ROLLOVER: A METHODOLOGY FOR RESTRAINT SYSTEM DEVELOPMENT

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ABSTRACT

Concern about crash conditions other than frontal and side crashes has accelerated restraint development with respect to rollover events. Previous analysis of rollover field data indicates the high probability of ejection and consequent serious injury or death to unbelted occupants. Partial ejection of belted occupants may also occur. Restraint development has focused on belt technologies and more recently, airbag systems as a method to reduce ejection and injury risk. Effective restraint development for these emerging technologies should consider a combined approach of field injury data analysis, computer simulation of rollover, corresponding validated test data and hardware development techniques.

First, crash data was analyzed for identified rollover modes (crash sequences) and injured body regions. This helped to determine possible restraint interventions. Computer models using a combined finite element and multibody approach were created, representing the vehicle and occupant kinematics observed in the rollover modes that were tested. After validating the occupant kinematics, models of an inflatable curtain bag were placed in the baseline model to evaluate the benefits of such a restraint system to both belted and unbelted occupants. Based on these results, a methodology was developed that allowed the curtain hardware to be developed based on a simple linear impact test. The development parameters include the curtain chamber layout, pressure requirements, and anti-ejection capabilities of the restraint system. Results from all data analysis, modeling and tests will be discussed in this paper.

The overall approach has basis in biomechanical tolerance and defines the necessary requirements and subsequent restraint solutions for improved occupant protection in a contemporary crash issue.

INTRODUCTION

In the past 30 years, a wealth of data has been gathered on vehicle rollovers. This data includes vehicle kinematics, occupant kinematics, test methods, simulations, and injury and field data analysis. The body of work has helped identify the primary modes of vehicular rollover, occupant motions and types of occupant injuries sustained and suggested countermeasures. The overall message is compelling given the sheer numbers of vehicles that rollover per year coupled with the unfavorable outcomes that have become associated with a rollover event.

Rollover Injuries

The literature is replete with the incidence and severity of rollover injuries in the field. Huelke (1)[*] reported on 377 front seat occupants in 266 passenger car rollovers. 30% of unrestrained occupants were ejected and half of those sustained fatal injuries. No restrained occupants were ejected. Only 6% of belted occupants had serious or fatal injuries. 33% of injuries to the head resulted from contact to interior surfaces. 50% of all fatal injuries were to the head. Head injury severity was not related to roof crush. Hight et al (2) described a highly detailed study of 139 vehicles in rollover with 225 occupants. 65% of the events were single vehicle crashes. 40% of 35 ejected occupants, all unrestrained, were fatally injured. Head/face/brain were injured about 70% of the time regardless of restraint use. The roof/side rail and header regions are listed as frequently contacted areas contributing to head injury.

Huelke continued his analysis of rollover injury in subsequent papers (3,4). The earlier citation discussed vehicle factors and restraints with respect to rollover injuries. Lap/shoulder belt usage nearly eliminated ejection in the cases analyzed and frequency of severe injury was greatly reduced. There is mention of the possible contribution of the B-pillar to injury potential of non-ejected occupants. Of seven belted fatalities investigated, one died from head injuries due to A-pillar contact and another from an intruding pole. The latter citation did an in-depth analysis of NCSS data files. More specific vehicle sites for injury potential of non-ejected occupants were identified. The head and neck regions sustained most injury from impacts to the side rail or side window glazing area and a vast majority of those

[*] Number in brackets designate references at the end of the paper

injuries were AIS<=2. The highest severity injuries for non-ejected occupants were in the chest and extremity areas.

In another study, Mackay et al. (5) investigated 158 vehicle rollovers in an urban environment with respect to crash characteristics, injuries, seat belt use, and ejection. Findings included that 63% of vehicles rolled only ½ revolution or less, 80% experienced 1 roll or less and only 3 had 3 or more rolls. Sixteen of nineteen ejections were unrestrained and ten of the nineteen ejections were fatal. Minor head injuries dominated restrained drivers (AIS 1). Mackay concluded, "ejection is an indicator of a severe collision" and not in itself a predictor of injuries, i.e., injury may have occurred inside the vehicle before ejection. Also, lower urban speeds may indicate different conclusions than highway speeds.

Two more recent studies further the nature of injury mechanisms. Digges et al (6) studies 4 years of NASS/CDS data with respect to AIS and HARM for ejected and non-ejected occupants. They found that for rollover crashes, ejections are only 10% of all cases, but 55% of all HARM. For non-ejected occupants, pillars/rail/header/upper side interior account for 18.6% of all harm from most serious injuries. When taking into account only interior structures, the pillars/rail/header/upper interior account for 28.9% of all interior harm sources. For restrained or unrestrained occupants, these same structures account for similar levels of harm to the head or head/spine indicating a major source of injury when occupants are not ejected. The authors suggest that interior surface padding or airbags may reduce interior contact risks. Parenteau and Shah (7) studied drivers in single vehicle rollover crashes using 5 years of NASS-CDS data. For ejected drivers in "roll-left trip-overs", 60% of complete and 80% of partial ejections were through the left front non-fixed glazing. For roll-right, 33% of complete ejections were through the left front non-fixed glazing. Serious head injuries dominated the ejected driver injury pattern, especially as the number of quarter rolls increased. The results also indicate different injury patterns for restrained and unrestrained, non-ejected occupants in right vs. left side tripped rollovers. Non-ejected belted drivers sustained more serious head and spinal injuries in roll-right events, while sustaining more upper extremity and thoracic injuries in roll-left situations. Non-ejected belted drivers had serious head injuries regardless of roll direction.

Rollover Testing

Test methods to understand both vehicle and occupant motions in rollover events have been reported repeatedly. The testing ranges from full vehicle to simulated occupant compartment, quasi-static methods that have helped demonstrate the violent nature of these events. The literature has included descriptions of initiation sequences and typical modes of rollover. A full treatment of rollover maneuvers and vehicle stability is beyond the scope of this paper, but the methodology to be described does assume at least 3 typical rollover modes that encompass most rollovers in the field: 1.) a tripped event at a high speed like the FMVSS 208 rollover test, 2.) a rollover induced by a unequal vehicle to road surface interaction (height or friction) that induces an occupant motion toward the side of the tripping before the roll event (so called curb-trip), and 3.) a roll with a longitudinal component induced by a roadside object such as a guardrail (screw ramp).

