ROLLOVER ACCIDENTS OF CARS IN THE GERMAN ROAD TRAFFIC – AN IN-DEPTH-ANALYSIS OF INJURY AND DEFORMATION PATTERN BY GIDAS[1]

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ABSTRACT
This paper describes the injury pattern of car occupants in rollover crashes by type, location and severity AIS. The accident cases were collected randomly within GIDAS (German In-Depth-Accident Study) at Hannover. Since 1999 in Germany a joint project between BASt (Bundesanstalt für Straßenwesen or the Federal Highway Research Institute) and FAT (Forschungs-vereinigung Automobiltechnik or Automotive Industry Research Association) is being carried out in Hannover and Dresden. The paper describes the methodology of this project with statistically orientated procedure of data sampling (sampling plan, weighting factors) on one hand and describes the results of the injury pattern of car occupants after rollover and gives indication for understanding where rollovers are happened and what kind of influences are exist on the other hand. The rollover movement characteristics will be described and the resultant deformation pattern analysed by a detailed survey.

For the study 434 cases of car accidents with rollovers are used for a detail comprehensive analysis. The portion of rollovers can be established at 2.3% of all accidents with casualties in the year 2003.The accidents happened in the years 1994 to 2000 in the Hannover area. The injury distribution will report about 741 occupants with rollover accident event. These accidents are compared with the others without rollover documented in the same sample of GIDAS under a representative random spot check methodology.

The distributions of injury frequencies, injury severity AIS for the whole body and for the body regions of occupants are presented and compared to technical details like the impact speed and the deformation pattern. The speed of the car was determined at the point of rollover and on the point of accident initiency. The characteristics of the kinematics followed in a rollover movement are analyzed and the major defined types of rollover are shown in the paper.

The possibilities of In-Depth-Investigation methods for the approach of finding countermeasures against rollover and explaining the biomechanics of injuries in rollover are shown in the paper as well.

INTRODUCTION

The participation in traffic is characterized by conflict situations that sometimes result in traffic accidents. About 20 % of all accidents occur without the participation others, mostly accidents happen at points where the road turns come to mind, however, solo-accidents also occur inside city boundaries and at other road sections. Especially noticeable within the group of solo-accidents, accident occurrences are those, where the vehicles slid sideways into the side part of the road and there sometimes rolled over. Publications show many indications relating to the corresponding severe injuries. Typically, the passengers did not use the safety belt, which is known to protect from the consequences of being ejected out of the car. Severe cervical spine and head injuries due to being ejected from the vehicle and the bodies hitting the ground outside the vehicle constituted the main injury focus points. Most serious and fatal injuries in rollovers result from ejection [Partyka 1979 - 1] and unbelted occupants have a higher risk of ejection than those belted, in cases of ejection 47% were severe or fatal injured (Hight 1972 - 2). Thus many of the publications on rollover injuries were written during the 60s and 70s, when the safety belt was not part of the standard equipment of cars.

Jones [3] reported that the fatality rates for single vehicle crashes mirror those for single vehicle crashes suggesting that the fatality rate is dominated by rollover crashes. NHTSA reported that for years 1992 to 1998 there was an average of about 227000 rollover crashes per year, following in 9063 fatalities per year. The analysis of FARS data in US shows that there are significant relationship between the risk of rollover in single-vehicle fatal crashes and engineering parameters that describe vehicle stability, i.e. track width to cg height ration was the strongest predictor for pickup trucks and utility vehicles, although for passenger cars wheelbase was a better predictor. Padmanaban [4] investigated

[1] cooperative study of FAT and BASt

about 2199 occupants involved in passenger car rollover crashes, 59% of rollovers involve one to two quarter turns, 23% involve three to four quarter turns, 15% five to eight quarter turns and 2.6% involve nine or more quarter turns. Parentau found for belted and unbelted occupants the risk to be seriously injured was higher for far than near-side occupants. For far-side occupants, the risk was highest for climb-over events and collision with other vehicles, while it was greatest for bounce-over events for near-side occupants.

In the recent years the number of persons killed in crashes reaches the highest level since 1990 driven by rollover fatalities likely due to the increase of the number of trucks and SUVs on the road and their increased likelihood to roll [Kratzke et al - 5]. Today rollovers have not so much incidence than in the past. Viano [6] reported that in the U.S. rollovers represent less than 5% of all vehicle crashes (NHTSA 1999), they account for approximately 15% of serious (AIS 3+) injuries and 20 to 25 % of fatalities. 81% of two-away rollovers were single vehicle crashes.

Even today, the majority of rollover accidents are reported from the Anglo-Saxon countries. It does turn out, though, that obviously the accident situations in the US are structured differently from the European countries. There the incidence of the accidents with resulting rollover is significantly lower frequent and also the severity of the injuries largely lower. In the traffic accidents happening in European countries a vehicle rollover does not mainly occur for solo-accidents, but also in the course of vehicle to vehicle accidents such after collision occurrences take place. Especially when 2 vehicles collide and in the course of the post-crash movement a change in friction between the tire and the road occurs, when the vehicle slide sideways either enters the unpaved verge or hits the curbstone sideways and this way a sideways overturning torque is implemented. Furthermore, there are accident situations, where vehicles climb the embankment next to the edge of the road and topple over due to the tilted plane. All these occurrences number among the group of rollover accidents. Kocherscheidt [7] reported that 2 to 5 % of all accidents in Germany are rollovers, in a special study of BMW cars 20 % rollovers were found. An influence of the driving speed could be analysed concerning the injury severity and the deformation depth. Also for german accidents it was pointed out by Miltner [8] that there is in case of not using a seatbelt a high risk for ejection with 68%. In a study published lately on accidents involving guardrails, it was pointed out that the increasing use of noise barrier walls and dams has followed in an increase of such accident occurrences [Otte - 9].

It is thus desired to determine the importance of accidents with resulting rollovers and especially identify the resulting injuries for the current accident occurrences on European roads, in order to implement special measures on the vehicle or in the road construction, to limit the negative effects of rollovers and their pattern.

APPROACH

In order to investigate the accident occurrences of vehicles with rollover consequences more closely, the evaluations of enquiries at the site of the accident are used. This results in accident documentations that were started by a scientific team on-site and later added to in retrospect. Since 1973 the enquiries at accident sites in Hannover have been conducted by the order of the Federal Highway Research Institute (BASt). Starting in 1985 these are conducted using a statistic sample plan, where annually 1.000 traffic accidents involving personal injuries are analyzed and from 1999 these have been conducted in cooperation with the Forschungsgemeinschaft Automobiltechnik (FAT) and the BASt in the areas Hannover and Dresden. All data is collected in a joint database GIDAS (**G**erman **I**n-**D**epth **D**ata **A**ccident **S**tudy). The methodology and sample selection are described in the publication by Otte et al [10]. These accidents were chosen randomly, which can be counted as representative cross-sections of the real accident incidence using a statistic weighting process. For the enquiries, the injuries are classified and documented according to the AIS-scale (**A**bbreviated **I**njury **S**cale - 11) and the damages to the vehicles are recorded according to the CDI (**C**lassification **D**eformation **I**ndex - 12). Driving and collision speeds are calculated from the traces found at the accident site, such as brake and skid marks, the final positions of the vehicles and impact traces on the side of the road using the basics of the physical impact shock theory. Based on such an extensive analysis of the traffic accident incidence, the consequences of roll-over accidents and the detailed vehicle movements can be reproduced.

BASIC MATERIAL

For the analysis of car accidents with rollover consequence 7,744 accidents from the years 1994 – 2001 from the accident sample collected in Hannover were evaluated, altogether 9,257 cars participated with 11,361 passengers, of these 434 cars resulted in a rollover. A rollover was defined to be a movement of the car, where the vertical axis of the vehicle turned at least 90° around the longitudinal or transverse axis to its final position. Thus 430 cars and 741 occupants with rollover constitute the basis of the study. Within the analysis the amount of cases can be different as basis of the diagrams and tables concerning different related

parameters. The presented percentage-values are based on statistical weighting procedure and is given additionally as n-values based on non-weighting numbers.
For these cases, an extensive in-depth analysis of the rollover incidents in the course of an analysis of individual cases was conducted. There, special information based on the existing accident reconstruction details and of a scaled drawing of the accident location was used for the analysis, these were amongst others:

- position of the individual impact on the vehicle
- direction of load at each impact
- deformation depth at the place of each impact
- estimated energetic reduction in velocity as a consequence of each impact
- location of each impact
- direction of load in relationship to the centre of gravity for each impact
- injuries in the course of each impact and place of impact inside the vehicle

Additionally, in order to allow a comparison of the results from this paper with other scientific publications, the vehicle movement, where the Rollover is concerned, was classified; the chosen classification is according to NASS (National Accident Sampling System), where a total of 11 different types of rollovers were differentiated (Figure 1). Parentau et al [13] made a careful study of NASS data and used the rollover-type-classification of NASS, they found that currently developed trip-over and fall-over tests reflect the largest proportion of rollovers in the field.

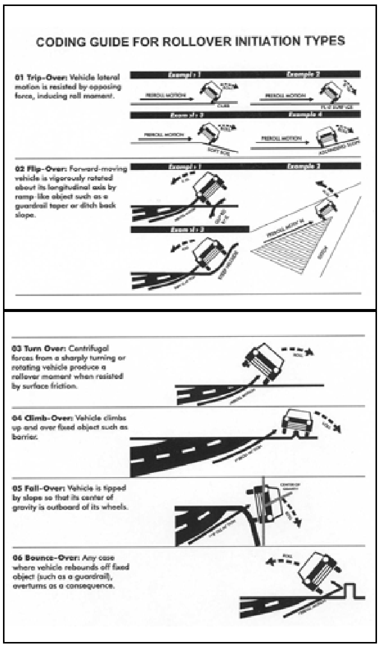

Figure 1. Classification of Rollovers (NASS-Datasampling)

All collisions of vehicles were recorded in chronological order and the driving velocity at the start of the first traces or at the point, when the vehicles left the road were calculated using standard software (PCCrash).
The frequencies of results will be presented with the percentage in weighted form and the numbers in absolute values. The injury severity is used by AIS (Association of Automotive Medicine) and used in the presented diagrams as 3 groups from minor (AIS 1), severe (AIS 2 to 4) and worst/fatal (AIS 5 and 6), with this classification a 90% correlation does exist to the definition of the national statistics based on police reports [Otte - 14].

TYPOLOGY OF ROLLOVER ACCIDENTS

Frequency distribution

Accident structure of rollover situations

The percentage of rollover accidents within the framework of accident investigation GIDAS Hanover has continuously declined and constitutes currently (for the year 2003) only 2.3 % (Figure 2). It is assumed that the significant decrease of the rollover risk after 1999 can be linked to the implementation of ESP (electronic stability program), as only after 1999 vehicles with ESP have been registered in accidents as the figure pointed out. Their percentage of all cars with ESP involved in accidents (with/without rollover) has increased to 11 % in 2003. ESP prevents the pulling of a vehicle after skidding has commenced. As rollovers can also be seen by vehicle-vehicle-collisions, there are also vehicles equipped with ESP among the rollover accidents.

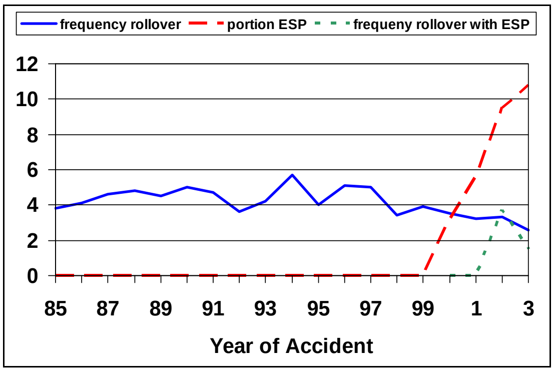

Figure 2. Portion of accidents with rollover (n=20996 Cars = 100%) on traffic accidents with injured persons

Frequently, the rollover constitutes a secondary event. The rollover seems to be an event occurring on special road segments. Nearly 90% of the cases were preceded by a collision (88% on highways, straight country roads and rural curves). A third of these were vehicle collisions, in a quarter of the cases a tree impact took place first. On intersections, the highest frequency of secondary effect of rollover as can be seen in Figure 3 is based on prior vehicle impacts (65% on rural roads, 67% on urban roads).

	rural				urban		
	highway (n=123)	straight line (n=151)	curve (n=79)	inter-section (n=19)	straight line (n=25)	curve (n=10)	inter-section (n=26)
rollover only	13.3	12.6	22.8	7.2	12.5	12.0	-
rollover first	5.5	5.7	1.9	-	5.4	-	-
rollover follows (100%)							
- vehicle impact	15.7	11.7	2.6	65.2	21.4	20.7	67.6
- object impact	65.5	70.0	72.7	27.6	60.7	56.3	26.0
- other impact	-	-	-	-	-	11.0	6.3

Figure 3. Rollover events within Accident Chronology

The risk of suffering an accident with rollover is highest for vans at 5.2% und SUVs at 14.3%, whereas only 3.9 % of standard car types were involved in a rollover accident (Figure 4).

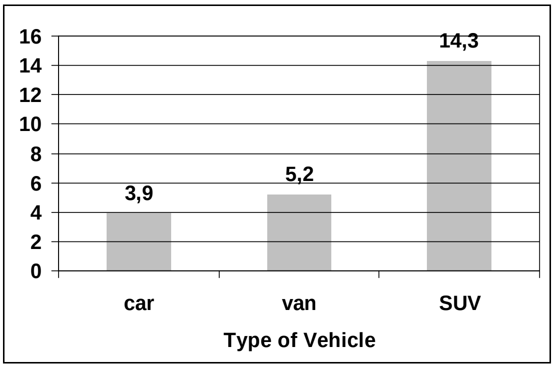

Figure 4. Portion of Rollover events on accidents with injured person related to type of vehicle

Half of all accidents with rollover occur on German streets outside urban areas (Figure 5). Rollovers while cornering are not rare at 16.9%, but in comparison to highways (26.2%) and straight highways (33%) much less frequent. Accidents resulting in a rollover occurred at rural intersections only at 4.5% - at urban ones however at 8.5%. 80.7 % of all rollover accidents occur outside city limits.

road type	rural				urban		
	highway	straight line	curve	inter-section	straight line	curve	inter-section
rollover n=434 (100%)	26.2%	33.0%	16.9%	4.5%	8.1%	2.7%	8.5%
MAIS 0	5.2%	2.3%	4.9%	6.7%	5.8%	-	11.5%
MAIS 1 (100%)	60.3%	66.1%	63.0%	78.1%	60.8%	53.6%	79.4%
MAIS 2-4	29.4%	28.6%	28.1%	15.2%	33.4%	46.4%	6.7%
MAIS 5/6	5.1%	3.0%	4.0%	-	-	-	2.4%
non-rollover n=8827 (100%)	8.2%	8.2%	2.5%	6.9%	23.2%	2.8%	41.1%
MAIS 0	39.2%	31.3%	15.4%	39.1%	66.0%	43.9%	61.8%
MAIS 1	49.3%	49.3%	52.6%	51.2%	30.3%	45.6%	34.3%
MAIS 2-4 (100%)	10.2%	16.4%	27.5%	9.3%	3.5%	9.9%	3.8%
MAIS 5/6	1.3%	3.0%	4.5%	0.3%	0.2%	0.6%	0.1%

Figure 5. Accident Location and Injury Severity of Rollover Events

If additionally the severity of the passengers and drivers of cars involved in rollover accidents is considered, the accidents on freeways, straight highways and in bends outside of urban areas turn out to be especially injury prone: about 29% of these accidents have a maximum injury severity of MAIS 2 to MAIS 4 and 3 to 5 % even fall under injury severity degrees MAIS 5/6. Injuries of a severity of MAIS 5/6 nearly completely missed in urban areas except at intersections (2.4%). Figure 5 shows a comparison with the situation in case of accidents without resulting rollover. A significant risk for resulting rollover consequences can be seen for rural roads and highways, thus roads where possibly a high velocity constitutes a significant influence.

For accidents resulting in rollover most of the vehicles leave the road and turn over at the roadside. Only within city limits do more than two thirds of all rollover accidents occur on the road. Rollover accidents after a tree impact on straight sections of a road do only occur on urban streets (5.4% of the rollover accidents on straight roads). Outside city limits, especially ditches next to the road constitute frequent places of impact (41% on straight roads, 36.6% in curves).

road type	rural				urban		
primary impact	highway (n=123)	straight line (n=151)	curve (n=79)	inter-section (n=19)	straight line (n=25)	curve (n=10)	inter-section (n=26)
road	48.9%	11.6%	13.4%	42.7%	60.4%	76.5%	86.2%
field, grass	20.6%	44.0%	46.7%	17.8%	14.7%	5.8%	11.6%
ditch, slope	25.6%	41.0%	36.6%	39.5%	9.3%	12.0%	2.2%
pole, tree	2.3%	2.4%	1.3%	-	5.4%	-	-
wall	-	0.6%	-	-	-	-	-
others	2.6%	0.4%	2.0%	-	10.2%	5.7%	-

Figure 6. Primary Impact Location of Rollover Events

A rollover accident can consist of several impact phases and the body of the vehicle can touch ground at different places within the course of the rollover motion (Figure 7). Only on highways and in curves did more than 3 impacts occur in the course of a rollover accident (0.2% of accidents with rollover on highways, 1.3% of accidents in curves).

	rural				urban		
number of impacts	highway (n=123)	straight line (n=151)	curve (n=79)	inter-section (n=19)	straight line (n=25)	curve (n=10)	inter-section (n=26)
1	65.9	70.4	71.0	80.9	89.3	73.0	80.4
2 (100%)	26.1	22.5	23.9	19.1	10.7	27.0	14.8
3	7.7	7.1	3.9	-	-	-	4.8
4	0.2	-	1.3	-	-	-	-

Figure 7. Number of Impacts during Rollover Events

Causes of rollovers

A rollover of a vehicle is the consequence of high lateral angular speed, caused by suddenly occurring great deceleration forces between tires and road surface. They can thus be the result of different friction values (μ-split) or of a sudden hooking in the area of the wheels, i.e. when sliding against a curb. In 3.0 % of the cases with rollover a curb stone was evident as cause of the rollover (Figure 8). In 38.0 % the car was swerved under μ-constant or μ-split conditions, in 45.4 % a sliding into an embankment downwards or upwards could be established. In 13.7 % a pre impact with another vehicle implemented the rollover movement.

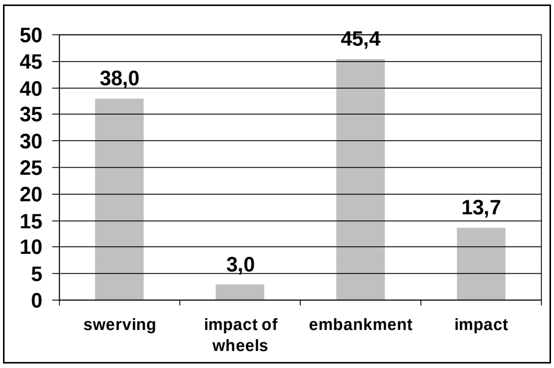

Figure 8. Cause of rollover of n=411 cars (n=23 unknown)

In 20.2 % of the cases with rollover the banquette area was even, compared to 51.2% of non-rollover accidents (Figure 9). Only for 17 % the surface was situated either higher or lower.
One third of all rollover events happened on grass/field surfaces (34.3%), collision objects like trees (1.8%) and walls (0.1%) were in 1.9 % rare as location of rollover impacts. A ditch and an embankment could be seen in 29 % as impact location (Figure 10).
This resulted in the greatest risks for a rollover in case of a ditch running parallel to the side of the road, into which the skidding vehicle slid (27.9 % of the accidents with rollovers happened with ditches related to 3.3 % of accidents without rollover).

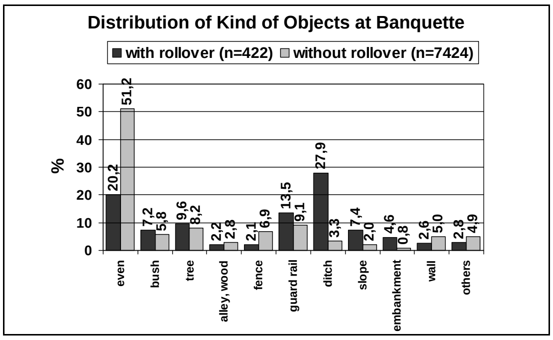

Figure 9. Kind of Objects along the Road in Accidents with and without Rollover

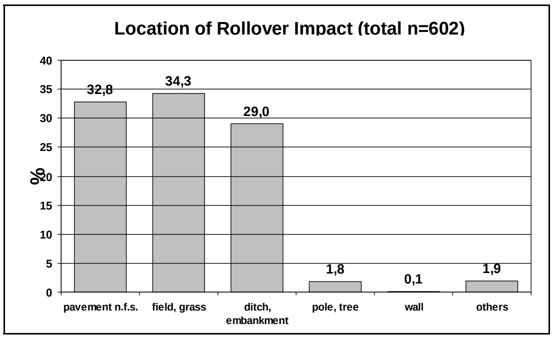

Figure 10. Frequencies of objects strucked at banquette in car accidents with and without rollover

PLACE AND SEVERITY OF INJURIES

Accidents with rollover consequences result in injuries more frequently than those without rollover. For accidents with rollover (maximum injury severity per car) only 5.0 % of the passengers in the car remained uninjured. In contrast, for all accidents with personal injuries 55.6 % of the passengers in the car remained uninjured. 37.4 % of the passengers in the car without rollover suffered injuries of the degree of severity MAIS 1 (with rollover 66.8%) and were thus classified as slightly injured (outpatient), 6.4 % suffered MAIS 2 to 4 (with rollover 25.8%) and 0.6 % suffered degrees of severity MAIS 5/6 (with rollover 2.4%).
In case of rollovers 68.7 % of the vehicles were involved in just one impact, 23.5 % in two impacts, 7.5 % in three impacts and 0.4 % more than three impacts. The severity of the injuries shows clearly that an increase of the number of impacts results in an increase of the severity of the injuries. For one impact only 28 % showed injuries of severity MAIS 2 and higher (MAIS 2+), for three impacts this number had increased to 43 %. It also turned out that a rollover on the road surface results with a probability of 30 % in injuries of the type MAIS 2+, a rollover at the side of the road however does not necessarily increase the severity of the injuries. Frequently in such cases even lower degrees of injury severity occurred. Thus only 28 % of the rollovers in the paved embankment and merely 18 % in the unpaved embankment were related to injuries of severity MAIS 2+.
Belted occupants have a lower risk for ejection (Figure 11). 1.6 % of the belted drivers and 2.4 % of the belted frontseat passengers and 2% of the rear seated occupants ejected during the rollover movement, compared to this 31.9 % of the unbelted drivers and 13% of the unbelted frontseat passengers were thrown out of their vehicles. The presented occupation distribution gives a 79.5% reduction for the driver of severe injuries MAIS 3+ by wearing a seatbelt.

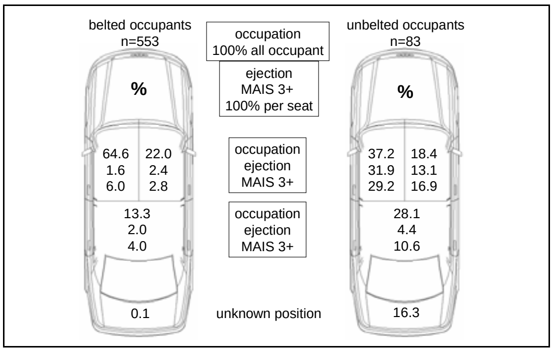

Figure 11. Occupation distribution, proportion of ejection and injury situation of cars with rollover

The type of the collision object and the place of impact on the vehicle seem to be of importance for the severity of the injuries. Concerning the place of impact on the vehicle, the vehicles were subdivided into different zones for the purpose of this study. The sides of the vehicles were subdivided into 6 different zones A – F and the vehicle as seen from above was divided into left - centre - right. This resulted in the frequency distribution of the places of impact on the vehicles depicted in Figure 12a-c.

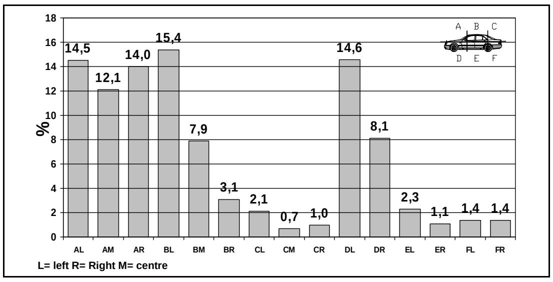

Figure 12a. Impact zones at car (first impact within rollover movement - n=599)

It is visible that an impact zone that occurred very frequently was the front part of the car (AL,AM,AR: total 40.6%) and at still 15.4 % also the position of the driver (BL) as impact zone of the first impact in the course of the rollovers. But also the underbody structure DL can be seen with 14.6% very often as first impact zone within an rollover. Especially the position of the driver is also that with the most severe injuries. 42 % of the passengers suffered injuries of a degree of severity MAIS 2+ when an impact zone BL occurred.

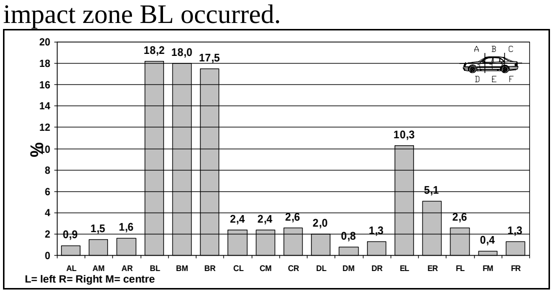

Figure 12b. Impact zones at car (second impact within rollover movement - n=534)

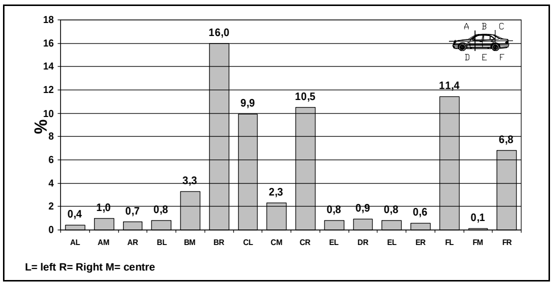

Figure 12c. Impact zones at car (third impact within rollover movement - n=391)

A rollover is mostly characterized by several different places of impact on the vehicle. A <u>second impact</u> in the course of the rollover was determined on very few parts of the vehicles (Figure 12b). Mostly there were places of secondary impact on BL, BM, BR – zones (in total 53.7%), thus in the area of the front passenger seat – with approximately 18 % each. Here, the severity of the injuries was usually significantly higher for the area of the passenger cell than outside the compartment. Only the <u>third impact</u> in the course of the rollover phase (Figure 12c) occurred mainly in the rear area of the passenger compartment (CL, CM, CR) but still also in the area of the front passenger seat at 16 % (BR). The most severe injuries were mostly registered in the course of the third impact, if this impact occurred in the front part of the roof of the passenger cell (AL, AM, AR).

13.8% of the injuries of car occupants were caused by the windscreen, 10.2% by the dashboard and 5.7% by the steering wheel (Figure 13). Side glasses of the vehicle caused 9.5% of the injuries within rollovers and 8.3% were registered as the roof parts. Remarkable is the fact that 7.4% of the injuries were caused outside the vehicle and 9 % were non contact injuries called “whiplash injuries”.

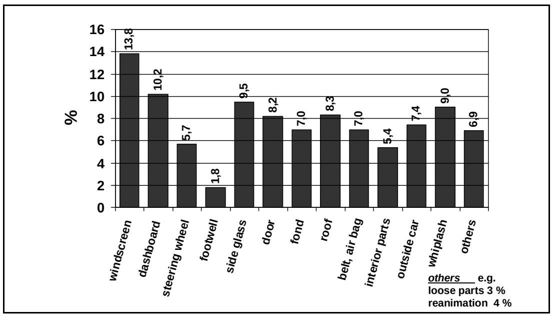

Figure 13. Injury causing parts of car occupants in rollovers (n=408 injuries caused by rollover)

KINEMATICS AND CHARACTERISTICS OF THE ROLLOVERS

Concerning the typing of the Rollover according to NASS classification it turns out that the most common accident type at 29.7 % is the Trip-Over type 3 (Figure 14). This is a type of accident where the rollover occurs on a gradient with soft surface and a sideways tilting vehicle. This type is followed by the type Trip-Over 2 at 17.6 %, where the vehicle skids sideways on a flat surface and topples over. All others of a total of 11 different types according to NASS occur at low frequencies. The type Flip-Over 2 occurs relatively frequently at 9.8 %, where a vehicle moves mainly along the longitudinal axis of the vehicle, reaches a ditch by rotating around its longitudinal axis and topples over. These three dominant rollover types build 57.1% of all rollover events.

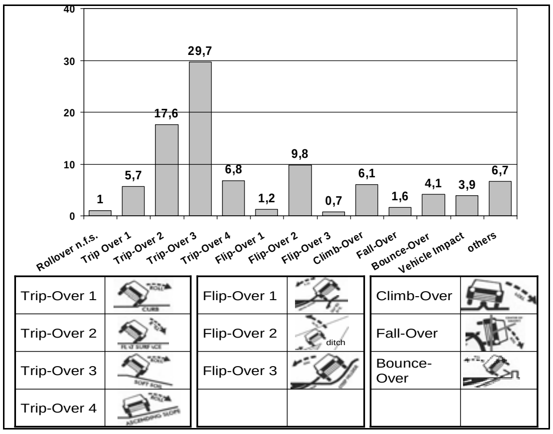

Figure 14. Frequencies of different rollover-types (NASS classification), n=422

Accidents in the shape of a rollover characteristic with a sideways knock are not very frequent (Trip-Over 1 - 5.7 %, Flip-Over 1 - 1.2 %, Bounce-Over - 4.1 %), and they seemed especially minor (Figure 15). Approximately 30 to 50 % of these resulted in uninjured occupants (MAIS 0). The lower severity of injuries can be explained by the more rotational speed the tilting car undergoes. In other types of rollover the impact to the car body suffer high deceleration loads. Regarding the resulting severity of injury, out of the accident types with increased frequency, the Trip-Over 2 seems to cause the worst injuries (26 % MAIS 2+), whereas especially remarkably in its complete distribution concerning the severity of injuries is the Flip-Over 3 with nearly 50% MAIS 2+, where a vehicle falls sideways off the road onto a significantly lower terrain. The type Fall-Over also remarkable, it has the lowest percentage of soft injuries, but very few in occurrency. The subsequent roof impact is correspondingly usually massive. In 56 % of the cases rollover occurs over the left side of the vehicle. No significant change of the resulting severity of the injuries in relation to the side of the rollover was found.

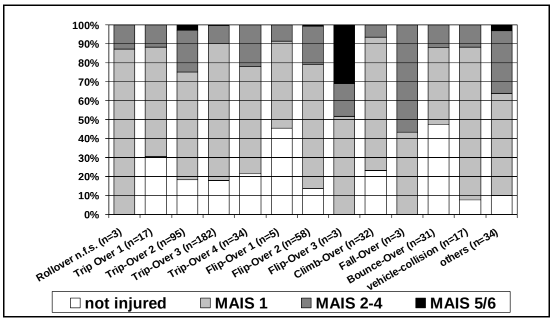

Figure 15. Injury severity grades of belted not ejected occupants for different kinds of rollover

INJURY SITUATION TO BODY

The main emphasis where injuries on the body after a rollover had taken place were concerned was placed mainly on head, thorax and arms. 42.5 % of the belted not ejected occupants in car accidents resulting in a rollover were injured on the head, 26.2 % on the thorax and 44.6 % at the upper extremities. In comparison with the injury image of belted occupants in car accidents without a rollover, there 34.5 % of head, 30.9 % of thorax and 18.4 % of arm injuries occurred. It was thus shown that under rollover conditions the risk for head and especially for arms is much more higher than without rollover. That is the same for neck injuries, which could be seen in 25.1% of rollover cases.

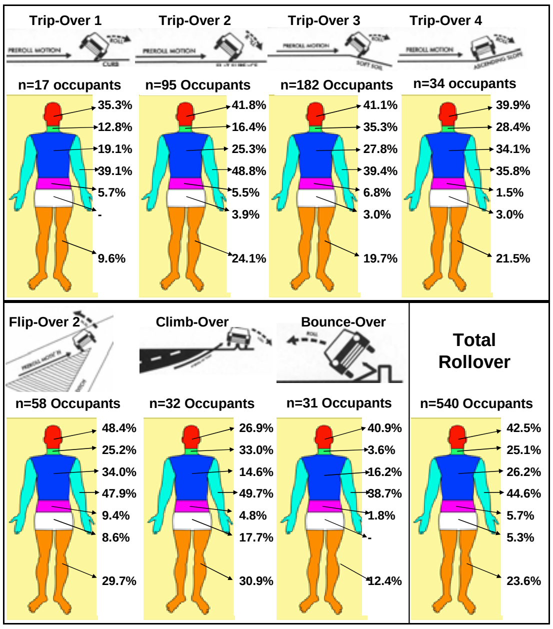

Figure 16. Frequencies of injured body regions of belted not ejected occupants for different kinds of rollover (100% all occupants each group)

The analysis of the injury pattern found this high risk for head impacts in rollover accidents especially when the car collided with additional impacts on other vehicles and objects before or after the rollover event (Table 1). 47 % of occupants of vehicles with additional impacts suffered soft tissue lesions on the head, 3.5 % fractures to the face and 11.4 % brain injuries compared to occupants of vehicles with isolated rollover, 37 %suffered soft tissue lesions, 0.8 % facial fractures and 9.5 % brain injuries. Table 1 explains that an isolated rollover is not a severe accident event, the severity is increasing if a pre- or post-impact to other vehicles or objects occurs.

Kind of Injuries	Rollover cases	
	isolated	additional impact
total (n)	91	650
soft tissue head	37.0%	47.0%
fracture face	0.8%	3.5%
fracture skull	-	0.8%
fracture base of skull	-	1.3%
SHT	9.5%	11.4%
soft tissue neck	-	1.9%
whiplash injury	23.1%	18.3%
fracture cervical spine	2.0%	2.8%
others neck	2.8%	1.5%
soft tissue thorax	25.9%	26.8%
fracture ribs	1.4%	2.6%
fracture sternum	-	1.1%
fracture shoulder	1.4%	2.9%
thoracic spine	0.9%	2.5%
thorax organic	3.3%	2.0%
soft tissue upper extr.	48.1%	39.7%
fracture upper arm	-	1.6%
fracture ellbow	-	0.3%
fracture lower arm	0.8%	1.9%
fracture hand	2.7%	2.5%

Table 1
Frequencies of injured body regions of belted not ejected occupants for different kinds of rollover (100% all occupants each group)

63 % of the vehicles with rollover skidded at the time the accident started, 90 % of the vehicles were driven at velocities exceeding 60 km/h at the moment the accident started (Figure 17). Thus a high driving speed is a typical feature of accidents with rollover consequences. Whereas for accidents without rollover consequences 90 % of the vehicles were driven at speeds exceeding 10 km/h and 70 % were doing less than 60 km/h the moment the accident started. On the other hand, the analysis of collision speeds of the vehicles with and without rollover did not show any significantly deviating velocity distribution. 80 % of the vehicles with rollover primarily collided in the course of the accident primarily at speeds of up to 52 km/h, without rollover it was 60 km/h. This means that obviously a large amount of speed can be dissipated after the accident has started, up to the point of collision in the course of the skid movement.

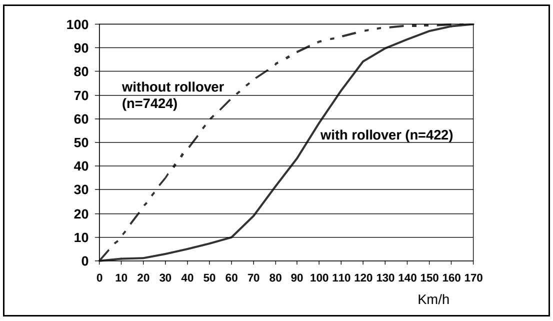

Figure 17. Cumulative frequencies of driving speeds of cars before reaction

DEFORMATION PATTERN ON THE VEHICLE AND INFLUENCE ON THE SEVERITY OF THE INJURIES

Very rarely more than one complete turn occurred in the course of rollovers. 16.7 % were classified as ¼-rotation, 52.1 % as ½ rotation, 6.5 % as ¾ - rotation. Only in 4 % of the cases more than a complete rotation of the vehicle was found. 88 % of the rollovers were consequences of previously occurred primary collisions.
The deformation depth of each impact was measured in the direction of the impact load. Deformations of up to 40 cm occurred by rollovers. Looking to the depth of deformation for cases with minor injury outcome compared to those with severely injured occupants, only small different accumulated frequency distribution of the deformation depth on the resulting severity of the injuries MAIS for the belted occupants was apparent (Figure 18). 80 % of the severely injured belted occupants MAIS 5/6 as well as 80 % of the MAIS 1 minor injured belted occupants suffered within the rollover, deformation depths of up to 15 cm.

