ROLLOVER EJECTION MITIGATION USING AN INFLATABLE TUBULAR STRUCTURE (ITS[a])

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ABSTRACT

The National Highway Safety Administration (NHTSA) and Simula Automotive Safety Devices (ASD-Simula) are conducting a joint research program to evaluate the effectiveness of the Inflatable Tubular Structure (ITS[a]) in mitigating ejection during rollover crashes. This research program involves full scale dynamic testing, component testing, simulation, and crash case reviews. All aspects of the program will be analyzed to evaluate the safety potential for ejection mitigation. The preliminary tests show that the ITS can be highly effective in mitigating complete occupant ejection, but cannot prevent arm ejections in rollover crashes.

INTRODUCTION

The ITS is a roof mounted inflatable safety device intended to provide head and neck protection in side impact crashes. When deployed, the ITS covers up a portion of the side window of the vehicle. Unlike conventional air bags, the ITS remains inflated for many seconds, well longer than the typical duration of a rollover crash. Due to its special configuration, the ITS does not require a reaction surface to function and retain the occupant inside the vehicle.

On average, annually 7,741 rollover involved fatalities were reported by the Fatal Analysis Reporting System (FARS) between 1988 and 1996. There were also between 43,000 and 58,000 annual rollover involved incapacitating injuries for the same time period, as reported by NASS GES. Approximately 59 percent of the rollover fatalities came from the 10 percent of the rollover involved occupants who are ejected, or partially ejected from the vehicle. Of these rollover involved ejections, 56 percent of the fatalities, and 49 percent of the seriously injured occupants, are ejected through the side windows. Significant safety improvement can be established by reducing ejection through side windows. Considering all accident types, an average of 7,741 people are killed, and 9,211 people are seriously injured each year in passenger car, light trucks, and vans in crashes involving ejection through side windows (NASS CDS 1988-1996).

The significant potential safety benefit is the impetus for the effort to find a device mitigating side window ejection.

SYSTEM DESCRIPTION

General

The ITS distinguishes itself from conventional air bag restraint systems in several critical areas. Basically, it is a fabric tube rigidly mounted at each end. Upon inflation, the patented design and construction method cause the tube to significantly increase in cross-section or diameter, while at the same time significantly shortening its length. Consequently, the ITS pulls itself from its stored location into the desired occupant restraint position while developing high tensile loads between its mounting locations. Because of the high tensile loads and internal pressure, the ITS provides significant restraint without relying on a bearing surface.

In order to function properly, the ITS must get shorter in length, since the stowed length, in all applications, L_o, is longer than the deployed length, L_i . The ratio of deployed length L_i to stowed length L_o is one of the most critical functional parameters of the ITS and is called the slack ratio. This shortening function is accomplished by using a specially woven fabric which significantly contracts in length and increases in diameter as internal pressure is realized (Figure 1). During the pressure build-up, an axial tension force is developed, since the fixed endpoints prevent the ITS from contracting freely.

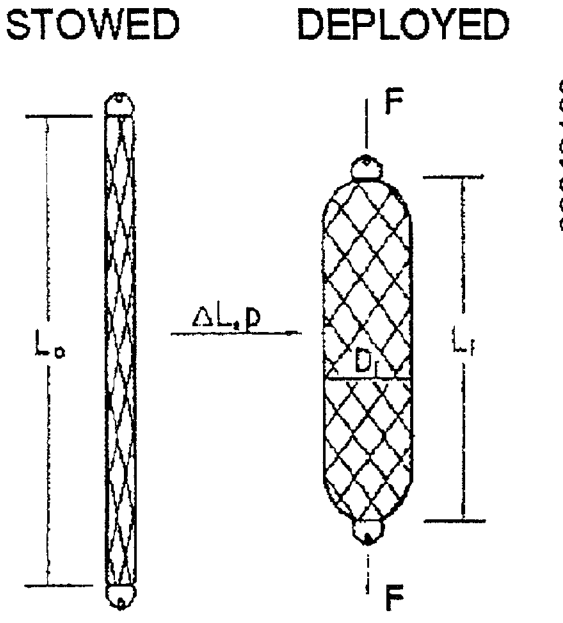

Figure 1 - Inflatable Tubular Structure principle of operation

The development of appropriate pressure and axial tension enable the ITS to perform its two main functions:

