The average lapbelt loop load measured in the rollcaged cars was 1,665 N compared with 1,374 N for the production roof cars.

The shoulder belt did not substantially change the dummy kinematics because these were lateral rollovers resulting in dummy movement generally in a plane lateral to the vehicle longitudinal axis. The lapbelt adjustment was observed as unchanged after each test and there was no evidence of shoulder belt extension.

INVERTED VEHICLE DROP TESTS

In the eight rollover tests, there was little repeatability in the precise occupant impacts. From test to test, there were always changes in vehicle angle and velocity and dummy position, so that no two dummies were exposed to precisely the same impact. In order to isolate repeatable roof impacts, vehicles containing dummies were dropped on their roofs at a carefully controlled angle and height.

DROP TEST PROCEDURE

Four drop tests with four combinations of vehicles and dummies were conducted. Two rollcaged vehicles were dropped, one with and one without safety belt usage, and two production vehicles were dropped, one with and one without safety belt usage. The cars were all 1983 Chevrolet Malibus. The dummies, rollcage, and belt adjustments were identical to those used in the rollover tests. For the unbelted drop tests, the dummies were allowed to free fall from the inverted seated position at the same time the vehicle was dropped. The cars were suspended 12 inches above a concrete floor with a 0 degree pitch and a 20 degree roll angle between the plane of the inverted roof and the ground. All of the cars were dropped with the driver dummy in the area of roof-to-ground impact and the right front dummy remote to the point of impact, as shown in Figure 14. One layer of 3/4 inch plywood was placed on the concrete surface to prevent damaging the laboratory floor.