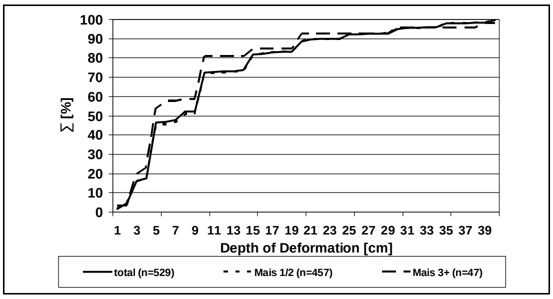

Figure 18. Cumulative frequencies of depth of deformation related to different injury severity grades for belted not ejected occupants

Each deformation on the car was related to the number of impacts during the rollover movement as primary, secondary or third contact. The deformation was measured with the deformation depth and assessed concerning the suffered speed change during this impact; this was done by an EAS-value (Energy Assessed Speed) even this could not be done exactly and in a physical allowed manner. This EAS value should be given an assessment for the severity of rollover impact to the car body shape. In these cases EAS is represent an assessment of the deformation-impact-configuration of the rollover movement. 80% of the values for impacts by the rollover can be found up to EAS 15 km/h (Figure 19). Similar distributions in the cumulative frequency curves of this value can be seen for primary, secondary or third contact. In contrast to this 80% of the EAS-values for cars with no rollover were estimated above EAS 10km/h.

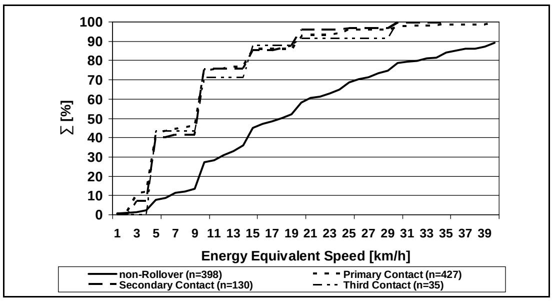

Figure 19. Cumulative frequencies of deformation energy assessed by EAS for cars with rollover for different impact situations

For the analysis of the injury severity related to the rollover movement, a special MAIS was built for all rollover related injuries. The so called "MAIS rollover" was plotted in a diagram related to the depths of deformation by rollovers (Figure 20). The injury severities by rollovers are for belted occupants mostly not above MAIS 2 and there are many uninjured occupants within a rollover movement. The Spearman correlation coefficient was calculated with 0.212, that means a small positive relationship between deformation depth and injury severity was found.

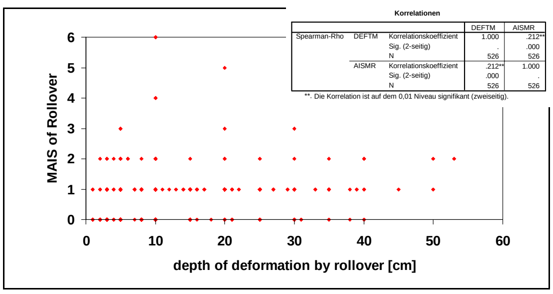

Figure 20. injury severity MAIS of rollover related injuries and the depth of deformation of those contact points on the cars with rollover (n=529)

A similarity can be established for non-rollover cases (correlation 0.051), but compared to the injury severity of rollover related deformations the injury severities of non rollover related deformations following in more significant correlation of these two parameters (Figure 21). Larger deformations are mostly linked with higher injury severities for deformations not related to rollovers. The Chi² test shows that the higher injury severity grades are more linked to non-rollover situations ($p < 0.001$).

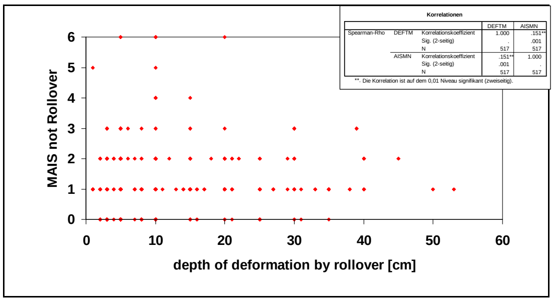

Figure 21. injury severity MAIS of non-rollover related injuries and the depth of deformation of those contact points on the cars with rollover (n=517)

From this analysis it can be seen that the injury severity MAIS of occupants after rollover resulted mainly from the injury severity of the head (Figure 22), because the head is exposed as flexible extremity part for the injury risk. It can be pointed out from the diagrams that the risk for severe head injuries is statistically starting for belted occupants with roof deformation depths of above 30 cm.

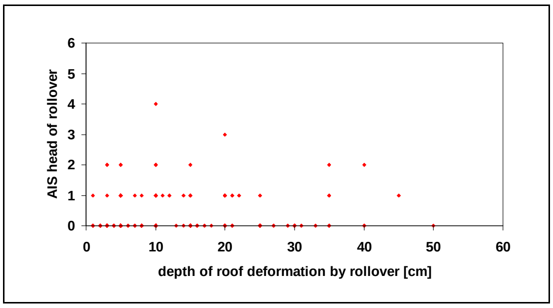

Figure 22. injury severity of the head of occupants with rollover related injuries and the depth of deformation of those contact points on the cars with rollover (n=438)

CHARACTERISTICS OF THE ACCIDENT SET-OFFS

From the detailed documents of the accident reconstructions, especially the in-scale drawing of the traces found on the accident site, such as brake and skid traces, the take-off angle of the road surface, the skid, brake/skid distance could be determined and the period of time from hitting the brake to the point of the primary impact could be calculated. Mainly very small angle deviations from the longitudinal axis of the road occurred, when the vehicle left the road towards the side. 65 % of the vehicles left the road at an angle of less than 5 degrees (Figure 23).

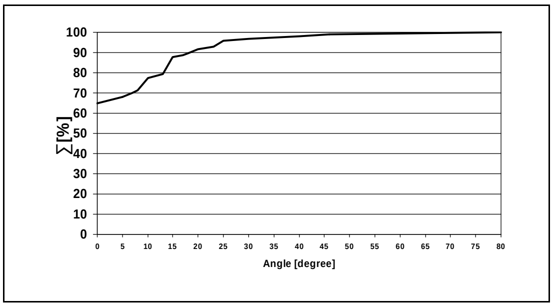

Figure 23. Angle of running off the roadway (n=334). This angle exists between the direction of car's centre of gravity and the direction of the road when leaving the roadway

Angles of more than 25 degrees occurred only in 5 % of the cases. This means that the take-off angle for accidents with rollover consequences does not exceed 25 degrees. An attitude angle for the vehicle to the left of up to 80 % between 0 and 120 degrees as well as to the right as to the left side can be determined (Figure 24).

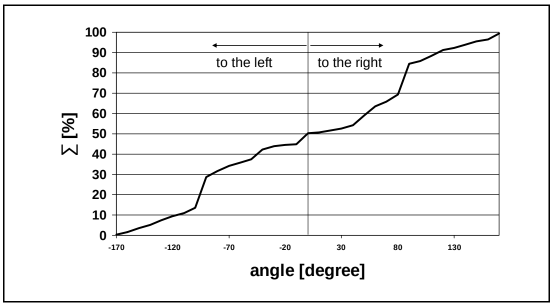

Figure 24. Cumulative frequencies of attitude angle at rollover (n=409)

For 80 % of the accidents with rollover consequences a time of up to 4.3 seconds elapsed from the start of the accident to the first impact during rollover. In only approx. 10 % of the cases periods of more than 5 seconds elapsed and 5% registered with more than 6 seconds (Figure 25).

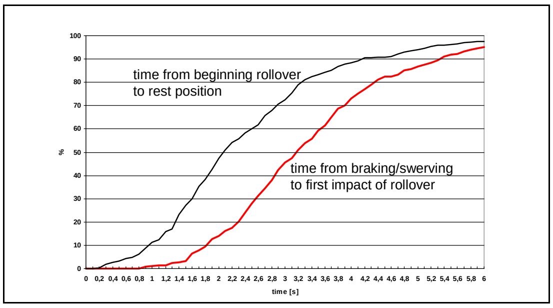

Figure 25. Cumulative frequencies over time from the beginning of the breaking/swerving movement to the first impact in the course of the rollover (n=308) and the whole time duration until the rest position of the car (n=295)

For the whole movement of a rollover to rest position a time duration of 1 to 4 seconds (80%) can be seen as useful in real accidents.

CONCLUSIONS

Rollovers are found in the traffic scenery in different situations, some are the result of a high rotation of the car and an increase of friction between tires and the road surface, others are the effect of a sudden hooking in the area of the wheels. For the German accident situation the study pointed out that a rollover could be observed in 3.7% of the accidents with casualties and that the percentage has been reduced over the years to the current state of 2.3% for the year 2003. It can be awaited in the future the number of rollovers accidents will further decrease regarding the fact that many vehicles will be equipped with ESP (electronic sliding protection). But the prospective should be not too optimistically because the study found cases of ESP equipped cars in rollover accidents as well. The portion of rollover events are at 11 % remarkable high for vans and off-road-vehicles. Rollovers mainly occur in connection with accidents on straight road sections and at intersections, especially on rural roads, 20% occurred in a curved section only. It could be seen that speed influence is a major parameter for accident causation following in rollover events. Ditches and Embankments are at 29% beside the unpaved surfaces of fields or pastures the most frequent collision object within a rollover movement, an impact against trees or walls can be seen only in less than 2 %. Nearly 70% of all impacts within a rollover occur on flat surfaces (paved, field, grass). Comparing accident situations with and without rollover the highest risk for rollovers can be established, if the road side is equipped with a ditch. 80 % of the rollovers were consequences of previously occurred primary collisions. In 3% only the rollover was initiated by a wheel movement against a curb stone, in all others the increasing friction value during the sliding motion was responsible for rollover momentum.

The type of the collision object and the place of impact on the vehicle as well as the number of impacts within a rollover movement influence the injury outcome. The position of the driver is often hit first, the second impact zone being the roof of the vehicle, while the rear of the roof is more often hit third. The position of the driver is with the one, where the most severe injuries occur.
The study shows that 3 different types of rollover make up nearly two thirds of all rollover cases: firstly the so-called "Trip-over, describing a lateral movement of the vehicle on a downward sloping ramp"and secondly the "Flip-over, these are also the ones with the highest injury risk for head injuries. The study came to the same results as Parentau et al [13] pointed out, that trip-over reflect the largest proportion of rollover in the field. But in contrast to Parentau which confirmed also the Fall-over test conditions as one major accident type, the presented study pointed out that rollovers in the characteristic of a lateral sideway movement and rotation via the longitudinal axis are seldom and not very severe. For the replication of frequent and severe real life rollover accidents a screwed movement of the car on a ramp via the longitudinal forward movement should be proposed as test procedure. This corresponds to examinations of Berg et al [15].
Only a small influence of the deformation depth on the resulting severity of the injuries MAIS was apparent. 80 % of the severely injured occupants MAIS 5/6 as well as 80 % of the MAIS 1 minor injured occupants suffered within the rollover, deformation depths of up to 15 cm. This is in agreement with other authors, i.e. an investigation by Piziali et al [16] came to the conclusion, that there is only association between roof crush and injury since the occupant is not in the vehicle. Putting the occupant in the vehicle does not change association to casualty. The here presented study found a correlation of Injury risk and roof deformation for severe head injuries AIS 3+, starting at roof deformation above 30 cm. Also Cooper and Mofatt [17] found a causal relationship between roof crush and injury risk. A recent article from Australia by Rechnitzer [18] that reviews previous literature and several case studies concludes that roof crush causes injuries in rollover accidents. Also Friedman[19] includes a NASS analysis to support their contribution that roof crush causes injuries. The NASS study finds that the occupant closest to the most significant roof crush is at highest risk of injury. Parentau [20] explained this effect on the situation of the crash, that near-side occupant´s head crossed the window plane more frequently than the head of the far-side occupant. This effect cannot be confirmed by the presented study, here the farside occupant suffered in 6.4% of the rollover cases an injury severity MAIS 3+ and 16 % were uninjured comparing to 5 % of the nearside occupants suffered MAIS 3+ and 20% were uninjured. The most severe injuries were mostly registered in the course of the third impact, if this impact occurred in the front part of the roof of the passenger cell.
The here presented study describes details of the initial part of the accident phase following in rollovers. 65% of the vehicles left the road at an angle of less than 5 degrees, angles of more than 25 degrees are very rare at 5%. An attitude angle for the vehicle movement from leaving the road, or after the primary impact, respectively to the first impact during the rollover was measured in 80% between 0 and 120 degrees to the left as well as to the right side of the road. For 80 % of the accidents with rollover consequences a time of up to 4.3 seconds elapsed from the start of the accident to the first impact during rollover. In only approx. 10 % of the cases periods of more than 5 seconds elapsed. This brings strategies of accidents avoidance in the main focal point of interest, there could be enough time for activating intelligent sensor technique for the development of different airbag systems.

The conclusions from the study can be formulated as follows:
1. rollover prevention
    - avoidance of vehicle sliding (63 % of cars with a rollover slipped before the rollover)
    - reduction of driving speed (80 % of cars with a rollover were driven >70km/h)
    - reduction of high friction values in the areas of the wheels (38 % of accidents with rollovers were initiated by lateral sliding effect μ- and μ-split)
    - recommendation for the implementation of a paved flat strip beside the road on the same height-level, avioding ditches, trees and other fixed objects
2. Injury prevention within rollover event
    - development of stiffer interior structures of the vehicle cell especially avoidance of the roof deformations > 30 cm
    - use of seatbelts, implemented with pre powered pull tight devices
    - positioning of padding together with additional implemented airbags in lateral head and roof position

The study shown that for belted occupants in the current accident situation, there is with approximately 2 % of accidents with casualties a low risk to be injured in a rollover movement on German roads. Comparing to vehicle to vehicle impacts an isolated rollover event can be established in principle with minor injury outcome for the current car fleet and their safety equipment. In contrast to earlier studies form the 70ies [Mackay 21] the injury outcome in current vehicles can be positive reduced by wearing seatbelts.

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NHTSA'S CRASHWORTHINESS ROLLOVER RESEARCH PROGRAM

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ABSTRACT

In 2002, the National Highway Traffic Safety Administration (NHTSA) identified rollover crashes as one of its highest safety priorities. NHTSA formed an Integrated Project Team (IPT) specifically to examine rollover crashes and to make recommendations as to how it could most effectively improve safety in this area. This paper presents the research program undertaken to carry out the crashworthiness related aspects of these recommendations.

The crashworthiness rollover research program can be separated into two main topics, ejection mitigation and protection for non-ejected occupants. The ejection mitigation program encourages the use of occupant containment countermeasures, developing performance requirements, and test procedures for evaluating these countermeasures, and developing test procedures to evaluate rollover sensors that will be used to deploy the countermeasures. The research program for the protection of non-ejected occupants includes evaluating roof crush test methods and rollover restraint performance. NHTSA's research plans, recent results, and their significance to the overall rollover problem are presented for each of these research areas.

INTRODUCTION

From 1995 to 2003, the National Automotive Sampling System Crashworthiness Data System (NASS-CDS) reports an average of 261,881 light vehicles involved in rollover crashes. Rollover crashes can be especially lethal; although they comprised only two percent of crashes, they accounted for almost one-third of light vehicle occupant fatalities (including 59 percent of sport utility vehicle [SUV] fatalities) in 2003. The rate of rollover in towed light vehicles with serious occupant injury (25 percent) was nearly four times as high as for towed vehicles with no more than property damage (6 percent). Fifty-eight percent of rollover deaths in light vehicles were associated with full or partial ejections. Light-vehicle rollover crashes resulted in 10,378 fatalities in 2003 and in approximately 245,142 non-fatal injuries per year (on average) from 1995-2003.

In 2002, NHTSA identified rollover crashes as one of its highest safety priorities. The Agency formed an Integrated Project Team (IPT) specifically to examine rollover crashes and make recommendations as to how it could most effectively improve safety in this area. The IPT report, "Initiatives to Address the Mitigation of Vehicle Rollover", was published in the Federal Register in June 2003 (68 FR 36534) [1]. It included vehicle strategies covering both the crash avoidance and crashworthiness perspectives. This report made wide-ranging recommendations on ways to mitigate rollover crash injuries, including several vehicle strategies, behavioral strategies, and roadway strategies. This paper documents the ongoing crashworthiness research efforts that were recommended by the IPT report.

Due to the complex nature of rollover, NHTSA has recognized the need to take a comprehensive approach to developing potential solutions. The Agency's crashworthiness efforts to reduce rollover fatalities and injuries focus reduction of occupant side window ejection, improvement to roof crush protection, and rollover restraint system effectiveness.

EJECTION MITIGATION

Ejection is a major cause of death and injury in light-vehicle rollover crashes. There were 9,859 people killed in 2003 and approximately 44,223 had non-fatal injuries in tow away crashes each year (on average) from 1995-2003 when they were ejected from light vehicles. Two-thirds of these ejections occurred in crashes involving rollover. Occupants stand a much better chance of surviving a crash if they are not ejected from their vehicles. For each year from 1995 to 2003, approximately 5,885 people were killed and 5,451 seriously injured when they were ejected through side windows.

Among the promising technological innovations to prevent occupant ejections are the use of side curtain air bags and improved glazing. NHTSA submitted a report to Congress on ejection mitigation using advanced glazing materials in November 2001. In May of 2004, NHTSA issued a Notice of Proposed Rulemaking (NPRM) proposing to upgrade Federal Motor Vehicle Safety Standard Number (FMVSS No.) 214 "Side impact protection" which, among other things, proposed to require a side impact pole test that would provide improved head protection to occupants. This proposed regulation would likely result in the fleet-wide installation of side air bags to protect the head. While these air bags would not necessarily be designed for occupant containment or for deployment in rollovers, they would prevent some number of side window ejections. This is the first phase of a three-phase approach the agency is taking to reduce side window ejections. The second phase is to establish occupant containment performance requirements, and develop test for this purpose. Details of the Phase 2 research are presented below. The third phase is to establish performance requirements for rollover sensors, to ensure that the air bags will deploy in a rollover crash. The agency has not conducted specific research in this area yet, but has collected considerable information in its effort to develop a research plan for rollover sensor performance requirements.

Phase 2 Objectives

The first objective for the Phase 2 research is to develop a test methodology, including a test device, to evaluate the retention performance of potential ejection mitigation systems. This includes establishing practical test parameters such as impact speed, impact locations, and performance criteria. For a test to be acceptable, it must show that good (or poor) performance in the laboratory test correlates to good (or poor) performance in the real world. The second objective is to evaluate the test methodology and performance criteria on potential ejection mitigation systems.

Test Methodology

Guided Impactor - NHTSA has been conducting research on ejection mitigation for several years. Since full-vehicle rollover crash tests have substantial variability in vehicle and occupant kinematics [2], it is necessary to develop a component-level test to evaluate the performance of potential ejection mitigation systems. Previous research with advanced side glazings has shown that guided impact testing is an acceptable method for measuring excursion. NHTSA's advanced side glazing status report [3] details the development of an impactor designed to replicate the loading of an occupant's head and shoulder during typical ejection situations. In brief, it consists of an 18 kilogram mass guided through a bearing attached to two supporting rails (see Figure 1). An existing featureless free-motion headform was selected for the impactor face. This rigid headform, covered with a headskin, was originally designed for the upper interior head protection research program. It averages the dimensional and inertial characteristics of the frontal and lateral regions of the head into a single headform [4]. Since it is a guided impactor, only uni-axial motion is measured, and it is capable of measuring dynamic deflection during an impact. The propulsion unit is based on a device by the General Motors Corporations [5], scaled to accommodate the heavier mass. The impactor can be placed inside the vehicle for testing the side window areas, and it can be positioned to strike different locations in those areas.

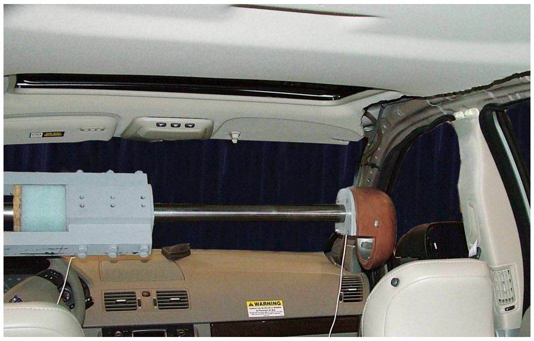

Figure 1. 18 Kg guided impactor.

Test Parameters - The level of a countermeasure's performance measured by the guided impactor can vary depending on impact locations and speeds used. A test matrix was proposed in a previous paper outlining the status of NHTSA's Ejection Mitigation Research to date [6]. An expanded matrix was used in subsequent testing. Each of the impact locations were evaluated using the test matrix shown in Table 1. The primary goal of this test matrix was to determine if the guided impactor is a suitable device for measuring the occupant retention performance of a variety of possible countermeasures, and if it is, to help identify and establish practical performance criteria.

Table 1.
Guided Impactor Test Matrix.

Impact Speeds	16 kph	20 kph	24 kph
Delay Time	6 sec	1.5 sec	1.5 sec
Advanced Glazing Systems Only			
Inflatable Systems Only			
Inflatable Systems With Glazing (pre-broken)			
Inflatable Systems With Glazing (unbroken)			

Different sized occupants traveling on various trajectories may encounter an opening at numerous locations within the side window portal. Therefore, four impact locations were identified to evaluate a countermeasure's window coverage and retention capability, as shown in Figure 2.

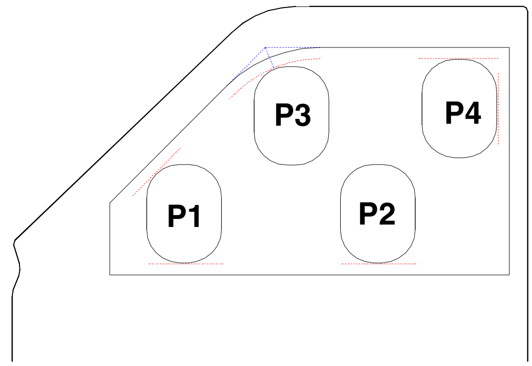

Figure 2. Headform impact locations.

Positions 1 and 4 are located at the extreme corners of the window/door frame and positioned such that a 25-millimeter gap exists between the outermost perimeter of the headform and window frame as represented by the dashed lines in Figure 2. Position 3 is near the transition between the upper window frame edge and A-pillar (diagonal) edge. Previous research with advanced side glazings identified this area as a weak point in limiting excursion. It is located by bisecting the angle that is created at the intersection of two lines running parallel to the upper and diagonal window frame edges. A 25-millimeter gap is maintained between a point on the outermost perimeter of the headform and the bisection point on the window frame edge. Position 2 is located at the longitudinal midpoint between positions 3 and 4, and positioned such that the lowest edge of the headform is 25 millimeters above the surface of the door at the bottom of the window opening.

At each impact location, different impact speeds and different time delays between air bag deployment and impact were used. Rollovers can be relatively long events. The reason for the time delays is that inflatable ejection countermeasures tend to lose pressure after deployment. This pressure can affect the retention capability of the countermeasure. To simulate ejection late in a rollover event, the air bags were impacted at an impact speed of 16 kilometers per hour after a delay of six seconds. To simulate an ejection early in a rollover event and in a side impact, a delay time of 1 ½ seconds was used. This condition was evaluated at two speeds, 20 and 24 kilometers per hour. The impact speeds were selected upon the film and data analysis reported in reference 3.

Ejection Countermeasure Candidates - Three ejection countermeasures were examined: two experimental roof rail mounted inflatable systems and advanced side glazings developed under previous NHTSA research. Details of the countermeasures used in testing can be found in reference 6, with one exception. The inflatable device known as the Advanced Head Protection System (AHPS®) developed by Zodiac Automotive US (formerly Simula Automotive Safety Devices, Inc.) was furnished with a modified design that allowed the device to deploy closer to the bottom of the window opening, thus providing more window coverage than the previous design (see Figure 3). The other inflatable system tested, a prototype window curtain provided by TRW, is shown in Figure 4.

Figure 3. Modified advanced head protection system (Zodiac).

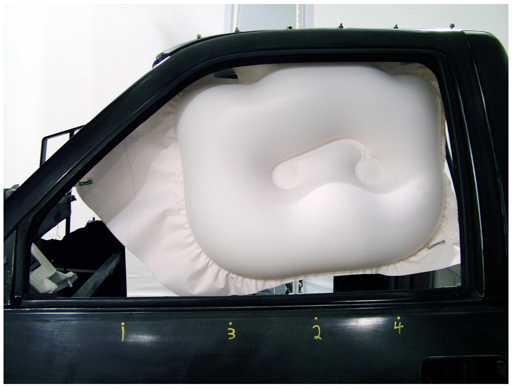

Figure 4. Prototype window curtain (TRW).

Both inflatable systems were evaluated for their effectiveness as stand-alone devices. In addition, the inflatable device supplied by TRW was tested for its effectiveness as part of a combination system (air bag plus side glazing). For testing described in this paper, only advanced glazing systems in the laminated construction were used and door/window frame modifications were limited to the C-channel along the vertical sides (A and B-pillar).

Guided Impactor Test Results

The two air bag designs were placed on a Chevrolet C/K pickup cab and used to evaluate the test methodologies described previously. Each curtain design was evaluated for allowable excursion (impactor displacement) beyond the side window plane. This zero reference point was established by touching the impactor face to a piece of standard tempered glass prior to testing. Negative numbers indicate that the impactor face did not reach the zero plane reference. The air bags were pre-inflated with shop air to pressures previously measured in deployments with an inflator (see Table 2).

Table 2.
Air Bag Static Pressures.

	1.5 sec	6 sec
TRW Air Curtain	62-kPa	28-kPa
Zodiac modified AHPS®	79-kPa	49-kPa

Results for guided impactor tests on TRW's prototype window curtain are shown in Figures 5 through 7. Impact position 1 was not sufficiently covered by this air bag and was unable to stop the impactor before the limits of travel were reached (about 180 millimeters beyond the plane of the vehicle window for this test setup). When combined with advanced laminated glazing, excursion was limited at the 16 and 20 kilometers per hour impacts, with the unbroken laminate showing some improvement over the pre-broken glazing.

At position 2, the window curtain stopped the impactor before reaching its physical stops at the three impact speeds. Excursion measurements were greatly improved with the addition of both unbroken and pre-broken laminated glazing.

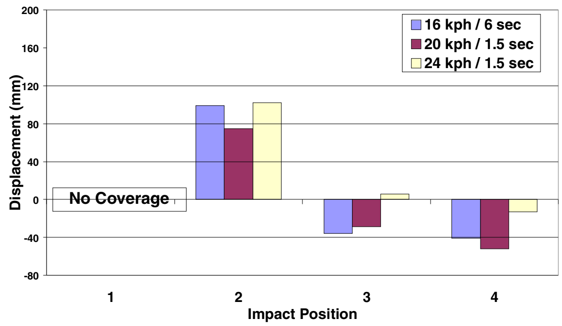

Figure 5. Maximum excursion beyond window plane - TRW air curtain system.

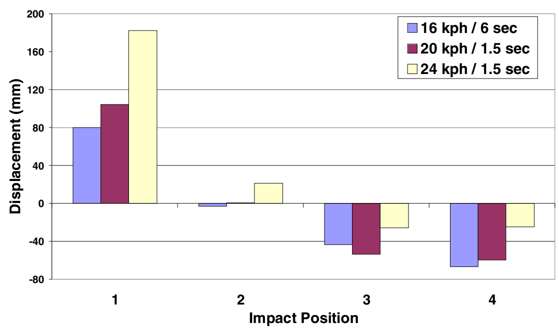

Figure 6. Maximum excursion beyond window plane – TRW air curtain/pre–broken laminated glazing.

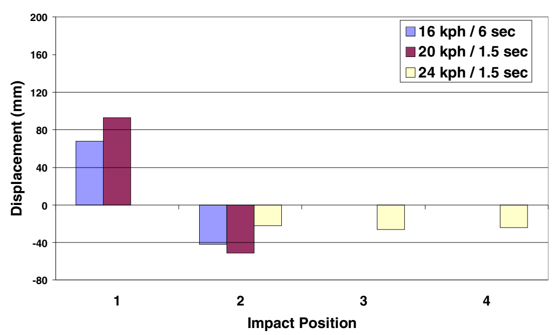

Figure 7. Maximum excursion beyond window plane – TRW air curtain/unbroken laminated glazing.

At positions 3 and 4, this inflatable system was able to contain the impactor at the three impact speeds with little or no excursion beyond the plane of the window. The addition of un-broken or pre-broken glazing produced only slightly better results, suggesting that the air curtain was predominantly responsible for limiting excursion at these impact locations.

Results for partial testing with Zodiac's modified Advanced Head Protection System are shown in Figure 8. Testing was restricted to positions 1 and 2 due to limited availability of this inflatable system. In the 16 kilometer per hour tests, with the lower bag pressure, the headform did not go beyond the plane of the window, while the headform was contained inside the vehicle at 20 kilometers per hour, with the higher bag pressure. Finally, at the 24 kilometers per hour impact condition, 12 and 19 millimeters of excursion were produced at positions 1 and 2, respectively.

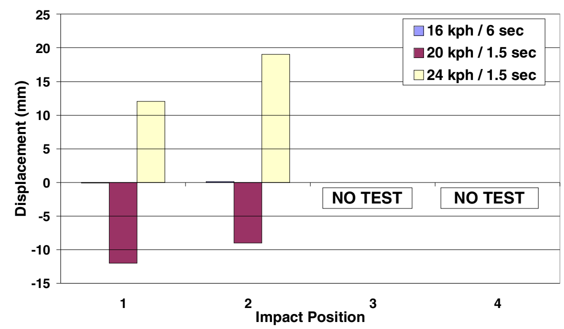

Figure 8. Maximum excursion beyond window plane – Zodiac modified AHPS®.

Repeatability - Several impact conditions were chosen for a study of the repeatability of the test parameters. The results are shown in Figure 9. Overall, the repeatability was quite good, although the 24-kilometer per hour tests at position 2 had the most variability (102 and 82 millimeters). A third test was conducted at position 2 under these same conditions (not shown in Figure 9), and it also resulted in 82 millimeters of excursion. One possible reason for the variability is that there was more tearing in the bag material at one of the side rail attachment points in the first test than in the next two tests. It is not known how much this tear affected the headform excursion.

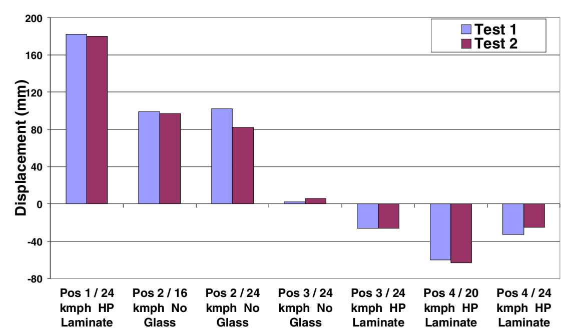

Figure 9. Repeatability results for selected impact conditions.

Dynamic Rollover Fixture

A series of tests was conducted on the Dynamic Rollover Fixture (DRF) using an unrestrained Hybrid III 6-year old dummy to further determine the effectiveness of experimental roof rail mounted inflatable devices, advanced side glazing, and combinations of these systems in retaining occupants during rollover type crashes. The testing also evaluated the countermeasures' potential for head and neck injury. These DRF tests build on the test matrix that was presented in reference 5. In previous testing with 50th percentile male and 5th percentile female Hybrid III dummies, loading on the inflatable devices in some tests produced gaps between the devices and the top of the door, allowing the shoulder and arm to escape below the bags. The current tests were conducted to determine if the gap produced was substantial enough to allow a smaller stature occupant to pass through.

Baseline Testing - Baseline testing was conducted with an open side window to determine if the DRF could produce full body ejections for the 6-year old dummy as it had done with the 50th percentile male and 5th percentile female dummies. The general kinematics for the 6-year old were similar to the other dummies, and full ejection was achieved in this testing configuration.

Inflatable Device Testing - In the testing of inflatable devices reported in this paper, the air bags were pre-deployed, and their set pressure was maintained throughout the test by the use of an air reservoir tank mounted on the platform. A small series of tests was conducted with the 6-year old dummy in upright-seated positions (no booster seat). Both inflatable devices contained the torso, head, and neck of the dummy, so complete ejection did not occur. However, the dummy loading on the systems produced gaps that did allow an arm and/or hand to pass through in some tests. The gap with the TRW system was similar to that seen in previous testing. The gap produced in testing with the modified AHPS was significantly less than in previous testing due to the modified design.

Another small series of tests was conducted with the 6-year old dummy lying in the prone position to simulate a near worst-case ejection condition. Using a specially constructed bench, the dummy was placed on its back at the height of the bottom of the window opening. The dummy was positioned on the table such that initial contact with the inflatable systems occurred at both positions 1 and 2 of the guided impactor test setup.

The dummy was completely ejected at both positions 1 and 2 in testing with the TRW prototype window curtain, while the modified AHPS contained the dummy inside the test buck in all testing. Figure 10 shows the prone 6-year old dummy being ejected under the TRW bag at position 1. Adding pre-broken advanced laminated glazing with the TRW system produced better results. The combined system contained the dummy inside the test buck in all tests conducted with this configuration.

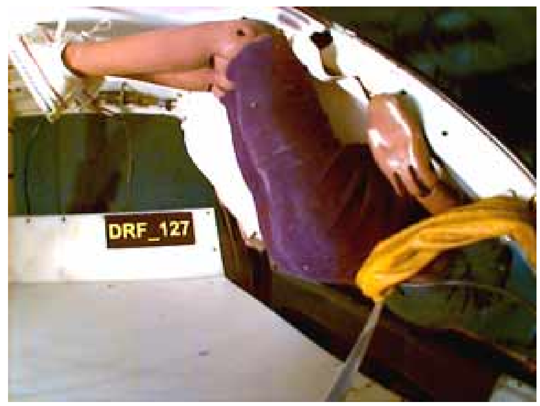

Figure 10. 6-year old dummy ejection.

PROTECTION FOR NON-EJECTED OCCUPANTS

FMVSS No. 216 "Roof crush resistance" establishes strength requirements/intrusion limits for passenger car and light truck roofs for protection in rollover crashes. Based on NHTSA's analysis of the National Automotive Sampling System Crashworthiness Data System (NASS-CDS) 1997-2002) data, approximately 1,400 belted, non-ejected occupants receive a serious or fatal maximum AIS injury to the head/neck/face each year when roof intrusion is present over the occupants' seating position. NHTSA has conducted vehicle tests to evaluate current fleet performance and potential new test procedures to upgrade FMVSS No. 216.

Belt slack and belt stretch inherent to some current lap/shoulder safety belt systems may fail to sufficiently restrain occupants from contacting the undeformed roof during a rollover crash. Thus, in order to realize significant benefit from increased roof strength, improved performance of restraints in rollovers may also be necessary. NHTSA will research the restraint performance and benefits or dis-benefits of systems such as pretensioners, belt load limiters, integrated belts and other advanced belt systems that may be activated with a rollover sensor.

ROOF CRUSH RESEARCH

The current FMVSS No. 216 requires that a passenger car roof withstand a load of 1.5 times the vehicle's unloaded weight or 22,240 Newtons (5,000 pounds), whichever is less, to either side of the forward edge of the vehicle's roof, with no more than 127 millimeters (5 inches) of crush. The same standard applies to light trucks and vans with a GVWR of 2,722 kilograms or less (6,000 pounds), without the 22,240 Newton force limit. The FMVSS No. 216 test procedure applies a quasi-static load to the roof through a load plate. This plate is placed over the driver or right front passenger seating position and is pitched forward 5 degrees and rolled 25 degrees, outside edge down, relative to the vehicle.

In the 1980s and 1990s, NHTSA conducted research toward a possible upgrade to FMVSS No. 216. This included conducting full-scale rollover crash tests, and one finding from this work was that this type of test was not repeatable. Additional research was performed, including a hardcopy analysis of real-world rollover crashes, extended quasi-static testing (i.e. crushed beyond current requirement), and inverted vehicle drop testing [7,8,9]. There were two significant findings from these efforts. First, the typical roof structure failure modes were the same for all three types of laboratory tests and were similar to those observed in the real-world rollovers. Second, while the peak loads from the dynamic drop tests were higher than those from the quasi-static tests, a correlation was found between the energy characteristics of the two types of tests. Additional drop and quasi-static tests were performed on one vehicle model in an attempt to validate this correlation. This effort produced more error than was desired, so the relationship was not validated.

During this time, several attempts were made to find a relationship between the level of roof crush and the injuries that occur in rollover crashes. Rollovers have complex and widely variable kinematics. When an occupant receives a significant injury from contact with roof structures, it is generally not clear if the occupant moved out of the seat to contact the roof, or if the roof contacted the occupant. Further complicating this effort was the lack of a measure of crash severity, which prevented researchers from separating vehicles damaged by a severe crash environment from vehicles with a weak roof structure. There have been several attempts to use quarter turns as a surrogate for rollover severity, but these have only been partially successful [10]. These older attempts to relate roof deformation and occupant head injury were generally not successful,. One study identified a relationship between injury and the amount of interior headroom reduction [11].

This paper is intended to provide a summary of the NHTSA roof crush research program. More detailed descriptions of the testing and discussion of the results are contained in the reports of references 12 and 13.

Objectives -There were three major objectives for this research. The first was to evaluate whether load plate angles that produced more lateral loading resulted in more realistic roof crush patterns. The second was to obtain roof force-displacement characteristics from a sampling of recent model vehicles. The third was to evaluate methodologies for relating roof strength to headroom.

Approach - This research was divided into three phases. The first objective was addressed in Phase 1, while the second objective was addressed in Phases 2 and 3. Methodologies for relating roof strength to headroom parameters were evaluated in all three phases, with one method used in Phases 1 and 2, and a second method used in Phase 3.

Based on previous NHTSA research, it was decided that the quasi-static roof crush procedure would be used in this program. The hardware and test parameters specified in the current FMVSS No. 216 were used, except that the tests were conducted until 254 millimeters (10 inches) of exterior crush was achieved, rather than the 127-millimeter maximum specified in the standard. This was to obtain roof force-displacement characteristics at a crush level well beyond that required in the current standard. Also, alternative load plate angles were used in Phase 1, and non-standard equipment and procedures were used in all three phases to obtain the headroom information.