1) In the absence of a bearing surface, the tension indirectly provides the reaction forces. This way, the ITS can prevent the occupant's head, torso, or legs (depending on the application) from moving into a crash intrusion zone, i.e., reducing the hazard of the occupant's hitting internal and external objects.

2) The pressurized, inflated ITS provides a cushion to blunt the impact and provide the normal restraint function of controlling occupant deceleration.

Unlike conventional air bags, which deflate in less than 100 ms from the start of deployment, the ITS is not vented. Since the pressure of the ITS is well over 1 bar, the relatively slow reduction in gas volume due to cooling allows the ITS to provide protection for several seconds.

One of the main applications is for side impact crashes. In this application, the Inflatable Tubular Structure (ITS) is intended to provide protection to the head and neck of car occupants in a side impact and in multiple-impact crashes and to reduce the chance of ejection in roll-over crashes.

System Description

The ITS is fixed to the "A" pillar at one end and to the roof rail aft of the "B" pillar at the other end, as shown in figure 2. A gas generator is electrically connected to a side-impact crash sensor which ignites the gas generator if the impact intensity exceeds a predetermined level.

The detailed packaging and the specific location of the gas generator are vehicle-dependent to facilitate optimum integration. The gas generator fills the tubular structure with gas. As the tube inflates, it gets bigger in diameter and shorter in length (Figure 3), and pulls itself out from under the headliner (not shown in Figure 2). The ITS positions itself between the head of the occupant and the side of the vehicle and any intruding objects.

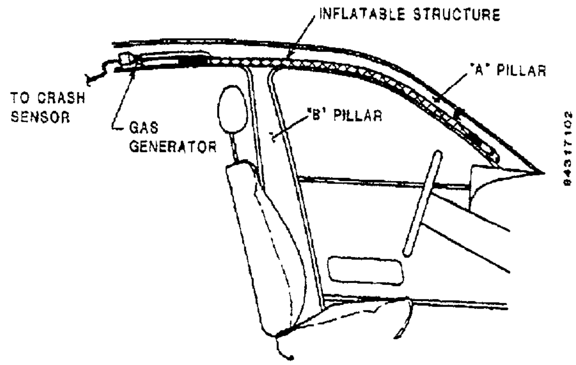

Figure 2 – Inflatable Tubular Structure in a stored position

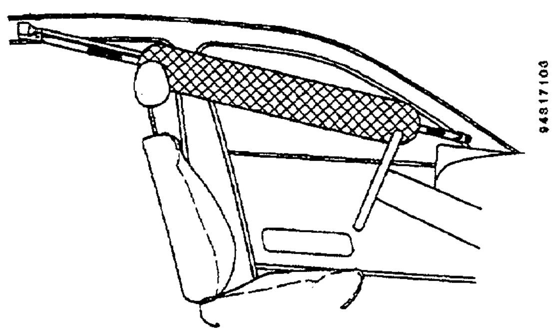

Figure 3 – Inflatable Tubular Structure in a deployed position

The location of the ITS end points at the "A" pillar and the roof rail determine the protection zone of coverage. The position and the orientation of the ITS were selected to protect a wide range of occupant sizes. Figure 4 shows how both 5th-percentile and 95th-percentile occupants would be protected without the need to perform any adjustments to the ITS.