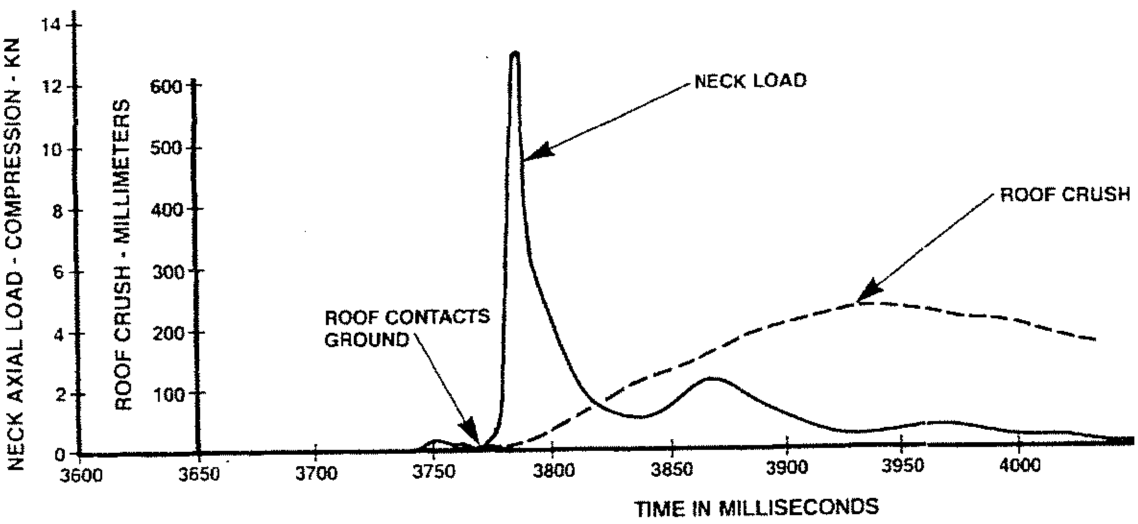

Fig. 13 Roof Crush and Neck Load vs. Time Driver Impact 7L4

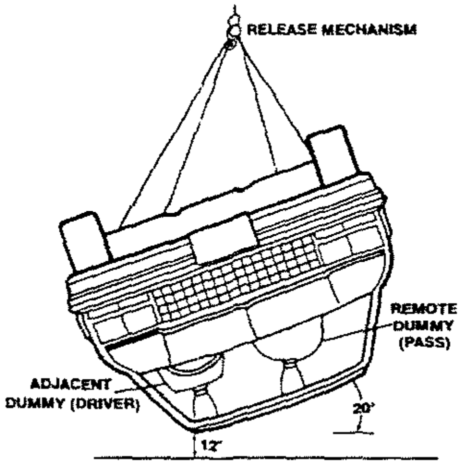

Fig. 14 Vehicle Drop Test

DROP TEST RESULTS – VEHICLE KINEMATICS

In all tests, the vehicles impacted the floor at the correct orientation with no change in roll or pitch as a result of the drop release. The roof velocity at impact was 8 ft./s.

The rollcaged vehicles had no perceptible crush on impact. Instead, after the initial ground impact of the driver's roofrail, they rebounded from the floor slightly and rotated and then fell flat to rest upon the roof. Due to the stiffness of the roof, there was a high rate of velocity change at points on the roof remote from the point of impact due to the absence of crush and subsequent ride down.

In the production vehicles, there was significant roof crush beginning on the driver roofrail and spreading in a contact patch across the roof. (The term contact patch is used here to describe the area of contact between the roof panel and the ground.) Photo analysis showed the roof crush to be a result of both vertical and horizontal movement of the vehicle body relative to the roof panel. In each case, the roof panel remained stationary relative to the ground and the pillars bent. There was a force component directed through the pillars to the vehicle body, causing it to displace laterally relative to the stationary roof panel. When uprighted, the roof panel appeared to have been displaced inboard and down relative to the car body. In reality, it was the vehicle body which moved outboard left and down relative to the roof when the vehicle was dropped. In both production roof drops, the car body moved approximately five inches outboard and nine inches downward relative to the top of the driver's side A-pillar. Figure 15 shows the roof crush pattern of the uprighted rollcaged and production roof cars following the drop tests. The roof crush observed in the production roof vehicles in these drop tests was greater than seen in most of the roof-to-ground impacts in the dynamic rollover tests. One of the reasons is that, in the rolling vehicle, the roof corners typically have a limited amount of time for ground contact, as shown previously in Figure 9. In the rollover tests, usually the roof corner remained in contact with the ground for only about 1/8 roll, or approximately 125 ms, limiting the amount of energy that can be absorbed through crush. Conversely, in the drop tests, there is no limit to the amount of time the roof is exposed to ground impact, so all of the potential energy is absorbed by the roof.

DROP TEST RESULTS – OCCUPANT KINEMATICS

The four test conditions of the rollcaged-belted, rollcaged-unbelted, production-belted, and production-unbelted offers many comparisons regarding the effects of roof crush and belts on dummies in the area of and remote to the point of impact. Figure 16 shows the axial neck loads and concurrent belt loads which were measured under these four test conditions. (There were actually five drops conducted. The rollcaged car with belted dummies was dropped twice due to a suspected camera malfunction on the first drop. The double data for the rollcaged-belted drop in Figure 16 reflects both drops.)

Due to the 20-degree roll angle of the car prior to each drop, there was a difference in the positions of the passenger and driver dummies relative to the roof panel. The driver dummy which was on the low side of the car, hung with the side of its head against the roof siderail and the top of its head against the roof panel. The passenger dummy hung at approximately 20 degrees toward the vehicle midline, leaving 1/8 inch clearance or less between the top of the head and the roof panel.

In the belted test, when the drop occurred, the dummies moved upward relative to the car i.e. toward the seat, due to elastic springback of the lap belt against the mass of the falling dummy, and then fell at the same velocity as the car. In the unbelted tests, the dummies fell at the same velocity as the vehicle.

In all tests, the neck loading resulted from the dummy head being in contact with the inside of the roof panel when the roof panel stopped due to ground contact. Dummy torso loading through the neck resulted in the axial compression loads.