Phase 1 Summary - To evaluate the effect of load plate angle, finite element (FE) roof crush simulations were performed on two vehicle models – 1997 Dodge Grand Caravan and 1998 Chevrolet S-10 pickup. Based on the results of these simulations, two sets of load plate angles were selected for use in the test program. These were the standard FMVSS 216 angles of five degrees pitch, 25 degrees roll (5x25 degrees) and an alternative set of ten degrees pitch, 45 degrees roll (10x45 degrees).

Roof crush tests were then performed on these two vehicle models, as well as on a pair of 2002 Ford Explorers. Each model was tested using the two sets of load plate angles (six total tests). The results of these tests were evaluated to determine whether any trends were observed when comparing the force-displacement data obtained from the 5x25 degree and 10x45 degree load plate angle configurations, and whether one configuration resulted in more realistic roof crush patterns than the other.

There was no trend observed in the force-displacement curves and peak loads between the two plate angle configurations. The S-10 pickups and Explorers exhibited similar characteristics, and the 10x45 degree configuration produced the higher loads. In contrast for the Caravans, the force-displacement traces were generally similar, and a slightly higher load was produced with the 5x25 degree plate angle configuration. Similarly, there was no trend observed in the energy required to crush the roof between the two plate angle configurations. The S-10 pickups and the Explorers required more energy to crush the roof with the 10x45 degree configuration (25 and 16 percent, respectively), while the Caravan required 12 percent less energy with that plate angle configuration.

When the measured damage patterns were compared for the two sets of load plate angles, it was noted that the 5x25 degree configuration produced more vertical crush, but the 10x45 degree did not consistently produce more lateral crush on either side of the vehicle. When the post-test photographs were compared, the differences in roof damage patterns were not obvious, and would most likely not be noted in a more subjective review of real-world crash investigation cases. Also, compared to the wide range of damage patterns seen in the NASS cases, the differences produced from the two load plate angle configurations were small, so it could be concluded that both configurations produce equally realistic roof damage.

Based on the results of Phase 1, there was no compelling evidence to suggest that a change in the load plate pitch and roll angles would produce more realistic roof damage. Therefore, it was decided that Phase 2 and 3 testing would be conducted using the standard angles of five degrees pitch and 25 degrees roll.

Phase 2 Summary - Ten vehicle models were selected for testing in this initial fleet evaluation. Three of these were tested under the selected conditions as part of Phase 1 – a 1997 Dodge Grand Caravan, a 1998 Chevrolet S-10 pickup, and a 2002 Ford Explorer. The other seven vehicles were each tested using only the 5x25 degree configuration. These were a 2002 Ford Mustang, a 2002 Toyota Camry, a 2001 Ford Crown Victoria, a 2002 Honda CR-V, a 2001 Chevrolet Tahoe, a 2002 Dodge Ram 1500 pickup, and a 1999 Ford E-150 Econoline van.

For these ten vehicles, the following procedure was used to evaluate headroom. First, the point representing the top of the head of a normally seated (per FMVSS No. 208) Hybrid-III 50th percentile male dummy was identified and documented. Next, the points on the interior liner and exterior roof directly above the top of the head were identified, marked, and documented. The vertical difference between the roof points and the top of the head was the initial headroom available, to both the interior liner and exterior roof. Three string potentiometers were mounted rigidly to the floor of the vehicle, and were extended and connected at the exterior roof point. Accurate measurements of the three string potentiometer locations and the common attachment point of the roof were made prior to testing. These data, along with the displacement-time histories of the potentiometers recorded during testing, allowed the three-dimensional displacement of the attachment point to be calculated at each moment during the test. The vertical component of this displacement was then subtracted from the initial headroom measurement at each point in time, resulting in a time-history of the headroom remaining. This was done using both the initial headroom to the liner and to the roof.

The force-displacement results from these tests are shown in Figure 11. The force data are presented as a percentage of the unloaded weight of each vehicle, and displacement is that of the load plate, in the direction of plate motion. Vehicle weights, initial headroom measurements, and peak loads are listed in Table 3. All ten vehicles were able to withstand 150 percent of their weight within about 50 millimeters of crush. Nine of the vehicles were able to withstand 200 percent of their weight with no more than 127 millimeters of displacement, six reached the 250 percent level, and only one reached the 300 percent level within the 127-millimeter limit.

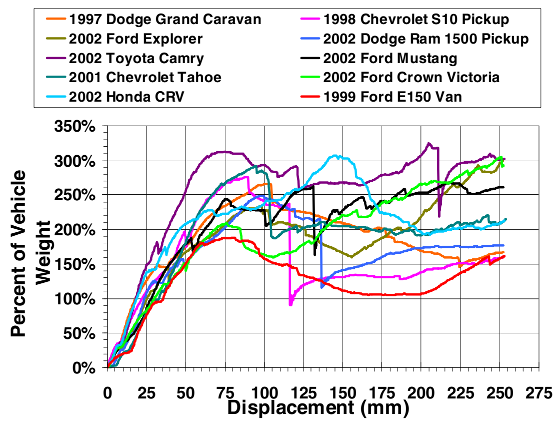

Figure 11. Phase 2 percent weight vs. displacement.

The force data (as a percent of unloaded vehicle weight) are shown versus the headroom remaining (to the liner) in Figure 12. All ten vehicles achieved the 150 percent level with most, if not all, of their initial headroom remaining. Nine vehicles reached the 200 percent level, and all nine had 60 millimeters or more of headroom remaining, with eight of these having about 100 millimeters or more left. Only the Ford E-150 van did not reach the 200 percent level before the end of the test (i.e. 254 millimeters of load plate displacement). It should be noted that at the end of the test, the E-150 van still had 56 millimeters of headroom remaining (due to its large amount of initial headroom), and the resistive force was rising again. It is not known how high the force would have reached if the test had been continued until no headroom remained. Eight of the vehicles reached the 250 percent level, and six of these had positive headroom remaining to the liner at that force. Four of the vehicles reached the 300 percent level, but only two of them had positive headroom remaining at that force, and both of these exceeded 100 millimeters.

Table 3.
Phase 2 Test Summary.

Vehicle	Vehicle Weight (N)	Initial Headroom (mm)		Peak Load (N)
		to liner	to roof	
Mustang	13,698	90.7	98.4	36,520
Camry	13,727	116.6	149.0	44,605
Crown Victoria	17,525	123.6	151.8	53,461
CR-V	14,492	155.8	167.8	44,599
Explorer	18,210	121.2	149.1	55,032
Tahoe	21,475	168.7	189.8	62,797
S-10 PU	13,357	131.6	143.5	36,862
Ram 1500 PU	19,420	157.7	187.5	48,246
Caravan	16,671	138.7	169.9	44,366
E-150 Van	22,373	191.8	253.0	42,212

The methodology of measuring headroom was also evaluated. Ideally, the motion of multiple attachment points would be recorded, but because of space and data acquisition limitations, only one point could be tracked. The limitation in selecting a single point was that it is not possible to predict prior to the test, which point will be the first to intrude into the occupant's head space.

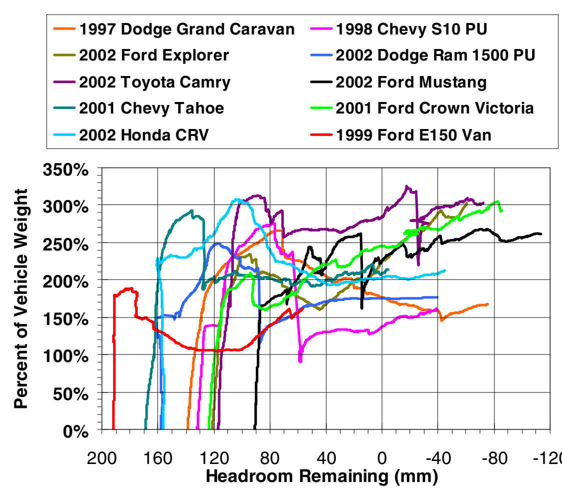

Figure 12. Phase 2 percent weight vs. headroom to liner.

Due to the significant amount of lateral displacement of the attachment point during the tests, it was determined that the point above the top of the 50th percentile male head would not likely have been the point of first contact with the head. But, since only the vertical component of the roof attachment point displacement was used to calculate the remaining headroom, for a flat roof, this calculation would be an accurate measure of when the headroom was compromised. For vehicles with more typically curved roofs, this methodology would tend to predict head-roof contact later than it would actually occur, although this is at least partially mitigated due to the curvature of the side of the dummy's head.

Therefore, it was judged that the methodology used in this study for determining the remaining headroom provided a reasonable estimate, particularly since the peak loads generally occurred well before there was no headroom remaining. But, since this was not always the case, a more accurate measure of when the headroom has been compromised was desired.

Phase 3 Summary - The Phase 3 tests were conducted using the same procedures as Phase 2, except for the measurement of headroom. Instead of tracking the position of a single point on the roof throughout the test, the point in time at which the interior liner entered the head space of a 50th percentile male occupant was determined. A Hybrid-III dummy was normally seated in the driver's position for the test, and a contact switch was used to document the time of liner-to-head contact. Initial headroom measurements were made in the same manner as for Phase 2. Eleven vehicles were tested in this series. These were a 2003 Ford Focus, a 2003 Chevrolet Cavalier, a 2001 Ford Taurus, a 2003 Chevrolet Impala, a 2003 Subaru Forester, a 2002 Nissan Xterra, a 2004 Honda Element (crushed to 222 millimeters, rather than 254 millimeters), a 2003 Ford Expedition, a 2002 Toyota Tacoma, a 2003 Ford-150 pickup, and a 2003 Chevrolet Express van (15-passenger)[13].

The force-displacement results from these tests are shown in Figure 13. Vehicle weights, initial headroom measurements, and peak loads are listed in Table 4. Figure 14 shows the peak resistive forces achieved for both the overall crush events and prior to head-to-liner contact. As can be seen, all 11 vehicles were able to resist at least 200 percent of their weight prior to head-to-liner contact. Eight of them reached the 250 percent level, four reached the 300 percent level, and two exceeded 400 percent. All seven sport utility vehicles, pickups, and van (LTVs) reached their overall peak force prior to head-to-liner contact. All four passenger cars, on the other hand, reached their overall peak force after head-to-liner contact occurred.

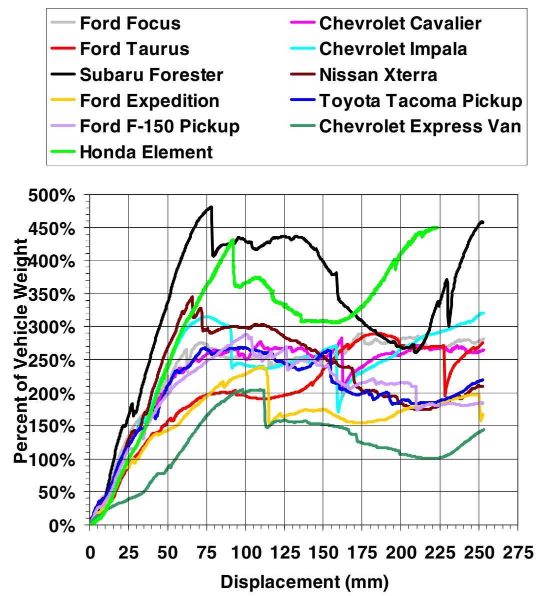

Figure 13. Phase 3 percent weight vs. displacement.

Table 4.
Phase 3 Test Summary.

Vehicle	Vehicle Weight (N)	Initial Headroom (mm)		Overall Peak Load	Peak Load Prior to Head-Liner Contact
		to liner	to roof	N	N
Focus	11,347	120.6	145.2	32,891	31,399
Cavalier	13,215	87.8	125.1	37,352	34,946
Taurus	14,816	133.0	153.2	43,000	30,109
Impala	15,074	125.9	152.2	48,443	47,591
Forester	13,744	145.9	183.4	66,136	66,136
Xterra	15,421	109.5	131.3	53,359	53,359
Element	15,456	228.6	ND	69,392	69,392
Expedition	24,090	144.0	187.3	57,369	57,369
Tacoma	13,767	100.5	112.4	37,039	37,039
F-150 PU	18,059	162.6	176.5	52,136	52,136
Express Van	28,169	151.0	192.7	57,661	57,661

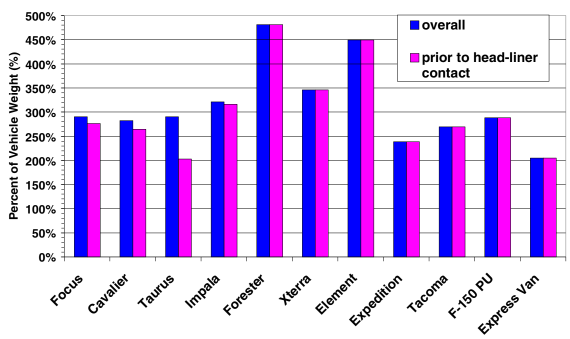

Figure 14. Phase 3 peak force measurements.

IMPROVED RESTRAINTS IN ROLLOVERS

Improvements to FMVSS No. 216 alone may not eliminate occupant contact with the roof in rollover accidents. In a conventional 3-point safety belt, inherent slack and stretch in the restraint system might contribute to occupant contact with an undeformed roof during a rollover crash. It is reasoned that improved performance of occupant restraints could prevent more occupant-to-roof injuries in rollovers.

In the mid-1990s, NHTSA initiated a research program to explore the effectiveness of various restraints in rollovers. A rollover restraint tester (RRT) was developed to simulate rollover conditions. It provided a controlled roll rate for a seated occupant and was followed by a simulated roof-to-ground impact. Occupant excursions toward the 'roof' were measured for common 3-point belt and other advanced restraints systems.

The advanced systems included a 3-point belt with a pretensioner and also a shoulder inflatable belt. Limited testing indicated that the inflatable belt performed the best, reducing occupant excursion by up to 75 percent when compared to the standard 3-point belt with a 50^{th} percentile male [14]. Due to agency priorities being redirected to address emerging frontal air bag deployment issues in the late 1990s, this program was suspended.

With interest in FMVSS No. 216 improvements and previous work highlighting the potential effectiveness of advanced restraints, this revived research program will provide an opportunity to evaluate currently and potentially available state-of-the-art countermeasures to improve occupant protection during a rollover.

Objectives - The main objective of the current research is to evaluate the effectiveness of current and advanced restraints in rollover crashes.

Currently, a number of automotive suppliers are working to improve restraint systems for rollover accidents. These existing and new restraint systems include, but are not limited to, integrated seats, pretensioners, inflating seat belts, curtains and pelvic style air bags. Many strategies to provide effective rollover restraint utilize inflatable devices in various combinations. These various options offer many challenges, underscoring the need to develop a research-oriented performance knowledge base.

Test Device - Another device, similar to the original RRT, has been developed for continuation of this program. The rollover simulated is one in which the vehicle becomes airborne at the initiation of the roll and then impacts the roof structure after rotating approximately 180 degrees.

Figure 15 is a schematic of the new rollover restraint test device. The device has four (4) main features consisting of

1) A support framework,
2) A counter-balanced test platform with rotating axle,
3) A free weight drop tower assembly, and
4) A shock tower.

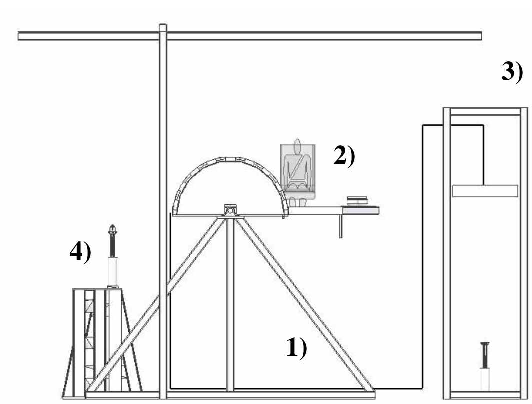

Figure 15. Rollover restraint tester.

The test platform, with vehicle seat, dummy and restraint device(s) attached, is mounted to the supporting framework. The free weight drop tower provides energy to rotate the test platform at a desired roll rate. Roll rate can be adjusted by changing the weight of the drop tower mass. To simulate the roof impact, the rotating platform impacts an adjustable shock-absorbing tower after approximately 180 degrees of rotation. Adjusting the shocks can allow testing of various impact pulses, simulating different 'stiffness' values of roof structures.

Proposed Testing - A preliminary set of tests will be used to verify the repeatability of the test device. Baseline tests will be conducted using a fleet representative front bucket seat with a standard, non-integrated lap and shoulder belt restraint system. The effect of varying D-ring position, a common mechanism for improving shoulder belt fit, will be evaluated in this initial 'verification' test format.

Each test will consist of a static and dynamic procedure. The static procedure consists of pre-test dummy measurements in both the upright and the inverted impact positions. This procedure will be used to analyze the innate belt slack and dummy excursion exclusive to each restraint system.

The dynamic test procedure will utilize the free-falling drop tower mass to provide a prescribed test platform roll rate. The selected dummy and restraint system will experience the desired kinematics through approximately 180 degrees of rotation until the impact occurs. The marked event will occur when the test platform first makes contact with the shock tower. Approximately two seconds of pre-event and one second of post event data will be collected during the dynamic test. Pre and post-test photographs and test video will be used to evaluate dummy excursion and restraint performance.

A specific test matrix will be designed to optimally evaluate various restraint systems that have the potential to mitigate excursion and/or injury in rollover accidents.

Much of the success and benefit from this research will be driven by cooperative efforts with first-stage suppliers and OEMs. This research could lead to the development of a test procedure(s), a test device(s), and more importantly, improved restraint systems for mitigating injuries during rollover events.

SUMMARY

NHTSA's crashworthiness rollover research efforts have been following through on the initiatives outlined in the Rollover IPT report. Considerable research has been completed in the ejection mitigation and roof crush area. There is considerable future research to be done to evaluate the effectiveness of restraint systems in rollover crashes and to develop test method(s) for evaluating rollover sensors.

REFERENCES

1. NHTSA Rollover Integrated Project Team, "Initiatives to Address the Mitigation of

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THE EFFECT OF OCCUPANCY ON THE ROLLOVER PROPENSITY OF PASSENGER VEHICLES

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ABSTRACT

This paper provides a statistical assessment of the effect of occupancy on the rollover propensity of passenger vehicles such as cars, SUVs, minivans, pickup trucks and 15-passenger vans. A logistic regression model has been built to predict the probability of rollover as an outcome of a single vehicle crash, based on occupancy as well as various other vehicle, crash and driver-related factors. The model uses all police-reported crash data from selected states over the period from 1994 to 2001 from NHTSA's State Data System (SDS). The metric used to compare the relative risk of rollover among the vehicles is the probability of rollover conditional on a single vehicle crash having occurred. A binary logit model is estimated using the Maximum Likelihood (ML) approach. The resulting parameter estimates and test-statistics are used to assess significance of the explanatory variables and to estimate the probability of rollover for plausible scenarios. The analysis has shown that occupancy, along with speed and road geometry, has significant effect on rollover propensity. While the overall pattern points to an increasing risk of rollover with increasing occupancy in all passenger vehicle categories, the magnitude of increase varies significantly among the vehicle classes. In fact, the increase in the modeled risk of rollover from nominal (driver only) occupancy to full occupancy is most pronounced for 15-passenger vans followed by Minivans, SUVs, Pickup Trucks and Cars. Apart from the relative risks at nominal and full payloads, there is also a wide disparity in the predicted probabilities of rollover at various occupancies between the vehicles. In fact, on high-speed roads at full occupancy, 15-passenger vans depict the highest risk of rollover, followed by SUVs, Pickup Trucks, Minivans and Passenger Cars, in that order. Charts depicting predicted probabilities by occupancy for various hypothetical scenarios of crash factors are presented for each vehicle class.

INTRODUCTION

Prior research has shown that heavily loaded passenger vans are observed to have a higher rate of rollover as compared to lightly loaded vans [1]. NHTSA's consumer advisory of April 2001 on the rollover propensity of 15-passenger vans[1] was based on this research. This paper presents data analysis that seeks to extend the prior research on this topic by assessing the change in the risk of rollover with increasing occupancy for all passenger vehicles such as passenger cars, SUVs, pickup trucks, minivans and fifteen-passenger vans.

Fifteen-passenger vans differ from most light-trucks in that they have a larger payload capacity and the occupants sit fairly high up in the vehicle. Loading these vans to their Gross Vehicle Weight Rating (GVWR) has an adverse effect on the rollover propensity due to the increase in center-of-gravity height. Loading the vans with passengers and cargo also moves the center of gravity rearward, increasing the vertical load on the rear tires.

This paper provides a statistical assessment of the change in the risks of rollover, conditional on other factors remaining the same, when the passenger vehicles are loaded up to their designed seating capacity and are involved in a crash. Of specific interest is to determine the disparity in the risks of rollover at nominal occupancies and full occupancies for each class of passenger vehicle.

OBJECTIVE AND METHODOLOGY

The objective is to statistically model the risk of rollover with increasing occupancy levels using crash data that is representative of crashes of all severity. The desired metric is the probability of rollover, conditional on a single-vehicle crash having occurred. This conditional probability of rollover is chosen, as every single-vehicle crash is an opportunity for a rollover to occur and the vehicle characteristics that contribute to rollover are not obscured by the effect of the forces of collision. The binary response model for rollovers states that the probability of rollover, conditional on a single vehicle crash having occurred, is a function of selected explanatory variables. The logit model, a widely used binary-response model, for rollover is

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[1] While these vehicles actually have seating positions for a driver plus fourteen passengers, they are typically called 15-passenger vans. Also, these vehicles are actually classified as buses under 49 CFR 571.3.

the analytical technique used in this analysis. This paper introduces descriptive statistics on the rates of rollover for the various vehicle categories before presenting the results of the logit model.

DATA

Crash data from five states that are part of NHTSA's State Data System (SDS) were used in this study [Table 1].

Table 1. States and Years of Crash Data chosen for Study

States	Years
Florida	1994 to 2001
Maryland	1994 to 2001
North Carolina	1994 to 1999
Pennsylvania	1994 to 2000
Utah	1994 to 2001

The data are a census of all police-reported crashes in that State comprising of serious crashes (those resulting in a fatality or injury) as well as those that only resulted in damage to property. Consequently, the data are representative of the population of police-reported crashes in these States for those years.

The risk of rollover, measured in terms of modeled probability of rollover for 15-passenger vans will be compared with other types of passenger vehicles at various occupancy levels [Table 2]. Fully loaded conditions for the various vehicles are shown in Table 2.

Table 2. Occupancies assumed as <u>fully loaded</u> conditions by type of vehicle

Vehicle Type	Number of Occupants
15-Passenger Van	15+
Passenger Cars	4+
SUVs	4+
Pickup Trucks	4+
Minivans	7+

Some of the vehicles may have a designed seating capacity that exceeds those shown in Table 2. It is not possible to identify the seating configuration of passenger vehicles from NHTSA's databases or VINs. Also vehicles with much larger seating capacities than those mentioned in Table 2, especially SUVs, have been late entrants to the fleet. The latest data year in this analysis was 2001 and it is reasonable to assume that the fleet was heavily weighted towards the seating capacities mentioned in Table 2.

RESULTS

Table 3 provides a description of the population of single-vehicle crashes and rollovers being studied for each vehicle category.

Table 3. Single Vehicle Crashes and Rollovers by Vehicle Type

Vehicle Type	Crashes	Rollovers	%
15-P Vans	1,441	315	22%
Passenger Cars	423,760	66,318	16%
SUVs	61,968	23,927	39%
Pickup Trucks	98,282	26,187	27%
Minivans	16,205	2,746	17%

Overall, the incidence of rollover in single vehicle crashes for 15-passenger vans, expressed as a percentage of vehicles involved in such crashes, is comparable with those for other types of vehicles. SUVs had the highest incidence (39 percent) among all the vehicle categories while passenger cars had the lowest incidence rates (16 percent). However, the issue at hand is to analyze the rate of rollover at various occupancies for the different vehicle types.

Figure 1 compares the rates of rollover for various vehicle types by when they are loaded to or under half their seating capacity versus loaded to over half their seating capacity. For the sake of this analysis, passenger cars, SUVs and pickup trucks with two occupants or less, minivans with three occupants or less and 15-passenger vans with seven occupants or less are defined as vehicles loaded to or under half their capacity.

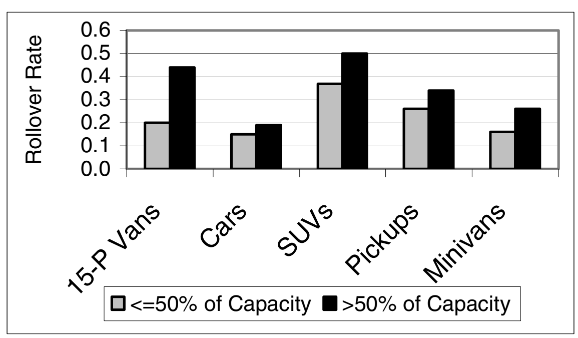

Figure 1. Rollover Rates in Single Vehicle Crashes by Vehicle Type and Occupancy.

As seen in Figure 1, when the vehicles are loaded to more than half of their seating capacity, the rates of rollover are higher as compared to when they are loaded to or under half their seating capacity.

However, the relative difference in the rates of rollover under the two different loading scenarios is most pronounced for 15-passenger vans. This relative difference is shown in Table 4 for other vehicle categories. It is noted that a 15-passenger van that is loaded to half its designed seating capacity has as many occupants as any other type of passenger vehicle that is fully loaded. The differences for all vehicle categories are statistically significant, as indicated by the p-values in Table 4.

Table 4. Rollover Rates in Single Vehicle Crashes by Vehicle Type and Occupancy

Vehicle Type	½ Seating Capacity or Under (a)	Over ½ Seating Capacity (b)	(b)/(a)
15-P Vans	0.20	0.44	2.2
Passenger Cars	0.15	0.19	1.3
SUVs	0.37	0.50	1.4
Pickup Trucks	0.26	0.34	1.3
Minivans	0.16	0.26	1.7
All Differences are Statistically Significant with p<0.001			

As shown in Table 4, occupancy seems to have a pronounced effect on the rates of rollover observed in single vehicle crashes. However, there are factors other than occupancy that can have an adverse effect on a vehicle's propensity to roll over. These may include the speed of travel, surface and weather conditions, experience/training of the driver and impaired driving. The speed of travel can be a significant factor in affecting rollover outcome because greater travel speed of the vehicle provides more energy to initiate rollover. Figure 2 un-confounds the effect of speed on the proportions shown in Table 4. In the absence of reliable measures of travel speed, the posted speed limit at the scene of the crash is used as a proxy for the speed of travel. Figure 2 shows, by vehicle type, the composition of the rollovers by occupancy and the speed limit of the road they were traveling at the time of the crash. The numbers in each of the bars in Figure 2 indicate the proportion of the rollovers in that category that occurred on high-speed roads (50+ mph). So, 62 percent of rollovers of 15-passenger vans that loaded to half or under half of their designed capacity were in high-speed roads. In comparison, 91 percent of rollovers involving 15-passenger vans that were loaded at or above half their designed seating capacity occurred on high-speed roads. Figure 2 shows that heavily loaded 15-passenger vans have a higher proportion of their rollovers on high-speed roads than do other light vehicles. Under similar circumstances, SUVs have comparable risks of rollover too.

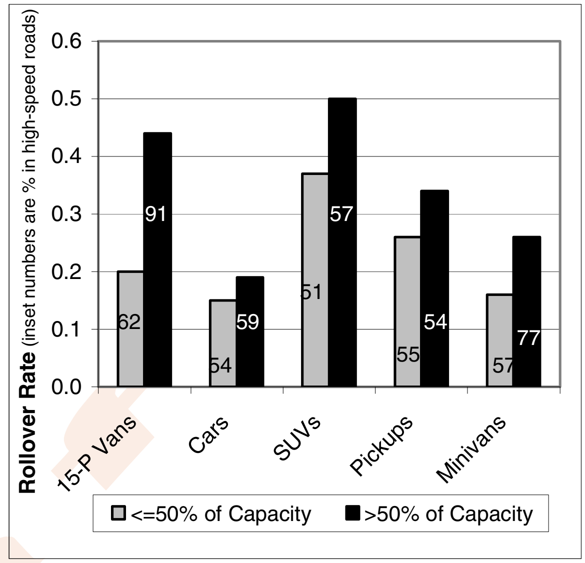

Figure 2. Rollover Rates in Single Vehicle Crashes by Vehicle Type, Occupancy and proportion in High Speed Roads.

Even though the rate of rollover under heavily loaded scenarios for 15-passenger vans is comparable with SUVs, it is much higher than the rate for other types of vehicles. It will be noteworthy to examine the relative disparity in the rates of rollover between heavily loaded (½ seating capacity or over) and lightly loaded (under ½ seating capacity) scenarios on high-speed roads. Table 5 depicts this relative risk ratio.

Table 5. Rollover Rates by Occupancy and Vehicle Type in Single Vehicle Crashes in High-Speed Roads (50+ mph)

Vehicle Type	½ Seating Capacity or Under (a)	Over ½ Seating Capacity (b)	Rel. Diff. (Ratio)
15-P Vans	0.30%	0.62%	2.1
Passenger Cars	0.22%	0.26%	1.2
SUVs	0.49%	0.61%	1.2
Pickup Trucks	0.36%	0.43%	1.2
Minivans	0.26%	0.34%	1.3
All Differences are Statistically Significant with p<0.001			

The disparity in the rates of rollover between light and heavy loading conditions on high-speed roads is the largest for 15-passenger vans. However, one can assess the true effect of occupancy on rollover propensity by taking into account the effect of various other factors that can affect rollover outcome.

Logistic Regression Modeling

Statistically, a logistic regression model is very suitable to predict rollover as a dichotomous outcome (yes or no), based on explanatory variables [2]. Logistic regression permits the joint estimation of the effect or significance of a variable in affecting rollover. If **Y** denotes the dependent variable in a binary-response model for rollovers, **Y** is equal to 1 if there is a rollover and 0 otherwise. The goal is to statistically estimate the probability that **Y=1**, considered as a function of explanatory variables. The logit model, a widely used binary-response model, for rollover is:

$$P(Y = 1 \mid \mathbf{X} = x) = \frac{1}{[1 + e^{(\alpha + \beta x)}]} \qquad (1).$$

This model can be rewritten, after taking the natural logarithm of both sides as:

$$Ln\left(\frac{P}{(1-P)}\right) = \alpha + \beta x \qquad (2).$$

where α is the intercept, β is the vector of coefficients and x is a vector of explanatory variables.

The explanatory variables used to model rollover as an outcome are shown in Table 6. The model uses metrics to represent various crash and driver-related characteristics and more importantly, the number of occupants in the vehicle. That is, for each vehicle type

Logit (Pr(Rollover)) = OCCUPANCY DARK STORM FAST HILL CURVE BADSURF MALE YOUNG OLD DRINK DUMMYMD DUMMYNC DUMMYPA DUMMYUT.

The factors used in the model mirror those used in NHTSA's New Car Assessment Program (NCAP) studies [3] with the exception of the Static Stability Factors and dynamic test results. This study is intended to provide insight into rollover propensity for broad vehicle categories and not specific models, which would have required the inclusion of such metrics.

Also included in the regression model were four variables DummyMD, DummyNC, DummyPA and DummyUT. The variables DUMMY<State> represent the change in Logit(Pr(Rollover)) due to the crash's taking place in that State as compared to an otherwise similar crash in Florida. They are included to control for differences in traffic patterns and reporting practices that effect rollover rates between the States.

Table 6. Rollover Rates by Occupancy and Vehicle Type in Single Vehicle Crashes in High-Speed Roads (50+ mph)

Variable	Description	Levels
Occ	Number of Occupants	**1 to 15+**
Dark	Light Condition	**1** if dark; **0** if not dark
Storm	Stormy Weather	**1** if stormy; **0** if not
Fast	Speed (Speed Limit as Proxy)	**1** if 50+ mph else **0**
Hill	Hilly Gradient	**1** if yes else **0**
Curve	Road Curves	**1** if yes else **0**
Badsurf	Adverse Roadway Surface Conditions	**1** if yes else **0**
Male	Male Driver	**1** if yes else **0**
Young	Young Driver (Under 25)	**1** if yes else **0**
Drink	Driver Impairment	**1** if yes else **0**

The roadway function class, i.e., if the site of the crash was a rural or urban area, was not used in the regression due to the unavailability of data. However, it may be assumed that speed limit, curve and roadway surface conditions may account for many of the differences reflected in the rural/urban dichotomy. The regression was done within each vehicle type in order to assess the effect of the various covariates on rollover outcome. The results of logistic regression model are presented in Table 7. The test statistics indicate the goodness of fit of model for each vehicle category.

Table 7. Results of Logistic Regression Model by Vehicle Category

Vehicle	Degrees of Freedom (DF)	$p > \chi^2$
15-P Vans	15	**< 0.0001**
Passenger Cars	15	**< 0.0001**
SUVs	15	**< 0.0001**
Pickup Trucks	15	**< 0.0001**
Minivans	15	**< 0.0001**

The joint estimation using the logistic regression model reveals that the variables with the most significant impact on rollover outcome among all vehicle categories are:

- **Fast** (high-speed road, 50+ mph)
- **Occupancy** (Number of vehicle occupants)
- **Curve** (curved geometry at site)

Table 8 depicts the estimates of coefficients for the significant variables by vehicle category. As seen in Table 8, occupancy, speed and curve are significant factors in predicting rollover outcome for all vehicle categories as indicated by their low p-values.

Table 8. Parameter estimates for Occupancy, Speed and Road Curvature by Vehicle Type

Vehicle	Estimate (Standard Error)	$p > \chi^2$
Occupancy		
15-P Vans	0.1135 (0.0229)	**< 0.0001**
Passenger Cars	0.0593 (0.0059)	**< 0.0001**
SUVs	0.1911 (0.0120)	**< 0.0001**
Pickup Trucks	0.1257 (0.0126)	**< 0.0001**
Minivans	0.1163 (0.0176)	**< 0.0001**
Speed		
15-P Vans	1.6138 (0.1756)	**< 0.0001**
Passenger Cars	0.8977 (0.0106)	**< 0.0001**
SUVs	0.9654 (0.0258)	**< 0.0001**
Pickup Trucks	0.9816 (0.0184)	**< 0.0001**
Minivans	1.1672 (0.0553)	**< 0.0001**
Curved Geometry		
15-P Vans	0.6874 (0.1802)	**< 0.0001**
Passenger Cars	0.6362 (0.0105)	**< 0.0001**
SUVs	0.4732 (0.0230)	**< 0.0001**
Pickup Trucks	0.6027 (0.0183)	**< 0.0001**
Minivans	0.5089 (0.0573)	**< 0.0001**

The coefficient vector β from the logistic regression model yields predicted probability of rollover as shown in Figure 3. Figure 3 represents the probabilities of rollover, conditional on a single vehicle crash, for a "favorable" scenario in terms of factors that affect rollover as an outcome. The "favorable" scenario is a combination of favorable driving conditions and factors for the terms included in the logistic regression model. This includes good light and weather conditions, low-speed road (under 50 mph), flat terrain, straight and good road conditions and no driver impairment.

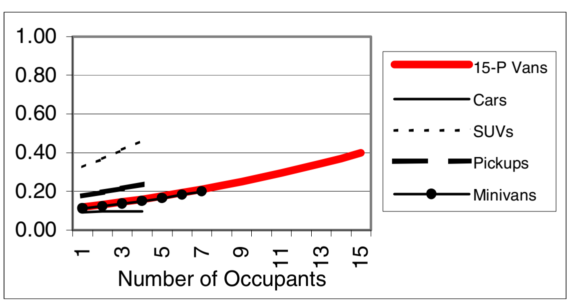

Figure 3. Conditional (single vehicle crash) probability of Rollover with Occupancy under normal scenarios.

As seen in Figure 3, the probability of rollover at nominal loads (driver only) shows a wide disparity among the vehicle types. SUVs have the highest probability of rollover under these circumstances followed by pickup trucks, 15-passenger vans, minivans and passenger cars. Under fully loaded conditions, SUVs and pickup trucks have comparable probabilities of rollover and were the highest among all vehicle categories. Pickup trucks, minivans and passenger cars exhibit probabilities that are lower than that of SUVs and 15-passenger vans under the same circumstances.

Figure 4 depicts the distribution of the probability of rollover for what can be considered as an "adverse" scenario to affect rollover. The adverse scenario includes statistically significant variables, **fast** and **curve**. The probabilities depicted in Figure 4 are for crashes occurring on curved areas on high-speed roads and other factors remaining normal.

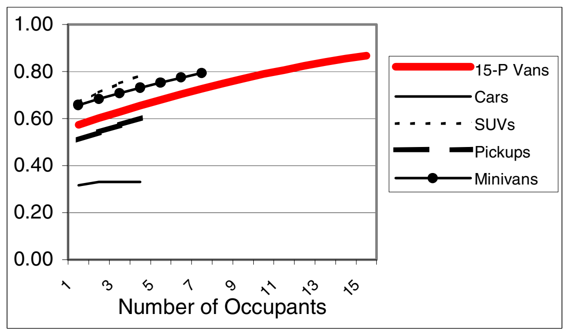

Figure 4. Conditional (single vehicle crash)_probability of Rollover with Occupancy under adverse scenarios.

Fifteen-passenger vans exhibit the highest probability of rollover under adverse scenarios at fully loaded conditions. Minivans, SUVs, pickup trucks and passenger cars have a lower probability of rollover under fully loaded scenarios under adverse driving scenarios.