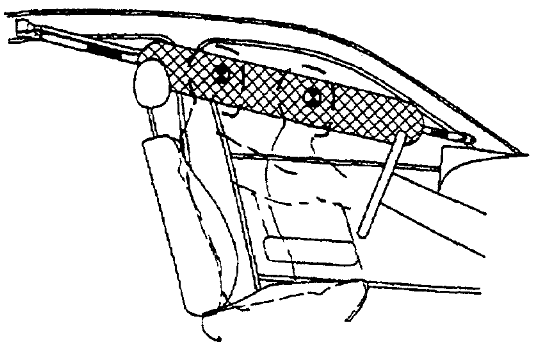

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Figure 4 – Inflatable Tubular Structure Protection for 5th through 95th percentile occupants

FMVSS 208 DOLLY ROLLOVER TESTS

Test Methodology

Three dolly rollover tests were conducted per FMVSS 208 criteria using one 1993 and two 1994 Ford Explorers. In this test, the vehicle is held tilted at an angle of 23 degrees and is slid in a transverse direction along the test track. The dolly has an initial velocity of 48 kph (30 mph) and is rapidly decelerated to initiate the vehicle rollover. Each vehicle was launched from the dolly fixture into a lateral roll with the left side (driver) down (see Figure 5). This test method was chosen because it was most likely to produce an occupant ejection.

Each vehicle was equipped with ITS devices adjacent to both front passenger seating positions. The doors were locked and windows rolled down prior to testing. The first two tests utilized two unbelted Hybrid-III dummies in the front seating positions. The passenger side dummy was restrained with a lap/shoulder belt in the third test while the driver side dummy remained unrestrained. The dummies were instrumented with tri-axial accelerometers in the head, chest and pelvis, a chest deflection potentiometer, and a Hybrid III neck transducer which measures axial tension and compression, anterior-posterior shear and bending moment, and lateral shear and bending moment. The movement of the dummies was documented by 5 onboard cameras.

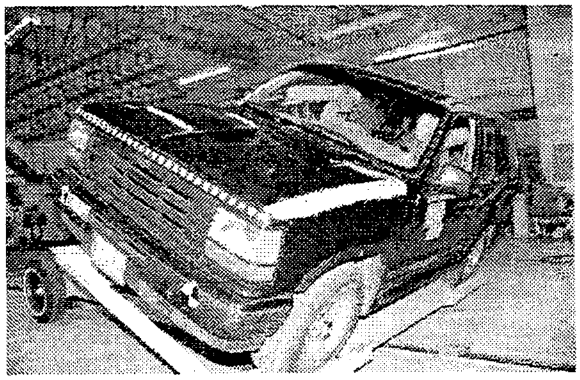


Figure 5 -- FMVSS 208 Rollover Dolly Fixture

The ITS devices were mounted to the dash panel and the rear seat belt mounts on the vehicle side header. Because the inflation time had not been evaluated for the first two tests, the ITS devices were inflated just prior to the start of the test. After analyzing these tests, a rollover sensing device was used in the third test to deploy the ITS systems, via a gas generator, at a predetermined point during the early stages of roll. The ITS devices in the first test measured 6 inches in diameter when fully inflated. The size and location of the ITS for the second rollover test were modified slightly. The front anchor points were moved inboard about 5 inches and the diameter of the ITS on the driver side was increased by 1 inch while the passenger side utilized a slightly more oval shaped device as shown in Figures 6a and 6b. In the third test, the anchor points remained the same while the ITS devices matched those of the first test.