In the rollcaged cars, both the adjacent and remote dummies had significant neck loads due to the initial velocity change of the rigid roof, and they had no secondary impacts. In the production roof cars, the dummy kinematics were more complex. The roof crush had no effect on the head impact velocity of the driver dummy because its head struck the inside of the roof panel just as in the rollcaged car. However, the subsequent lateral movement between the vehicle body and the roof allowed the driver dummy torso more leftward movement relative to its head, which may account for the reduction in the

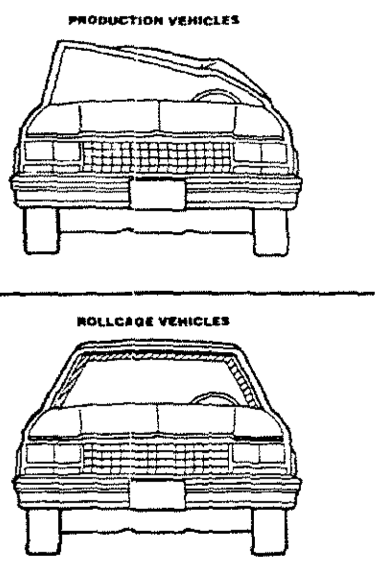

Fig. 15 Roof Crush Pattern of Production and Rollcage Vehicle After 12" Drop Test

axial neck load. The right front dummy in the production cars initially had a reduced axial neck load as a result of the longer impulse afforded by the ridedown of the crushing roof. Later, however, a second neck load was measured by the remote dummy when the roof-to-ground contact patch spread to its side of the roof, and the portion of the roof in the area of its head came in contact with the ground.

Each of these drop tests was filmed to study contact between the dummy buttocks and the seat cushion. In all of the tests, there was never any displacement of the seat cushion, either measured or observed, to the extent of a normally depressed seat. The dummy neck load was always solely due to arresting its own momentum without any load from the seat.

DROP TESTS – EFFECTS OF ROOF CRUSH

Similar neck loads were observed in the production and rollcaged vehicles for the unbelted driver dummies seated in the area of impact. This was not true for the belted driver dummies. The driver dummy in the production vehicle had significantly lower neck loads than the dummy in the rollcaged vehicle. Overall, in these drop tests, roof crush did not appear to adversely affect the neck loads to the unbelted or belted dummies which were seated in the area of impact.

When neckloads of the passenger side dummy remote from the point of impact were compared, differences were observed. The unbelted passenger in the rollcaged roof car immediately received an axial neck load (4100 N) although the head was remote to the point of impact. This was due to a higher velocity change of the entire roof panel. In comparison, the unbelted passenger dummy in the production roof experienced a significantly lower initial neck load (2300 N) due to the roof crush. However, it experienced a second impact (2400 N) when the roof-to-ground contact patch spread to its side of the car.

For the belted passenger dummy, again the production roof ridedown reduced the initial impact neck load (1000 N) versus an average of 2885 N for the rollcaged cars but resulted in a higher neck load (4230 N) when the contact patch reached the remote side. Roof crush reduced the neckload during the ridedown phase but increased the neck load when the spreading contact patch caused roof-to-ground impact in the area of the dummy head.

DROP TEST – EFFECTS OF SAFETY BELTS

The driver dummy in the rollcaged car had similar neck loads whether belted or not belted (6915 N belted versus 7070 N unbelted). In the production roof car, the belted driver dummy received a lower axial neck load than the unbelted driver dummy (4750 N versus 6650 N).

In the rollcaged car, the belted-passenger dummy had lower neck loads than the unbelted-passenger dummy (2885 N versus 4100 N) and had the highest belt loads of any test. It appeared that the added head clearance of the remote dummy leaning towards the center of the roof allowed the belts to reduce the neck load compared to the unbelted dummy.

Comparing the effect of belts versus no belts for remote occupants in production cars gives confusing results. The unbelted passenger dummy had two significant neck loads: First, at the initial impact of the roof to the ground and, second, when the contact patch of the roof crush spread to its side of the vehicle. This resulted in neck loads of 2300 N and 2400 N, respectively.