As seen in Figures 3 and 4, the probability of rollover as indicated by the logistic regression model indicates a progressively worsening risk of rollover with increasing occupancy for all vehicle types including 15-passenger vans. The probability of rollover with just the driver in the vehicle ranges from 0.12 in favorable conditions to above 0.57 in adverse conditions. However, when the van is loaded to or above its designed seating capacity, the corresponding probabilities increase to an estimated 0.39 and 0.87, respectively. This trend, while observed for all types of vehicles, is most pronounced for 15-passenger vans because of the sheer multiplicative effect of the larger seating capacity for 15-passenger vans. In order to put the conditional probabilities into perspective, Tables 7 and 8 present the disparity in the risks of rollover between nominal and fully loaded scenarios under normal and adverse driving conditions, respectively.

Table 9. Probability of Rollover under Nominal and Fully Loaded Conditions in Single Vehicle Crashes under *Normal* Scenarios

Vehicle Type	Driver Only (Nominal)	Fully Loaded	Rel. Diff. (Ratio)
15-P Vans	0.119	0.398	3.34
Passenger Cars	0.091	0.096	1.05
SUVs	0.326	0.462	1.42
Pickup Trucks	0.176	0.237	1.35
Minivans	0.110	0.149	1.35

Table 10. Probability of Rollover under Nominal and Fully Loaded Conditions in Single Vehicle Crashes under *Adverse* Scenarios

Vehicle Type	Driver Only (Nominal)	Fully Loaded	Rel. Diff. (Ratio)
15-P Vans	0.574	0.868	1.50
Passenger Cars	0.317	0.329	1.03
SUVs	0.671	0.783	1.17
Pickup Trucks	0.510	0.602	1.18
Minivans	0.656	0.793	1.21

As seen in Tables 9 and 10, among passenger vehicles, 15-passenger vans seem to exhibit the greatest disparity in the risks of rollover between nominal and fully loaded conditions for both normal and adverse driving scenarios. While SUVs show comparable probabilities of rollover under both scenarios, the disparity between the risks is less than that for 15-passenger vans.

In a comparison of extremes, there is a seven-fold increase in the risk of rollover between lightly loaded 15-passenger vans under normal scenarios as compared to fully loaded ones under adverse scenarios [0.119 versus 0.868].

CONCLUSIONS

While the increment in the risk of rollover with every unit increase in occupancy for 15-passenger vans was comparable to other passenger vehicles, 15-passenger vans exhibited a much higher risk of rollover when they were loaded at or above their designed seating capacity under both normal and adverse scenarios. Speed and geometry of the road were other factors that significantly affect the risk of rollover for all types of passenger vehicles.

The disparity in the risk of rollover between nominal and fully loaded conditions is the greatest for 15 passenger vans. This is of significant interest for drivers of vanpools and other organizations that use these vehicles. Drivers of these vehicles should be educated to this disparity in the risk of rollover when they are driving by themselves as compared to when they are transporting a vanload of people.

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INJURY PATTERNS IN ROLLOVERS BY CRASH SEVERITY

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Paper Number 05-0355

ABSTRACT

Earlier studies by the authors have proposed separating rollover crashes according to belt use, ejection status, and single vs. multiple harmful events. These different classifications were associated with differences that could substantially alter the risk of serious injury. For each classification, metrics to characterize rollover severity were presented. For most single vehicle crashes, the number of roof contacts with the ground was found to predict injury risk. For multi-harmful event crashes the extent of damage caused by the most severe non-rollover harmful event, combined with the number of roof impacts was found to predict injury risk.

This paper examines NASS/CDS 1995-2003 to determine the injury distribution by body region for the most frequently occurring rollover classifications that result in MAIS 3+ injuries from sources inside the vehicle. The examined classifications of rollovers include: belted not-ejected and unbelted not-ejected. For each category the injury patterns by body region were presented. Differences in injuries in near-side and far-side rollovers were evaluated.

In general, head injuries were the most frequent MAIS 3+ injury for belted occupants. However, trunk injuries were more frequent for belted occupants in near-side rollovers. It was found that a higher fraction of severe injuries occurred in far-side rollovers compared to near-side rollovers. This tendency held for rollovers with one roof impact or less as well as higher severity rollovers.

The frequency of injury and ejection for near and far-side rollovers was examined. The MAIS 3+ HARM distribution by body region was examined as a function of number of roof impacts and direction of roll for not ejected front seat occupants. About 46% of the occupants were exposed to far-side rollovers, but more than half of the injuries occurred in far-side rollovers.

To examine occupant kinematics in injury producing rollovers, a MADYMO 6.1 model of a front occupant compartment of a mid-size SUV with a belted Hybrid III dummy was used. The model was validated against an available staged test with a similar configuration.

Computer modeling suggest that a higher tripping acceleration results in higher roll rates which, in turn, can lead to increased number of roof impacts. Associated with the increase in roll rate was an increase in the maximum head velocity.

The data analysis and computer modeling suggest the need to assess the severity of the vehicle loading that causes the vehicle to rollover. The severity of the tripping forces may be related to the risk of injury.

INTRODUCTION

In an earlier study, crash factors that increased the risk of MAIS 3+ injuries were examined (Digges 2003). That study used NASS/CDS 1995-2001 data. These years were selected because more detailed information on rollovers was recorded in the case files beginning in 1995. The added data included the number of roll quarter-turns up to 16 and a category for end-over-end rollovers. Prior to 1995, the number of quarter- turns beyond four was not measured or recorded. The post 1995 NASS/CDS also recorded the extent of damage from planar crashes that may have occurred prior to or during the rollover. These added variables permitted a more robust examination of how planar damage and number of quarter-turns may influence the risk of injury. The earlier study found that the number of times the vehicle roof faces the ground was a statistically significant factor that predicted increased injury risk for single vehicle rollovers. For rollovers that were preceded by planar crashes, the combination of number of vehicle inversions and the extent of planar damage were predictors of injury risk. However, there was insufficient multiple impact data to obtain significance for this combination of predictors.

Many authors have found that ejection and partial ejection are outcomes that substantially increase injury risk. Countermeasures to reduce ejection casualties generally focus on preventing the ejection rather than preventing the injury after ejection occurs. Casualty reduction countermeasures for non-ejected occupants focus on preventing the injury. The safety features may be different for near-side rollovers than for far-side rollovers. Consequently, it is desirable to separate and study the injuries that occur to non-ejected occupants in rollovers and to examine both near-side and far-side injury patterns. The focus of this paper is to assess the injuries that occur to non-ejected occupants.

DATA QUERIES

The data set described in this paper was queried from The Crashworthiness Data System (CDS), a database of The National Automotive Sampling System (NASS), years 1995 through 2003. Definitions were prepared below for: occupant selection, rollover codification, crash configuration, restraint usage, rollover crash orientation, ejection status, injured body region groupings, injury severity, and occupant counts versus injury counts.

Occupant Selection

As described in previous works, occupancy rates of the various vehicle platforms dictated the selection of drivers. In order to remove bias and balance reporting, the right outboard passenger of the front seat, if present, was included.

Occupants were selected based upon seating position and age. The occupants of age 12 years and older were retained in this study. Occupants less than 12 years old were considered to lack biomechanical tolerance owing to their lack of osseous development and abundance of evolving soft tissue. This also accompanied the public safety mandate of placing children in rear seating positions until these occupants reached 12 years of age.

Quarter Turn Codification

Prior to 1995, rollover crashes were coded through the third quarter turn. Upon reaching the fourth quarter turn, one complete revolution, and above, these were grouped. Currently, the NASS CDS allows for discernment through the fourth complete revolution, 16 quarter turns. Rollover crashes of greater than 16 quarter turns have been grouped in the database.

In the current study rollover quarter turns have been grouped by roof impacts owing to the statistical significance of the relationship between the number of roof impacts and injury severity for restrained occupants, who comprise the majority of rollover occupants. Owing to similarities in the occupant outcomes for two roof impacts and three or more roof impacts, this category was aggregated into two plus roof impacts.

In addition to the classification of quantifiable quarter turns, rollover crashes may be defined as end-over-end rollover crashes or rollover with unknown details. The end-over-end rollover crash was excluded from consideration, within this context, owing to its severe nature and varying crash dynamics, from lateral rollover crashes. It was further reasoned that this type of rollover would merit an individual severity metric. The rollover of unknown detail was excluded since the number of quarter turns was not quantified and it could not be established whether the rollover was lateral or longitudinal.

Crash Configuration

Initially, an aggregate number of rollover crashes and characteristics were considered. Upon disaggregating this data, single and multiple vehicle impact rollover crashes were identified as having different injury characteristics, as well as vehicle crash dynamics.

Single vehicle crashes were disaggregated by object contacts. Those crashes involving fixed objects were identified as a separate severity metric. Further, the non-fixed object cases were identified as pure rollover cases.

Multiple vehicle crashes were disaggregated owing to their elevated occupant injury severity, approximately twice as high as in the single vehicle case.

Restraint Usage

Within the context of the rollover crashes, the concept of restraint usage was considered and modified from the traditional reporting. All of the manual and passive restraint systems, defined in NASS CDS, were considered in determining belted, ineffectively/inefficiently belted, and unbelted drivers.

The belted occupants were those whose restraint selection would potentially provide protection against the forces imparted during a rollover crash. Those occupants protected by a lap belt, lap and shoulder belt combination, or a three point automatic belt were considered restrained for purposes of rollover.

The ineffective/inefficient restraint use category contemplated those occupants who were protected by something other than the previous category. These included certain elements of passive restraint use also. Ineffectively and/or inefficiently restrained occupants, with regard to rollover, were those using: shoulder belt, unknown belt type, other belt type, shoulder belt with child safety seat, lap belt used child safety seat, lap and shoulder belt with a child safety seat, unknown belt type with child safety seat, other belt type with child safety seat, unknown usage of belt, two point automatic belt, unknown type of automatic belt, and unknown availability but automatic belt in use.

The unbelted occupants did not benefit from any rollover mitigating active or passive restraint. The unrestrained group was comprised of any occupant not described in the restrained and ineffectively and/or inefficiently restrained categories.

Rollover Crash Orientation

Rollover crash orientation was based upon the seating position of the driver and rollover crash direction. The rollover crashes were categorized as far side or near side rollover crashes.
Rollover crashes with occupants seated on the left side of a right side leading rollover crash or occupants seated on the right side of a left side leading rollover crash were considered far side rollover crashes.

Rollover crashes with occupants seated on the right side of a right side leading rollover crash or occupants seated on the left side of a left side leading rollover crash were considered near side rollover crashes.

Ejection Status

The ejection status of an occupant was defined using the NASS CDS classification. These were: unejected, completely ejected, partially ejected, and ejection status unknown. Unejected occupants were those who remained within the vehicle during the crash. Completely ejected occupants were those who were expelled through an exit portal of the vehicle during the crash. Partially ejected occupants had some portion of their body stay within the vehicle while the remaining portion was exposed to the exterior of the vehicle. Ejection degree unknown encompassed some form or amount of occupant expulsion for which the extent was not ascertainable. In this study, ejected occupants have been presented as an aggregate of completely and partially ejected or individually.

Injured Body Region Groupings

The NASS CDS was ultimately chosen owing to its very complete case definition. Not only were the crash, vehicle, and general occupant attributes available but also specific injury description by type and severity.

Using the AIS 90 classifications of The Association for the Advancement of Automotive Medicine (AAAM), a complete injury description was possible. Further, NASS CDS, when possible, related the injury to the crash mechanisms inherent to a specific crash. The body regions were defined as: head, face, neck, thorax, abdomen, spine, upper extremity, lower extremity, and unspecified.

In this study, the body regions were collapsed into four major regions. The head was comprised of the head and face. The spine was comprised of the neck and spine. The trunk was comprised of thorax and abdomen. Finally, the extremities were comprised of the aggregate of upper and lower extremities. The injuries to unspecified body regions were excluded from this analysis.

Injury Severity

An injury severity scale, known as the Abbreviated Injury Scale (AIS), accompanied the AAAM injury classification. The AIS, defined as an ascending measure of the risk of mortality, associated each injury type, by injured body region, injury level, and injury aspect, to a severity level. AIS is defined as: zero (no injury), one (minor injury), two (moderate injury), three (serious injury), four (severe injury), five (critical injury), six (maximum injury), and seven (injury severity unknown). The classification of no injury was established to be used as a maximum injury definition, since uninjured body regions would not be listed.

In this study, serious injuries were of concern and the development of a metric that would assess increased severity with the increase of the measured quantity (roof impacts). Two groups were studied, those occupants sustaining maximum injury severity of three and greater and injury counts of AIS three injuries and greater. The first constituted an occupant count, if this group had injuries detailed, these would include AIS one and two injuries. The second group constituted an injury count, which excluded AIS one and two injuries, if these existed.

A complete accounting of fatally injured occupants was absent when grouping the seriously injured occupants, sustaining MAIS 3+ injuries. Although AIS six injuries might result in fatality, the occupant treatment must be consulted in NASS CDS. Upon this indication of fatality, the occupant may be considered deceased as a result of the crash or by disease. Further, not all fatality injured occupants receive a maximum injury classification of six. In fact, a fatally injured occupant may have received an MAIS level as low as one or two. This case has been linked to a lack of medical records substantiating injuries and the NASS researchers and injury coders registering only documented injuries. A second method of classification of seriously injured occupants arose with MAIS 3+F occupants. These were occupants who sustained MAIS three through six injuries or fatally injured occupants with MAIS one or two injuries. For the injuries presented in this study the first method, MAIS 3+ injuries, was considered since the injuries were considered individually, as well as a group of seriously injured.

Occupant Counts versus Injury Counts

In reporting MAIS 3+ or MAIS 3+F occupants, the occupants have been reported once, where the occupants were specified. In the study of injury mechanisms, specifically, the present disaggregation, all injuries were included at any injury level. This was done to describe all injuries present at the various injury levels and rollover crash orientations.

For front seat occupants involved in near and far side rollover crashes with a quantifiable number of quarter turns, 389,423 were estimated to have sustained MAIS 3+ injuries. This was estimated from a raw sample of 5,239 occupants. Annualized estimates yielded 43,269 estimated occupants taken from 582 occupants over the nine years queried. Occupants classified with an other or unknown rollover crash orientation, end-over-end or some absent occupant parameter, numbered 13,015 (176 raw cases.) These were annualized and accounted for 1,446 (20 raw cases.)

INJURIES AND INJURY RATES FOR EJECTED AND NON-EJECTED OCCUPANTS

An overview of the NASS/CDS 1995-2003 injury data is shown in Tables 1 through 3.

Table 1 shows the number of belted and unbelted front seat occupants 12 years old and older by belt use and ejection status. Table 2 shows the associated number on MAIS 3+ injuries in each category. Table 3 shows the rate of MAIS 3+ injuries per 100 occupants exposed to each of the cells in the Table 1 matrix.

Table 1.
Rollover Exposed Front Seat Occupants by Belt Use and Ejection Status

OCCUPANTS	Belted	Unbelted
NO EJECTION	1,958,515	577,096
COMP. EJECT	4,113	102,357
PART EJECT	44,688	35,815
EJECT DEG UNK	545	3,413
TOTAL	2,007,861	718,681

Table 2.
MAIS 3+ Injured Front Seat Occupants by Belt Use and Ejection Status

MAIS 3+	Belted	Unbelted
NO EJECTION	23,373	23,644
COMP. EJECT	397	26,450
PART EJECT	2,121	3,454
EJECT DEG UNK	0	654
TOTAL	25,891	54,202

Table 3.
MAIS 3+ Injured per 100 Front Seat Occupants Exposed by Belt Use and Ejection Status

MAIS3+/100	Belted	Unbelted
NO EJECTION	1.2	4.1
COMP. EJECT	9.6	25.8
PART EJECT	4.7	9.6
EJECT DEG UNK	0.0	19.2
ALL	1.3	7.5

It is of interest to know how the populations in Tables 1 and 2 divide between near-side and far-side rollover crash exposure. Table 4 shows the percentage of the belted populations that are in far-side crashes. In the table complete and partial ejections have been combined. Table 5 shows similar data for the unbelted populations.

It may be noted in Tables 1 and 4 that of the 48,801 occupants that were totally and partially ejected belted occupants, 34.9% were in far-side rollovers. However, 64.7% of the MAIS3+ injuries among belted ejected occupants were in far-side rollovers.

Fortunately, this injured population is small. It comprises 10% of MAIS 3+ injuries to belted occupants in rollovers, and 3% of combined belted and unbelted MAIS 3+ injuries.

Table 4.
Percent of Belted Occupants In Far-side Rollovers and Percent Of Belted MAIS 3+ Injured Occupants In Far-side Rollovers by Ejection Status

BELTED FAR-SIDE	Occupants	MAIS 3+
NO EJECTION	46.3%	50.4%
ALL EJECTION	34.9%	64.7%
TOTAL	46.0%	51.8%

Table 5.
Percent of Unbelted Occupants In Far-side Rollovers and Percent Of Unbelted MAIS 3+ Injured Occupants In Far-side Rollovers by Ejection Status

UNBELTED FAR-SIDE	Occupants	MAIS 3+
NO EJECTION	46.5%	65.6%
ALL EJECTION	50.0%	47.4%
TOTAL	47.2%	55.2%

INJURIES BY BODY REGION

In examining injuries by body region, we include all injuries to an occupant. The previous data used the MAIS scale, which considered only the most severe injury. In rollover crashes, occupants frequently sustain multiple injuries. Sometimes there are multiple injuries to the same body region and even to the same organ. Accounting for multiple injuries to the same body region presents challenges in how best to minimize biases. A variety of methods have been used, but there is no generally accepted procedure. The data to follow includes all injuries, including multiple injuries to the same body region or organ.

Tables 6 and 7 display the number of injuries by AIS and body region for belted and unbelted front seat occupants that are not partially or completely ejected.

Table 8 summarizes the AIS 3+ HARM to belted and unbelted not ejected occupants and shows the percentage distribution by body region. AIS 3+ HARM is calculated by applying the injury cost weighting factor to each category of AIS injuries. The weighting factors are from NHTSA (NHTSA 2001). The units of HARM units are equivalent fatalities. The relevant occupants are front seat not ejected occupants age 12 and older.

Table 6.
Injuries to Belted Not Ejected Relevant Occupants by Body Region and AIS

BELTED NOT EJECT	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	AIS 6	AIS Unk	Total
HEAD	843,413	72,741	12,249	7,897	2,347	320	771	939,739
SPINE	456,396	22,633	8,484	623	860	175	235	489,405
TRUNK	273,014	29,104	26,570	4,051	853	190	2,727	336,509
EXTREM	1,479,526	76,502	22,000	0	0	0	152	1,578,178
UNSPEC	38,409	48	476	119	0	1,104	0	40,155
TOTAL	3,090,756	201,027	69,778	12,690	4,060	1,790	3,885	3,383,987

Table 7.
Injuries to Unbelted Not Ejected Relevant Occupants by Body Region and AIS

UNBELTED NOT EJECT	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	AIS 6	AIS Unk	Total
HEAD	452,922	80,568	18,767	15,732	5,133	230	2,710	576,062
SPINE	110,928	24,784	9,137	346	823	184	0	146,201
TRUNK	123,911	11,617	16,997	5,491	2,009	312	1,341	161,678
EXTREM	484,041	49,721	20,860	13	0	0	359	554,993
UNSPEC	43,086	82	102	0	1,106	291	0	44,668
TOTAL	1,214,889	166,771	65,864	21,582	9,071	1,017	4,409	1,483,601

Table 8.
AIS 3+ HARM and Percentages for Belted and Unbelted Not Ejected Relevant Occupants by Body Region

Body Region	Belted HARM	Belted % HARM	Unbelted HARM	Unbelted % HARM
HEAD	5,898	35%	11,058	49%
SPINE	2,083	12%	2,064	9%
TRUNK	5,172	30%	5,521	25%
EXTREMITY	2,622	15%	2,490	11%
UNSPECIFIED	1,193	7%	1,241	6%
TOTAL	16,968		22,375	

NEAR AND FAR SIDE INJURIES BY BODY REGION

Earlier research reported a higher risk for occupants in far-side rollovers as compared to near-side rollovers (Parenteau 2001). A further investigation of roll direction difference is merited.

Table 9 shows the distribution of AIS 3+ HARM for not ejected belted front seat occupants by direction of rollover. The percentage of injuries that occur in far-side rollovers is shown for each body region. Table 10 shows similar data for unbelted not ejected front seat occupants.

Table 9.
AIS 3+ HARM for Belted Not Ejected Relevant Occupants by Body Region in Near and Far Side Rollovers and Percentage of AIS 3+ HARM in Far-side Rollovers

Belted Body Region	Near	Far	% Far
HEAD	2,192	3,706	63%
SPINE	626	1,458	70%
TRUNK	2,726	2,446	47%
EXTREM	1,228	1,394	53%
UNSPEC	1,193	0	0%
Total	7,965	9,003	53%

INJURIES BY NUMBER OF VEHICLE ROOF IMPACTS

Earlier studies by the authors found that a crash severity measurement for rollovers is the number of times the roof has the opportunity to face the ground (Digges 2003). During the quarter turn that the roof faces the ground, no impact may occur or multiple impacts may occur. For accounting convenience, any of the above are classified as one roof impact with regard to the severity metric.

Table 10.
AIS 3+ HARM for Unbelted Not Ejected Relevant Occupants by Body Region in Near and Far Side Rollovers and Percentage of AIS 3+ HARM in Far-side Rollovers

Unbelted Body Region	Near	Far	% Far
HEAD	2,877	8,181	74%
SPINE	613	1,452	70%
TRUNK	2,045	3,476	63%
EXTREM	1,099	1,391	56%
UNSPEC	235	1,006	81%
Total	6,869	15,506	69%

Tables 11 and 12 show the distribution of AIS 3+ injuries by body region by number of roof impacts for belted and unbelted, respectively. The 2+ roof impacts category includes all number of quarter-turns greater than 5. The 1 category is for all quarter-turns less than 6. One quarter-turn was included in the 1 category for convenience and because of small numbers.

Table 11.
AIS 3+ HARM for Belted Not Ejected Relevant Occupants by Body Region and Number of Roof Impacts

Belted	Roof Impacts	
Body Region	1	2+
HEAD	28.6%	6.1%
SPINE	10.3%	2.0%
TRUNK	19.4%	11.1%
EXTREM	11.7%	3.7%
UNSPEC	6.8%	0.2%
TOTAL	76.8%	23.2%

Table 12.
AIS 3+ HARM for Unbelted Not Ejected Relevant Occupants by Body Region and Number of Roof Impacts

Unbelted	Roof Impacts	
Body Region	**1**	**2+**
HEAD	46.0%	3.4%
SPINE	8.4%	0.9%
TRUNK	23.1%	1.6%
EXTREM	10.3%	0.8%
UNSPEC	5.5%	0.0%
TOTAL	93.4%	6.6%

INJURIES BY ROLL DIRECTION AND NUMBER OF VEHICLE ROOF IMPACTS

Tables 13 and 14 present the percentage of the AIS 3+ HARM from Tables 11 and 12 that are in far-side rollovers.

Table 13.
Percent of AIS 3+ HARM for Belted Not Ejected Relevant Occupants That Occur in Far-side Rollovers by Body Region and Number of Roof Impacts

Belted Far-side	Roof Impacts	
Body Region	**1**	**2+**
HEAD	64%	56%
SPINE	67%	88%
TRUNK	64%	18%
EXTREM	49%	68%
TOTAL	56%	42%

Table 14.
Percent of AIS 3+ HARM for Unbelted Not Ejected Relevant Occupants That Occur in Far-side Rollovers by Body Region and Number of Roof Impacts

Unbelted Far-side	Roof Impacts	
Body Region	**1**	**2+**
HEAD	74%	71%
SPINE	69%	80%
TRUNK	64%	55%
EXTREM	54%	77%
TOTAL	69%	69%

SIMULATIONS OF NEAR AND FAR ROLLOVERS

A rollover crash can generally be divided into three phases – tripping, airborne, and ground contact. Some rollovers may repeat the airborne and ground contact phases more than once. Injuries may occur during any of these phases. The occupant kinematics will vary depending on belt use and roll direction relative to the occupant. Consequently, the roll direction may also influence injury outcome.

To better understand the occupant kinematics in near-side and far-side rollovers, computer modeling of rollovers was conducted (Burel 2003, Dahdah, 2005). The baseline acceleration for the model was from an actual vehicle rollover test. The test was of an SUV exposed to an 18 mph tripping acceleration pulse. The roll was induced by an impact with a curb as the vehicle slid sideways. The lateral acceleration reached a maximum of 12 G about 15 ms after impact with the curb. After about 24 ms the acceleration reversed signs. It again reached about 6 G between 150 and 200 ms. The initial acceleration pulse lasted about 24 ms and was due to the curb impact; the subsequent acceleration was both lateral and vertical. It was produced by the release of energy from the suspension system. The tripping acceleration induced a roll rate of about 270 deg/sec. To evaluate variations in the tripping pulse, the baseline pulse was scaled using the same time duration, but proportionally increasing or decreasing the acceleration. Tripping pulses on 5, 10, 15, 20, and 25 mph were simulated for near-side and far-side rollovers. The roll rates that resulted from these pulses are shown in Table 15.

Table 15.
Roll Rates that Resulted from Modeling the Tripping Pulse

Trip Velocity mph	Roll Rate Deg/Sec
5	70
10	150
15	230
20	310
25	380

An initial difference noted between the near-side and far-side rollovers was that the role of the safety belt differs. For far-side rollovers, the seat rises under the occupant and the lap belt is temporarily unloaded. In near-side rollovers, the seat falls away from the occupant after the initial launch of the vehicle has ended. In addition, interaction with the door can restrict the lateral motion of the occupant.

The modeling indicated that the occupant's maximum head velocity increased with the severity of the tripping pulse and the resulting roll rate that it induced. The results are shown in Table 16.

Table 16.
Maximum Head Velocities Resulted from Modeling Tripping Pulses of Different Severity by Roll Direction

Trip Velocity mph	Max Head Velocity m/sec Near-side	Far-side
5	1.65	0.55
10	3.70	1.38
15	4.17	3.29
20	4.20	4.69
25	4.25	5.73

Maximum belt loads and head excursion were also found to increase with increased severity crash pulse. These results suggest that the tripping pulse could be another indicator of rollover crash severity.

CONCLUSIONS

This study investigated injuries to front seat occupants 12 years and older in near-side and far-side rollovers. The study excludes cases in which the belt use was unknown or the belt was improper for rollover protection. End-over-end rollovers were also excluded. All completely and partially ejected occupants were excluded from the analysis of injuries by body region.

The examination of ejections and partial ejections in the relevant population showed that 55% of the unbelted occupants with MAIS 3+ injuries were ejected. This compared with 9.5% for the belted population. Most unbelted injuries are from complete ejections, comprising 88% of the combined complete and partial ejections. In contrast 84% of belted ejections are partial ejections.

The relevant belted and unbelted populations were exposed to near-side rollovers slightly more frequently than far-side rollovers. However, the number of occupants with MAIS 3+ injuries was greater for both belted and unbelted populations in far-side rollovers. The relevant population of unbelted occupants was ejected about equally in near-side and far-side rollovers. Far-side partial ejections for belted occupants were much less frequent than near-side partial ejections, but when they occurred they were more likely to produce serious injuries.
An examination of the AIS 3+ HARM by body region shows that for belted and unbelted not ejected occupants, head injuries are the largest fraction at 35% and 49%, respectively. Trunk injuries comprised 30% of the belted HARM and 25% of the unbelted HARM.

An examination of AIS 3+ HARM by roll direction indicates that far-side rollovers consistently produce the largest fraction for unbelted not ejected occupants. Over 70% of the head and spine HARM for this unbelted population is in far-side rollovers. For belted not ejected occupants, the HARM was more evenly split between near and far-side rollovers. Trunk injuries were more frequent in near-side rollovers but all other body regions were at higher risk in far-side rollovers.

The distribution of AIS 3+ HARM by the number of roof impacts shows a very large difference between belted and unbelted. For the belted, 38% of the AIS 3 + injuries and 23% of the AIS 3+ HARM occurs in rollovers with more than one roof impact. This compares with only 6.6% of the HARM for the unbelted. Previous studies have shown that the ejection risk increases with number of roof impacts. Consequently, the number of injuries in multiple roof impacts is much higher when the complete unbelted population is considered.

Countermeasures to reduce rollover injuries to the belted population need to consider protection in rollovers with more than one roof impact because 34% of the AIS 3+ injuries and 23% of the AIS 3+ HARM to the relevant belted population occur in these crashes. More than half of AIS 3+ HARM to relevant belted occupants occurs in far-side rollovers.

Modeling of rollover events indicates that the severity of the tripping pulse is an indicator of rollover crash severity. There is a need to collect crash data on measurements that would allow the prediction of the severity of the tripping pulse.

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A STUDY OF NASS ROLLOVER CASES AND THE IMPLICATION FOR FEDERAL REGULATION

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ABSTRACT

NHTSA identified 273 NASS rollover crashes occurring from 1997 through 2000 in which the light vehicles had more than 6 inches of residual roof crush. The agency analyzed these cases, but we have studied them in much more detail. We found a number of important, consistent features that demonstrate conditions that produce rollover injuries, and strongly indicate how rollover casualties can be reduced using readily available technologies. We found: (1) nearly two-thirds were essentially flat ground rollovers without complications; (2) the windshield was always broken when the front of the roof was damaged; (3) virtually all had major damage over an A pillar and a substantial majority had front fender damage indicating that forward pitch in at least one roof impact was roughly 10 degrees; (4) where the vehicle executed more than ½ roll, the initially trailing side of the roof generally had the greatest crush; (5) safety belt use was critical to the pattern of injuries and ejections; (6) the type of roof damage is a function of its design and the nature of the roof impacts; (7) nearly one fifth of the occupants had MAIS 3 or greater injury to the head, face, or cervical spine; and (8) when non-ejected occupants received head, neck or upper torso injuries, they were generally seated on the initially trailing side under a significantly crushed part of the roof. Our study strongly suggests which countermeasures would best address the problem of light vehicle casualties in rollovers, discusses various candidate countermeasures, and estimates the casualty reduction that would result from them. Finally, we discuss the implications for Federal policies.

INTRODUCTION

Several years ago, the National Highway Traffic Safety Administration (NHTSA) asked the public for "views and comments on what changes, if any, are needed to the roof crush resistance standard," Federal motor vehicle safety standard (FMVSS) 216. Shortly afterward, Administrator Jeffrey Runge, M.D. said, "NHTSA plans to propose an upgrade of its roof crush standard to require roofs to allow less crush during a rollover event." As of January 2005, the agency had received 120 comments. Virtually all comments from outside the auto industry support strengthening the standard. The authors of this paper have submitted a large volume of data that should help the agency develop an effective amendment to that and related standards.

NHTSA estimates that 16,000 light vehicle occupants receive serious, non-fatal injuries and that more than 10,000 are killed in rollovers annually. Of those, NHTSA estimated that 28 percent were not ejected and were injured from roof contact (almost all were from roof intrusion); and that half were ejected. While NHTSA did not connect ejection with roof crush, the Malibu tests showed that a strong roof substantially reduced tempered glass side window breakage which would reduce ejection.

The Malibu I tests [Orlowsky] showed "All of the [4] partial ejections were through side window openings as a result of glass breakage. The only total ejection was through a windshield opening. . . . The rollcaged [strong roof] vehicles had less glass breakage than the standard roof vehicles. In the standard vehicles, 18 of the 20 side and rear windows were broken, and all were broken due to roof deformation as a result of ground contact. For the roll caged vehicles, only five of the 20 side and rear windows were broken, and one of the side windows was broken by occupant loading." All of the ejected dummies in these tests were in vehicles with weak (production) roofs, and were seated on the initially trailing, or far side of the vehicle. Thus, the need for motor vehicle safety associated with roof crush in rollovers – including for occupants who are ejected – is substantial. Furthermore, rollover casualties are becoming more numerous with the increasing use of light trucks as private passenger vehicles. SUVs, in particular, are grossly overrepresented in producing AIS 3+ injuries in rollovers.

RECENT NHTSA RESEARCH AND ANALYSIS: THE 273 NASS CASES

Last year, NHTSA released two bodies of information that it is using to develop and support an amended FMVSS 216. The first [Pack], is a list of 273 National Accident Sampling System rollover cases with significant roof crush from accident years 1997-2000. We have prepared detailed tables of these cases that are available from the authors on request (allanp@xprts-llc.com). The NHTSA authors selected these cases from the 1997-2000 NASS files involving rollovers with at least 2 quarter turns (one-half roll) of the vehicle. The vehicles were selected as 1995-2001 light vehicles that weighed 10,000 pounds or less, had no post manufacture modifications, (one case, NHTSA 2000-11-73, involved a pickup truck that had a large rack over the bed and did not meet the criterion), were not towing a trailer, *and had at least 6 inches of roof crush.*

NHTSA characterized these rollovers as "very serious rollover crashes." Their severity was apparently judged by the amount of residual roof crush which is a measure of the weakness of the roof, not the severity of the rollover. These crashes, even when they involve multiple rolls, do involve forces that are easily survivable if the occupant is reasonably protected. They sometimes have serious outcomes (AIS 3+ injuries, ejections, etc.) and may appear to be serious because of the amount of damage sustained by the vehicle, but these are both the result of failures of the vehicle's structure or its rollover occupant protection system. Furthermore, just as the agency is concerned with applying countermeasures to higher speed frontal and side crashes; it should be primarily concerned about applying countermeasures to these crashes that have serious injury consequences.

In 87 of the cases (32%), the vehicle executed only ½ roll. It executed ¾ to 1¼ rolls in an additional 80 cases (29%), and 1½ or more rolls in the remaining 106 cases (39%). A collision preceded the roll (and in most cases contributed to the onset of the rollover) in about 35 cases. In a few cases, the initial impact caused the most serious injury.

A majority of rollovers occur on reasonably flat ground and do not involve significant collisions with anything but the road or ground. Of the 273 NASS cases, 63 percent were "pure" rollovers: rollovers that were not tripped by anything more than traction with the road or ground, that involved no significant collision before the rollover, no collision with anything beyond the ground during the rollover, and no unusual contour to the ground over which the vehicle rolls. Another 14 percent involved a significant collision before the rollover (such as with another vehicle or a guardrail), and 23 percent involved other unusual conditions (collisions with trees during the rollover, or an encounter with a major change in ground elevation).

We observed windshield separation or breakage in pictures of *all* 260 of the vehicles in for which pictures were available and in which there was any significant damage to the front of the roof. The NHTSA study found that the windshield was "intact" in 66 of the cases and had a characterization of the windshield in all 273 cases. We found that in seven cases, there were no pictures or snow that made a determination of the condition of the windshield impossible. We found only 6 in which the windshields were unbroken and fully bonded, none of which involved significant damage to the front of the roof. We do not believe that the NHTSA analysts were sufficiently critical in their evaluation of windshields of these vehicles. We have observed in FMVSS 216 tests, that when the windshield breaks (typically at around 8 cm of crush) the strength of the roof declines dramatically. This has led us to conclude that once the windshield cracks or separates to any degree, it ceases to contribute to roof strength.

Damage was observed on the top of at least one front fender in more than 80 percent of the cases for which there were pictures, indicating that the vehicle was pitched at least 10 degrees during at least part of the time it was inverted. This is approximately the angle formed with the horizontal by a line between the top of the roof over the A pillar and the top of the front fender of virtually all contemporary production light vehicles.

The types of roof damage varied depending on the nature of the crash, the structural weaknesses of the roof, and other factors. However, there were certain common features. The greatest damage was to the front of the roof in all but a handful of cases, for example. The initially trailing, front side of the roof sustained the most damage or both sides of the roof were seriously damaged in 187 cases (163 had major damage to the trailing side only) while 60 involved primary damage to the initially leading side of the vehicle. The remaining 24 were indeterminate or the case file did not have sufficient information. The damage to the roof was likely to have involved a collision with something other than approximately flat ground in about 65 of the cases out of the 273.

Thus, of the cases where sufficient information was available, 75 percent had major damage to the initially trailing or far side of the roof (some of which involved major damage to both sides of the roof). We observed buckling of at least one structural member of the roof in 208 of the cases – 80% of those for which there were pictures. These cases also show that many vehicles roofs are weak at the junction of the major structural elements, the post to pillar connections and the pillar to roof rail and windshield header connection.

Of the 60 cases with primary roof damage at the front on the initially leading side, 47 were less than 1½ rolls (of those, 30 were only ½ roll). Only 7 were more than 1½ roll, and there were complicating factors in most of these. For example, the investigator's reconstructions were questionable in a few of these cases and in a few it appears that the vehicle may have both rolled and yawed so that the direction of the roll changed during the accident. In several, the roof was so massively damaged, it defied easy classification. As a consequence, the estimate that 75 percent of the cases had major damage to the far side of the roof is conservative.

It is important to note that residual roof damage does not reflect the maximum deformation of the roof for two reasons. The first is that the steel from which roofs are made have some elasticity, so that they bounce back (typically 20 to 30 percent) from their maximum deformation. Second, each time the roof strikes the ground, it will deform in the direction of the force applied to it. The force on one side of the roof may force it toward the opposite side, but the force on the opposite side will tend to restore it to its original configuration. This effect was demonstrated in the Malibu tests. This conclusion comes from observation of the videotapes of the vehicle interior associated with this test program. These films are available from Docket NHTSA 1999-5572.