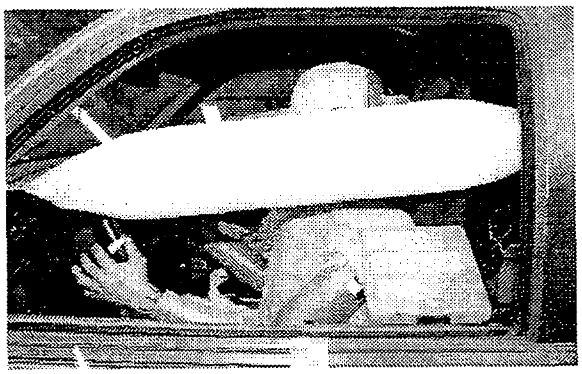


Figure 6a -- Driver Side ITS Used in Second Test

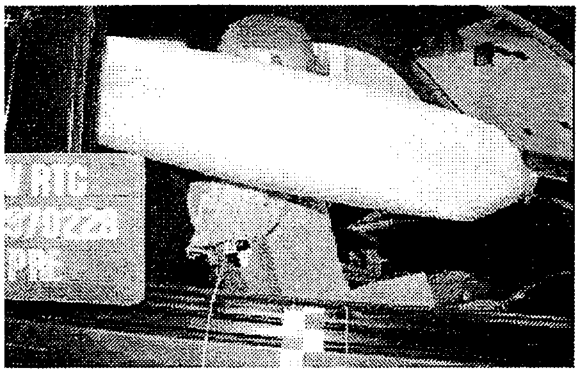


Figure 6b -- Passenger Side ITS Used in Second Test

Results of First Rollover Test

The event trigger signal was lost during the release stages of the cart resulting in lost data in the early stages of the rollover event. This also prevents knowing the event's true time zero. However, reasonable approximations of the entire event can be made by analyzing the data from the second and third tests. The test did provide excellent vehicle and occupant kinematics for evaluating the safety potential of the ITS devices. The vehicle rolled 11 quarter turns and came to rest on the passenger side. The test lasted approximately 4.5 seconds with peak roll velocities reaching 6.34 rad/sec early in the event (approximately 1.4 seconds). The driver side of the roof was exposed to the ground first followed by the passenger side.

The vehicle's rotation kept the dummies high in their seats and against the side interior throughout the entire test. The driver dummy made significant contact with the roof for an extended period of time. As the test, progressed the dummy orientated itself so the buttocks moved out the window opening. The high speed films show that significant excursion out the side window was prevented by the ITS system which reduced the open area (see Figure 7a). The passenger dummy contacted the ITS with its shoulder before impacting its head against the roof side rail. It is evident that the ITS system controlled the dummy's kinematics. Throughout most of the event, the lower arm of the passenger dummy remained out the window, below the ITS device, and made frequent contact with the ground. As seen in Figure 7b, the dummy's head was supported by the ITS, preventing movement outboard through the window.

Figure 7a -- Driver Side ITS Minimizing Dummy Excursion Out Window Opening

Although the dummies experienced repeated head impacts with the vehicle's interior compartment, no significant HIC numbers were recorded. This also applies to the chest deflection measurements. However, the high compressive axial loads recorded by the neck transducer indicate that there is a strong probability of neck injury, which is typical to unbelted occupants in such rollover events. The dummies' injury measurements are shown in Table 1 along with injury threshold values. Because of the loss of time zero in the event, it is not possible to determine from film analysis whether these high compressive neck loads occurred as a result of impacts with the ITS or the vehicle interior.

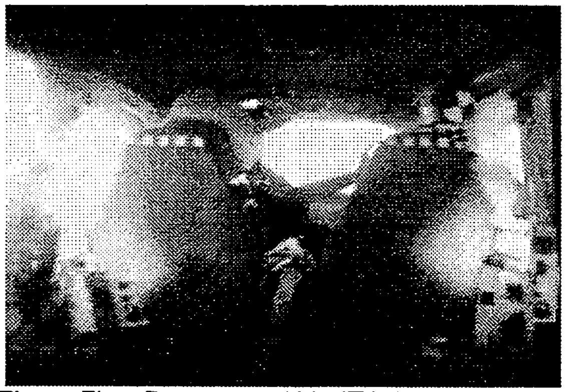


Figure 7b -- Passenger Side ITS Preventing Dummy Head Excursion Through Window

INJURY MEASURE	DRIVER	PASSENGER	INJURY THRESHOLD
HIC	26.2	19.5	1000
3 ms Chest G's	14.3	14.6	60
Chest Deflection, mm	4.6	1.4	50
Maximum Upper Neck Shear Force (fore/aft), N	365 / 561	278 / 413	1100 / 1100
Maximum Upper Neck Shear Force (lateral), N *	564	802	
Maximum Upper Neck			