McKibben et al. (8) described occupant kinematics during a FMVSS 208 rollover test. For a right side (passenger rollover), the "dummies move upward and toward the right (passenger side of the interior)" and "remain pressed into the right side and upper corners of the roof/pillar junctions through most of the first and second revolutions". It is not until in the last roll that more "violent accelerations of occupants" occur. This early paper also complained of the inconsistent behavior of the same vehicle make/model when subjected to the FMVSS 208 rollover method.

Sakurai et al. (9), described testing of 12 full-vehicle screw ramp type rollovers to study roof deformation and the interaction with the crash dummy (belted). The vehicles were driven at 50 kph onto raised ramp at a prescribed angle. Ten of the twelve vehicles sustained one complete roll. The study showed that max neck loads occurred before maximum roof crush indicating that roof height may be better predictor of neck loads.

Johnson and Knapton (10) ran eight staged full vehicle rollover tests of which 7 were driven into a turned down guardrail at speeds between 57 and 72 mph (91-115 kph). The eighth test was a typical FMVSS 208, 30 mph (48 kph) dolly tripped event. Dummies were either unrestrained or restrained with lap or lap/shoulder. Findings included that a significant number of rolls were achieved (1-4) unlike field data (90.1% have one roll or less). Occupant head and torso velocities measured at impact sites around the vehicle give a measure of energy the occupant has during the event. Occupants can strike windows and pillars at velocities as high as 20 feet/sec (6.1 m/s). This value will be compared later in this paper to modeling data. Also, one lap/shoulder belted dummy "seemed to have less violent motion" than unrestrained dummies. Partial ejections were equal between restrained and unrestrained occupants, however most restrained occupants wore lap belt only.

Test devices simulating occupant excursion during rollover have been published frequently (11-13). These tests have been used to demonstrate seat belt design features and effectiveness of pretensioners on the head excursion of occupants. These test methods are useful to test belts in a one roll application, but are limited in assessing the effects belts may have during multiple rolls events where the occupant motions may be more severe in the later stages of more violent events.

Computer Simulation of Rollover

Simulation of rollover events using computer methods can take many forms. Modeling allows parametric changes to be made that are prohibitively expensive to test and also allows the same model to be run repetitively without inconsistent kinematic (vehicle or occupant) behavior. There are the simulations that are more concerned with vehicle attitude and the effect of suspension and inertial properties on rollover as reported by Day and Garvey (14). The model in their study included a 3-dimensional description of the vehicle including inertial properties, tire model and crush strength. Attempts to match roll kinematics of vehicle interaction with 3D terrain were made successfully. They also mention that simulation including occupants would be "time-consuming" and require more information about the vehicle accelerations as an input for the occupant model. Chace and Wielenga (15) described a comprehensive method to build a system level model of vehicle rollover in ADAMS using component evaluation test methods. Validation of vehicle kinematics was achieved. The authors suggest that mitigating rollover potential could be evaluated through vehicle component changes and evaluated in the model.

Others try to capture the vehicle deformation during the roll event and predict material behavior. Sakurai (9) modeled the vehicles that were rolled as described above using the PAM-CRASH non-linear finite element software. He found that the model predicted roof deformation data well and could be used to evaluate occupant behavior in future studies. Rollover simulation to study occupant kinematics traces roots back to the original occupant models of the early 1980's. Robbins and Viano (16) describe using vehicle accelerometer data and high speed film analysis as inputs to an MVMA 2D model of a production sedan. A linked, nine segment, rigid occupant model was placed in typical seating position. Occupant kinematics including ejection from a "pure roll" event are described. Authors promote simulation as an inexpensive method "to study occupant and vehicle motions in the mind-boggling geometry of rollover."

More sophisticated three dimensional rollover modeling appeared in the mid to late 1980's and continues to the present with such codes as the Articulated Total Body (ATB) and MADYMO. Obergefell et al (17) published a study simulating occupant motions during rollover using the ATB code. They modeled a vehicle undergoing a violent (60mph) rollover as a result of interaction with a turned down guardrail and also included a restrained driver. Film and data analysis helped derive 6 axis input data to drive the model. A 4.5 second simulation of the event showed good agreement of dummy kinematics (test to model) during the entire event. It also indicated that belted occupants can undergo a large amount of movement. Concern was raised over belt/body segment interactions during the entire simulation.

These authors have published other papers using this modeling method over the years. Cheng et al (18) developed an ATB model to replicate occupant motions from one NASS case (a belted driver and unbelted passenger in a light pickup rollover crash). Occupant outputs from the modeled dummy were used to predict injury results. The belted driver had only a minor injury and model results indicate low accelerations to head/chest regions. The ejected passenger suffered fatal injuries and model data showed high injury criteria values (exceeding threshold). Ma et al (19) used a previously defined rollover and occupant model to look at the effect of glazing on occupant kinematics and injury. Contact force deflections for head to glazing for a variety of vehicles were evaluated. Head impact velocities in the 3-8 m/sec range (unbelted passenger) were seen for a variety of glazings tested. Predictions for head/neck injuries are given.

Simulations using linked rigid body, MADYMO modeling techniques have also appeared in the literature. Renfroe et al have published papers (20,21) attempting to model occupant motion in MADYMO during a prescribed motion to the vehicle c.g. taken from outputs of reconstruction programs. Vehicle crush and suspension/tire modeling were done and showed good match to vehicle test data (FMVSS 208). Predicted occupant accelerations (head, chest) showed similar trends to test data, but authors did not have sufficient interior stiffness or crush data to determine occupant injury potential. They suggested the model could be used to evaluate restraints in rollover conditions. Bardini and Hiller (22) used a combined MADYMO and vehicle dynamics prediction program approach to determine sensor fire time for rollover events. Both a curb trip type and embankment roll were modeled. No roof crush was used. Correlation of vehicle behavior to an embankment test was done qualitatively. Trajectory of head with and without belt pretensioner was done indicating containment of head within vehicle frame when a pretensioner was fired. (curb trip type roll). Lack of good test data and concerns over dummy lateral neck behavior were mentioned.

The body of research here demonstrates a profound experience in the understanding of the rollover event, causes and type of injuries, and methods to reduce those injuries through test and simulation methods. What appears to be lacking is a unified approach to put together field data, simulation, and test analysis to create a countermeasure that may have the ability to mitigate the injuries that occur.