Table 1.
Distribution of rollovers and their casualties from the 273 NASS cases

	NASS R/O Cases with 6"+ Crush all cases	NASS R/O Cases with 6"+ Crush MAIS 3+ injury	2001 R/O Fatalities (FARS)	1997-2001 R/O serious, non-fatal injuries (NASS est.)
Passenger Car	95 (35%)	46 (40%)	5,343 (45%)	15,535 (52%)
SUV	101 (37%)	42 (36%)	2,142 (21%)	5,930 (20%)
Pickup	65 (24%)	25 (22%)	2,643 (26%)	6,595 (22%)
Van	7 minivans (3%) 5 full vans (2%)	3 (3%)	793 (8%)	1,600 (5%)
R/O after Collision	35 (13%)	13 (11%)	18%	(80% of rollovers are single vehicle accidents)
R/O incl. other*	67 (25%)	36 (31%)	1%	
Total	273 (100%)	116 (100%)	10,121 (100%)	29,660 (100%)

* includes collision with other vehicle, tree, or other during rollover; major drop; etc.

Table 2.
Area of primary roof damage in the 273 NASS cases and of cases with MAIS 3+ head or neck injuries

Primary Roof Damage	Total Number of Cases	Cases with MAIS 3+ Head or Neck (cervical spine) Injury
Initially Trailing Side, Front	163* (65% of those with front damage)	39 (64% of front damage cases)
Both Sides, Front	24 (10% of those with front damage)	6 (10% of front damage cases)
Initially Leading Side, Front	60 (23% of those with front damage)	13 (21% of front damage cases)
Rear, Other or Unknown	24	3

* 22 of the total cases and 6 of the cases with MAIS 3+ injury may have involved a collision between the roof and another object such a vehicle or a tree.

The NHTSA analysts spend a substantial amount of time discussing the specific nature of the roof failures (that the pillars themselves "largely remain straight" with bending "occurring at or near both ends . . ." While this is interesting, it is an artifact of the specific design characteristics of the roof. This would be interesting to vehicle designers who are committed to improving roof crush resistance, but tell little about what action is necessary to develop a better test for roof crush resistance.

The fact that in all 273 cases there was more crush than is permitted in FMVSS 216 shows that there were 273 roof failures. These failures put the occupants of the vehicles involved at risk even if they were not actually seriously injured. In fact, the serious injury rate in these rollovers was considerably higher than the rate for rollovers generally. In these cases, approximately 40 percent resulted in MAIS 3 or greater injury, or a fatality. In rollovers generally, fewer than ten percent result in such injury.

To some degree, serious injuries (or perhaps their absence) in rollovers involve a certain serendipity. Unlike severe frontal or side crashes in which major forces must be sustained by the occupants, in rollovers, the basic forces are low – the result of a change in velocity that is very rarely greater than about 2 m/sec (5 mph). Thus, when injuries are sustained, they are the result of failures: ejection of unrestrained or poorly restrained occupants, structural collapse, lack of padding, or other factors.

In their analyses, the NHTSA engineers looked at the injuries, attempting to find some correlations between roof crush that compromised headroom and injury. This discussion seems to assume that restrained occupants remain in their normal seating positions in a rollover, which they do not. Even restrained occupants are typically forced upward and outward in relation to the vehicle during a rollover because of centrifugal force, and because most safety belts do a mediocre job, at best, restraining them under rollover conditions. Unrestrained occupants can be thrown almost anywhere in, and too often outside a vehicle. The NHTSA analysts also neglected to analyze the relationship between injured occupant seating position and the location of major roof crush.

There are some correlations between roof performance and injury. For example, ejections cannot occur unless there is a path for ejection: a broken window or open door. Side windows virtually always break when there is substantial roof crush, but are often intact when the roof damage is minor. A restrained occupant's head, face or neck are likely to be seriously injured only if they are subject to extraordinary forces because of roof buckling or collapse, or because they are ejected.

Of the 65 cases with MAIS 3+ or fatal injuries to the head, face or neck (cervical spine), 25 were belted, and 25 involved occupants who were not ejected (some of whom were not belted). Three were not front seat occupants. Five were belted occupants who were partially ejected. The partial ejection and injury to a belted occupant's head is unlikely unless there is substantial distortion of the roof. This occurs typically when there is matchboxing of the roof in the direction away from the occupant's seating position. In such a case, the occupant does not typically go outside the vehicle. Rather, the envelope of the vehicle moves so that it no longer contains the occupant. In 23 of the cases, the vehicle had a significant collision before or during the rollover, and nine occupants in these cases were belted, but received MAIS 3+ head or neck injuries.

Fifty-one cases had MAIS 3+ or fatal injuries to parts of the body other than the head and neck. All but a few of these injuries to belted occupants, were to extremities rather than to the thorax. Many cases with MAIS 3+ trunk injuries involved collisions before the roll. The total number of AIS 3+ is higher than the overall numbers for injuries presented in NHTSA's October 2001 Notice. This is probably a function the fact that NHTSA selected only cases with at least 15 cm (6 inches) of roof crush.

Table 3.
Area of MAIS 3+ injury in 273 NASS cases

Area of Injury	Number of MAIS 3+ Injuries
Head, Face or Cervical Spine only	58 (18 belted, non-ejected occupants)
Head, Face or Cervical Spine plus Other Injury	7
Torso	34 (4 to thoracic spine)
Extremity	15

Table 4.
Ejected occupants by injury in 273 NASS cases

Injury	Not Ejected	Partial Ejection	Complete Ejection
MAIS 3+ or fatal head or neck injury	23+	12	27
Other MAIS 3+ or fatal injury	26+	6	23
MAIS 1 or 2 non-fatal injury	139+	8	15

Note: many vehicles had more than one occupant so this table underestimates non-ejected occupants.

Approximately 91 occupants in these cases were ejected. Of these, 39 received MAIS 3+ or fatal head or neck injuries. The most seriously injured occupants (24 of which were MAIS 1 or 2 injuries) were partially or fully ejected. Most were not belted, but there were some injuries to extremities among belted occupants.

Among the 39 cases where an occupant with an MAIS 3+ or fatal head or neck injury was ejected, 27 involved more than one half roll. Only 2 had primary damage to the near side of the roof or complicating factors. Only 13 of these rollovers involved passenger cars, 8 of which had at least 1½ rolls.

Three cases with MAIS 3+ head or neck injuries involved collision with another vehicle or object before the rollover and another 20 collided with something during the rollover, complicating the accident. In four cases, the occupant suffered MAIS 3+ thoracic spine injuries, but only two (both ejected) did not involve complicating or unusual factors. Six fatally injured occupants were coded as MAIS 1 or 2. Although an AIS 6 is virtually always a fatality, and fatalities are somewhat likely with AIS 4 or 5 injuries, a fatality may occur with lower AIS level injuries. In some cases, however, limited information may result in a fatality being coded as AIS 1 or 2.

Among the occupants in the 273 cases selected, 173 who suffered the most serious injury in the rollover were coded as wearing safety belts while 114 were coded as not wearing them. A few were coded "unknown" or were not coded. There was not a particularly strong correlation between non-use of safety belts and the number of rolls in the crash. The rate of safety belt use in this file is not consistent with other data that indicates only about half of all occupants involved in rollovers are belted. According to NHTSA (1) "Seventy-eight percent of the people who died in single-vehicle rollover crashes were not wearing the vehicle safety belt, and 64 percent were partially or completely ejected from the vehicle (including 53 percent who were completely ejected)."

CONCLUSIONS FROM THE 273 ROLLOVERS

From these data, we can draw the following conclusions concerning regulatory approaches to countermeasures:

- Increasing safety belt use is critical to reducing AIS 3+ injuries to the thorax and lower extremities.
- Belt use is critical to reducing occupant ejections. However, injuries to occupants' arms that have gone outside the vehicle's envelope can be controlled only by reducing side window breakage. In a few cases, partial ejection was coded for a head or neck injury where the occupant did not move significantly from his or her normal seating position. In these cases, the roof distorted so that its envelope no longer contained the occupant's head. In 1968, Ford engineer J.R. Weaver stated "It is obvious that occupants that are restrained in upright positions are more susceptible to injury from a collapsing roof than unrestrained occupants who are free to tumble about the interior of the vehicle. It seems unjust to penalize people wearing effective restraint systems by exposing them to more severe rollover injuries than they might expect with no restraints." The Malibu tests confirmed that belted occupants have increased probability of severe head or neck injury.
- Any roof crush test that does not result in windshield failure in most contemporary vehicles *before* compliance is determined (either breakage or separation from the body) is not applying sufficient or realistic forces.
- A realistic test of roof crush resistance, whether quasi-static or dynamic, must be conducted at a pitch angle of at least 10 degrees.
- A test of roof crush resistance, whether quasi-static or dynamic, must reasonably emulate the conditions of an initially trailing side roof impact to address a substantial majority of AIS 3+ head and neck injuries. This includes application of the force at a roll angle significantly greater than 25° as occurs with the initially trailing side of the roof in a majority of rollovers.
- Although passenger cars are a substantial proportion of the vehicles that roll over, SUVs are highly overrepresented in rollovers and particularly in rollovers with AIS 3+ injuries. Pickups are also overrepresented, but to a smaller degree. Thus, any test of roof crush resistance must address the particular geometric and roof strength issues of light trucks.
- A substantial increase in roof strength has the potential to reduce AIS 3+ head and neck injuries to non-ejected occupants by 50 to 80% depending on the degree of increase under far side impact conditions and the performance of the vehicle's restraints.
- Roughly half of all other AIS 3+ injuries – mostly ejections – that are not a consequence of a collision with another vehicle or an external object would be reduced with a stronger roof if it significantly reduced side window failure. This would be enhanced by attention to the design of side window systems (perhaps including laminated side glazing) to close ejection portals.
- The minority of cases in which there are major vehicle collisions before or during the rollover are among those most difficult to address. However, the traditional approaches – occupant compartment integrity, crash energy management, good occupant restraint, and appropriate interior padding – should improve occupant safety in such conditions.

QUASI-STATIC TEST RESULTS

NHTSA released the results of a number of quasi-static tests of roof crush resistance in May 2004 [VRTC]. These tests were generally conducted according to the procedures of FMVSS 216, but NHTSA tested three pairs of identical vehicles with the platen being forced into the vehicle through a stroke of 254 mm (10 inches) rather than the 127 mm specified in the standard. One of the pair of vehicles was tested at the 5º pitch and 25º roll specified in the standard while the second was tested with the pitch angle increased to 10º and the roll angle increased to 45º. The vehicles were a mid-sized SUV (2002 Ford Explorer), a mid-sized pickup (1998 Chevrolet S10 pickup) and a minivan (1997 Dodge Grand Caravan). The platen is driven by two rams, one over the front roof contact point and one toward the rear.

The interpretation of these tests provided by Donald Willke of NHTSA was:

- No trend in energy absorbed
- No trend in far side lateral crush
- More vertical crush in 5 x 25 deg.
- Any differences were very subtle
  - Not distinguishable in subjective evaluation of photographs of roof damage

We disagree substantially with these conclusions based on the test results themselves. These tests produced residual crush that was different from that observed in real-world rollovers in NASS (see Figure 1), for example, and that were somewhat different from each other reflecting the angle at which the platen was forced into the roof (note particularly the differences in A and B pillar damage). The force on each hydraulic ram used to press the platen into the roof was separately recorded, and the force displacement curves in these two cases are substantially different in all three pair of tests.

In the tests of the 2002 Ford Explorer conducted at 5º pitch and 25º roll, failure of the windshield resulted in a substantial reduction in the vehicle's roof crush resistance, as measured by the forward ram (see curve at left side of Figure 3), from a peak at about 85 mm (3.3 inches) displacement of 24,000 N (5,400 pounds) to about 10,000 N (2,250 pounds) at 130 mm (5 inches) displacement. At that point the rear ram was supporting 24,000 N (because the platen was fully engaged with the B pillar and rear roof structure. However, the force on the rear ram went down to less than 4,000 N (900 pounds) after the B and C pillars had failed at about 210 mm (8 inches).

Although the roof was able to sustain a maximum force of 55,000 N, this does not realistically represent roof crush resistance in a range of roof crush that would be likely to cause injury. The vehicle would have passed FMVSS 216 at about 70 mm of ram travel, yet the roof was clearly failing during this test. Very little was learned by continuing the test beyond 125 mm (5 inches) of platen travel except that the B and C pillars failed as the force on them increased. Furthermore, in an actual rollover, the injury and window failures would probably have occurred well before the roof had crushed 254 cm.

Figure 1. The NHTSA test vehicles: at 5º pitch and 25º roll at top and at 10º pitch and 45º roll at bottom. The damage is similar only in that the damaged roof's contour follows the shape and angle of the platen used in the test.

Because of the roof's tumblehome, the platen in the Explorer 10º pitch and 45º roll test almost immediately engaged the base of the A pillar which conveyed substantial force resistance. Although it is difficult to tell from the photograph (page 30, VRTC report), it also appears that the platen was not properly positioned on the Explorer's roof. The longitudinal centerline of the lower face of the platen is supposed to be located "on the initial point of contact" with the roof, while the photograph makes it appear that it is at least 5 cm below that point. This placement is critical. Had the platen been moved up somewhat, it would probably not have engaged the top of the door directly. The results would not have been much different, given that the platen engaged the A pillar just above its connection with the A post so that the lower body provided a substantial part of the platen's resistance. Nevertheless, even if the test had been properly conducted, its results could not be taken seriously. We avoided this problem in our tests by using a 305 mm wide platen. In this test, the rear ram (curve at right side of Figure 3) did not exceed 3,000 N (675 pounds) until the roof had crushed about 170 mm (6.5 inches), and never exceeded 11,000 N. The front ram increased virtually monotonically to a peak of about 50,000 N at 170 mm at which time instrumentation problems caused a loss of further data.

In the tests of the Dodge Caravan and the Chevrolet S-10 at 10º pitch and 45º roll, the rear ram picked up virtually no force in either test. Most of the crush resistance appeared to come from the base of the A pillars in both of these tests.

The width and placement of the platen in the tests at 10º pitch and 45º roll meant that this primary resistance was provided by the vehicle body (through the base of the A pillar), not the roof, so that these were not tests of roof crush resistance at all. Our own tests, in which the roof crush resistance is only about half of what is measured in tests at 5º pitch and 25º roll, are conducted with a 30 cm wide platen that applies the force only to the roof itself. Furthermore, we test at 10º pitch and 50º roll only after we have conducted a test on the first side of the roof at 10º pitch and 25º roll to a deformation of 127 mm. Our tests show lower roof strength on the second side because the windshield has already failed in the first side test and because the roofs we have tested show poor lateral shear resistance.

Since part of the rationale for increasing the roll angle is that lateral friction forces on the roof tend to move the force vector more laterally, simply rotating the large (76 cm wide) platen around to 45 degrees, as was done in this case, causes it to unrealistically engage the lower body structure rather than putting a realistic lateral shear force on the roof itself.

Figure 2. Four NASS 2002 Explorer case vehicles (2002-078-143, 2002-12-168, 2002-011-129, and 2001-11-048).

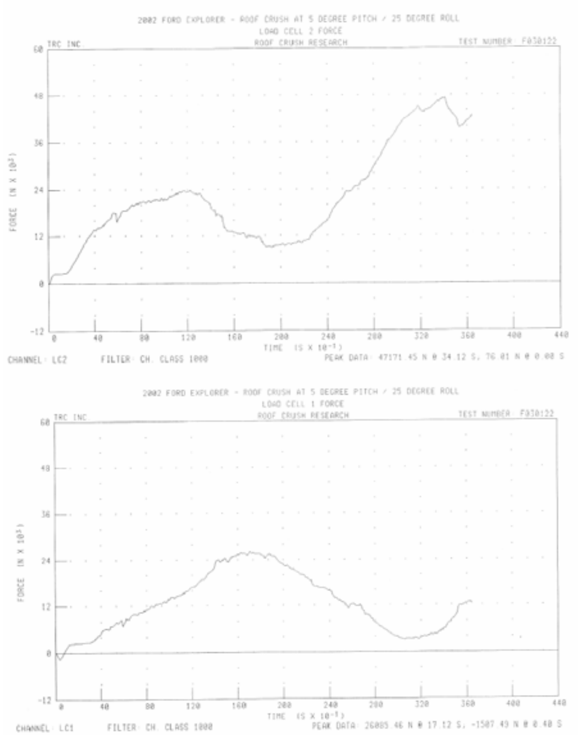

Figure 3. Curves of Force versus time (which is proportional to displacement) for the 2002 Ford Explorer in NHTSA's test at 5º pitch and 25º roll under FMVSS 216 test conditions carried out to 254 mm of displacement. The upper curve is the force at the front of the platen while the lower curve is the force at the rear of the platen.

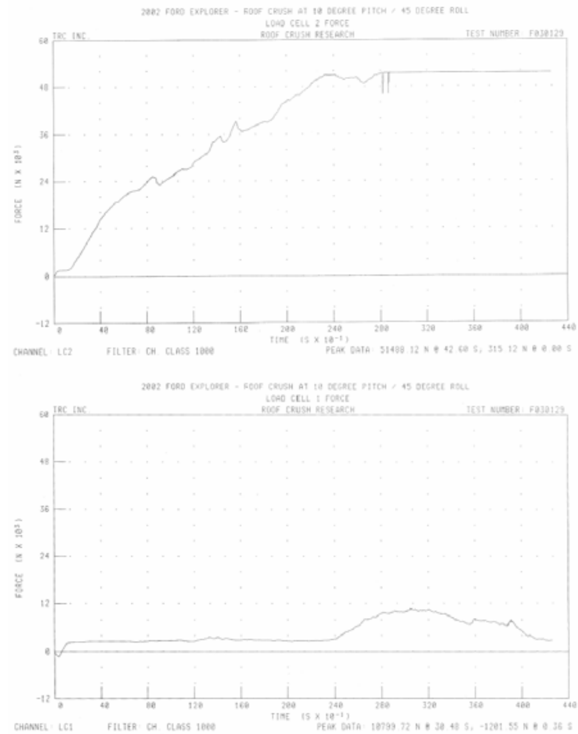

Figure 4. Curves of Force versus time (which is proportional to displacement) for the 2002 Ford Explorer in NHTSA's test at 10º pitch and 45º roll under FMVSS 216 test conditions carried out to 254 mm of displacement. The upper curve is the force at the front of the platen while the lower curve is the force at the rear of the platen.

In each of these NHTSA tests, the roof flattened against the platen rather than collapsing and buckling as is typical of vehicles in dynamic rollovers (See Figure 1). For comparison, we looked at 10 NASS cases involving 2001 and 2002 Explorers with significant rollover roof damage but no complicating factors (four of which are shown in Figure 2). The damage to these roofs was more complex, involving buckling, greater rearward or lateral displacement of the roof panel, and other features. There were three other 2002 Explorer rollovers in NASS, two of which resulted in little or no roof damage, and one of which was catastrophic.

We do not believe that either of NHTSA's tests, and particularly the tests conducted at 10º pitch and 45º roll, represent realistic loading. The 5º pitch and 25º roll platen applies the force at too shallow an angle to represent an initially trailing side roof impact which is the dangerous side for an occupant in a rollover. In the 10º pitch and 45º roll test, the wide platen engaged the A pillar base early in the test.

We completely disagree with the conclusion of the NHTSA test engineer that they produced similar results. The tests conducted at 5º pitch, 25º roll show a substantial loss of roof crush resistance after the failure of the windshield, particularly as measured by the forward ram. This behavior is not observed in the 10º pitch and 45º roll test of the Explorer, for example. In the latter tests, virtually all of the resistance to the platen comes from the forward ram. It appears that much of that resistance comes from the lower body, not the roof. The final damage in the two cases reflects the angle of the platen in the test, and is not representative of damage observed in actual rollover accidents.

It is useful to compare the NHTSA test program with a test program conducted by General Motors twenty years ago [Arums]. In those tests, GM was attempting to determine the impact of various windshield adhesives. The GM tests, conducted at a roll angle of approximately 50º, show the importance of a well-bonded windshield in meeting FMVSS 216 and the importance of the roll angle in determining a roof's strength-to-weight ratio. In these tests, the GM engineers also found that at between 160 and 200 mm of crush, the crusher picked up the lower end of the A-pillar and the crush resistance consequently rose substantially.

We do not necessarily reject the quasi-static test to show minimum roof performance. However, the test must be conceived to ensure that it measures roof crush resistance realistically. Continuing the test to 254 mm (10 inches) of crush provided little new information about the performance of the weak roofs that were tested by NHTSA. A well-designed roof should not be capable of crushing to this extent in a typical flat ground rollover.

CRITERIA FOR A ROOF CRUSH TEST

In his research, Willke measured the headroom in the various vehicles he tested. He used the FMVSS 208 dummy seating criteria, which is highly unrealistic for his purpose in several respects:

- It represents only the 50th percentile male.
- The seat track position at mid-point is far ahead of the position a 50th percentile male would use in actually driving or riding in a vehicle.
- The static seating position does not take account of the degree to which safety belts permit excursion in rollovers. This excursion comes from the basic geometry of the belts, the point in a rollover at which the retractor reel is locked up, the degree to which belting spools from the retractor, and other factors.

We are not convinced that headroom is a useful measure for purposes of a roof crush standard. Furthermore, it is a serious complication of this test and its interpretation that adds little or nothing to its validity. Because roof crush should be minimal under any circumstances where the roof contributes to occupant protection, short of conducting a dynamic test that includes head and neck injury criteria, we suspect that a measure of roof intrusion such as is in the present standard may be sufficient for a quasi-static test of roof intrusion.

AMENDED STANDARD REQUIREMENTS

If the roof crush resistance standard is amended, it must meet the requirements of the National Traffic and Motor Vehicle Safety Act of 1966 (as amended):

- The standard must meet "the need for motor vehicle safety" (rollover casualties are one-third of all motor vehicle occupant fatalities and severe injuries, so the need is clear).
- It must be "practicable" (i.e. it must not seriously compromise vehicle function, it must be possible to design and build production vehicles that comply, and the cost of compliance must be consistent with the benefits that will result. The practicability of countermeasures that would enhance rollover occupant protection – a strong roof, and rollover triggered safety belts and window curtain air bags – has been demonstrated in the Volvo XC90 and other vehicles that have one or more of these features).

- A standard "provides objective criteria" (that is, a compliance test must be repeatable, reproducible, and that it not be unreasonably difficult or costly to determine compliance).
- The standard governs "the performance of motor vehicles" to which it is applied and protects "against unreasonable risk of death or injury to persons in the event that accidents do occur."

AMENDING THE ROOF CRUSH STANDARD

There are four steps that must be completed in a program leading to the development of a new or amended Federal motor vehicle safety standard:

1. Assess how roofs of current vehicles perform in real world crashes. This is investigated by looking at both particular rollovers (to understand roof failure modes and how they occur) and at crash data bases, such as National Accident Sampling System (NASS) cases, to determine how common are roof failure modes that are associated with serious to fatal injury.
2. Determine the consequences of poor roof performance: how does a poorly performing roof injure occupants both by directly striking an occupant's head and by opening ejection portals. This is investigated by looking at the consequences of actual rollovers (also using, for example, NASS cases), particularly on human injury and ejection. We have done the assessment of roof performance and its consequences using the 273 NASS cases that were identified by NHTSA, and the results are reported below. Research and testing are necessary to emulate the actual conditions of rollovers (such as with the Malibu tests, and testing conducted on Jordan Rollover System [JRS], and Controlled Rollover Impact System [CRIS]) to determine actual conditions that produce injury or other critical failures, and what performance improvements can reduce injury potential. There needs to be a similar criterion for neck injury in rollover crashes.

3. Determine the appropriate human head impact and neck tolerance for use as injury criteria in a standard. There is a substantial body of biomechanics research that shows human head and neck tolerance levels or injury criteria under various impact conditions. The Head Injury Criterion (HIC) is generally accepted as a measure of the potential for closed head injury. We have advocated that an axial neck force loading of 7,000 N be adopted as the neck injury criterion for this purpose. A neck shear and a moment tolerance would also be useful.
4. Develop a test or tests that reasonably emulate the critical aspects of roof performance under highly controlled conditions of rollover that currently produce serious to fatal head or neck injury. Identify the salient features of rollovers that can be repeatedly and reproducibly tested on vehicles at reasonable cost. The test must reasonably discriminate between roofs that provide good occupant protection in the field and roofs that inflict or contribute to occupant injury in rollovers.

There are several aspects of the process of developing a compliance standard that are critical. The results of any compliance test must be compared with performance under actual rollover conditions of a vehicle that can pass the test to ensure that passing the test is consistent with good rollover occupant protection performance. Similarly, vehicles that perform poorly under actual rollover conditions (which include virtually all contemporary vehicles) must also fail the compliance test. Another way of looking at this question is that if a proposed test is conducted on a vehicle that has a stronger roof (such as a Volvo XC 90 and a 2003 Subaru Forrester that Willke showed could sustain significantly more than four times its weight in force on its roof to 150 mm (6 inches) of roof crush in a FMVSS 216 test.) and a poor or marginal performer (most other contemporary vehicles) the former should be able to pass the test while the latter should not.

FMVSS 216 has used a quasi-static test for decades. There are serious questions about the degree to which a quasi-static test can fully deal with the question of rollover occupant protection, but there are good theoretical and practical reasons for using such tests for a minimum standard to represent a dynamic phenomenon. However, quasi-static tests have limitations. For that reason, NHTSA abandoned its original quasi-static side impact test in favor of a dynamic test.

We have previously reported on our Jordan Rollover System, a repeatable dynamic rollover test device that has the flexibility and the precision to determine the adequacy of a quasi-static roof strength test. We have found that a roof with a strength-to-weight ratio that is as high as 3.5, when measured according using the FMVSS 216 procedure, is unlikely to ensure reasonable rollover occupant protection performance. We strongly suspect that it would require a strength-to-weight ratio of at least 4.5 to 1 in this test to ensure such protection. As we have said before, a major problem with FMVSS 216, which makes such high strength to weight ratios necessary, is that the test angles are too shallow to emulate realistic rollover conditions, and it tests only one side of the roof.

The experimental evidence demonstrates that the injury mechanism in rollovers is from the speed of intrusion of the roof into an occupant's head that results from structural failure, and is not directly related to residual crush. The intrusion amplitude at the dummy's head (wherever the head is likely to be) must be at least several inches and the maximum intrusion velocity for a neck injury must be more than 14 ft/sec to injure most healthy individuals. For a head injury the velocity must be at least 22 ft/sec. Because modern, lightly loaded vehicles roll with as much as 10 degrees of pitch (as evidenced by front fender contact when inverted) the rapid intrusion begins after the windshield has fractured or separated, when the front, initially trailing side of the roof sustains an increasingly lateral force from its contact with the ground.

Under these conditions, the ground contact region of a weak roof will deform toward the vehicle's center of gravity in either a matchbox motion or with buckling of the roof's structural elements and panel. The structural buckles are the result of bending at their ends, or toward the center as a result of end loading. A structure that is buckling near its mid-point moves transversely at 3 to 4 times the speed of the end that is sustaining the buckling force, and can inflict serious injury to or through an occupant's head that is in its path. Much of the tempered side glazing also fails when structural elements surrounding it buckles, opening avenues for partial or complete ejection.

While a quasi-static test can verify a strong roof's strength, it is unlikely to show the dynamic failure mechanism of a weak roof, particularly if the load is applied in a direction that is not representative of the forces that the roof will encounter in an actual rollover. If a roof's structure were essentially elastic, the correspondence between the quasi-static and dynamic test would be fairly good, but actual roof structures behave in a highly non-linear fashion, with major losses in strength when the windshield fails and when key structural elements buckle. It is this behavior that may not be adequately demonstrated by a test such as FMVSS 216, even if the force criterion were raised substantially.

On the other hand, quasi-static testing at a more realistic angle could provide a better picture of a roof's ability to resist the actual forces of a rollover impact with the ground. Under these conditions, a force as low as 2.5 times the vehicle's weight would be likely to ensure good rollover occupant protection.

We have confirmed that a roof that can sustain a load of 2.5 times the vehicle weight in a two-sided roof crush test at realistic loading angles can sustain loading from a dynamic rollover tests on the Jordan Rollover System without roof intrusion velocities that would inflict head or neck injuries. Our analysis of NHTSA's selected case files confirm, from an occupant protection perspective, what a quasi-static roof strength test must achieve. If the agency does not substitute a dynamic rollover test for FMVSS 216, it must at least confirm the effectiveness of the test procedure and criteria it proposes with a dynamic rollover test that measures the intrusion velocity at the occupants head.

It would be unscientific and unconscionable to promulgate a revised standard without confirming its effectiveness under dynamic conditions using one of the available dynamic test procedures to confirm the tests validity. We have offered our Jordan Rollover System and our other test equipment for this purpose.

ALTERNATIVES TO REGULATION

The imposition of an FMVSS is not the only mechanism for improving motor vehicle safety performance. NHTSA has used the New Car Assessment Program (NCAP) with some success to improve frontal and side crash performance as well as rollover resistance of new vehicles. The advantages of a consumer information program such as NCAP are that they (1) impose no requirements on automakers, (2) impose no lead time for achieving particular performance levels, (3) can specify multiple levels of safety performance rather than just a minimum, and (4) have been reasonably effective in encouraging manufacturers to strive for higher levels of safety performance.

It is unfortunate that manufacturers generally do not compete on safety in the absence of high quality, widely-disseminated consumer information. There are some interesting exceptions, however. Volvo has a somewhat deserved reputation for making safer vehicles. Certain safety equipment, such as electronic stability systems and side curtain air bags, has been voluntarily offered as standard equipment on luxury vehicles and as optional on others. Some equipment, such as side impact air bags and safety belt pretensioners, is not required but can help manufacturers meet some FMVSS.

Concern over product liability or bad publicity has apparently caused some manufacturers to include certain safety features or performance that goes beyond what is required. Manufacturers, fearing bad publicity, formed a committee to write voluntary guidelines for crash compatibility between SUVs and passenger cars. A similar committee on SUV rollover safety was promised, but was never formed.

THE SCIENCE OF ROLLOVER OCCUPANT PROTECTION

A critical factor in the debates over what happens to occupants in rollovers and over whether and how occupants might be protected is the lack of a comprehensive attempt to apply scientific methods to these questions. In fact, there has been little serious debate aimed at resolving these questions within a proper scientific forum.

Much of the research and testing that has been done within the industry, such as the development of and testing conducted with the Controlled Rollover Impact System (CRIS), has been aimed at trying to prove the thesis that a strong roof cannot improve the survivability of rollovers. While the testing conducted by General Motors, generally referred to as the Malibu tests, has given us an important and valuable data source on the subject, it required a massive effort to get the company to release the detailed data and film from these tests. Furthermore, some of the interpretation provided in scientific papers by those who conducted the tests has been misleading and highly controversial at best.

A major exception is the unpublished and (unfortunately) confidential work conducted by Volvo in its development of the XC90 utility vehicle. In essence, Volvo recognized the obvious: if there is no major impact between an occupant's head and the vehicle roof, there can be no head or neck injury. From this principle, Volvo developed a stronger roof structure and restraint system, with rollover triggered pre-tensioners that reduces the severity of, or prevents such contact.

NHTSA has conducted only limited testing and analysis to assess rollover occupant protection. However, some of this work has been inconclusive and its research design has been questionable (see discussion of recent NHTSA testing above). Furthermore, NHTSA has devoted little of its biomechanics resources to developing a well-accepted neck injury criterion. We have attempted to conduct research and testing to resolve these issues, but lack of funding has limited what we can achieve. The only other major institution that might have the resources to enter this debate, the Insurance Institute for Highway Safety, has neglected any significant research or testing in this field.

There have been papers presented in various meetings and journals discussing aspects of the question ranging from the biomechanics of head and neck injury to analyses of rollover crash data. However, even the refereeing of these papers and discussions following such presentations have not ensured that the best science on the subject has gained prominence and general acceptance.

Using the NHTSA [Blincoe] study as a basis, we estimate that the direct economic cost of rollover occupant injuries and fatalities is conservatively well over $20 billion (and the public's willingness to pay for eliminating a majority of rollover casualties approaches $100 billion per year). Thus, the potential for even a modest reduction in such casualties would justify a major investment in research, development and testing. Once we have found reasonable, practicable performance goals, the cost of these losses would further justify a significant expenditure in improving the rollover occupant protection performance of motor vehicles. It is a great tragedy – certainly equivalent to other major public health challenges – that our society has yet to make commitments to proper scientific resolution of these issues, and investments that would halt this unnecessary loss of life and limb.

EVIDENCE IN THE RULEMAKING DOCKET

A major body of test data, research and other information exists that should be used to shape and support an amendment of FMVSS 216. The authors have submitted massive amounts of information and analysis to the docket (NHTSA-1999-5572) to help the agency in this work. Perhaps the most critical information was the following:

- The General Motors Malibu tests from the 1980s. These fully instrumented FMVSS 208 dolly rollover tests compare the performance of production 1983 Chevrolet Malibu sedans with the performance of similar vehicles that have had a strong roll cage installed within them. Tests were conducted both with unrestrained Hybrid III dummies in the front seats and with dummies restrained by three-point belts that have cinching latch plates to limit excursion. The extensive photographic documentation and instrumentation used in these tests provides an excellent source of detailed information on what happens in rollovers, and particularly on the effect of a strong roof on rollover occupant protection.
- Extensive biomechanics research conducted on both cadavers and on Hybrid III dummies that gives good evidence on human neck injury tolerance and what injury criteria should be used for the Hybrid III in testing. We have consolidated the results of these papers [Nusholtz, Nusholtz, Sances] and have determined that a head impact speed of between 7 and 10 mph (which corresponds to a neck load in excess of 7,000 N on a Hybrid III dummy) is the threshold for cervical spine injury to a normal human being.
- Numerous internal research and test documents, primarily from General Motors Corp. and the Ford Motor Co. that show that these companies understood far more about their vehicles' performance under both quasi-static test conditions and actual rollovers than they revealed in their docket comments in FMVSS 216 rulemaking. In particular, there are documents showing that the strength of their roofs in FMVSS 216 tests was highly dependent on windshield integrity and that the strength of their roofs under the more lateral loading that is typical of far side roof impacts was substantially less than under the loading specified in FMVSS 216. Many of these documents have been included in the submissions by the authors to Docket NHTSA-1999-5572.

CONCLUSIONS

Analyses of the NASS crash data can be combined with rollover test data to develop a realistic test for roof crush resistance and to determine what other countermeasures that would produce a substantial reduction in rollover occupant injuries. The specific considerations we found in our analysis of the available data include the following:

- An effective safety belt use reminder, as recommended by the Transportation Research Board of the National Academy of Sciences, Committee for the Safety Belt Technology

Study, should be part of any program of rollover occupant protection. Of course, this would have benefits far beyond protection in rollovers.

- The primary roof damage, and occupant head and neck injury occur on the initially trailing side of the vehicle where the roll angle of the force is greater than 25º. Thus, a test conducted by simply increasing the force criterion in FMVSS 216 will not accurately capture the critical aspect of roof performance under actual rollover conditions. It is important to recognize that the roll angle at which a significant force is applied to the roof continues to increase as a weak roof contacts the ground and the roof collapses. The Malibu tests have shown that strong roof tends to contact the ground for a shorter period of time so that the mean roll angle of the force is lower for a stronger roof.
- A minimum requirement for roof crush resistance must test the roof at a pitch angle of 10º and under conditions of initially trailing side roof impacts. These impacts are at roll angles substantially greater than the 25º roll angle specified in the present FMVSS 216 standard.
- A test conducted by simply increasing the angles in FMVSS 216 without making some provision to ensure that the force is applied primarily to the upper part of the roof will not accurately measure roof crush resistance.
- Some attention must be given to the need for preserving the integrity of side windows (particularly the front side windows) in a rollover. There is strong evidence from the Malibu rollover tests that tempered side glazing breakage can be reduced by a strong roof. More attention in vehicle design to preserving the integrity of side glazing under rollover conditions will reduce both partial and full ejection of occupants in rollovers. This would be particularly important for reducing partial ejection of responsible occupants who are wearing safety belts.
- The excessive roof damage observed on light trucks strongly suggests that their roof geometry – width, flatness, and the distance of the corners of the roof from the vehicles' principal axis of rotation – play a role in determining roof crush resistance even at the same force levels. Thus, a test of roof crush resistance should take this geometry into account in some way. Testing at an angle significantly greater than 25º may help to address this question.
- A quasi-static test of roof crush resistance applied to a strong roof will give similar results regardless of the details of its application. Thus, it is important that the test be designed in such a way that the weaker roofs of most contemporary light vehicles will fail, but strong roofs will crush relatively little – and will not collapse or buckle – under application of realistic forces. In particular, the test should ensure that the windshield cannot be used as a major contributor to roof crush resistance if it will routinely fail in an actual rollover.

It is clear from the cases in the NASS file provided by NHTSA that vehicle roofs are performing very poorly under typical rollover conditions. Some automakers, and particularly General Motors, have argued that head and neck injuries to occupants in rollovers are not related to roof crush. GM Safety Executive Robert C. Lange, for example, recently said, "There is no relationship between roof strength and the likelihood of occupant injury given a rollover." NHTSA has also suggested that ejected occupants would not be helped by having greater roof strength. In the analysis presented in their 2001 notice [NHTSA (2)], the 13,374 "Ejected Seriously Injured Occupants in Light Vehicle Rollover Crashes" were essentially dismissed as if roof crush was not relevant to those injuries.