Tension/Compression, N	417 / 1212	306 / 1838	1100 / 1100
Maximum Upper Neck Bending (flex./ext.), N-M	27 / 56	88 / 15	190 / 57
Maximum Upper Neck Bending (lateral), N-M *	61	44	

*No injury Criteria Exists

Table 1 -- Injury Measurements for First Rollover Test

The driver side dummy made two significant contacts with the driver side ITS. The tension was measured in the ITS webbing and is shown if Figure 8a. During the first roll, the driver's lower shoulder impacted the ITS and on the second roll, the dummy's pelvis contacted the ITS device.

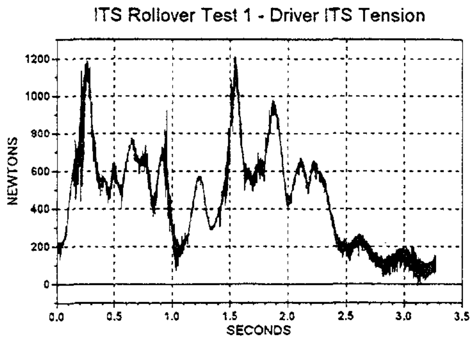


Figure 8a -- Driver Side ITS Webbing Tension

The passenger dummy's neck/shoulder region engaged the ITS throughout most of the test. The tension measurement in the passenger side ITS device is shown in Figure 8b. The tension values in both driver and passenger ITS units indicate significant loading by the dummies. This may suggest that in absence of the ITS, the dummy segments would have been moving outboard through the window opening.

From the occupant kinematics, it appeared that the desired location of the ITS was to position itself between the head and shoulder, thus limiting dummy movement towards the vehicle roof. The high speed films showed that the ITS did not remain over the middle part of the window opening but was instead positioned over the top of the opening. This allowed the dummy more vertical movement with a greater potential for high compressive neck loads. This could be attributed to loss in web tension due to roof deformation. These observations were addressed in the second rollover test.

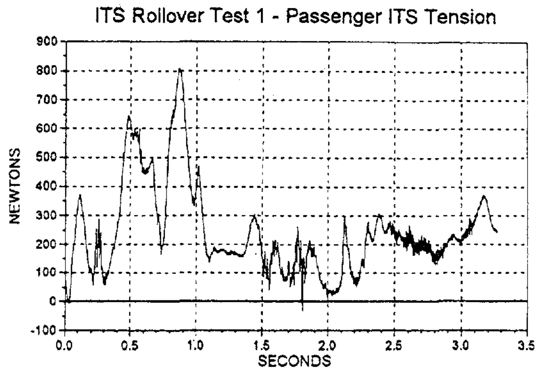


Figure 8b -- Passenger Side ITS Webbing Tension

Results of Second Rollover Test

Prior to running the second rollover test, the ITS system's front anchor points were moved inboard 5 inches to position the ITS closer to the head. This positioning is actually more in line with passenger vehicles. However, because the sides of the SUV are usually more vertical and not bent inboard as much as a passenger car, the ITS system's positioning with respect to the head was two far outboard in the first test. In addition, the system's rear anchor point was positioned 6 inches down from the roof to minimize the effect of roof deformation on the ITS tension.

The second rollover test also provided excellent vehicle and occupant kinematics for evaluating the safety potential of the ITS system. The vehicle rolled 10 quarter turns and came to rest on the roof. The test lasted approximately 6 seconds with peak roll velocities reaching 7.34 rad/sec 1.675 seconds after the roll was initiated.

As the rotational velocity developed, the unrestrained dummies left their seated position and moved towards the upper door and roof areas. Both dummies engaged the ITS system with their neck/shoulder regions. It appears as though the combination of improved inboard positioning and a larger ITS system improved the ejection mitigation capabilities and reduced the vertical movement of both dummies. However, this positioning did not prevent total vertical movement as the force of the dummies were able to move the ITS systems from the desired location over the middle of the window opening to near the top. Both dummies recorded high axial compressive neck loads at several points throughout the test. Table 2 lists the dummies' injury measurements and injury threshold values.