METHODOLOGY AND RESULTS

This paper intends to portray a methodology of combining several disciplines to help define a restraint system that offers rollover protection. The methodology and results are closely entwined thus the traditional splitting of these sections would interfere with the logic and flow of this paper. The following sections describe and report the results of the field data analysis, computer simulation and validation , and the subsystem testing that leads to the conclusions of this paper.

Field Data Analysis

Although much work analyzing NASS, FARS and other collected data has occurred as previously described, it made sense to determine initial strategies for protective devices based on examination of a limited amount of field case analysis. NASS-CDS case studies are now available on the Internet (for 1997 and 1998 NASS-CDS current to submission of this paper) through the NHTSA web-site. Complete crash descriptions including pre- and post-crash vehicle descriptions, occupant injury description and coding, and crash scene photos can provide additional insight into a crash event that pure statistics cannot.

The web-site provides a filter to retrieve cases that are of interest to the user. The subsequent sections of the paper will show the simulation and test methodology for a rollover restraint system for sport utility vehicles. Thus, in the NASS data analysis of electronic cases, single vehicle, sport utility vehicle crashes, limited to one adult occupant fatally injured were requested. 14 crashes were retrieved and subject to further review and analysis. Of the 14 cases, 12 involved a rollover event or rollover was the crash type listed. This frequency of rollover (86%) for fatal crashes is somewhat higher than reported by NHTSA for sport utility vehicles (over 60%). Occupant injuries, source of most severe injury, number of rolls (if applicable) are examples of data taken and tabulated for further analysis.

The data generated from the 14 case studies was collated into a spreadsheet containing all relevant vehicle and occupant data. The spreadsheet of information is shown in the Appendix of the paper (Table 1). In general, the vehicles were involved in severe crashes (high speed and multiple contacts including rollover). Interestingly, eight of the twelve vehicles involved in a rollover sustained only one half of a revolution or less with the other 4 vehicles sustaining one roll or more. Of the 22 occupants in the 14 crashes, 14 were killed, 8 of those partially or fully ejected. Five of the fatally injured, ejected drivers exited the vehicle through the left front or left rear window. All but two of the fatalities were unbelted whereas 5 of the 8 non-fatally injured occupants were belted. All 14 fatalities had reported head or spine injuries while only one non-fatal occupant sustained a head injury (AIS 2 skull fracture). Rail and pillar contacts were the major source of injury (mostly brain and head) for the fatally injured occupants. The occupants surviving had bony fractures either in the lower extremities or the chest region. This data is typical with previously reported analysis, but the cases shed more light on the mechanisms and types of injury.

Two cases merit further discussion of with respect to crash conditions and injury. Case 3 involves a sport utility vehicle with 4 occupants (an unbelted adult driver, a lap-shoulder belted right front adult passenger, and 2 belted children in the rear seat outboard positions). The driver unsuccessfully negotiated a curve, over-corrected and left the roadway while rotating counterclockwise. The vehicle struck a small tree and rolled one-half revolution via its right side. The driver was ejected and sustained a fatal brain injury as a result of impact to the left roof rail as he exited the vehicle through the left front window. The right front passenger sustained a fractured pelvis and multiple rib fractures from contact to the right side interior structures of the vehicle. The rear seat children sustained minor or no injuries.

In case 8, an elderly belted male driver in a compact sport utility vehicle was traveling on a high speed divided highway when it made an inappropriate maneuver to avoid a merging vehicle. The vehicle rotated counterclockwise and departed the roadway rolling 1.5 times via its right side initially. The driver was partially ejected from the left rear window of the vehicle and sustained a fatal brain injury along with multiple rib fractures probably from left B-pillar contact. His adult female right front passenger (belted) sustained a right clavicle fracture (AIS =2) from right B-pillar contact.

These two cases describe injuries and their sources for both unbelted (and ejected) and belted occupants. If a restraint system can be designed to prohibit ejection and prevent head contact to interior structures, then the risk of serious injury or fatality may be greatly reduced. The multiple roll event in case 8 leads to the next section of this methodology that describes modeling an event that contains multiple rolls of a sport utility type vehicle and deducing the occupant kinematics.

Computer Simulation Approach (Background)

Given the lack of repeatability reported on the FMVSS208 rollover test procedure (8) and the expense of performing such testing, computer simulation was evaluated as a tool for aiding rollover restraint development. Such a tool would have the added benefit of permitting the evaluation of the restraints using different sizes and type of occupants.

The objective was to create a rollover model that would allow the restraint designer to evaluate the benefits of various restraint systems from the viewpoint of occupant injury due to internal vehicle interactions and ejection prevention. It was recognized that the model needed to account for the load the vehicle subjects the occupant to, the occupant itself, and the restraint system. It would have to be representative of the test condition with respect to occupant kinematics so that objective restraint evaluation could occur following various simulations. As an added outcome it was likely that the rollover model would yield occupant kinematic data that could be used to create a subsystem test condition. This condition would idealize the rollover situation and hence cut down on the need for full-scale vehicle tests while providing a hardware development opportunity that was based on a repeatable condition.

Vehicle System Level Modeling The vehicle model consisted of geometry representing the vehicle interior, the occupant, and restraint systems of interest. It was recognized early on that due to the long duration of rollover events the model would be quite computationally intensive, and so Finite Element Methodology (FEM) would not be realistic for effective restraint design work. For this reason it was decided to use the multibody capabilities of the MADYMO software for this activity except in the area of inflatable restraint modeling (23).

The geometry of the test vehicle (sport utility type) was obtained from an Oak Ridge National Laboratories (ORNL) study that was conducted for the National Highway Traffic Safety Administration (NHTSA) and resulted in a full finite element mesh of the vehicle. This mesh was converted to a MADYMO facet surface that has the advantage of a representative geometric description with a relatively low computational effort compared to FEM (Figure 1). Vehicle interior components such as the front seats and instrument panel were modeled with ellipsoids and cylinders (Figure 2).

Hybrid III 50th%ile occupant models were positioned within the vehicle based on an FMVSS208 rollover test conducted at the Transport Research Center (TRC) in East Liberty, Ohio, USA. Rollover curtain airbag models were also included in the model as FEM components as per the tested condition (Figures 3a and 3b). Description of the curtain airbag design and function will follow later in this section.