We strongly disagree with both of these conclusions. The 273 NASS cases make the point that head and neck injury – particularly to restrained occupants – correlate highly with roof crush; and that a majority of such injuries occur on the initially trailing side. Furthermore, both partial and complete ejections strongly correlate with roof crush and the consequent destruction of side glazing. Rollovers involve crash energy management (absorption) rates that are an order of magnitude lower than the rates for survivable frontal and side crashes. (The requirements of FMVSS 208 involve absorption of the kinetic energy of a 30 mph barrier impact, the energy of which is the square of the vehicle speed. FMVSS 214 defines the side impact requirement from a barrier moving at 33.5 mph, but with the energy absorption being somewhat lower because a rigid barrier is not involved. A rollover involves roof impacts at speeds of less than 5 mph.) If occupants can be contained within the vehicle and if the occupant compartment can keep its basic integrity, a good restraint system and roof padding should keep occupants' heads from roof contacts that produce head and neck injuries.

If NHTSA wants to reduce injuries in rollovers, and intends to comply with Federal administrative law, it has ample evidence on which to propose amendments to its standards. Compliance with strong roof crush requirements will substantially reduce serious rollover occupant injuries and will not be particularly costly or difficult to meet. There is little excuse for failing to understand and use the available evidence to propose effective amendments to its standards that will dramatically reduce rollover casualties.

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APPENDIX A

Inter-Organization

Milford Proving Ground
Current Product Engineering
General Motors Corporation

Date: June 27, 1984

Subject: Cab Roof Crush - Rollover Simulation

From: I. Arums, Safety & Crashworthiness Systems

To: J. D. Green, Safety & Crashworthiness Systems
D. Millittelo, Truck & Bus

Engineering judgment, based on viewing of rollover accident damage patterns, indicated first cab contact with the ground to be either the front or rear corner of the cab at the roof to door junction.

A single test simulation of these loadings was developed using the SRDL static crusher against an angled cab with 1' x 3' plywood-faced load cells measuring the cab's reaction forces. Since rotation of the cab onto its roof, as in a rollover, was not feasible, a test endpoint was defined as either door side glass breakage or load cell contact with the door handle.

Seven cabs - held at 38 to 41 degrees - were tested; analysis of the data is attached as Figures 1 through 20. Figures 21 - 27 are photographs showing the general deformation of each cab.

CONCLUSIONS

1. Door side glass does not fracture because of door frame deformation in this test mode. (Test #L18019 applied 200 mm. of crush at top of door frame without side glass fracture.) The tempered glass fractures if contacted by the load cell edge or bolts on load cell.

2. Bonded backlites, as well as bonded windshields, are structurally significant. They interact with the roof so that localized buckling instead of translation occurs.

3. Bonded backlite together with bonded windshield eliminated most of the deformation in the "A" and "B" pillars on the side opposite the load. BONDING of BOTH REDUCED by a FACTOR OF TWO the "MATCHBOXING" of the cab; the translation of the roof as an unbent panel (see Figure 7). BONDING of BOTH INCREASED by a FACTOR OF TWO the LOAD carrying ability of cab (see Figure 10).

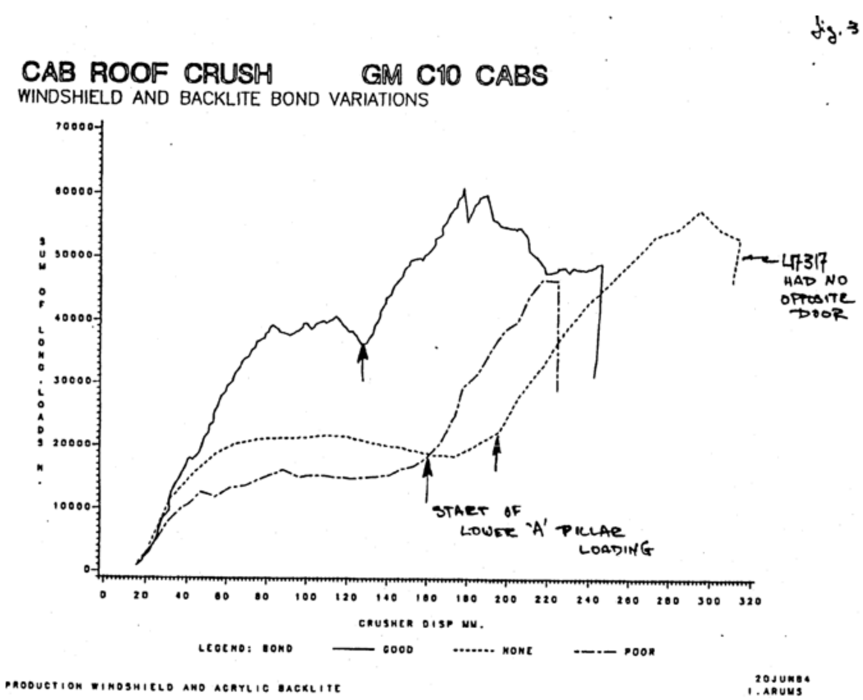

Figure A1. GM Memorandum on the role of windshield glazing in roof crush.

TEST AND SIMULATION TOOLS IN A ROLLOVER PROTECTION DEVELOPMENT PROCESS

Mike Linstromberg
Gerd Scholpp
Oliver Scherf
Siemens Restraint Systems GmbH
Germany
Paper No. 05-0122

ABSTRACT

In 2003, rollover accidents caused more than 10.000 fatalities and 229.000 injuries in the US alone. In view of this statistic and in order to provide a better occupant protection, the interest in the behavior of the vehicle structure and passive restraint systems under rollover loads is continuously growing.

In order to ensure a realistic reconstruction of the vehicle behavior in development tests, four new different test setups have been elaborated according to accident analysis results. For the restraint system development, knowledge about the borderline between roll and no roll is essential. To save expensive prototypes, this borderline is determined before performing first tests by using numerical simulations. The test and simulation tools support a comprehensive development process, which allow the adaptation and optimization of protection systems for rollover.

One key component of the restraint system is the algorithm, which has the task of rollover accident detection and determination of the optimal system activation time. For the latter task, knowledge about real occupant movement is essential. The low acceleration and rotation rates over a long period, which occur during some rollover constellations, lead to considerable movement deviations between the test dummy and the human. The firing time therefore, based on the dummy movements can only be determined approximately. Great optimization potential exists for activation algorithms which are adapted to humans. This adaptation is possible with a new developed simulation tool, which takes the possible muscle work of the human against occurring rollover loads into account. It determines the occupant movement during a rollover and has been validated to the human behavior by sled tests.

INTRODUCTION

The American traffic accident statistics, which is publicized by the National Highway Traffic Safety Administration (NHTSA) included for the year 2003 more than 6.3 million police reported motor vehicle crashes that occurred in the United States. More then 42,000 people lost their lives and nearly 2.9 million people were injured in motor vehicle crashes.

In these so called traffic safety facts the rollover accident is a separate category. For the year 2003 nearly 3 % of all passenger vehicles in crashes were rollover events (see Figure 1). This represents a minority in regard to the overall accident details.

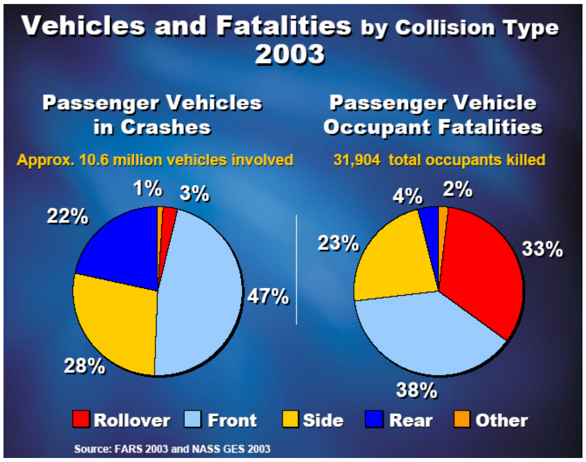

Figure 1. Vehicles and fatalities by collision type 2003

An other impression comes up by looking at the fatalities that occurred in crash events. Here the rollover is on the 2nd grade with nearly 33 % (see Figure 1) and the violence of rollover events is discernable.

In order to protect the occupants in rollover crashes in a better manner, passive safety elements like belt pretensioner and curtain airbags have to be activated in occurrence of such an event. The use of pretensioners help to retain the belted passengers in their seats and the activation of curtain airbags cushions the impacts of the head with interior parts, external environmental objects and prevent partial or full occupant ejection.

For the integration of passive safety elements in occupant protection the algorithm is one key point.

Here full scale rollover crash tests provide information about the sensor signals and the requested trigger time for the activation of these pyrotechnical protection devices under rollover loads. The test results are also useful to analyze the compartment intrusion and damage to the structure, which might occur.

Supplemental to the full scale tests, numerical simulation is a perfect development tool to consider the enormous number of possible rollover constellations and to figure out the borderline between roll and no roll events. This helps to save expensive prototypes during the development. In a further step numerical simulation can help to consider the real human movement behavior in some critical rollover constellations to prevent misuse cases and to optimize the firing time for the occupants.

TESTS DUMMIES

The rollover presents a new area in passive safety development. This explains why an anthropometric test dummy does not yet exist for rollover load cases. Pertaining to this, modifications to existing dummies or the development of new dummies in the near future have not been planned. This applies to Europe as well as to the US. For performing hardware tests an existing test dummy had to be chosen which has been developed for frontal, rear or lateral impact loading cases.

The crash tests, which are presented in this paper, are carried out with the EuroSID. An exception is the FMVSS 208 rollover test. Here the Hybrid III 50% dummy is specified by the corresponding directive. The EuroSID is a lateral impact dummy which is specified in the 96/27/EG directive for the protection of motor vehicle occupants.

The lateral impact dummy was chosen because 97 % of rollover accidents that happen in the field are rolling over the vehicle's x axis. Only 3% of rollover accidents are so-called pitch-over cases which are also described as end over end cases. These involve rolling over the vehicle's Y axis. Due to this distinct split it becomes clear that the area of application for the anthropometric test dummy is rather lateral than frontal.

A further point making the case for the EuroSID is it's availability due to it being laid down in the 96/27/EG directive. New developments in the dummy sector such as THOR or the World-SID are rare and currently not available in the testing labs. This is also the case for the Bio-SID. It is admittedly older but is mostly just used for development purposes.

A further argument supporting the choice of the EuroSID is his reproducibility. This goes hand in hand with the calibration of a dummy. All test dummies for frontal impact, for example the Hybrid III dummy, are exclusively calibrated for this loading case only. This explains why it's reproducibility laterally can not be determined, due to the lack of a calibration method in this direction.

Due to the high frequency of head injuries from rollover accidents, reproducibility should be particularly paid attention to in this body area (see Figure 2).

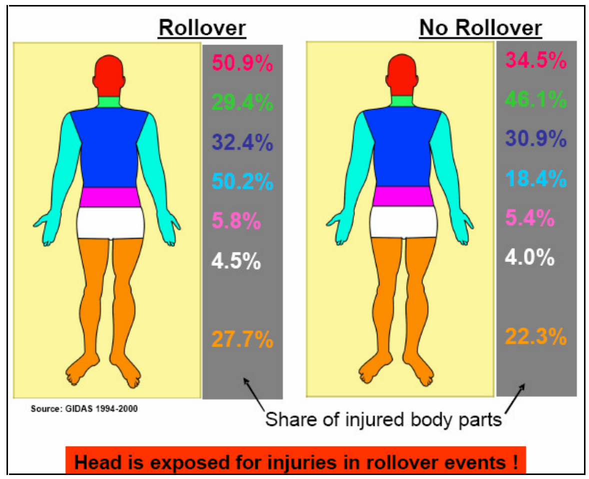

Figure 2. Injuries in roll/ no roll events [3]

This is the reason why the US-SID was not selected as a rollover dummy for hardware tests. The head and neck of the US-SID are not calibrated. Reproducibility of the head accelerations therefore and also of the neck-head kinematics is not possible.

The biofidelity, which describes the behavior similar to humans, is restricted with all anthropometric test dummies and has already been examined in many studies, for example by Professor Kallieris [1] from University of Heidelberg, to analyze the differences between anthropometric test dummies and humans.

Biofidelity of new developments on the dummy sector has certainly improved in comparison to older test dummies. However, these dummies have not been thoroughly investigated and the availability already discussed, is not adequately given.

Generally speaking, the test dummies developed for frontal impact react very stiff, particularly the neck-head areas under lateral loads. The US-SID and the Bio-SID were developed for lateral loads. However they use components in the neck-head area from dummies which have been configured for frontal loading cases. This explains, why the neck-head area is very stiff, even with both lateral impact dummy representatives. In this case the EuroSID is an exception. The neck-head area consists of a construction which is more flexible. Due to this the EuroSID does not show the stiffness of the other anthropometric test dummies described.

TESTS TOOLS

The following description of the different test set ups, represents an overview of the tests that have been developed by Siemens Restraint Systems together with other suppliers and OEMs.

The field relevance for the laboratory tests was assessed in a study from C. Parenteau [2] for the US by using field data from the National Accident Sampling System-Crashworthiness Data System (NASS-CDS) from 1992-1996.

The NASS-CDS consists of police reported tow-away traffic crashes in the US and defines different initiation types for rollover. The definition includes trip-over, fall-over, flip-over, turn-over, end-over-end, climb-over and bounce-over (see Figure 3).

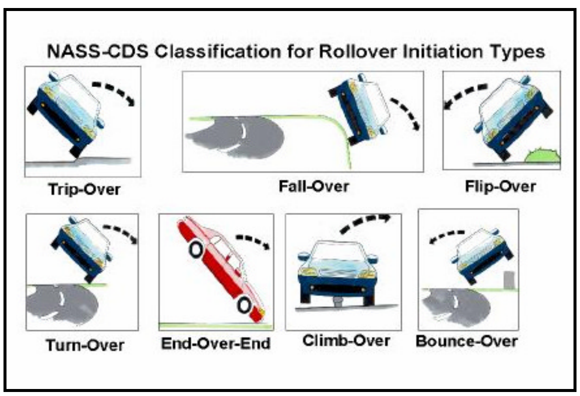

Figure 3. NASS classification for rollover initiation types

The **soil-trip** rollover is a lateral movement of the car into a sand bed. The car is placed on a flying floor and slides laterally into the sand after a sharp deceleration of the sled with deformation tubes (see Figure 4).

This test induces a fast occupant movement, which requested an early firing time. The lateral acceleration is in a middle range over a long period. The roll conditions of the test car varied with the adjusted velocity and the used soil.

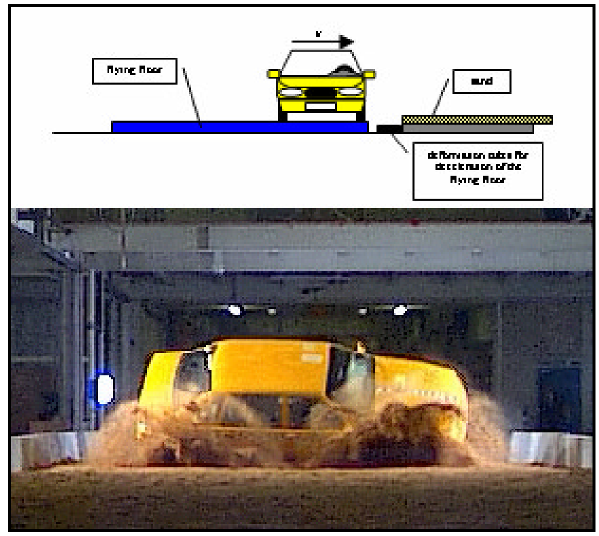

Figure 4. Soil-trip rollover test set up

In the US, the soil-trip represents 91 % of the trip-overs in the field for passenger cars and 93 % for LTVs (light truck vehicle). With this the soil-trip test covers nearly 52 % of the rollover crashes for passenger cars in the field and nearly 48 % for LTVs.

A study from Siemens Restraint Systems and the medical university of Hannover concerning rollover accidents in Germany between 1994 and 2000 shows the same result [3]. In this study 6713 passenger vehicle crashes were analyzed from the German In-Depth Data Accident Study (GIDAS).

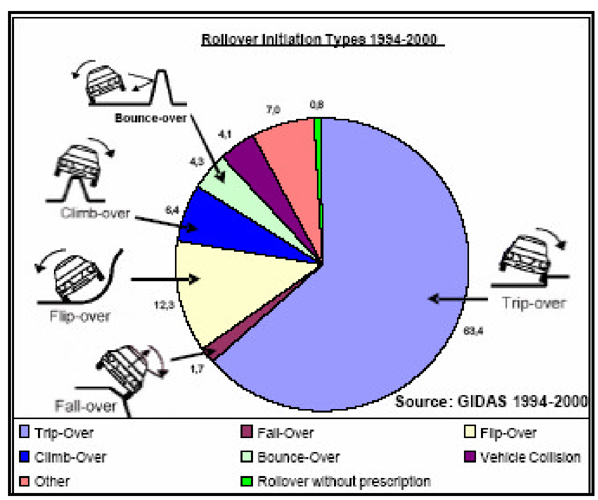

Figure 5. GIDAS Rollover initiation Types 1994-2000

4.2 % of the involved passenger vehicles rolled over. The distribution of the rollover initiation types in this study states the trip-over as the most frequent reason for rollover in Germany (see Figure 5).

In the **embankment** rollover test the vehicle is leaving the crash track and drives on a slightly declined slope of a ditch (see Figure 6). The surface of the slope is sand to enable a lateral sliding of the car. Different approach angles and slope angles can be adjusted in this test set up. Also steering can be considered, which is necessary in some cases to ensure rolling over.

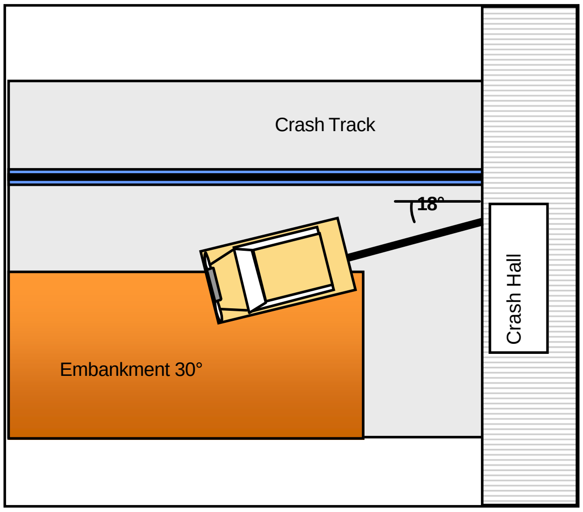

Figure 6. Embankment rollover test set up

This test induces a slow occupant movement, which requested a relatively late deployment time. The lateral acceleration is in a lower range. The roll conditions of the test car vary with the adjusted velocity, approach angle, slope angle and steering actuation.

The field relevance for this laboratory test was assessed for the US with 100 % of the fall-overs in the field for passenger cars and LTVs. With this the embankment test covers nearly 13 % of the rollover crashes for passenger cars in the field and nearly 15 % for LTVs.

For Germany the embankment test plays not such a significant role, because fall-overs are less frequent in the field, with 1.7 % of all rollover events in the years 1994 - 2000.

The **ramp** rollover test is performed on the crash track. During the test, the vehicle drives with one side of the car over a ramp (see Figure 7). Different ramp types are used to realize roll and no roll events (see Figure 8).

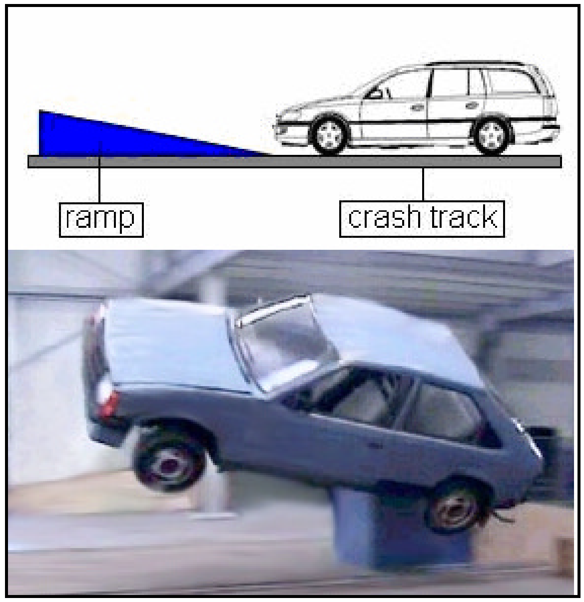

Figure 7. Ramp rollover test set up

This test induces a fast occupant movement, which requests an early deployment time. The lateral acceleration is in a middle range. The roll conditions of the test car vary with the adjusted velocity and used ramp type.

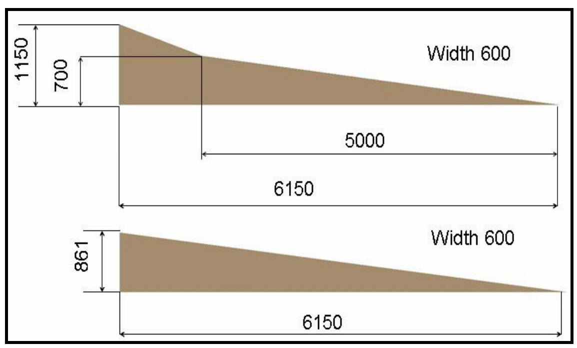

Figure 8. Different ramp types

The field relevance for this laboratory test was assessed for the US with 83 % of the flip-overs in the field for passenger cars and 74 % for LTVs. With this, the embankment test covers nearly 10 % of the rollover crashes for passenger cars in the field and nearly 5 % for LTVs.

For Germany the ramp test plays a more significant role, because flip-overs are more frequent in the rollover accident field, with 12.3 % of all rollover events in the years 1994 - 2000.

The **curb-trip** rollover test has only a lateral movement. The test car is placed on a flying floor and hits laterally against a curb with the wheel rims. The height of the curb depends on the wheel size. After the impact between the wheel rims and the curb, the sled is decelerated by deformation tubes without influence on the car movement (see Figure 9).

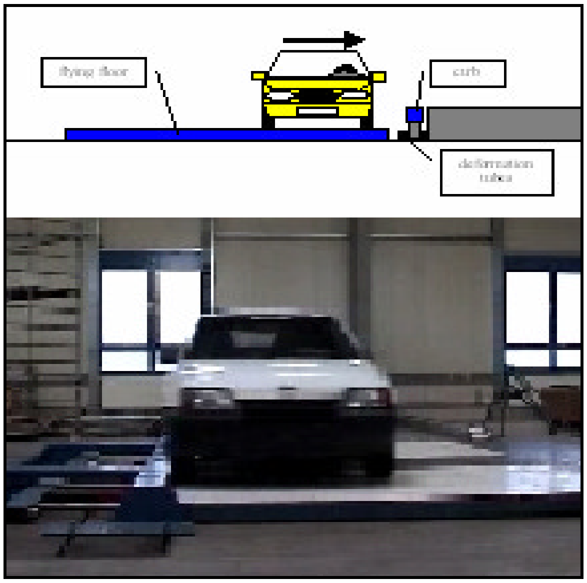

Figure 9. Curb-trip rollover test set up

This test induces a rapid occupant movement, which requests an early deployment time. The lateral acceleration is in a higher range. The roll conditions of the test car vary with the adjusted velocity and used curb high.

The field relevance for this laboratory test was assessed for the US with 51 % of the bounce-overs in the field for passenger cars and 47 % for LTVs. Additional the curb-trip test was assessed for the U.S. with 8 % of the trip-overs in the field for passenger cars and 6 % for LTVs. With this the curb-trip test covers nearly 9 % of the rollover crashes for passenger cars in the field and nearly 7 % for LTVs.

For Germany the curb-trip test plays also a significant role. Although bounce-overs are less prevalent in Germany, with 4.3 % of all rollover events in the years 1994 - 2000, trip-overs are more frequent in the rollover accident field in Germany, with 63.4 % of all rollover events in the years 1994 - 2000.

For the **FMVSS 208 rollover** test the car is placed on a sled inclined under 23°, which is moved laterally (see Figure 10). The test velocity is 30 mph. After a sharp deceleration of the dolly with deformation tubes, the car is thrown off the sled under high roll conditions around the longitudinal axis of the car.

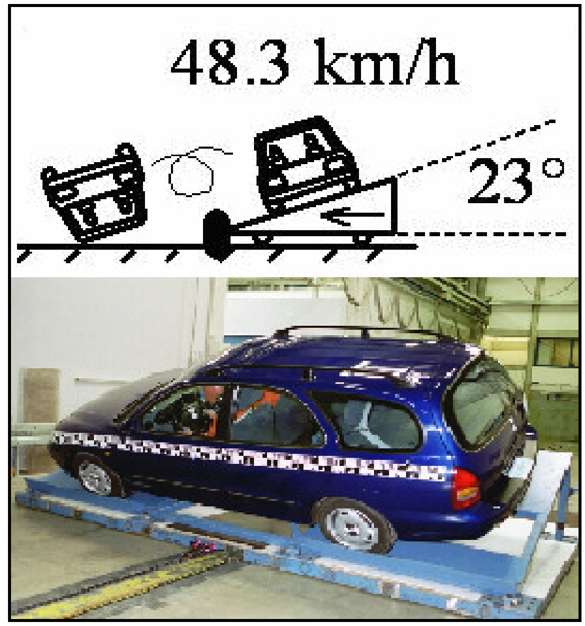

Figure 10. FMVSS 208 rollover test set up

This test is used to analyze the behavior of the vehicle structure under rollover loads and here especially the remaining survival space for the occupants.

The field relevance for this laboratory test is very low. This statement is valid for passenger cars and LTVs in USA and Germany.

As well, different **misuses** rollover tests are performed on a proving ground or in the laboratory.

Figure 11. Proving ground for rollover misuse tests

The tests are implemented to avoid inadvertent activation of the pyrotechnical protection devices and to increase the robustness of the rollover algorithm (see Figure 11).

Tests for rollover misuse typically include up and down hill driving, hill jumping, slalom, elk test, U-turn, figure eight and sliding. Results of misuse programs from lateral and frontal applications like curb impact or washboard track will be considered for the rollover algorithm, too.

SIMULATION TOOLS

For the protection of the occupants in rollover events roll bars, belt pretensioners and the curtain airbags have to be activated in order to retain the belted passengers in their seats, to cushion the impacts of the head and to prevent partial or full ejection. The key component for activating these pyrotechnical protection devices is the algorithm. The algorithm has to determine the system activation time in cases of rollover event detection. The system activation time is defined as the Requested Time To Fire (RTTF). The RTTF is determined through the time, when the head of the occupants penetrates the space, which is necessary for the curtain airbag deployment. This information is provided by rollover crash tests and will be supported by numerical simulation with ADAMS and MADYMO.

The rollover protection development process contains the crash and misuse tests and the simulation. (see Figure 12).

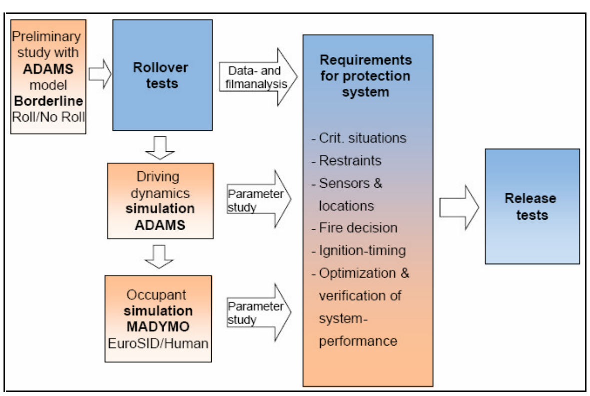

Figure 12. Rollover protection development process

Here ADAMS is used for the simulation of the vehicle dynamics, while MADYMO is used for the prediction of the RTTF.

ADAMS is an adequate software tool to simulate vehicle dynamics. The different test set ups for rollover like ramp, soil-trip, embankment and curb-trip were generated in ADAMS as road models for simulation (see Figure 13).

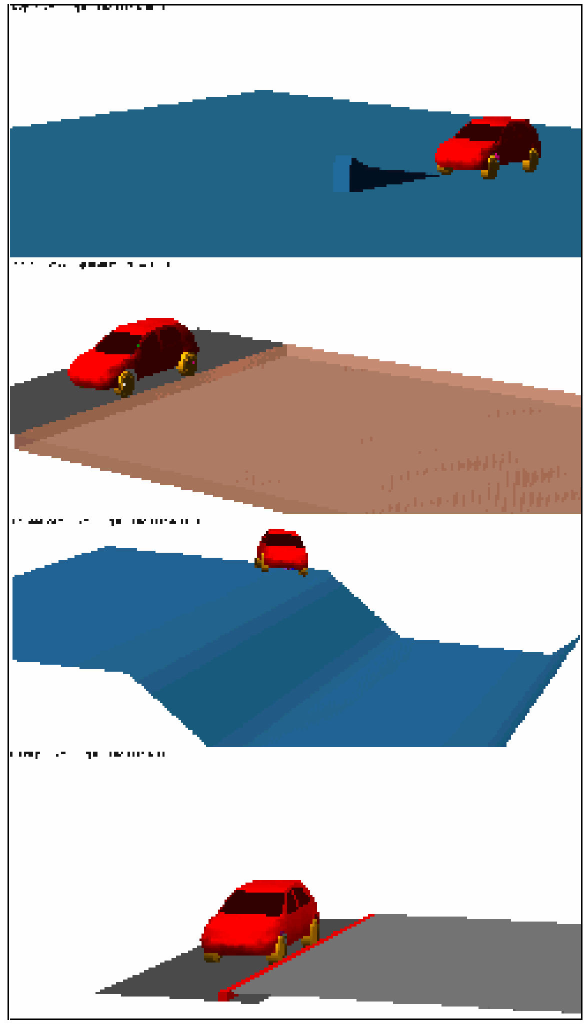

Figure 13. ADAMS road models; above: embankment, middle: ramp, down: curb-trip

Also some misuse rollover tests are simulated with ADAMS like lane change and slalom.

In the beginning, ADAMS simulation is used to restrict the borderline between roll and no roll for the baseline crash tests in a preliminary study. For this first step, a car model is used, which is validated against all available test data in this development stage e.g. driving tests.

The data of the performed rollover crash tests will then be used to validate the ADAMS models for rollover (see Figure 14).

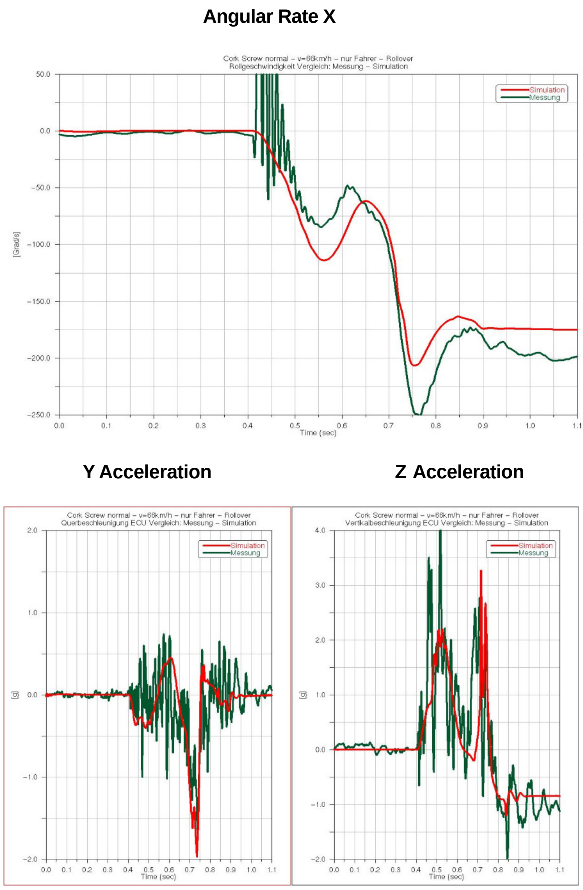

Figure 14. Validation of ADAMS against rollover crash test

After validating these models a parameter study will be performed in ADAMS. Here e.g. different car loads, different ramp geometries, different velocities, different approach and slope angles are considered.

The outputs of every ADAMS simulation run are e.g. accelerations, displacements and angles in X, Y and Z direction for a specific point in the car. The result of the parameter study with ADAMS represents the basis for the MADYMO simulation.

For the **MADYMO simulation** a model of the specific passenger compartment has to be generated. Usually this is done with CAD data, which is provided by the car manufacturer. In the compartment model different contact characteristics for door trim, B-pillar trim and seats are considered, to represent the different stiffness of the interior.

The movements of the occupants are represented in the MADYMO simulation by using EuroSID dummy models. Typically the MADYMO model contains a driver and a passenger occupant (see Figure 15). The rear passengers on the second or third row can also be considered if necessary.

The movements of the simulation EuroSID dummy models are validated against the dummy movements in the performed rollover crash tests.

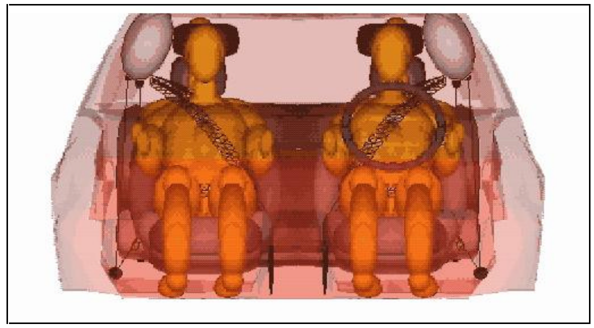

Figure 15. MADYMO model for driver and passenger

For the validation, the movement of head, neck and shoulder is considered to get the information for the RTTF. The MADYMO simulation enables to consider the occupant movements in far more possible rollover constellations, than in crash tests.

Critical rollover cases in regard to the dummy movements and the upcoming loads can be simulated with an **adapted dummy model** [4]. This dummy takes the possible muscle tension of human beings against the occurring rollover loads into account.

A critical situation is defined, when the dummy during a test permanently penetrates the necessary space for the curtain airbag deployment before the measured loads indicates a rollover. If, in the ongoing test, then a roll event is introduced by counter steer or tripping, the head of the occupant is Out of Position (OoP). Activating a state of the art curtain airbag, which deploys from the roof downwards, will keep the occupants head out of the car in this situation. This is the opposite of the intended effect of the curtain airbag and will lead to severe or fatal injuries for the involved occupants. This critical situation can occur in rollover cases with low acceleration and rotation loads, e.g. in embankment rollover tests.

The standard simulation dummy model maps only translational load directions. The rotational movement as it happens during a rollover is not considered. A dummy simulation model, which takes such a behavior into account, is not available at the moment. Therefore it is necessary to analyze the difference between dummy and human movement behavior and to modify the standard simulation EuroSID dummy model in MADYMO for a better forecast of the human behavior during rollover situations.

In order to provide a basis for the simulation model a series of sled tests were performed with a bungee driven sled for translational and/or rotational movements with low accelerations. For the validation 5 different test constellations for dummy and volunteer were performed.

The performed tests contain pure translation or pure rotation or a combination of both (see Table 1). The pulses are a cutout from the acceleration curves of performed rollover crash and misuse tests.

Table 1.
Test constellations

Test No.	Specification
1	Pure translation
2	Pure rotation
3	Translation with following superposed rotation
4	Pure low translation (0,3 x test no. 1)
5	Rotation with following superposed translation

Because of the in section "test dummies" mentioned reasons an EuroSID dummy was used. For the comparability, a volunteer was chosen with a mass of 74.5 kg and a height of 1.78 m, which is very close to the dimensions of the EuroSID, which has a mass of 76 kg and a height of 1.75 m (see Figure 16).

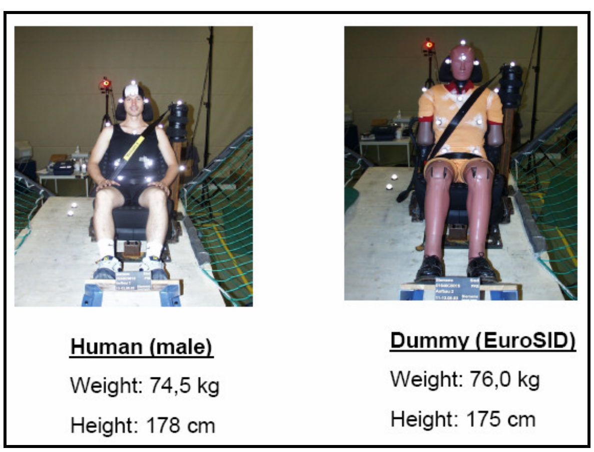

Figure 16. Test set up of the sled with dummy and volunteer

On the sled a seat, footrest and B-pillar with retractor and belt deflection point was mounted (see Figure 16). The belt pretensioner was not in use to avoid injuries on the volunteer.

The dummy and the volunteer have been marked on several points with targets for film analysis to compare the different movement behaviors (see Figure 17).

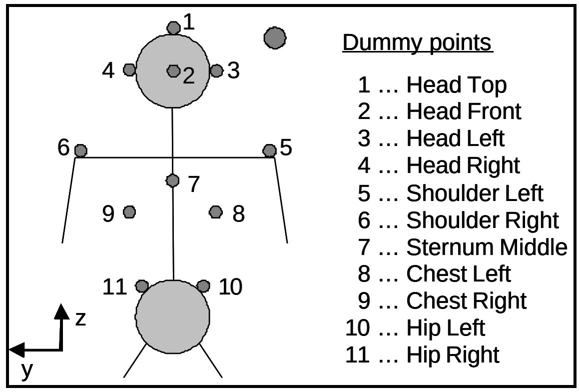

Figure 17. Position dummy target points for film analysis

In the comparison between dummy and volunteer, the differences in head movement behavior can be seen (see Figure 18).