INJURY MEASURE	DRIVER	PASSENGER	INJURY THRESHOLD
HIC	89	43.8	1000
3 ms Chest G's	32.5	18.8	60
Chest Deflection, mm	3.7	4.5	50
Maximum Upper Neck Shear Force (fore/aft), N	245 / 168	530 / 645	1100 / 1100
Maximum Upper Neck Shear Force (lateral), N *	525	1276	
Maximum Upper Neck Tension/Compression, N	768 / 1199	522 / 5114	1100 / 1100
Maximum Upper Neck Bending (flex./ext.), N-M	12 /17	60 / 31	190 / 57
Maximum Upper Neck Bending (lateral), N-M *	80	89	

* No injury Criteria Exists

Table 2 -- Injury Measurements for Second ITS Rollover Test

The measurements indicate that there was a low likelihood of serious head of chest injury but a strong probability of neck injury. Film analysis showed that the injurious neck loads were caused by dummy contact with the vehicle roof. Figure 9 shows the vehicle's orientation along with the passenger dummy's position during which high neck loads were recorded. The vehicle's orientation is typical for many of the high neck load recordings. Film analysis shows that in the majority of ground impacts where the dummy recorded high axial neck loads, the dummy essentially remained in contact with the same part of the vehicle perimeter and simply pressed harder against it as the roof struck the ground.

High compressive neck loads also occurred where the unrestrained dummy moved laterally inboard, towards the impacted side of the vehicle, and did not gain from the restricting action of the ITS in the vertical direction. Figure 10 shows the vehicle and dummy positions for this scenario.

Throughout the test, the outboard arm of both dummies remained outside the vehicle and experienced contact with the ground on several occasions

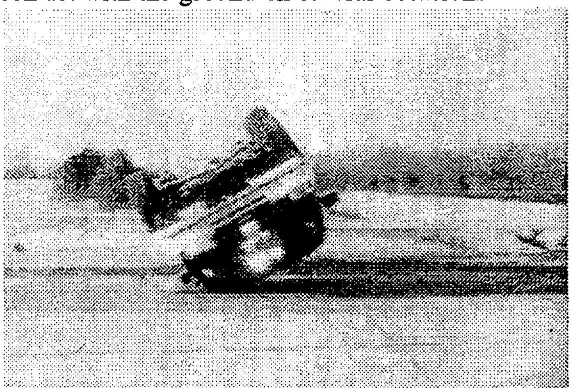
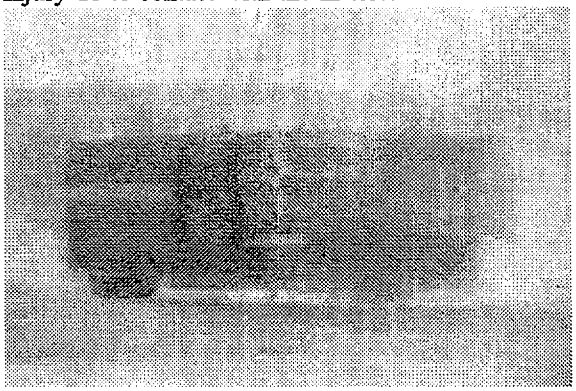


Figure 9 -- Vehicle Orientation and Corresponding Driver Side Dummy Position in Which High Compressive Neck Loads Typically Occurred

Figures 11a and 11b show the tension loads on the ITS webbing as the driver and passenger dummy interacts with the ITS. The high peak loads correspond with the dummy loading it sideways. The significant tension values on both the driver and passenger ITS units indicate a significant loading of the ITS by the dummies. This may suggest that in the absence of the ITS, the dummy segments would have been moving the window opening.