A series of contact interactions were defined to account for occupant-occupant and occupant-interior impacts. This required the approximation of the stiffnesses that control the interaction between the occupant and the structure. As detailed interior stiffness data was not available, it was decided to tune the stiffness of the occupant head in the rollover model based on the test responses. In this way a representative contact interaction could be determine for the model based on the test measurements. The final step was to make the vehicle interior move in a manner representative of the test condition. In the FMVSS208 rollover test the vehicle linear accelerations and angular velocities were measured at the vehicle center of gravity (CG). A multibody joint was created at the vehicle CG in the rollover model and its relative linear and angular position were prescribed based on the test data.

This, in conjunction with the use of a multibody approach, also meant that roof crush modeling would be difficult to incorporate. Studies in the past such as that performed by Huelke et al (1) have shown that roof crush does not have a significant effect on occupant injury response in the FMVSS208 rollover event. As such this was not considered to be a critical omission that would greatly limit the validity of the model.

In this manner the model was not rolling due to interactions between the vehicle and the ground, but because it's position was being prescribed as a function of simulation time. This had the advantage of not requiring accurate suspension data or roof crush data so that the rolling behavior could be modeled realistically. Thus the rollover event was treated as a boundary condition which the occupants were subjected to, reducing model complexity and solution time.

Proposed Model Validation Approach At this point it was possible to validate the model to the test conditions and evaluate its utility. It was recognized that due to the erratic nature of the rollover event a traditional model validation that considers timing and magnitude of peak values could not be performed. This is especially true because high head accelerations, for example, occur

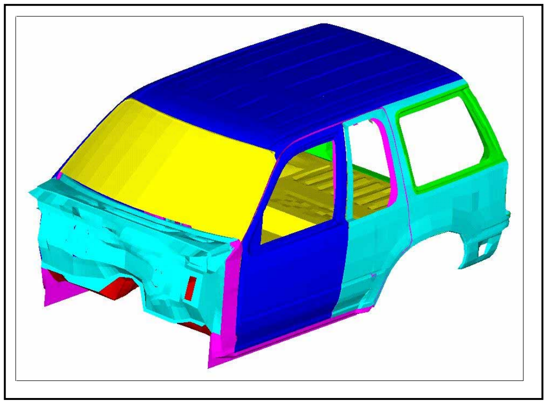

Figure1. Vehicle Environment.

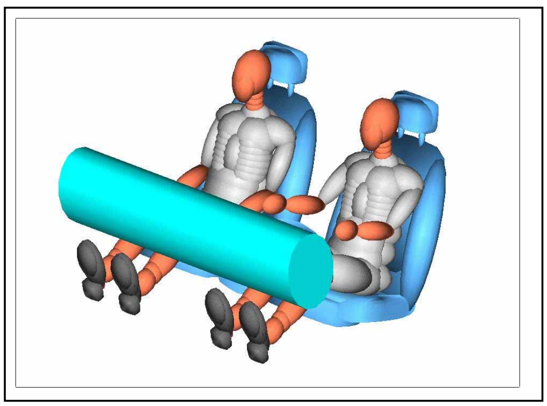

Figure2. Interior with Hybrid III 50^{th}%ile's.

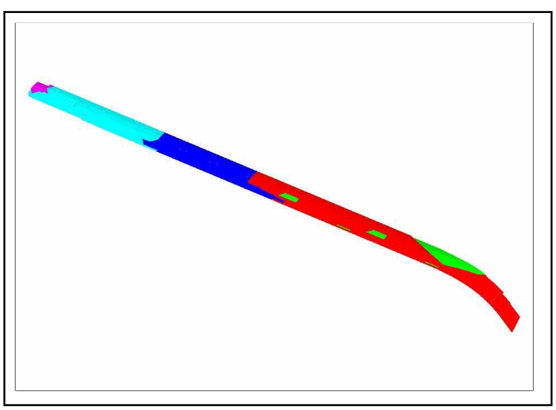

Figure3a. Folded Rollover Curtain.

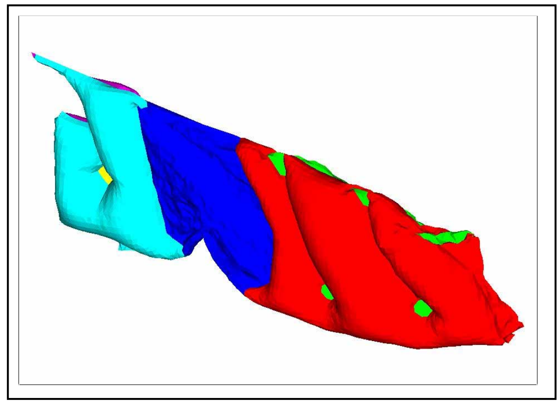

Figure3b. Deployed Rollover Curtain.

at multiple points in the event. Capturing the timing and peak magnitude of such an occupant response later in the rollover will depend on capturing all previous responses accurately. Accumulation of small errors in a model that contains so many of these interactions precludes such a validation. For this reason it was decided to take the following approach.
First, subsystem components such as the curtain bag were validated in isolation to the rest of the model by simulations of simple pendulum tests. The overall model was initially validated by comparing occupant motion in the model to the available film analysis data. This was deemed to be most important for the driver occupant as this occupant contacts the vehicle lateral and upper interior when the vehicle commences rolling. For this reason, the path of the head during this initial motion was validated in the model. In a similar manner the driver head acceleration was validated also. Both of the validations focused on obtaining a good match for the magnitude and timing of the considered response in the first 500msec of the rollover test.
Following consideration of the initial occupant motion, the model to test behavior was considered more generally. It was decided that peak response magnitudes occurring in the test should be match in the model without consideration of the timing to the occurrence of these peaks. In this way the model was validated based on gross responses rather than specific ones. The primary occupant responses considered in this way were the head acceleration and the head trajectory. These injury indicators have a strong relationship with the types of real world injuries reported as significant in statistical rollover event studies and in the case studies examined for this paper (6).

Validation The model of the rollover test was validated according to the early driver and passenger head kinematics. The head motion is compared to the motion yielded by test film analysis below in

Figure 4. Similarly the head acceleration response of the driver due to early interior contacts was validated (Figure 5). These curves showed that both the path followed by the drivers' head and the response of the head under impact loading in the model are representative of the test. Given the high occurrence of head injury that the NASS case study analysis (Appendix) has found, the model accurately captures the kinematic and impact response of the body region of prime interest for rollover protection.