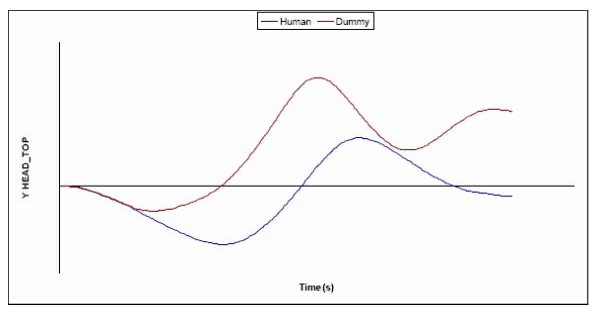

Figure 18. Head top displacement for dummy and volunteer during test number 5

The results of the volunteer tests show different behavior within a certain range of lateral loads. While the human being acts actively against his body displacement with muscle tension, this is impossible for the dummy.

Therefore the dummy is only beneficial for lateral loads, because the response regarding rotation of a vehicle is exclusively a result of the dummy inertia.

The volunteer reacts differently on translational and rotational movement. For pure translation the volunteer is not able to resist against this motion. In case of rotation the volunteer reacts against this movement to keep the upper body and the head upright.

Major differences between human and dummy in lateral head displacement can be stated for low accelerations, low rotation rates and temporal long lasting loads, which occurs e.g. in embankment tests. Minor differences are realized for higher accelerations and rotation rates and temporal short lasting loads, which occurs e.g. in soil trip tests.

For the validation of the MADYMO model, the correlation of the points head top (1) and chest left (8) and right (9) had been used. The head targets are the main points to get information of the RTTF for human occupants, which are needed for activating the curtain airbag (see Figure 19).

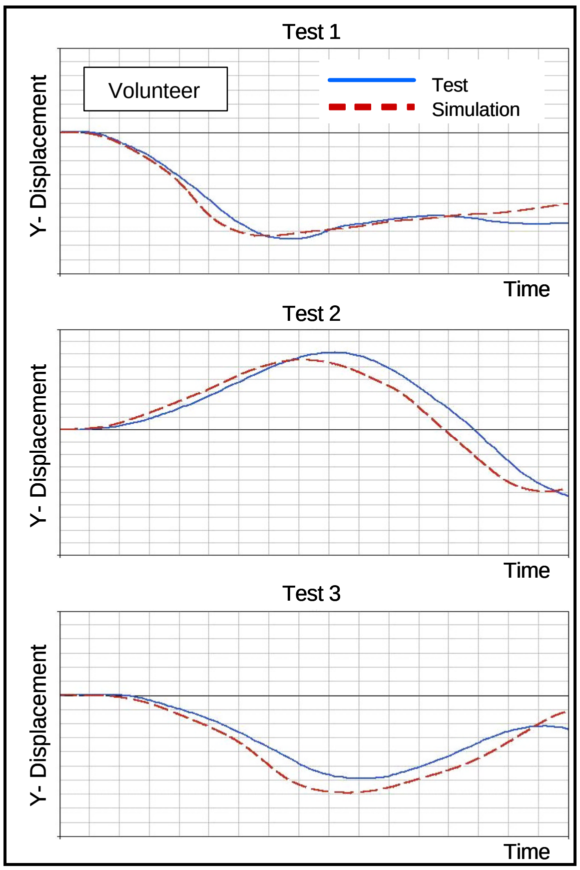

Figure 19. Head Top displacement curves for simulation model in comparison to the sled tests with volunteer

Due to the already mentioned active work against the body displacement, the head of the volunteer penetrates the deployment space for the curtain airbag distinctively later then the dummy. Therefore there is more time available for rollover sensing and curtain airbag deployment for human occupants (see Figure 20).

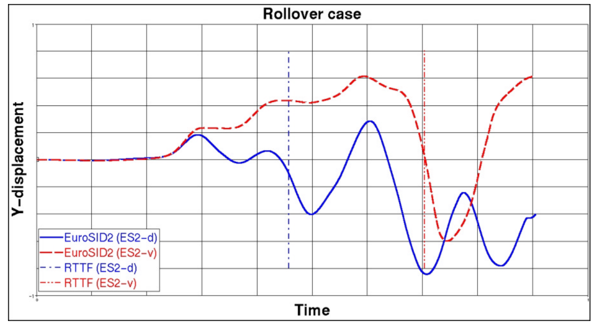

Figure 20. Head displacement and RTTF during rollover case

The positive effect of the active work on the RTTF depends on the input signals for rollover cases and is actually limited to the lateral loads which were reached during the tests. For rollover cases with high accelerations a shifting of the RTTF can not be observed.

For more information about this adapted dummy model see [4]

CONCLUSION

Rollover events often result in severe injuries or fatalities. Most often the heads of the occupants are affected. Therefore rollover detection and protection systems are focusing more and more. For the US some legal regulations are expected in the future. The first step is done by NHTSA with the rollover resistance rating for new cars. For a dynamic rollover crash test the soil-trip seems to be suitable because of the high field relevance of this test set up.

By using the presented test and simulation tools a comprehensive development process for rollover protection is possible. The adaptation and optimization of the protection systems for rollover events are considered in this process. Additionally the differences in movement behavior between human and dummy are considered to analyze critical situations and to provide the best possible rollover protection for the occupants together with high misuse performance simultaneously.

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ROLLOVER CRASH ANALYSIS OF THE RTV USING MADYMO

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ABSTRACT

A full vehicle model of the RTV is developed in MADYMO including steering, tire and suspension. The suspension characteristics were validated using experimental accelerations measured over bumps. A torque controller is simulated to maintain set speed of the RTV in simulations. The model is used to predict rollover limits using Slowly Increasing Steer, J-Turn, and Road Edge Recovery maneuvers. The rollover limits with three different loading states, RTV without passengers, RTV with unrestrained passengers, and the RTV with restrained passengers have been studied. Comparison with other commercial vehicles indicates that the rollover limiting speed of the RTV in dynamic maneuvers is low.

Keywords: RTV, Rollover, Slowly Increasing Steer, J-Turn and Road Edge Recovery.

INTRODUCTION

Hindustan Motors launched a ‘Rural Transport Vehicle’, popularly known in India as RTV, in 1998 [Figure 1]. The vehicle is popular because of its small size and shape, has a capacity for conveyance of 15 people simultaneously and that it runs on the inexpensive CNG. Incidents of rollover of RTV have been reported in several cities and there were 11 reported in Delhi recently. This is out of proportion to the vehicle proportion. This paper reports investigations of rollover stability of the RTV based on dynamic maneuvers. Our findings are that the RTV may have low resistance to rollover and hence may not be suitable for deployment in zones having peak speeds in excess of 45 kmph.

Figure 1 RTV

The conventional measure of rollover stability has been the static stability ratio. The NHTSA of USA has proposed dynamic rollover maneuvers using which Forkenbrock et.al. (2001)&(2002) had conducted experiments procedures to determine the rollover characteristics of 2001 Chevrolet Blazer, 2001 Toyota 4 Runner, 1999 Mercedes ML320, and 2001 Ford Escape. Subsequently, Gawade et.al (2003) had developed models in MATLAB to predict rollover characteristics of three wheel-scooter taxis for these standard maneuvers.

In this paper the rollover characteristics of RTV in dynamic maneuvers has been predicted using a model of RTV developed in MADYMO. The maneuvers simulated were Slowly Increasing Steer, J-Turn, and Road Edge Recovery maneuvers as reported in Forkenbrock et.al. (2001)&(2002).

The model was built using parameters available in the manufacturers catalog and field measurements. For validating the suspension characteristics of the model, a of the RTV was run over a bump and the resultant vertical accelerations were measured. The bump-pass was simulated in MADYMO, for the equivalent operating conditions.

Unlike earlier reported tests and simulations, three different loading conditions were studied to evaluate the effect of the number of passengers. The three situations considered were the RTV without passengers, RTV with unrestrained passengers, and RTV with restrained passengers. There is variation in rollover stability under these loading considerations.

PARAMETERS OF RTV

Some technical specifications for RTV were obtained from the manufacturer's catalog and remaining data, necessary for modeling, is obtained through measurement. Though the overall mass of the vehicle was known, the masses of the various components have been estimated to obtain the same CG location. Stiffness and damping properties of the suspension was determined experimentally by loading them and studying the decay curve in free vibration. The technical specifications of RTV as available from manufacturer catalog are given in Table 1.

Table 1
Technical specification of the RTV

Engine weight	205 Kg
Engine size	710* 640* 863 mm^3
Wheel base	240 mm
Wheel track	150 mm
Weight of RTV	1460 Kg

RTV MADYMO MODEL

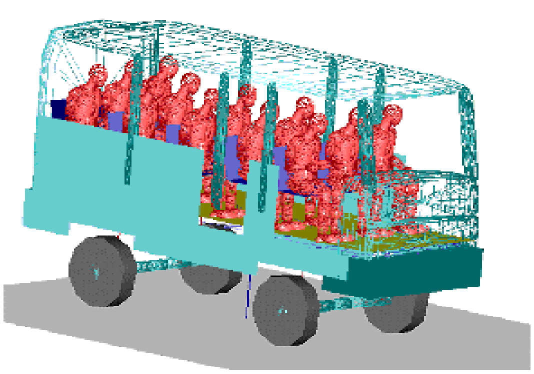

Figure 2 RTV MADYMO Model with passengers

Full vehicle model of RTV was developed. To simulate rollover maneuvers following features were incorporated in the model:

1. Steering mechanics
2. Suspension
3. Tyre model
4. Tyre-road interaction
5. RTV seat modeling
6. Differential torque controller

The tyre damping ratio and tyre stiffness was not determined experimentally but has been taken 0.011 and 300 KN/m respectively, based on the work of Hinch et.al. (1991) and Lupker et.al. (1991)

Validation of RTV MADYMO Model

In dynamic maneuvers, in addition to the geometry, the suspension parameters play a significant role. Experiments were conducted to measure the vertical acceleration of RTV chassis over a bump for varying velocities of RTV to validate the suspension model.

The vertical acceleration of RTV chassis was acquired using an accelerometer attached to the chassis, as shown schematically in

Figure **3** at the rear of the RTV. The location was selected as the maximum acceleration while passing over a bump is expected at the rear. Acceleration was sampled at the sampling frequency of 1000 HZ through the 'e-DAQ' (data acquisition system) and filtered digitally.

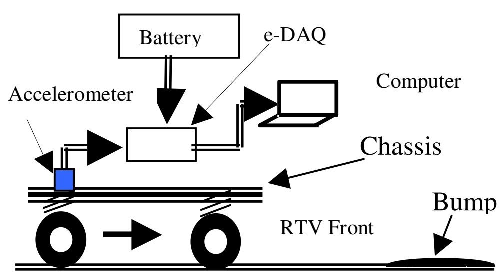

Figure 3 Experimental setup

A comparison of the experimental and simulation results in time domain is shown in Figure 4 and Figure 5 . Vertical accelerations predicted by the MADYMO model of the RTV agrees well with for velocities of the RTV, 20km/hr and 25 km/hr, except at the end of the bump where all the wheels of the RTV has traveled over the bump. In this region, the decay of the vertical acceleration of the chassis, as predicted by the theoretical model, is slower as compared to the experimental results. Data necessary for modeling components other than those listed above, like chassis compliance were not available to us and could be contributing to the discrepancy.

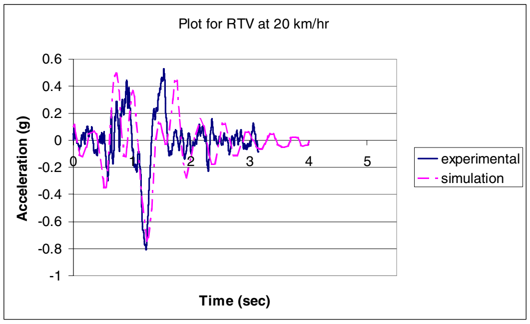

Figure 4 Experimental and simulation results at 20 km/hr

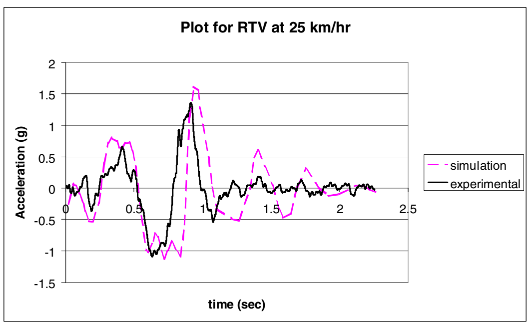

Figure 5 Experimental and simulation results at 25 km/hr

ROLLOVER MANEUVERS

The standard NHTSA rollover maneuvers as described in Forkenbrock et.al (2003) were used for the evaluation.

Slowly increasing steer maneuver

The Slowly Increasing Steer (SIS) maneuver is used to characterize the lateral dynamics of each vehicle, based on the “Constant Speed, Variable Steer” test defined in Forkenbrock et.al (2003) was simulated. In this maneuver, vehicle running at the maximum velocity in the normal driving condition (taken as 60 km/hr for RTV) is steered at increasing angles till wheel lift off is indicated. The SIS is used to determine the parameters for the J-Turn and RER maneuvers and in itself is not considered a good measure of rollover stability.

To execute the SIS maneuver, the vehicle is initially driven in a straight line at a constant speed. Hand wheel (steering) position was linearly increased from zero to 270 degrees at a rate 13.5 degree per second, as shown in [Figure 6]. Hand wheel position was held constant at 270 degrees for two seconds, and then returned back to zero degrees in four seconds. During the maneuver, the lateral acceleration of the RTV is tracked. The lateral acceleration was plotted with respect to time and the linear segment was identified to be between a 0 to 0.4 g as shown in [Figure 7]. Using the slope of the best-fit line, the steering-wheel position at middle point of the linear range of lateral acceleration, was estimated as 53.86 degrees (this corresponds to 2.15 degree rotation of front wheel). This hand wheel position was used in simulations for maneuvers of J-Turn and RER steering inputs, as described in later sections of this paper.

In field tests, the driver or computerized drive actuates the accelerator pedal in a vehicle to maintain a constant speed. The speed drops quite rapidly when steered if the vehicle is in free roll. So a differential torque controller was modeled to maintain constant speed for the RTV in the slowly increasing steer maneuver. The design of the controller is detailed in [Gawade]. The entrance speed of the RTV, in the simulations for SIS maneuver, was 16.67 m/s and the minimum entrance speed of the RTV in the simulation was 16 m/s as shown in [Figure 8]. In simulating of SIS maneuver, speed drops by 0.67 m/s, which is a tolerable 4.091 % variation.

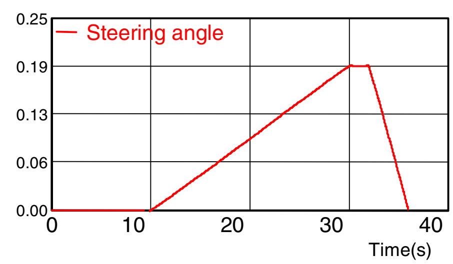

Figure 6 Steering input in the simulation for SIS maneuvers

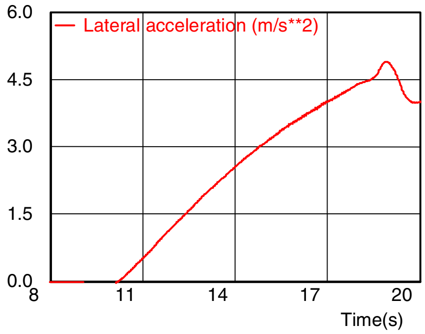

Figure 7 Lateral acceleration of RTV in the simulation for SIS maneuvers

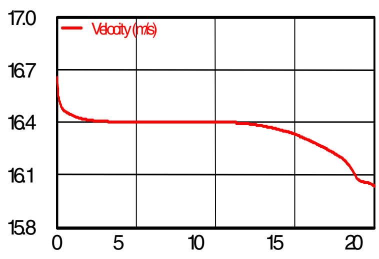

Figure 8 RTV speed variation in the simulation for SIS maneuvers

J-Turn Maneuver

The NHTSA J-turn maneuver entails a sudden and large steering input. Large handlebar angles are chosen to saturate the lateral force response of the tires of the vehicle. The maximum handlebar angle is held constant for next four seconds and followed by the handlebar returning to zero. This maneuver models an extreme driver reaction and mimics what might happen when a driver initiates a severe turn to avoid a road discontinuity or suddenly stalled vehicle. For J-turn, it is necessary that the steering goes well beyond the limiting lateral acceleration, thus saturating the tire response. The path traced resembles the alphabet 'J', giving the test its name.

The initial steering-wheel magnitudes for simulating the J-Turn maneuver, were calculated by multiplying the steering-wheel angle that produced an average of 0.2g in the Slowly Increasing Steer maneuver by a scalar of 8.0 which corresponds to 16.5 degrees rotation of the front wheels. The rate of steering-wheel ramp was 1000 degrees/sec, or 40 degrees/sec at the front wheel (steering ratio for RTV is 25:1). Initial steer was performed in 0.413 seconds. This is shown graphically in figure 8. The entrance speeds in the simulations for the J-Turn maneuver was varied until the 'two-wheel lift' condition is reached. In the 'two-wheel lift' condition, the inside wheels lift at least by at least two inches from the ground. Also note that this is a free running maneuver, so the torque controller is not activated.

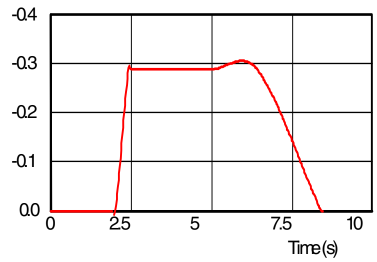

Figure 9 Steering input for J-Turn maneuvers

NHTSA J-Turn maneuver simulations were conducted for three different loading conditions viz. RTV without passengers, RTV with restrained passengers and RTV with unrestrained passengers.

RTV without passengers

The NHTSA J-Turn simulations are performed for increasing entrance speeds starting from 5 m/s in steps of 1 m/s. The termination condition (two-wheel lift) was observed at the entrance speed of 8 m/s. During a downward iteration of the vehicle speed in steps of 0.1 m/s, at the entrance speed of 7.5 m/s two-wheel lift was not detected. This speed is taken as the rollover limit for the RTV without passengers on a J-Turn. The lateral acceleration, roll angle and speed variation of the RTV during the maneuver is shown in figures 9-11

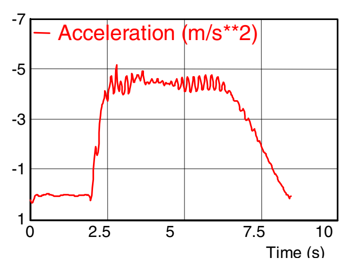

Figure 10 Lateral acceleration of RTV without passengers

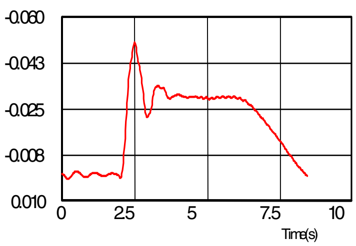

Figure 11 Roll angle of RTV without passengers

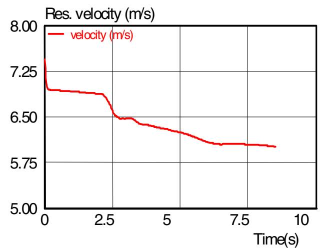

Figure 12 Resultant speed of RTV without passengers during J-turn maneuvers

<u>RTV With restrained passengers</u>

To simulate the effect of being seat belted, passengers are restrained on to the RTV seat. Since we were interested in studying vehicle rollover and not evaluating the safety of individual passengers, kinematic joint were defined between passenger dummy and the seat that allowed rotation but disallowed translation between the dummy-pelvis and the seat. The rollover limit of the RTV with restrained passengers is 6.8 m/s, a drop of 0.7 m/s from that estimated for the empty vehicle. This reduction is due to increase in CG height of the vehicle.

<u>RTV with unrestrained passengers</u>

For this simulation, a contact interface was defined between the passenger dummies and the seat. The contact interface allows separation between the dummy and seat, but does not allow penetration. The NHTSA J-Turn rollover limit was predicted to be 6 m/s for RTV with unrestrained passengers. In this case, the simulated dummies were thrown towards the outside during the maneuver, thus reducing the stability.

Road edge recovery maneuver

The RER maneuver attempts to induce two-wheel liftoff or rollover at a lower lateral acceleration than the NHTSA J-turn by making a large turn, holding for a short duration at the maximum steering angle and then suddenly reversing the steer. The reversing is initiated when the roll rate approaches zero for the first time, which corresponds, to the maximal roll angle of the vehicle. This procedure hence requires one to 'sense' the attitude of the vehicle. During the counter steer, the handle bar turned to an equal angle in the opposite direction. Following the second turn, the handlebar is held fixed for a short duration and brought back to zero. This maneuver models, in an extreme way, what might happen when a driver performs a double lane change or two-wheel off-road recovery maneuver.

The steering-wheel magnitude for initial and counter steer were symmetric, and were calculated by multiplying the steering-wheel angle in the center of the linear range in the SIS maneuver by a scalar of 6.5 and is equal to 30.73 degrees of the steering wheel rotation. The rate of steering-wheel ramp was 720 degrees/sec, which is equal to 28.8 degrees /sec for front wheel. Initial steer was performed in 0.9 seconds. The steering input is shown graphically in Figure 12.

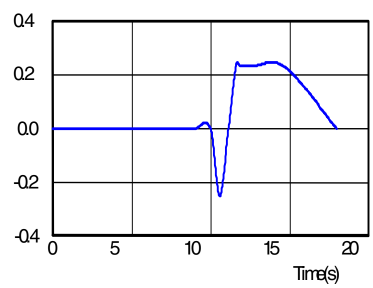

Figure 13 Steering input in simulation for RER maneuver

RER maneuver simulations were conducted for the same loading conditions used for the J-turn; RTV without passengers, RTV with restrained passengers and RTV with unrestrained passengers.

<u>RTV Without passengers</u>

The rollover stability for the RER maneuver is predicted to be 8.75 m/s for the RTV without passengers. The lateral acceleration, roll angle, roll rate and speed in the maneuver is shown in Figures 13-16

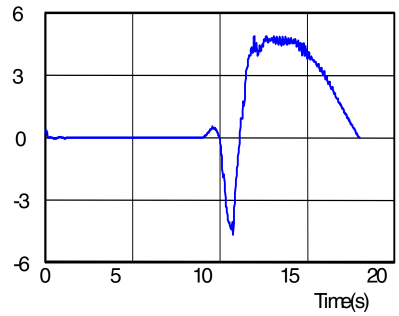

Figure 14 Lateral acceleration of RTV without passengers for RER maneuvers

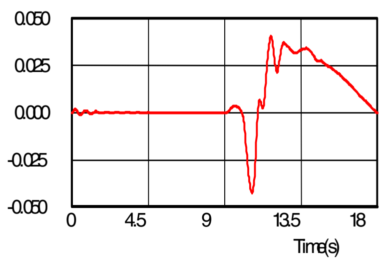

Figure 15 Roll angle of RTV without passengers for RER maneuvers

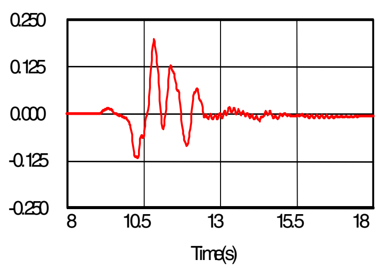

Figure 16 Roll rate of RTV without passengers for RER maneuvers

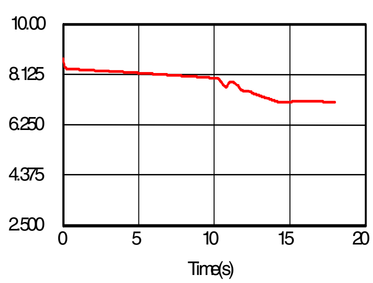

Figure 17 Speed of RTV without passengers in the simulation for RER maneuvers

RER with passengers

The rollover stability for the RER maneuver is predicted to be 7.5 m/s for RTV with restrained passengers.

The rollover stability for the RER maneuver is predicted to be 7 m/s for the RTV with unrestrained passengers

COMPARISON OF MANEUVERS

J-Turn and RER maneuvers were simulated for the modeled RTV with three different loading conditions. A comparison of the predicted stability during both maneuvers is presented in [Table 2]. From the table, it is indicated that for either maneuver, the stable entrance speed is maximum in RTV without passenger and minimum in RTV with unrestrained passengers. This is to be expected as the center of gravity shifts upwards on inclusion of the passengers. The stable entrance speed is higher for RTV with restrained passengers than the unrestrained. The sideways outward movement of passengers during steering of RTV moves the CG outwards, closer to the line of support, thus reducing the stability.

Table 2
Results summary of rollover simulations

Loading condition	Limiting speed (m/sec) for J-Turn	Limiting speed (m/sec) for RER
RTV without passengers	7.5	8.75
RTV with restrained passengers	6.5	7.5
RTV with unrestrained passengers	6	7

NHTSA has conducted experiments for standard rollover maneuvers on existing vehicles [Forkenbrock, 2002,2003]. Published results are compared with the present RTV simulation results. The comparison is presented in Table 3. Results show that entrance speed for RTV is low compared to general commercial vehicles.

Table 3
Limiting entrance speed (m/sec) for rollover maneuvers

Vehicle	J-Turn	RER
2001 Chevrolet Blazer	17.29 m/s	16.09 m/s
2001 Toyota 4 Runner	20.5 m/s	17.06 m/s
1999 Mercedes ML320	20.04 m/s	….
2001 Ford Escape	…	21.51 m/s
RTV	7.5 m/s	8.75 m/s

CONCLUSION

Model of RTV has been developed in MADYMO and the heave mode validated by measuring the acceleration of the RTV passing over a bump. The model is used for predicting rollover characteristics of RTV in dynamic maneuvers. The comparisons of results show that rollover stability of the RTV is predicted to be inferior to conventional vehicles for which there is measured data. Considering that the RTV is capable of running speeds of the order of 60 km/h, it would seem that the RTV is prone to rolling over in urban roads that sustain these speeds.

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DEVELOPMENT OF MADYMO-BASED MODEL FOR SIMULATION OF LABORATORY ROLLOVER TEST MODES

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ABSTRACT

Types of vehicle rollovers can be classified into two categories: untripped and tripped. Untripped rollovers are relatively rare events resulting from high lateral friction forces between the tires and road. Tripped rollovers are the result of lateral forces caused by the tire or wheel digging into the road or ground or from striking a curb or other obstacles. As reported in the open literature, various test methods for conducting rollover events such as SAE J2114, Side Curb Trip, Critical Sliding Velocity, and Corkscrew have been used. This paper presents the development of MADYMO-based models for simulating vehicle kinematics in these four modes.
The CAE methodologies using MADYMO is interactively developed with the test methodologies. Experimental data obtained from these test modes are used for developing rollover CAE models for replicating vehicle motions under similar test conditions. Analyses of simulated results provide feedback to improve the test procedures. Testing with improved procedures provide additional new data for continued model refinements. MADYMO-based CAE tools thus provide quality models with better simulated and/or predicted results. MADYMO rollover models consist of sprung and un-sprung masses, suspension systems and tires, whose characteristics are extracted from ADAMS-based vehicle handling model. Use of the MADYMO-based models to support rollover testing, rollover sensing algorithm development, and rollover protection system development will be described. Since MADYMO modeling described in this paper is a rigid-body based approach, model limitations and issues associated with rollover simulation will also be discussed. In addition, model correlations with test data in these four modes and future areas of improvement will be presented.

INTRODUCTION

For many years, NHTSA has conducted research investigating the underlying causes of vehicle rollover accidents, developing rollover test procedure, and developing vehicle and roadway design criteria to help reduce both the number and the severity of rollover accidents. The rollover process, which involves a complex interaction of forces from suspension systems, tires, power-trains, and road surface, is one of the most complicated types of safety analysis. To study the vehicle and/or occupant kinematics during rollover crashes, mathematical models are useful tools for understanding essential rollover mechanics and evaluation of restraint system performance in mitigating occupant ejection. Tools available for such analysis include vehicle dynamic handling models, occupant gross-motion simulators [1-3] and finite element (FE) analysis programs.

A BRIEF REVIEW OF ROLLOVER MODELS

Rollover models are basically mathematical analyses which describe equations of motion derived for a simplified vehicle system consisting of one rigid body or two/three rigid bodies connected by joints and springs. Models are specifically developed for studying rollover mechanics under specific conditions. Jones [4] used a simple one-degree-of-freedom model to study the mechanics of vehicle rollover as a result of curb impact by treating the contact force at the curb as impulse forces in determining the vehicle kinematics. Ford and Thompson [5] developed a two-dimensional model as an initial attempt to predict the rollover characteristics of a vehicle. Their model is basically a 2D rigid-body of an automobile to allow simulation of vehicle ground contact and airborne motion. Lund and Bernard [6] developed a one-rigid-body model for analysis of simple rollovers to study the mechanics of the tilt table test and critical sliding velocity. Rollover simulation using a nonlinear model was reported by Eger et al. [7], using two rigid bodies with non-linear springs to represent suspension systems.

Other commercially available programs that have been used in vehicle dynamic handling are ADAMS by MDI [8] and PC-Crash by Maclnnis [9]. These models can simulate vehicle kinematics for inputs to Crash Victim Simulators (CVS), such as CAL3D/ATB and MADYMO for occupant kinematics simulations.

Both CAL3D/ATB and MADYMO programs are gross-motion simulators for vehicle occupant dynamics in three-dimensional motion in a crash environment. Prasad and Chou [10] published a detailed review of these models. Applications of these simulators in rollovers are presented below.

CAL3D/ATB.

Since the early 80's, CAL3D (later known as ATB which stands for Articulated Total Body), has been used for rollover studies. Rollover simulations were made possible in CAL3D with an improved option, which allows specification of vehicle angular motion. Kaleps et al. [11] and Obergefell et al. [12] conducted simulations of rollovers lasting up to 4 seconds. Use of ATB in the study of the occupant kinematics and the vehicle motion during rollover tests were presented in a series of papers. In the first paper of this series, Smith et al. [13] used ATB to study the occupant dynamics during a rollover by identifying some input parameters that were needed in the simulation. These included occupant' body segment shape and weight, moments of inertia, and body joint torque properties. In addition, vehicle interior geometry and its motion, the contact characteristics for the occupant and vehicle interactions, and the seat belt characteristics were also needed. The primary purpose of models developed by Ma et al. [14] and Cheng et al. [15] were developed to simulate occupant kinematics with or without restraint systems. The vehicle rollover motion was input to the models by describing its translational and rotational acceleration time histories. These time histories were obtained from rollover tests. Cheng et al. [16] further reported application of CAL3D/ATB to study vehicle and occupant kinematics in a rollover. Using the ATB models, evaluations of vehicle glazing materials were also made to study potential occupant ejection mitigation and head injuries reduction during rollover accidents

MADYMO.

The multi-body code MADYMO offers many options for defining the dynamic environment with interaction characteristics. This flexibility allows reasonable replication of some rollover tests. To simulate a rollover phenomenon, the vehicle model needs to be developed. In the development of rollover models, the contact between the vehicle and the ground plays a key role in determining the rollover consequence. Selection of appropriate contact parameters between the vehicle and the ground, such as stiffness, coefficient of friction, hysteresis and damping, is extremely important. However, lacking such data generally leads to "trial and error" methods to establish appropriate values for these parameters. In order for further application of the models, it is essential that their correlations with the test results be established.

MADYMO applications to rollover simulations have appeared in the literature. Blum [17] explored feasibility of using MADYMO to simulate rollovers in various conditions. Aljundi et al. [18] gave a brief description of rollover impact simulation using a MADYMO package. Yaniv et al. [19] developed a MADYMO model and validated against test results for restrained occupants with an inflatable tubular structure (ITS). Their model was then run to evaluate the effectiveness of ITS in preventing occupant ejection during rollover events. Sharma [20] used the model to help develop a rollover component test methodology for evaluating restraint systems under a NHTSA contract. Renfroe et al. [21] presented the MADYMO modeling of vehicle rollovers and resulting occupant kinematics. MADYMO models in general give fairly good predictions of vehicle kinematics at its initial and airborne phases during a rollover, and can be applied to (1) help establish threshold(s) for rollover sensor system development, and (2) guide and determine the initial conditions for rollover tests. Recently, Frimberger et al. [22] adapted MADYMO for occupant simulation in corkscrew type rollover situation. It should be mentioned that the rigid-body approach in the aforementioned simulations precludes itself from predicting vehicle structural crush and its effect on occupant kinematics during a rollover. In order for predictive structural model development, use of finite element analysis and test data from numerous rollover modes are needed.

In this paper, MADYMO-based models are developed to simulate certain full vehicle rollover test modes as described below.

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FULL VEHICLE ROLLOVER TESTS

Types of rollovers can be classified into two categories: untripped and tripped. Untripped rollovers are relatively rare events resulting from high lateral friction forces between the tires and road. Tripped rollovers are the result of lateral forces caused by the tire or wheel digging into the road or ground or from striking a curb or other obstacles. In both cases, the rollover event is preceded by the vehicle going into a maneuver, that has a relatively high lateral velocity. Different test methodologies such as SAE J2114, Side Curb Trip; Critical Sliding Velocity, and Corkscrew, as shown in Figure 1, for simulating rollover events have been used and reported in the open literature. A brief description of each mode is given below.

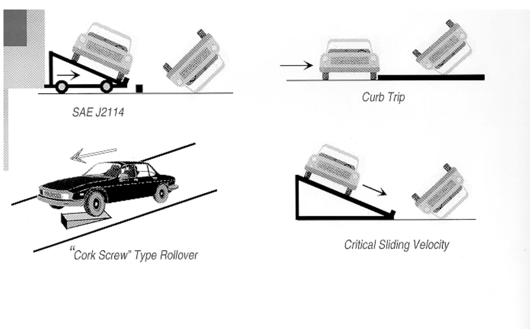

Figure 1 - Examples of various rollover test modes.

SAE J2114 Test Mode:

The SAE J2114 rollover test procedure is shown in Figure 1, along with other test modes to be described later. The test vehicle is placed laterally on a rolling cart at an angle of 23 degrees from the horizontal with the lower-side of the tires against a 4 inch (10.16 cm) high rigid flange so that the lower-side tires are 9 inches (22.86 cm) above the ground. The vehicle and rolling cart are accelerated to a constant velocity of 30 mph (50 kph) and the cart is then stopped in a distance of not more than 3 feet (0.914 m) without transverse or rotational movement of the platform during its deceleration. The cart deceleration must be at least 20 g's for a minimum of 40 milliseconds.

Side Curb Trip Mode:

The vehicle is placed laterally on a sled against a curb, which is about 6 inches (15 cm) high or high enough to allow rim interaction with it. The sled is towed to a pre-determined velocity (which is determined by a CAE rollover model of the specific vehicle) and released from the tow device prior to impact with the curb. In this test mode, the vehicle will experience a lateral acceleration of approximately 7 to 12 g's.

Critical Sliding Velocity Mode:

In this mode, the test vehicle is laterally placed at the top of a slanted ramp, which can be adjusted to any slanted angle. The wheels of the vehicle sit on "frictionless padding", which are guided in the slanted ramp. The vehicle slides down the ramp if the slanted angle is large enough, and initiates rollover when the tires impact the flange located at the bottom of the ramp as shown in Figure 1.

Corkscrew Mode:

This test mode requires a test ramp. Figure 2 shows various ramp configurations with different height, width, and length that appeared in the literature. It should be pointed out, however, that the SAE J857 test is currently obsolete. During the test, a vehicle with sufficient longitudinal velocity runs over the ramp, with wheels from one side of the vehicle on the ramp, while wheels from the other side of the vehicle on the ground. The vehicle gains a high asymmetric acceleration from the z-direction. When it leaves the ramp, the vehicle rotates along its longitudinal axis until it impacts against the ground.

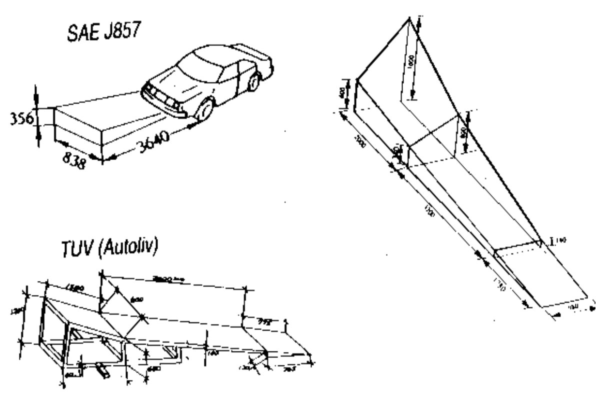

Figure 2 – Various ramp configurations.

TYPICAL TEST DATA

Some typical data obtained from the afore-mentioned rollover tests are shown in Figure 3. These data are the angular rate time histories, which can be integrated to yield angular displacement (or rotation) time histories. Both angular rate and rotation are important parameters for rollover sensing algorithm development. The aims at developing MADYMO-based are to provide such information through simulations.

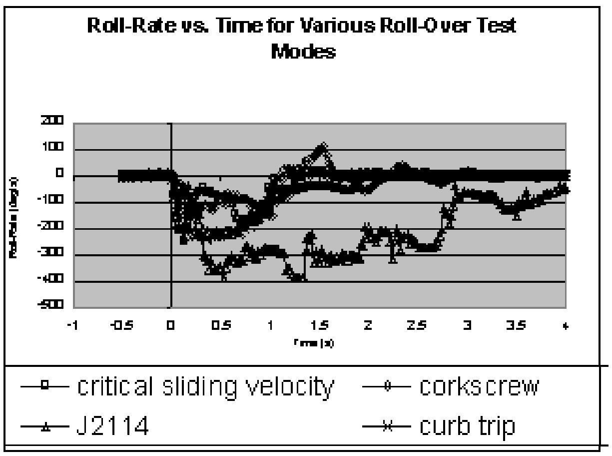

Figure 3 – Typical sample data from rollover tests.