It is reasoned that if the occupant were to be held by seat belt during the rollover event, the efficiency of the ITS would be increased - allowing the ITS to support the occupant at all times, thereby mitigating not only ejection, but also further reducing injury do to contact with the interior of the car.



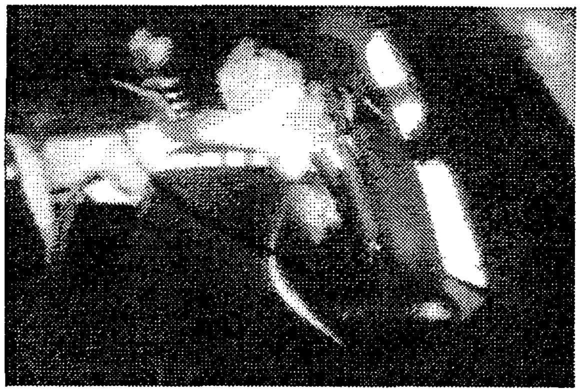


Figure 10 -- Vehicle Orientation and Corresponding Passenger Side Dummy Position in Which High Compressive Neck Loads Occurred

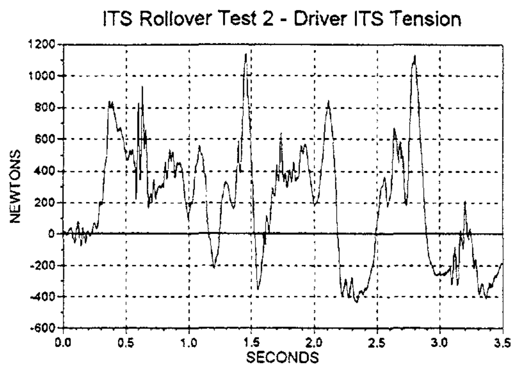


Figure 11a -- Driver Side ITS Webbing Tension

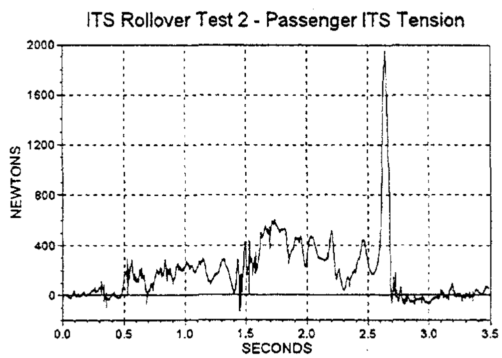


Figure 11b -- Passenger Side ITS Webbing Tension

Results of Third Rollover Test

The primary purpose of the third rollover test was to investigate the characteristics of the occupant/ITS interaction using a fully functional ITS system. A roll sensor was incorporated that initiated deployment of the ITS by means of a gas generator. The system was designed to inflate when the sensor (and therefore vehicle) rotated 35 degrees with respect to horizontal. This number was arbitrarily chosen after analyzing the films from the previous tests. At this point in the test, the dummies have not yet left their seats, nor have any body segments begun to move outboard toward the vehicle perimeter. The inflator received an external signal at 250 milliseconds as a backup precaution. Although the anchor positions were identical to the previous test, the smaller diameter ITS system was chosen for both driver and passenger. The passenger dummy was also restrained by a lab/shoulder belt.

As in the previous tests, this test provided excellent vehicle and occupant kinematics for evaluating the ITS system's safety potential. The vehicle rolled 12 quarter turns and came to rest on its wheels. Unfortunately, the angular rate gyroscope, used to measure roll velocity, failed in the early stages of the test. Analysis of the film and sensor data indicated that airbag deployment was the result of the sensor signal. Both ITS systems deployed and were in position over the window opening prior to any dummy contact.