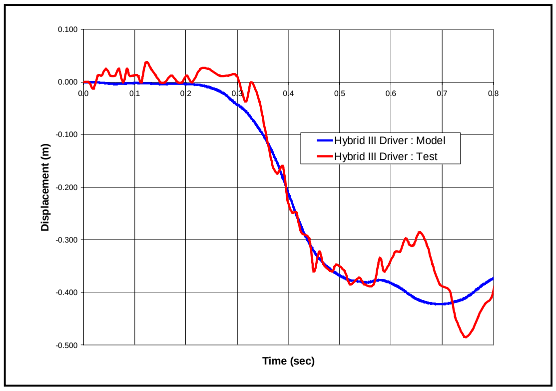

Figure4. Driver Head Path During Initial Motion.

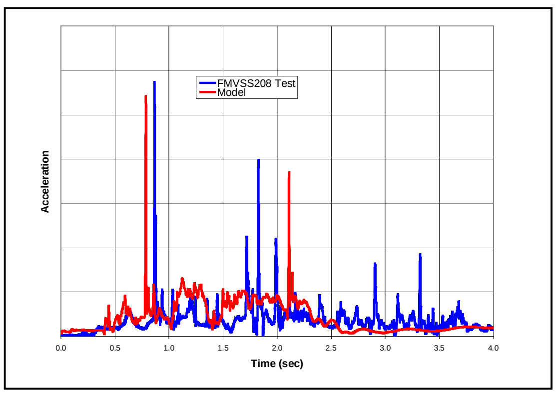

Figure5. Driver Head Resultant Acceleration.

Subsystem Testing

It was recognized while analyzing model results that due to the level of sophistication the model gave a good insight into the behavior of the occupant during a rollover. Of particular interest was the ability to monitor the velocity of the occupants relative to the vehicle interior. Figure 6 shows the head velocity relative to the vehicle for the driver in the initial simulation with Hybrid III 50th%ile occupants. This reveals that the peak head velocity with respect to the vehicle interior is 5.4m/s and agrees well with at previous studies (10,19). This data is useful as it could be used as input to a subsystem condition that could aid development of a simplified test. By assuming that the occupant head and neck were traveling at this velocity towards the curtain restraint system, an energy level that the inflatable curtain was required to sustain was established. In a similar manner, a model using belted occupants arrived at a peak head velocity of approximately 2.7m/s.

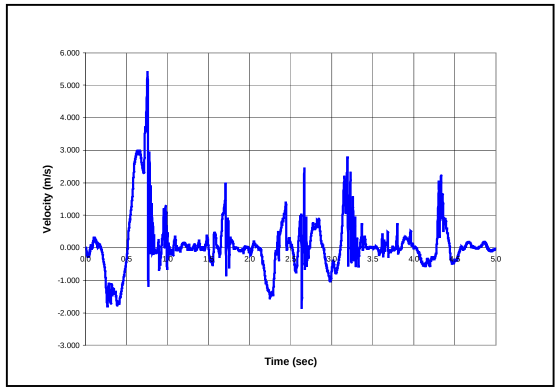

Figure6. Driver Occupant Head to Vehicle Interior Relative Velocity.

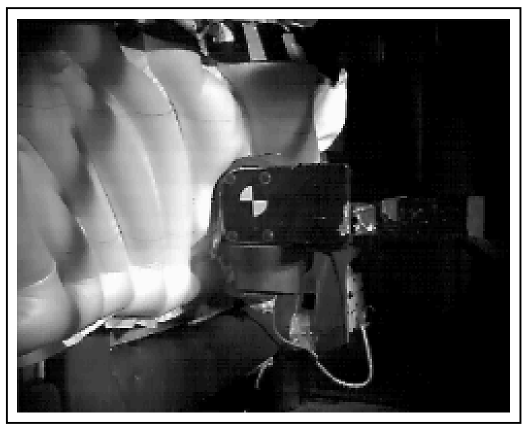

Figure7. Linear Impactor test using headform.

Thus, hardware could be designed and tested against this condition prior to the execution of full vehicle rollover tests. The subsystem test can be conducted using linear impactor or a pendulum test. When using a linear impactor, the mass of the head and neck, represented by a head form (Figure 7), is fired into the inflated bag with the speed required to simulate the occupant head and neck impacting the curtain bag in the FMVSS208 rollover. If the pendulum is being used, then the energy level equivalent to an occupant head and neck impacting the airbag is calculated. Based on this energy level and the pendulum mass, a different speed is calculated for the pendulum. Similarly, a head form is attached to the pendulum to impact the curtain airbag.

<u>Performance Criteria</u> In evaluating the protective capabilities of the curtain in the subsystem test, it was decided to set performance criteria based on the head form not permitted to bottom out against a rigid plate behind the curtain airbag, that is, no strike through was allowed. From this testing, long duration pressure requirements for the curtain airbag could be evaluated for a given design and compared to actual curtain bag performance. This evaluation sets a minimum pressure requirement for the rollover curtain airbag. Similarly, the same subsystem test can be used to calculate the amount of motion the curtain airbag allowed outside of the vehicle. This could be used to set the performance criteria on the physical design to estimate the ability of the design to mitigate ejection of the occupant. In the ejection subsystem tests, different mass and speed are used to set the performance criteria.

<u>Pressure Map Concept</u> The rollover performance of the curtain airbag for unbelted occupants is just one of the design criteria for such a restraint system. In addition to this it should mitigate occupant head injury in lateral impacts due to internal and external contacts. Criteria such as the FMVSS201 side impact pole test requires protection of the occupant in a lateral impact which, by its nature, has a shorter injury exposure time for the occupant compared to rollover. Based on occupant head velocities, pressure requirements for a side impact / rollover system can be determined. These requirements will be unique to each vehicle. Using the head velocities from the models, a curtain bag can be impacted at equivalent energy levels (either with a pendulum, linear impactor or in a model) to determine the pressure at which strike through occurs. These can be used to form pressure requirements for the bag in side impact and rollover. A head mass is impacted into the curtain airbag with a pole or a rigid wall behind it. The impactor must not strike through the bag. Recognizing this leads to the concept of the "Pressure Map". An example of such a Map is shown below in Figure 10. The pressure map is built using different categories, which are explained below.