The belted dummy under these test conditions had a lower initial neck load due to the combination of belt restraint and the ridedown of the roof panel due to the roof crush. However, when the roof crush contact patch reached its side of the vehicle, the passenger dummy experienced a neck load (4230 N). Overall, it appears that the belt provides some benefit during the ridedown phase as long as the contact patch does not spread to a point in the area of the dummy head. At that point, the belt no longer has a significant effect in reducing neck loads.

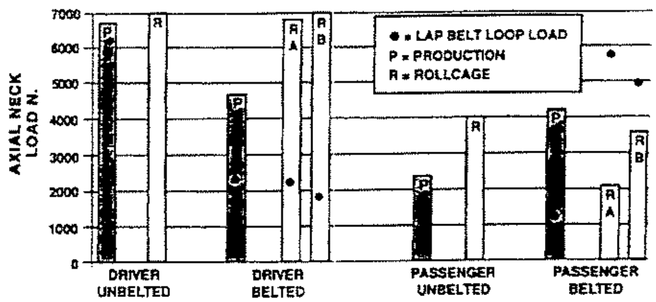

Fig. 16 Axial Neck and Seat Belt Loads for Drop Tests

DROP TEST CONCLUSIONS

1. The dummy at the point of ground impact (driver) always had a significantly higher neck load than the dummy remote to the point of impact (passenger), with the exception of the belted dummy driver in the production vehicle where the load was only slightly higher.

2. The comparison of neck loads between rollcaged and production vehicles in this test series is as follows:
   - A. The unbelted dummy remote to the point of impact in production vehicle had significantly lower neck loads than the dummy in the rollcaged vehicles.
   - B. The belted dummy remote to the point of impact in the production vehicle had significantly higher neck loads than the dummy in the rollcaged vehicle.
   - C. The unbelted dummy at the point of impact in a production vehicle had essentially the same neck loads as the dummy in the rollcaged vehicle.
   - D. The belted dummy at the point of impact in a production vehicle had significantly lower neck loads than the dummy in the rollcaged vehicles.

3. In production vehicles for the dummy remote to a point of impact, the safety belt helped reduce neck load as the ridedown from roof crush occurred. However, a higher neck load was measured later in the impact as the roof-to-ground contact patch spread to the remote side of the car.

4. Inverted vehicle drop tests isolate specific principles of dummy-to-roof interaction but fail to incorporate the continuously rolling motion of the car during actual rollover collisions.

SUMMARY

VEHICLE KINEMATICS

The rollcaged and production roof vehicles rolled essentially the same distances with the same number of rolls. The number of roof-to-ground impacts on the production vehicles was much greater due to roof/ground interaction differences.

DUMMY KINEMATICS

Hanging upside down, a belted 50th percentile male has his head against the roof. The centrifugal force of rollovers tends to maintain the belted occupant erect with his head upward and outboard.

NECK INJURY MECHANISM

Neck loads resulted from "diving" type impacts where the head stops and the torso momentum compresses the neck, with the magnitude proportional to the impact velocity. Roof deformation never caused the dummy to be compressed between the roof and seat.

Safety Belts

Safety belts prevented both ejections and projected impacts with the vehicle interior in the dolly rollover tests. Safety belts did not result in reduction of head/neck loads for dummies in the area of ground impacts.

Rollcaged vs. Production Cars

The dummies in both production and rollcaged vehicles had numerous potentially injurious impacts. The driver in the rollcaged vehicles had fewer potentially injurious impacts than the driver in the production vehicles. This was due primarily to the fact that the production vehicles had 53 percent more roof rail-to-ground impacts than the rollcaged cars. The passenger in the production vehicles had fewer potentially injurious impacts than the passenger in the rollcaged vehicles. Overall, the dummies in the rollcaged vehicles had a lower number of potentially injurious impacts and a lower average neck load than the dummies in the production vehicles. Under similar roof rail-to-ground impacts, there was no increase in level of protection in the rollcaged vehicles over the production roof vehicles.

The absence of deformation may benefit belted occupants if it results in the belted occupant not contacting the roof. The reduction of roof deformation in the rollcaged vehicle had no effect in reducing neck loads for the dummies in the area of ground impact.

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