The driver dummy lifted off the seat and moved toward the perimeter of the vehicle, constrained by the upper door and roof areas. The dummy's neck/shoulder area contacted the ITS throughout most of the test and positioned the bag over the upper area of the window opening. The passenger dummy moved more laterally towards the window opening and made contact with the deployed airbag in the neck/shoulder region and remained there for most of the test. The dummy's vertical movement was significantly reduced by the lap/shoulder belt. Both dummies' outboard arm remained outside the vehicle's perimeter throughout the test with each outboard shoulder appearing to make ground contact at various times.

The dummies' injury measurements are listed in Table 3 along with injury threshold values. As was the case for the previous tests, the rollover caused no significant head or chest injuries.

INJURY MEASURE	DRIVER	PASSENGER	INJURY THRESHOLD
HIC	138	82	1000
3 ms Chest G's	21.8	16.7	60
Chest Deflection, mm	1.8	1.4	50
Maximum Upper Neck Shear Force (fore/aft), N	352 / 762	3843 / 1046	1100 / 1100
Maximum Upper Neck Shear Force (lateral), N *	913	3379	

Maximum Upper Neck Tension/Compression, N	823 / 4703	1093 / 850	1100 / 1100
Maximum Upper Neck Bending (flex./ext.), N-M	27 / 22	33 / 3.4	190 / 57
Maximum Upper Neck Bending (lateral), N-M *	79.4	33	

* No injury Criteria Exists

Table 3 -- injury Measurements for Third Rollover Test

The driver recorded high axial compressive neck loads at several points during the test. Film analysis showed that the majority of these high loads occurred when the dummy head was in contact with the roof rail area and experienced a large force in the neck due to displacement of the vehicle structure. The passenger dummy did not experience any significant axial neck loads. This is attributed to the restraining effect of the lap/shoulder belt. However, high shear forces were recorded which were the result of severe roof crush on the passenger side.

Summary of Test Results

The three full scale rollover tests have demonstrated that the ITS has significant potential for reducing complete ejections during rollover crashes. However, there is a significant potential for arm ejections. From 1988 through 1996, NASS CDS reported an annual average of four occupants with AIS 2 or greater arm injuries due to external contact during rollover. These cases are weighted to an annual estimate of 13 rollover involved occupants with AIS 2 or greater arm injuries due to external contact. These full scale tests also demonstrated a significant potential for neck injury for non ejected occupants.

Simulation Results

MADYMO simulations were conducted for the first two rollover tests. These simulations were validated against the test results and then rerun without the ITS present to evaluate if ejection were indeed prevented.

The baseline simulations were validated to reproduce the occupant kinematics measured in the two tests. When the ITS devices were removed, all four of the unbelted occupants in the first two tests were ejected.

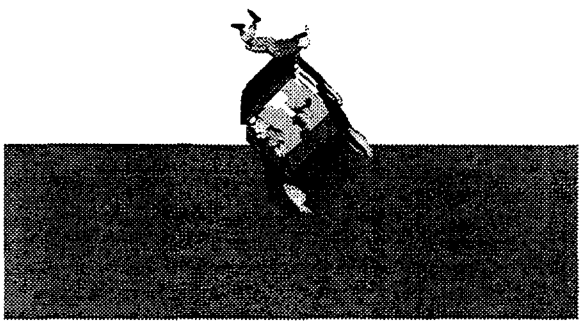


Figure 12 -- Driver Ejection during simulation of the first rollover test without an ITS

Future Research

The baseline testing has establish the potential of ejection mitigation using the ITS. Further work is needed to optimize the ITS location and deployment timing for rollover accidents. Toward this end, the ITS will be tested in a more repeatable rollover test device so that optimizations studies can be conducted.

CONCLUSIONS

The ITS devices have demonstrated a strong potential for reducing side window ejection in rollover crashes. While the kinematics of any single rollover crash are generally not repeatable, the general nature of this mitigation concept should result in significant safety benefits. The potential benefit of the ITS should be further realized in light of the fact that it had been developed for side impact head protection. Therefore, ejection mitigation and head contact with the interior of the car are additional benefits of the same single safety device. Follow on research will focus on optimizing the safety performance of the ITS in rollover environments.