<u>18mph Side Pole Criteria</u> This test procedure is proposed by NHTSA to evaluate the performance of head protection devices such as head/thorax side airbags, head airbags and the curtain airbags. The vehicle test procedure slides the vehicle laterally into a 10" pole, with the pole vertical centerline aligned with the ATD head center of gravity. Of all assessed OEM and regulatory performance tests, this was the most severe side impact procedure identified. The narrow impact zone of this test means that the head-to-pole contact speed is often close to the initial vehicle contact velocity. Which means that if the same subsystem test explained previously is used, then the minimum pressure required to prevent the strike through can be calculated if the head travelling at a velocity of 8.05m/s (18mph) is fired into the bag. Since this event is a short duration event, this minimum pressure calculated is required for 100 msec from the bag deployment.

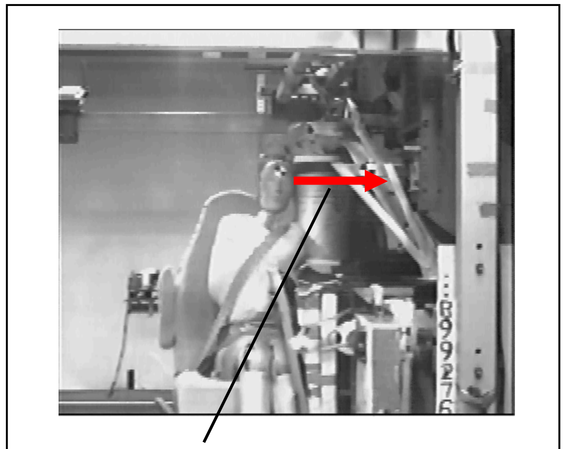

Figure8a. Occupant head velocity for pole impact.

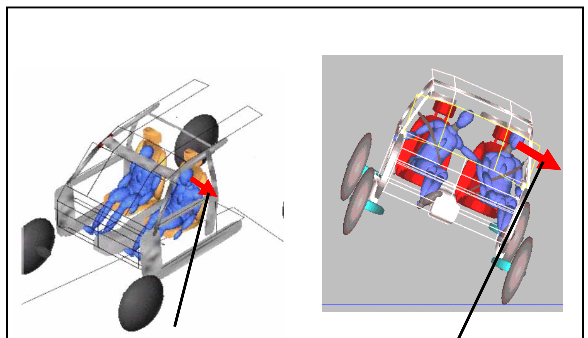

Figure8b. Occupant head velocity for FMVSS208 rollover events.

<u>Rollover Head Protection Criteria</u> In order to assess pressure requirements for head protection in long duration rollover, simulation and testing were conducted. The results showed that in terms of occupant injury severity due to internal and external head contact, and also in terms of event duration, the FMVSS208 rollover procedure was more severe than other rollover modes such as the screw ramp and curb trip procedure. The models created of a SUV in the FMVSS208 rollover yielded a maximum head to interior/exterior object contact velocities for belted and unbelted 50th%ile occupants. These velocities were 5.4m/s (12.1mph) for the unbelted case (see Figure 6) and 2.7m/s (6mph) for the belted case. Figure 8a and 8b above graphically summarize these findings. The minimum pressure calculated for these cases is estimated to last for 6 seconds.

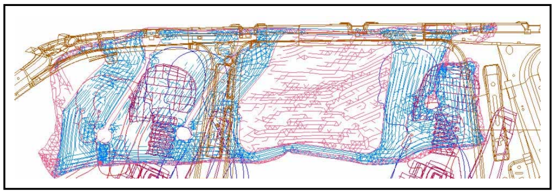

Figure9. Coverage study for proposed curtain airbag showing position of various sized occupants.

<u>Rollover Ejection Prevention Criteria</u> The ability of the bag to prevent occupant ejection is mainly a factor of the bag shape, that is, how much of the side structure are covered by the bag and which size occupants are protected. The ability of the bag to maintain pressure is also important because an inflated bag has a shorter longitudinal length than a flat bag. Experience has determined that the lowest pressure at which the bag keeps its inflated shape is approximately 10kPa (1.5psi). This pressure value is used to define the bag shape required to cover the various size occupants. The current approach for anti-ejection design is to maximize the coverage of the side glazing while considering other factors such as bag volume, fill time, and seat belt interaction. The pressure requirement merely addresses the issue of the bag holding shape. Figure 9 shows a coverage study for a particular bag design with different size occupants. Also, the same subsystem test can be used to evaluate ejection provided that mass and speed are representing the unbelted occupant condition.

Based on the criteria discussed above a "Pressure Map", which defines pressure magnitudes and time duration for different events the curtain bag restraint should protect for, can be built as shown in Figure 10. The results obtained from the linear impactor tests may be used to develop a pressure map for each particular bag design. The methodology explained in the previous section, starting from the bag coverage study and up to building the pressure map is currently being used to design the curtain bag. This procedure is conducted using computer simulation and before any prototype curtain bag is built.

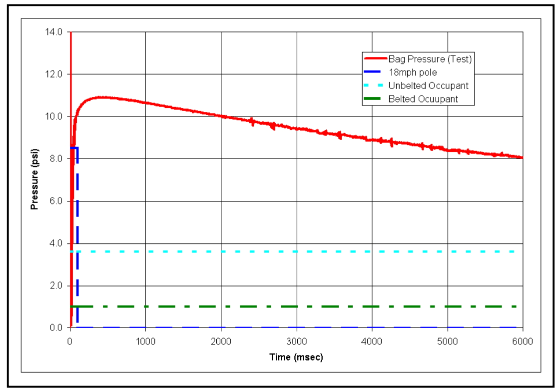

Figure10. Pressure map concept for side impact and rollover curtain air bags.

DISCUSSION

This paper presented a methodology as a means to develop restraint hardware for rollover crash conditions that removes the dependency on previously reported variability in rollover testing. It also directly addresses the field data issues and the underlying injury mechanisms by providing a modeling and testing approach that is feasible and less costly. Such a methodology permits the evaluation of the restraints using different sizes and type of occupants.

Much discussion about countermeasures for ejection and injury mitigation in rollover crashes has been offered. Digges (24) offered inflatable devices as a way to reduce a significant HARM from ejection and head protection for non-ejected occupants, but he did not elaborate on design. James et al (25) indicated that modified current production seatbelt systems can reduce vertical head excursions, but will not eliminate head contact to roof, roof rail or lateral motion of the head into open window areas. Clearly, the field case analysis indicates that the prevention of head and torso translation of the unbelted occupant beyond the vehicle openings should result in a less severe injury outcome. Furthermore, prevention of head or torso contact to interior structures (rails, glazing, pillars) or intruding objects (trees, other vehicles) that an occupant in a rollover event is likely to contact should decrease risk for serious or fatal injury.

The modeling results presented show the usefulness of this computer modeling approach as a tool for rollover restraint development. As the motion of the vehicle is prescribed, different design conditions with respect to the occupant and restraint system can be evaluated objectively without having to remove the effects of test or model variability. It is important to note that the guidelines established for occupant velocity during a rollover may not be true for all occupants and vehicles. The result is likely to be dependent of vehicle architecture and packaging. However, results for head velocities from the model are similar to those reported by NHTSA who reported "head to glazing impact velocity varied from 14 kph to 20 kph" (3.88-5.55 meters/sec) in a passenger car model in their Advanced Glazing Research studies (26). Through further computer simulation, however, these guidelines can be established for a particular vehicle and occupant combination.

It is even possible to use computer based occupant databases such as human body models to look at the restraint design benefits. This would free the dependence of the design from the crash dummy and directly apply the result to protecting humans in these violent crash environments. As a further use of the simulation approach, a short study is planned to establish how a more representative human model might compare to the Hybrid III 50th%ile in the presented rollover scenario. These are occupant models of a global formulation and are validated to full body responses determined from cadaver and human volunteer testing (27).

The culmination of the modeling is to prescribe a simple test condition that leads to a robust design of an inflatable restraint system. The design meets the needs of the unbelted and belted occupant to reduce the likelihood of head strike through or ejection for the duration of the roll event. It can also apply to the short duration side impact requirements by testing for the same strike through condition merely by changing speed of the headform. Evaluation of multiple designs and shapes can be done efficiently to allow selection of the best design for full scale tests.

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REFERENCES

1.) Huelke, D.F, Marsh, J.C., Dimento, L, Sherman, H., Ballard, W.J. (1973). Injury Causation in Rollover Accidents. In : Proceedings of the 17th Conference of the American Association of Automotive Medicine, pp. 87-115.

2.) Hight, P.V, Siegel, A.W. Nahum A.M. (1972). Injury Mechanisms in Rollover Collisions. In : Proceedings of the Sixteenth Stapp Car Crash Conference, pp. 204-225. SAE Paper No. 720966. Warrendale, PA.

3.) Huelke, D.F., lawson, T.E, and Marsh, J.C. (1976). Injuries and Vehicle Factors in Rollover Car Crashes. Accident Analysis and Prevention, Vol. 9, No. 2-B, pp. 93-107.

4.) Huelke, D.F. and Compton, C.P. (1983). Injury Frequency and Severity in Rollover Car Crashes as related to Occupant Ejections, Contacts and Roof damage. Accident Analysis and Prevention Vol. 15, No. 5, pp. 398-401.

5.) Mackay, G.M., Parkin, S, Morris, A.P., and Brown, R.N. (1993). The Urban Rollover: Characteristics, Injuries, Seat Belts, and Ejection. In: Proceedings of the 13th International Technical Conference on Experimental Safety Vehicles., Washington, D.C., Paper No. S6-O-08, pp. 741-747.

6.) Digges, K.H., Malliaris, A.C. and DeBlois H.J. (1993) Rollover Injury Causation and Reduction. In Proceedings of the 26th International Symposium on Automotive technology and Automation, pp. 681-685.

7.) Parenteau, C.S. and Shah, M. (2000) Driver Injuries in US Single-Event Rollovers. In: Side Impact Collision research, SP-1518, pp. 1-8, SAE Paper No. 2000-01-0633, Warrendale, PA.

8.) McKibben, J.S., Clark, G.S. and Carlson L.E. (1974). Development of Techniques to Prevent Occupant Ejection During Rollover – Volume 1 – Executive Summary, DOT HS 801-122, 54pp.

9.) Sakurai, T. Takigawa, Y, and Ikeno, H. (1993). Study of Passenger Car Rollover Simulation. In Proceedings of the 13th International Technical Conference on Experimental Safety Vehicles., Washington, D.C., Paper No. S6-O-10, pp. 747-753.

10.) Johnson, A.K. and Knapton, D.A. (1984). Occupant Motion During a Rollover Crash. DOT Report No., DOT HS 806 646, 10pp.

11.) Pywell, J.F., Rouhana, S.W, McCeleary, J.D., and deSaele, K.H. Characterization of Belt Restraint Systems in Quasistatic Vehicle Rollover tests. In: Proceedings of the 41st Stapp Car Crash Conference, pp. 265-276, SAE Paper No. 973334, Warrendale, PA.

12.) Arndt, M.W. Testing for Occupant Rollover Protection (1998). In: Advances in Safety technology, pp. 27-32, SP-1321. SAE Paper No. 980213, Warrendale, PA.

13.) Moffatt, E.A, Cooper E.R., Croteau, J.J., Parenteau, C, and Toglia, A. (1997). Head Excursion of Seat Belted Cadaver, Volunteers, and Hybrid III ATD in a Dynamic/Static Rollover Fixture. In: Proceedings of the 41st Stapp Car Crash Conference, pp. 509-523., SAE Paper No. 973347, Warrendale, PA.

14.) Day, T.D. and Garvey J.T. (2000). Applications and Limitations of 3-Dimensional Vehicle rollover Simulation. In: Accident Reconstruction: Analysis, Simulation, and Visualization, pp. 423-436. SAE Paper No. 2000-01-0852, Warrendale, PA.

15.) Chace, M.A. and Wielenga, T.J. (1999). A Test and Simulation Process to Improve Rollover Resistance. In: Vehicle Dynamics and Simulation, pp. 115-127, SP-1445, SAE Paper No. 1999-01-0125, Warrendale, PA.

16.) Robbins, D.H and Viano, D.C. (1984). MVMA 2-D Modeling of Occupant Kinematics in Rollovers. In: Mathematical Simulation of Occupant and Vehicle Kinematics, pp.65-77, SAE Paper No. 840860, Warrendale, PA.

17.) Obergefell, L.A., Kaleps, I., and Johnson, A.K. (1986). Prediction of Occupant's Motion During Rollover. In: Proceedings of the 30th Stapp Car Crash Conference, pp. 13-26, SAE Paper No. 861876, Warrendale, PA.

18.) Cheng, H., Rizer, A.L., and Obergefell, L.A. (1995). ATB Model Simulation of a Rollover Accident with Occupant Ejection. In: Accident Reconstruction: Technology and Animation V., pp. 21-31., SAE Paper No. 950134, Warrendale, PA.

19.) Ma, D., Rizer A.L., and Obergefell, L.A. (1995). Dynamic Modeling and Rollover Simulations for Evaluation of Vehicle Glazing Materials. SAE International Congress and Exposition, pp. 1-11, SAE Paper No. 950050, Warrendale, PA.

20.) Renfroe, D.A., Partain J.F. and Lafferty J. (1998). Modeling of vehicle rollover and evaluation of occupant injury potential using MADYMO. In: Accident Reconstruction: Technology and Animation VIII., pp. 33-50., SAE Paper No. 980021, Warrendale, PA.

21.) Renfroe, D.A. and Partain, J.F. (2000). Modeling of Occupant Impacts during Rollover conditions. . In: Accident Reconstruction: Analysis, Simulation, and Visualization, pp. 451-459. SAE Paper No. 2000-01-0854, Warrendale, PA.

22.) Bardini, R. and Hiller, M. (1999). The contribution of occupant and vehicle dynamics simulation to testing occupant safety in passenger cars during rollover. In : Safety Test Methodology, pp. 41-49, SP-1434, SAE Paper No. 1999-01-0431, Warrendale, Pa.

23.) MADYMO Users Manual, Version 5.4, TNO Automotive, Delft, The Netherlands, 2000.

24.) Digges, K. and Malliaris, A.C. (1998). Crashworthiness Safety Features in Rollover crashes. SAE paper No.982296, pp. 35-39, Warrendale, PA.

25.) James, M.B., Allsop, D.L., Nordhagen, R.P., and Decker, R.L. Injury Mechanisms and Field Accident Data Analysis in Rollover Accidents. In: Occupant Protection and Injury Assessment in the Automotive Crash Environment, SP-1231, pp. 213-223, SAE Paper No. 970396, Warrendale, Pa.

26.) NHTSA (1996). Computer Modeling of Rollover Accidents. National Highway Traffic Safety Administration Public Meeting for Advanced Glazing Research.

27.) Happee, R., Hoofman, M., Kroonenberg van den, A.J., Morssink, P. and Wismans, J. (1998). A Mathematical Human Model for Frontal and Rearward Seated Automotive Impact Loading. In Proceedings of the 42nd Stapp Car Crash Conference, P-337, pp. 75-88, SAE Paper No. 983150, Warrendale, Pa.

APPENDIX

Table 1
NASS-CDS Results From Internet Query (=Fatal, Single Vehicle, Utility Vehicle, Adult Occupant)

Case	Roll?	# of Rolls	Occupant	Most Serious Injury	Source	Max AIS	Belted?	Ejected?	Path	Age	height(cm)	weight(kg)	Comments
1	N	n/a	DR	Sp.cord lacer./mult. thor. Inj.	u/k	fatal	N	N	-	27	163	76	Climb over guardrail, plunge into water
1	N	n/a	Fr. Pass	Multiple head injuries	u/k	fatal	N	N	-	29	163	69	Climb over guardrail, plunge into water
2	Y	0.25	DR	Skull fx./cerebral trauma	Left B-Pillar	fatal	Y	N	-	20	173	86	side impact plus small roll into tree
3	Y	0.5	DR	Brain stem injury	Left side rail	fatal	N	Y	L FR win	67	165	64	R side roll
3	Y	0.5	Fr. Pass	Multiple rib fx./pelvis fx.	Right interior	4	Y	N	-	62	165	56	R side roll
3	Y	0.5	L. Row 2	hroat abrasion/scalp contusion	belt/roof	1	Y	N	-	10	150	39	R side roll
3	Y	0.5	R. Row 2	No reported injuries	-	-	Y	N	-	10	127	34	R side roll
4	Y	1	DR	Multiple head injuries	Left B-Pillar	fatal	N	Y-Part	L rear	44	180	104	L side roll
5	Y	0.25	DR	aortic lacer./brain	header/roof	fatal	Y	N	-	29	178	82	L side roll with tree impact
6	Y	1.25	DR	Multiple head injuries	Ground	fatal	N	Y	L FR win	30	168	84	Vehicle lands on driver
7	Y	2	DR	Femur Fx	Ground	3	N	Y	L FR win	22	160	122	L side roll
7	Y	2	Fr. Pass	Multiple head injuries	Ground	fatal	N	Y	R FR win	46	180	75	Vehicle lands on R. Front pass
7	Y	2	R. Row 2	u/k	u/k	u/k	N	Y	R R win	22	u/k	u/k	
8	Y	1.5	DR	Multiple rib fx./brain injury	B-pillar	fatal	Y	Y-Part	L FR win	76	u/k	u/k	R side roll
8	Y	1.5	Fr. Pass	R. Clavicle fx	R. B-pillar	2	Y	N	-	60	u/k	u/k	
9	Y	0.25	DR	Humerus fx/skull fx	L int/L rail	2	Y	N	-	56	160	64	Partial L side roll with tree impact
10	Y	0.5	DR	Brain stem injury	u/k	fatal	N	Y	u/k	25	188	77	L side roll
11	Y	0.5	DR	Traumatic brain injury	roof	fatal	Y	N	-	45	173	75	L side roll
12	Y	0.5	DR	closed head	header/roof	fatal	N	Y-part	Sunroof	44	188	84	R side roll
12	Y	0.5	Fr. Pass	bruised leg	R side int	1	N	N	-	46	173	58	
13	Y	0.5	DR	skull fx/rib fx	u/k	fatal	N	Y	u/k	33	198	107	Lside roll
14	N	-	DR	Multiple head injuries	other vehicle	fatal	N	N	-	34	178	78	Heavy truck underride: dr bag deployed