MADYMO ROLLOVER MODELING MERHODOLOGY

In MADYMO, the vehicle is modeled as a system consisting of the vehicle body and the suspension sub-systems. Inclusion of the suspension sub-system allows simulation of wheel's bouncing/jouncing effect on the vehicle body in addition to the deformation of the tires during rollover events. The resulting deflection, which is dependent of spring and damping characteristics of the suspension system, has substantial effects on the rollover kinematics. In the suspension sub-system model, a translational joint is used to model the wheel bouncing in the vehicle vertical direction. In addition, a revolute joint is applied to model the spin of the wheel/tire, which is essential in rollover simulation of a vehicle driving forward over a corkscrew ramp.

Vehicle parameters that need to be included in the model are: wheel base, track width, roof height, CG height, weight, moments of inertia in roll/pitch/yaw directions, suspension spring rate and damping. The exterior and interior profiles of the vehicle are represented by a series of ellipsoids, including the windshield, seat back, seat cushion, door trim, steering wheel, etc. The contact between the vehicle and the ground is characterized by specifying load-deflection curves for the contact between the vehicle ellipsoid and the plane representing the ground. Contacts between the dummy and vehicle interior components are determined by the contact between ellipsoid-to-ellipsoids, representing the vehicle interior and the dummy segments, respectively. The behavior of tires is modeled using ellipsoids with prescribed stiffness, damping and coefficient of friction. These characteristics are approximations for demonstrating the vehicle/occupant kinematics with very limited representation of vehicle structural energy absorption during the rollover. For occupant restraint system performance, MADYMO provides a finite element capability for not only modeling the belts and/or curtain airbags, etc., but also simulating structural deformation during vehicle contact with the ground. Flexible structural modeling using MADYMO still needs to be evaluated for possible future applications. However, this study focuses on the development of rigid-body-based MADYMO rollover models for simulating four test modes as shown in Figure 1.

<u>a) Simulation of SAE J2114 Rollover Test Mode</u>:

A MADYMO-based model for simulating SAE J2114 rollover test procedure consists of the following:

<u>Vehicle and Test Platform Sub-models</u> - This model, as shown in Figure 4, consists of vehicle, test platform and ground sub-models. The ground is modeled as a plane and is the global reference frame from which all the parameters were measured. The vehicle is modeled with two (2) body systems consisting of vehicle and engine masses. The engine is connected to the vehicle CG by a very stiff joint via Cardan restraints. The total mass of the vehicle is about 2000 kgs. Hyper-ellipsoids of the 8th order are used to represent the vehicle parts such as windshield, doors, roof, tires and engine. The coordinates of the vehicle CG and mass moments of inertia about the CG are obtained from actual vehicle

test data. The vehicle is initially oriented at an angle of 23 degrees from the horizontal and resting against the flange as described above. The test platform is modeled as one body system. Hyper-ellipsoids are used to represent the inclined platform, and base of the platform.

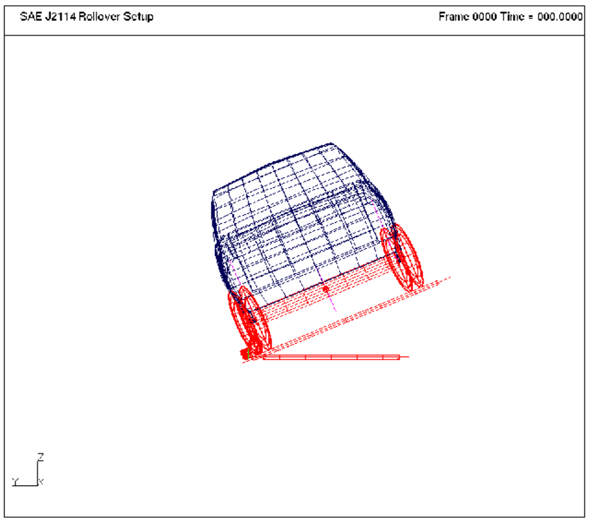

Figure 4 – MADYMO model for SAE J2114 test mode simulation

Initial Conditions & Acceleration Field - The vehicle is prescribed an initial velocity of 30 mph along with the platform in the lateral direction with reference to vehicle. The platform is then stopped in a short distance (less than 3 feet) while maintaining a deceleration rate of at least 20 g's for 40 msec. This is achieved by prescribing an acceleration field on the "platform alone" in the lateral direction opposite to its motion. In the tests conducted in this study, honeycombs are used as a stopping mechanism.

Contact-Interactions - Plane-Ellipsoid sub-model is used for contact interactions for calculating contact forces. Contact is specified between tires of the vehicle and the platform along the flange. Contacts are also specified between all parts of vehicle and ground (e.g., tires/ground, engine/ground, roof/ground and doors/ground). Contact stiffnesses between contacting surfaces have been specified by means of force-deflection characteristics.

Required inputs for generating the SAE J2114 model are a) vehicle geometry in both exterior and interior dimensions, b) vehicle parameters, such as vehicle c.g. location, moments of inertia, track width, wheel base, vehicle weight, etc. c) suspension system and tire parameters such as suspension linkage geometry, spring and damping characteristics, tire dimensions, moment of inertia, tire characteristics, etc., and d) initial conditions: vehicle test velocity, vehicle position, etc.

Figure 5 shows a sequential rollover motion of a vehicle in the SAE J2114 rollover test procedure. Figure 6 presents a comparison of the simulated results in roll rate and lateral acceleration with the test data, exhibiting a favorable agreement in roll-rate time history. Lack of prediction in lateral acceleration is due to many assumptions used in the rigid-body modeling. Some test parameters that affect rollover performance are listed in Table 1, along with MADYMO model limitations.

Figure 5 – Sequential rollover motion of a vehicle in SAE J2114 test procedure

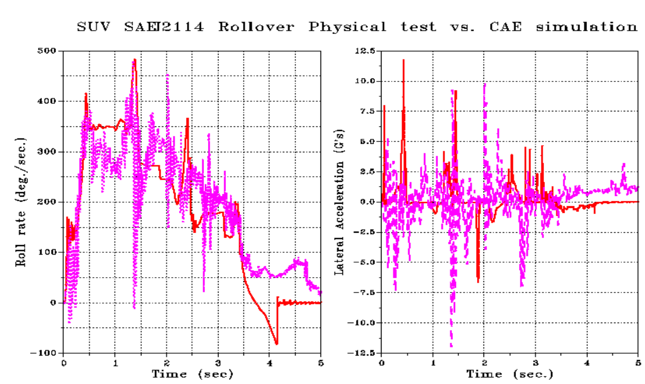

Figure 6 – Comparison s of simulated results with the test data – roll rate and lateral acceleration

b) Simulation of Critical Sliding Velocity (CSV) Mode:

Figure 7 shows the model used for simulating the CSV mode. A system, which models the vehicle carrier, should have the same mass as the actual test fixture. This carrier system is connected to the global system with a translational joint and a specific inclined angle from the test. Flange height should be shorter than the height it represented. Half the height of the flange is used to specify the semi-axial length for the ellipsoid. The travel distance and the deceleration force acting on the vehicle carrier are specified in terms of force-displacement function for this translational joint. Zero force is specified during the free travel of the vehicle carrier. The resistant force is specified to model the deceleration force from the honeycomb, which is used to decelerate the vehicle carrier. The magnitude of the deceleration force is based on the honeycomb used. Both the vehicle and the carrier have zero initial velocity and have a gravitation force of one g in the vertical direction. Major factors affecting the vehicle roll rate in this mode are: flange/tire contact stiffness, flange/tire contact friction, tire/vehicle carrier contact stiffness, stiffness of vehicle suspension system.
Two cases, i.e. no-roll and roll, are simulated. In the no-roll case, the fixture was set at an angle of 11^0, and the comparison of results between the simulation and the test is shown in Figure 8. The simulated result in roll-rate shows a higher peak than the test data. For the roll case, the inclined angle of the test fixture was set at 19^0, and Figure 9 presents both the simulated and test results. Simulated results in both roll-rate and lateral acceleration look good in this case. The simulated result in roll-rate deviates at approximately 0.8 second is mainly due to the setup of the test where the vehicle was restrained with tethers to prevent the test vehicle from being rolled over the test fixture, thus saving the vehicle for repeated use.

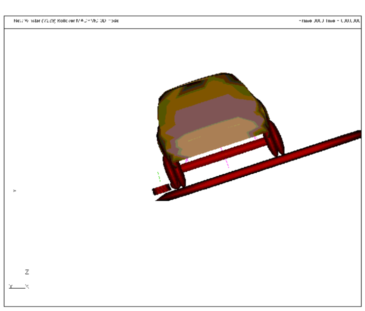

Figure 7 – A CSV MADYMO model

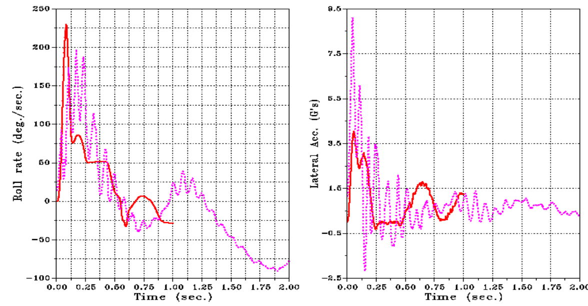

Figure 8 – No-roll case in CSV – simulation vs. test

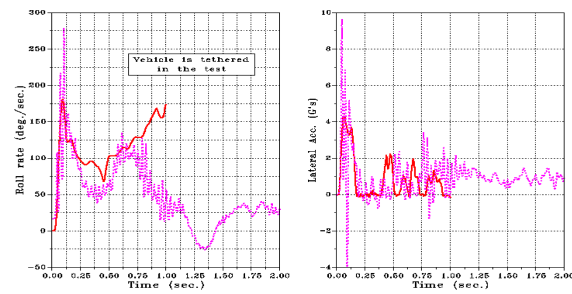

Figure 9 – Roll case in CSV – simulation vs. test

c) Simulation of Side Curb Trip Mode:

A side curb trip MADYMO model is shown in Figure 10. This model uses the same modeling procedure as the one for critical sliding test, except that the translational joint has zero (0) inclined angle with respect to the ground and an initial lateral velocity for the vehicle only is needed. The vehicle carrier is treated as a side flange padded by honeycomb, and no initial velocity is specified on it. The major factors, which affect the vehicle rollover, are: vehicle lateral velocity, flange height, flange/tire contact stiffness, and friction. The roll case of this mode is simulated using an initial lateral velocity of 16 mph. Figure 11 exhibits the simulated results when compared with the test data. The initial peak in roll-rate compares well with that from the test, while the model still predicts higher peaks in lateral acceleration.

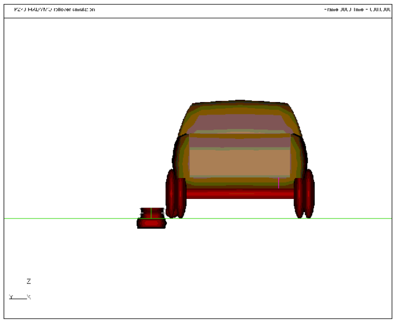

Figure 10 – A Side Curb Trip MADYMO model

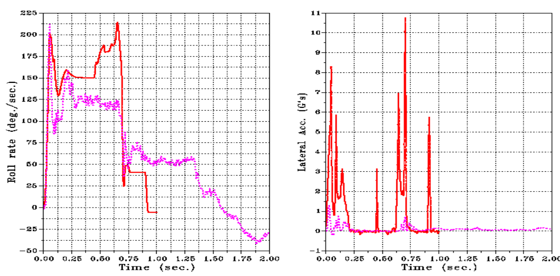

Figure 11 – Comparisons of results of Side Curb Trip – simulation vs. test

d) Simulation of Corkscrew Mode:

A corkscrew ramp MADYMO model is shown in Figure 12. In this model, a finite element tire sub-model is used. The geometric configuration of the corkscrew ramp can be modeled either using ellipsoids, planes associated with the global system or a rigid body associated with a system which is fixed on the ground. Contact between the tires and the ramp must be defined, and a higher friction coefficient for the contact needs to be specified to ensure that the vehicle stays on the ramp. The vehicle forward (or longitudinal) velocity is specified as an initial velocity for the vehicle system. Position the vehicle and make sure the right-hand-side tire ride on the correct position of the ramp. The major factors, which determine the vehicle rollover are: vehicle forward velocity, and the riding position of the vehicle on the ramp. In order to improve the model prediction, a finite element tire sub-model is used instead of ellipsoids. Figs. 13 and 14 show comparisons of roll-rate and lateral acceleration for the no-roll and roll cases, respectively. Results show favorable agreement between the simulation and the test.

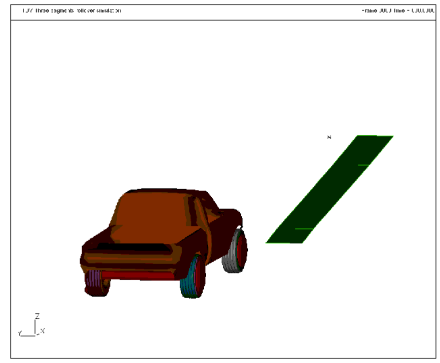

Figure 12 – A Corkscrew ramp MADYMO model

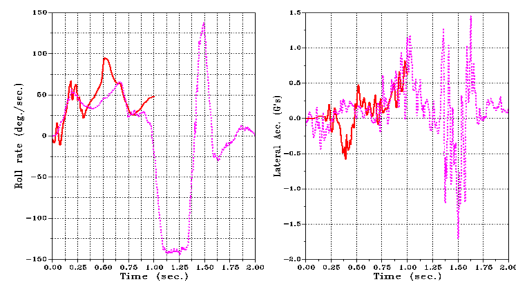

Figure 13 – No-roll case in Corkscrew ramp mode – simulation vs. test

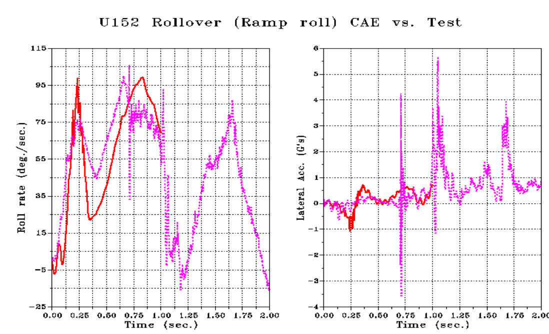

Figure 14 – Roll case in Corkscrew ramp mode – simulation vs. test

FUTURE CAE MODELONG AND TESTING

For future MADYMO-based CAE rollover modeling, efforts should be directed towards:

- Developing algorithms to allow specifying path for vehicle motion;

- Refinement of suspension model for improved side curb impact simulation;
- Developing mechanisms to allow provisions in simulating wheel separation from the axle during impact, if any;
- Using finite element vehicle interior for better contact simulation instead of plane/ellipsoid contact elements
- Developing a suspension model database
- Exploring MADYMO's magic formula for tire modeling
- Exploring MADYMO's finite element capability for structure simulations

In addition, a feasibility study needs to be conducted to develop hybrid modeling methodology by partly using rigid-based technique to obtain vehicle kinematics in rigid-body motion phase, and then using the information from the rigid-body phase data for deformable structural study in calculating stress/strain when the vehicle contacts ground.

To support the above modeling effort, testing is needed to provide data, which characterize (1) tire properties in lateral direction, (2) dummy joint properties in lateral direction and rotation about AP (Anterior-Posterior) direction, and (3) force-deflection pertaining to dummy/vehicle interior interactions.

CONCLUSIONS

Rollover models of varying degrees of complexity based on rigid-body assumptions are reviewed. The analytical studies and model simulations are becoming useful method for determining the influence of vehicle parameters on vehicle response. In this paper, MADYMO-based models for simulating vehicle kinematics in SAE J2114, side curb trip, critical sliding velocity and corkscrew ramp are developed. Simulated results are compared with test data, exhibiting good agreement between them. The rigid-body based MADYMO models are easier to run to provide trend analysis and design direction for rollover restraint system development. However, it should be noted that the rollover modeling techniques described herein do not include the ability to reconstruct a rollover event. Development of rollover models is a continuous improvement process, which requires experimental data for validation and refinement. In the future, this technology will continue to grow with possible use of finite element analysis for rollover modeling to study vehicle structural deformation and occupant kinematics interacting with the restraint system and vehicle interior.

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Table 1. Rollover modes and CAE model summary.

Test Mode	Test parameters that affect performance	MADYMO Model Limitations
SAE J2114 (23-degree)	▪ Road conditions: dry/wet; concrete/ asphalt; evenness; surface roughness ▪ Friction ▪ Deceleration pulse of dolly: G's & duration ▪ Stopping mechanism: hydraulic/ pneumatic/honeycomb ▪ Vehicle initial ground contact ▪ "Curb" height: (currently 4") ▪ Platform inclination: (currently 23-degree) ▪ Dolly height and tire pressures ▪ Platform orientation (0 vs. 45-deg.) ▪ Test Vehicle wheel rim types; tire size ▪ Test vehicle tire pressures	▪ Engineering judgment with assumed parameters (friction, etc) ▪ Numbers of rigid body system used. ▪ Rigid vs. deformable ▪ Currently tire modeling technology is unavailable ▪ Allowable interactions ▪ Multi-directional friction capability
Critical Sliding Velocity	▪ Test fixture ▪ Sliding surface condition and friction ▪ Lubricant material used to reduce friction ▪ Sliding angle (C.G. may be shifted) ▪ Sliding distance ▪ Release mechanism ▪ Pre-to-run time (tire/lubricant reaction)	▪ Only consider the following vehicle parameters (i.e. C.G. height, track width, moments of inertia) are needed. ▪ Need wheel/curb interaction data
Side Curb Trip	▪ Curb height ▪ Curb stiffness ▪ Tire pressure ▪ Tire & rim types ▪ Velocity ▪ Tire/curb interaction ▪ Test method: vehicle on cart vs. vehicle slides on ground	▪ Suspension model is good for up-and-down motion ▪ Wheels are rigidly attached to axle. Cannot simulate wheel breakage ▪ Lack of information on wheel/curb contact characteristics
Corkscrew	▪ Ramp shapes: height, length continuous vs. segmental ▪ Ramp surface: flat vs. spiral ▪ Wheel/ramp friction ▪ Ramp top edge/vehicle interaction ▪ Vehicle travel path: straight vs. curve ▪ Tire pressure ▪ Velocity ▪ Steering wheel: lock vs. unlock	▪ Need good suspension model for accurate timing for roll ▪ Limited capability in simulating interaction between ramp top edge and suspension ▪ Lack of multi-directional friction capability ▪ Can simulate locked steering wheel case only

REPEATABILITY TESTING OF A DYNAMIC ROLLOVER TEST FIXTURE

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Paper Number 05-0362

ABSTRACT

A new dynamic rollover test fixture, the Jordan Rollover System or JRS, has been developed. This fixture has the ability of testing vehicles or bucks in a controlled manner with preset initial conditions including roll rate, drop height, roadway speed, contact yaw, pitch and roll, etc. The test vehicle is held between drop towers and dropped and rolled at a predetermined time to interact with a moving roadway. The vehicle can contact the roadway on either one or both sides of the roof. As the vehicle interacts with the roadway, the vehicle is supported laterally, in the direction of the moving roadway, and longitudinally and is free to rotate and move vertically without support. After contact with the roadway, the test specimen rotates to rest without any additional contacts. In order to examine the repeatability of the test fixture, a test buck was prepared. The test buck incorporates a replaceable roof structure approximating a production vehicle roof structure. The repeatable roof buck was tested with set parameters. During the tests, the crash pulse was measured utilizing on board instrumentation and load cells in the road way. After each test, the roof was replaced. Examining the crash pulse between the tests and the initial conditions allowed the repeatability of the JRS to be determined. The JRS fixture was found to be highly repeatable.

INTRODUCTION

Previous dynamic rollover test methods have been widely criticized as non-repeatable. All of these methods; ramp rollovers, dolly rollovers, etc, result in a vehicle moving through an entire roll sequence where small differences at the beginning of the sequence can result in large differences in the outcome of the test. For instance in dolly rollovers, the interaction between the vehicle and the dolly as the vehicle is released and interaction with the ground at the initial contact can vary which results in downstream changes in the dynamics of the vehicle. These changes can include different vehicle loadings, contact point, dummy injury measures, etc. This can be seen in studies with repeated tests on the same vehicle that result in a range of number of rolls, roll distance, etc. In these tests, even though the initial parameters are repeatable, the consequential parameters that arise in the multiple rollovers result in different downstream vehicle dynamics.

In order to design a repeatable dynamic rollover test, these consequential parameters must be removed or minimized. The consequential parameters are any test feature that can change the desired impact(s). With this in mind, two dynamic rollover test methods have been introduced that have the first vehicle/road interaction a roof contact, since this is the part of the sequence in question. One method is the Jordan Rollover System previously introduced in several technical articles [1,2,3]. This system removes the consequential parameters present in the earlier test methods allowing for repeated dynamic contacts on a test specimen at desired test parameters and prevents further contacts between the vehicle and roadway, isolating the effects of the test impacts.

DESCRIPTION OF FIXTURE

The Jordan Rollover System is designed to evaluate the performance of a vehicle's roof and rollover occupant protection system under highly controlled, dynamic conditions. The test fixture combines well-defined vertical, lateral and roll impact conditions with vehicle rotation in a single impact or sequence of impacts. The system can be used for vehicle and safety systems development, consumer information testing and regulatory purposes.

The device, shown in Figure 1, holds the ends of either a body-in-white or a complete vehicle between two drop towers that permit it to be rotated about its longitudinal axis. The impact surface moves horizontally, along tracks, below the suspended vehicle. An energy source similar to that used in an impact sled propels the roadway. In the test sequence, the vehicle is positioned at the desired pitch and yaw angles. The vehicle can be rotated at up to about 1 revolution per second.

The rotation is coordinated with the release of the vehicle and with the propulsion of the road surface so that the vehicle body strikes the road plate at a specified roll angle. After the vehicle is released, only its lateral and longitudinal motion continues to be controlled except that the vehicle's vertical motion is halted before it strikes the tracks where the impact surface moves.

Figure 1. Jordan Rollover System with vehicle mounted and ready for testing.

The test may be designed to permit impacts with both sides of the roof in a single test. The road plate moves at a speed of up to about 20 mph (32 km/hr) and moves out from under the vehicle after the impact or impacts. The inertial frame of reference for this test moves at the speed of the impact surface at the time of the initial roof contact. After the vehicle impact(s), the test specimen will be suspended as its rotation ceases without further vehicle impacts.

If it is desired, a second test can be staged on the same vehicle. The impact surface is returned to its initial position, the vehicle is lifted to the starting position and the parameters are adjusted appropriately. The test can then be repeated.

Instrumentation and cameras can record the results of the test in a myriad of configurations depending upon the variables to be examined. For instance, test dummies can be used to assess and measure the total performance of the rollover occupant protection system, or string potentiometers and accelerometers can measure the dynamic roof crush and intrusion.

DESCRIPTION OF TEST BUCK

In order to test the repeatability of the system, a test buck was created that mimicked the strength and dimensions of a production vehicle roof, but was built for ease of roof replacement, see Figure 2 and 3. With the test buck, testing was allowed to occur at an increased pace by just replacing the roof of the vehicle and not the entire vehicle in the fixture.

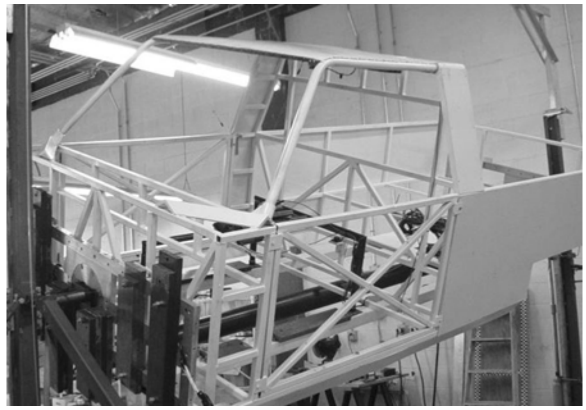

Figure 2. Pictures of the replaceable roof buck.

Figure 3. Pictures of the replaceable roof buck.

The overall dimensions of the buck and geometry were based on a small pickup truck. The roof was composed of seven components; two shaped tubes forming the A-pillars and side rails, a front and rear header, a roof panel and two side stiffeners for the roof panel, see Figure 4. The A-pillar tubes are 1 inch schedule 40 pipe (1.325 inches in outer diameter, .125 inches thick) and made of mild steel. The tubes were chosen based on an examination of cross sections of two production A-pillars in an attempt to have a similar bending stiffness. This was done in order to achieve between 4 to 6 inches of deformation in the tests and show the effects of a failing roof structure on repeatability. The headers are pieces of angled steel 1 by 1 by .125 inch thick. The roof panel was a sheet of 20 gauge (.036 inch) cold rolled steel. The edges of the roof panel were notched and formed around the .5 by .125 inch thick side stiffeners. The roof was held together by a series of spot welds 2 inches apart.

The roof is replaced by cutting the A-pillars at the top of the A-post at a set location. The remainder of the assembly can then be removed as one piece. New A-pillar tubes are then placed into the holders and the roof panel assembly is placed between the tubes. The panel is then spot welded to the side tubes and another test can be conducted. All the roofs were made by the same methods and with the same material.

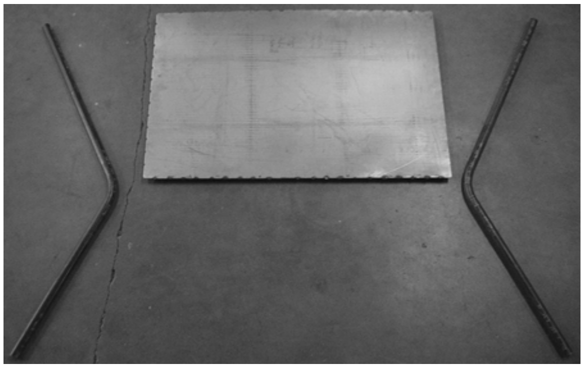

Figure 4. Replaceable roof structure.

DESCRIPTION OF TESTS

Three tests were conducted examining the repeatability of the system. Previous tests indicated that the system was very repeatable from test to test when examining road speed, angles, impact location, etc. However, multiple tests on the same structure to determine the repeatability of the test system and the repeatability of the test structure had not been done.

In all of these tests the initial conditions were kept constant and are described in Table 1.

Table 1.
Initial test parameters

Test Parameter	Initial Setting
Yaw Angle	10 degrees
Pitch Angle	10 degrees
Contact Roll Angle	135 degrees
Contact Roll Rate	188 deg/sec
Drop Height	4 inches
Roadway Speed	15 mph
Buck Weight	1670 lbs

The test system repeatability is shown by consistent speeds, impact locations, angular positioning, drop height, etc.

The vehicle repeatability is shown by the effects of the structure on the far side impact with the roadway, the vertical load cell results, etc.

Each test included instrumentation in both the roadway and the test buck. Roadway instrumentation included 6 vertical and 2 lateral load cells, see Figure 5. The data is recorded at 10,000 data points per second and synchronized with the other test instrumentation and the high speed cameras.

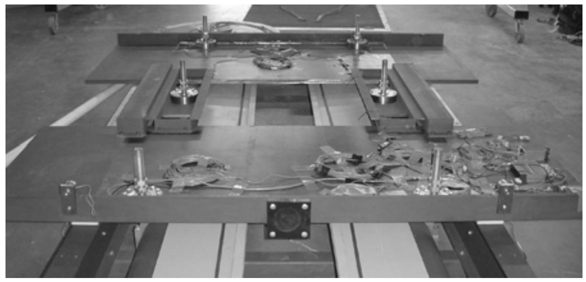

Figure 5. Roadway sled shown without the roadbed to show the instrumentation.

Vehicle instrumentation included tri-axial accelerometers near the rotational axis at about the CG and at the top of the A-pillar and string potentiometers on both the near and far side attached 4 inches inboard of the top of the A-pillar. The instrumentation was placed at the same position in the same manner in each of the tests.

TEST RESULTS

All of the tests were conducted as planned with a near and far side contact on the roof structure. After the contacts, the vehicle rotated to rest without additional contacts. All data and cameras functioned properly. Photographs of the post test condition of each test article are shown in Figures 6, 7 and 8.

Test Parameters

The majority of the test parameters are mechanically fixed and identical from test to test. The only non-mechanically fixed parameters are governed by the air pressure used to power the pneumatic drive system which in turn drives the mechanically coupled rotation of the vehicle and movement of the roadway. The measured roadway velocity in the three tests was 13.5 mph, 13.1 mph and 14.3 mph.

Figure 6. Vehicle Post Test 1.

Figure 7. Vehicle Post Test 2.

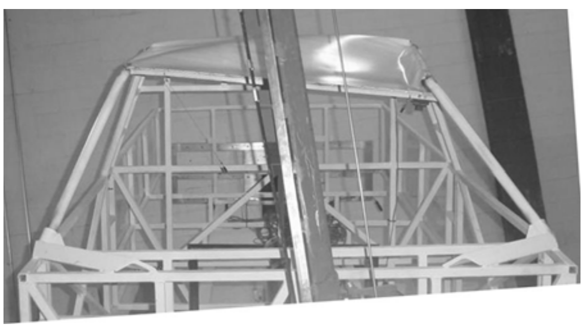

Figure 8. Vehicle Post Test 3.

Roadway Contact Locations

Figure 9 illustrates the roadway impacts for both the near and far side contacts. Figure 10 shows the near side contacts after the third test and that the contact marks coincide to the same point on the roadway and overlap. The far side contacts are dependent upon the structure and there is some small variation.

Vertical Load Cells

The crash pulse is measured by six vertical load cells with the data algebraically summed to determine the vertical load on the roadway. Figure 11 illustrates the results for each of the three tests.

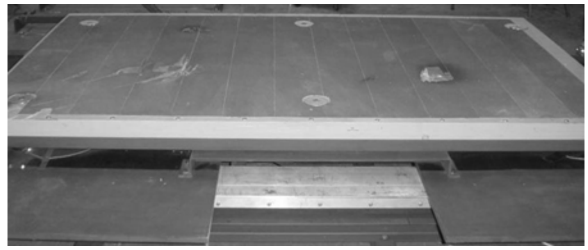

Figure 9. Roadway contact marks from the three tests. The near side contacts are on the right and far side on the left.

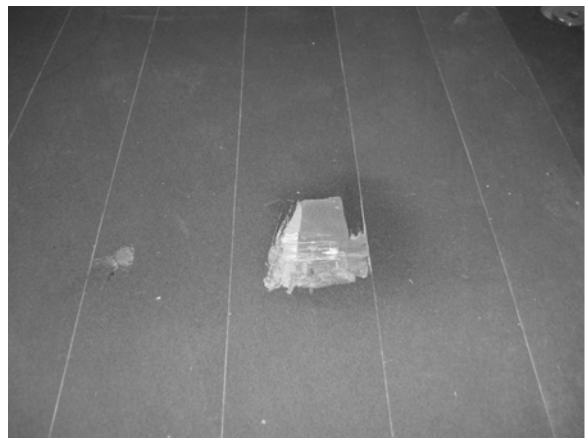

Figure 10. Close up of the near side contact marks from the three tests.

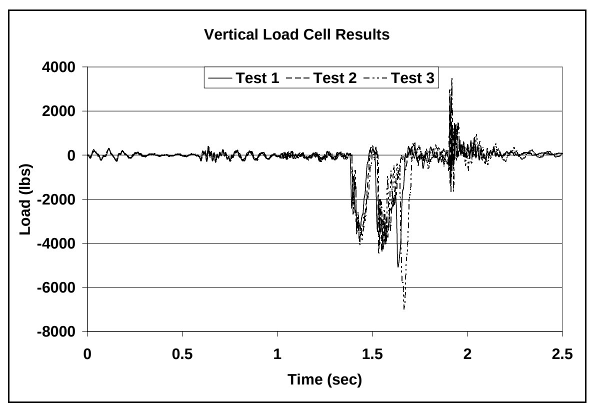

Figure 11. Vertical load cell results for each of the three tests.

In Figure 11, it can be seen that in every test the first contact between the vehicle and the road occurs just prior to 1.4 seconds after the triggers are actuated. This contact is the near side of the roof, the passenger side in these tests, striking the roadway. All three curves are very similar through the entire first contact from approximately 1.38 seconds to 1.5 seconds and until near the end of the far side contact at approximately 1.62 seconds. At that point, the data traces differ due to the interaction between the body structure at the base of the A-pillar and the roadway. This structure, shown in Figure 12, is strong enough to support the weight of the test buck and results in a higher load. The marks from this structure striking the ground are evident on the roadway, see Figure 13.

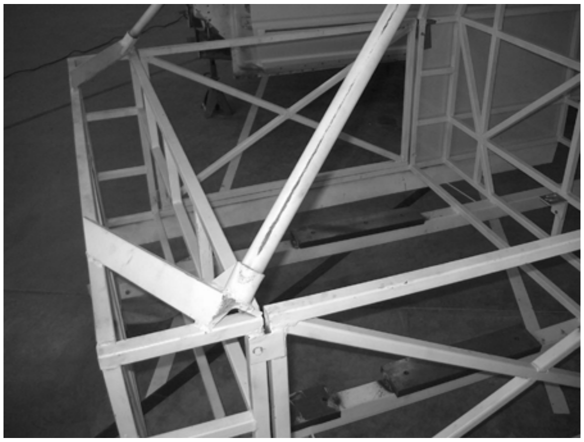

Figure 12. Photograph of the body structure at the base of the A-pillar.

Figure 13. Photograph of the roadway illustrating the contacts with the structure at the base of the A-pillar.

The roof impacts during the contacts on the first side are very similar for the three tests with overlapping contact locations on the roadway and similar load levels. The average maximum load during this contact for the three tests is 3800 lbs with a maximum percentage variation of 10% and a standard deviation of 350 lbs.

For the second contact, the loads on the roof structure are also similar. The only difference is after the roof contact when the body of the vehicle can come into contact with the roadway. For the roof portion of the second contact, the loads are very consistent from test to test with an average maximum load of 4270 with a maximum percentage variation of 4.5% and a standard deviation of 180 lbs.

Lateral Load Cells

Lateral load cells were included in the roadway to determine the loads on the roadway in the direction of the roadway's motion due to the acceleration phases and the vehicle contacts. It was determined after the first test that the cells were improperly attached. This allowed for a limited measurement only and was continued in the following two tests as a means for comparison between these tests. These traces, see Figure 14, are very similar from test to test and illustrate the acceleration pulse as the roadway comes to rest against the decelerator.

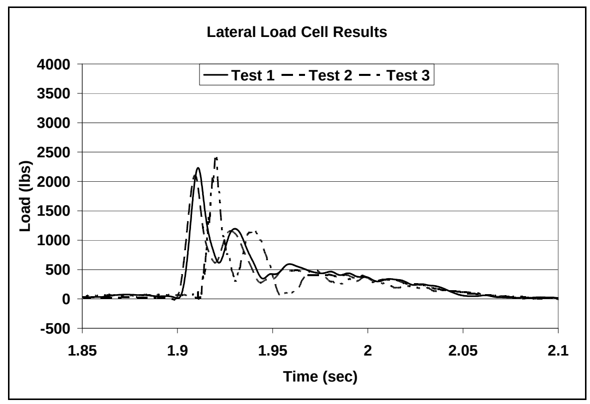

Figure 14. Lateral load cell data from the three tests.

String Potentiometers

The passenger (near) and driver (far) side string potentiometers results are graphed below in Figures 15 and 16. The deformation is similar in the tests with the exception of a greater deformation on the third test due to the header beam moving below the A-pillar tube as the result of a weld failure.

In Figure 15, the near side impact is clearly seen beginning in all three tests at approximately 1.4 seconds. For tests 1 and 2, the peak displacement is approximately 1.9 inches. As the load is removed from this side of the roof, the deformation is reduced to less than .5 inches at approximately 1.5 seconds. Differences in the header deformation due to the second impact result in a residual deformation of 1 inch in test 1 and .6 inches in test 2. For test 3, the peak displacement is 2.6 inches during the near side contact. The additional displacement is due to spot weld failure allowing the header to move below the A-pillar tube. This also causes a second peak in the data trace as the far side contact pushes the beam down further displacing the near side header/A-pillar. The residual deformation for this test is 1.5 inches on the near side.

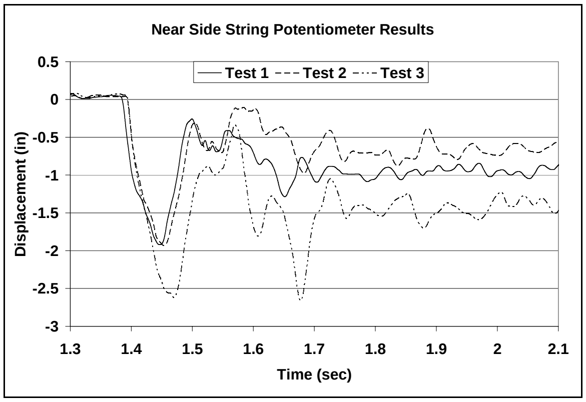

Figure 15. Passenger's (Near) side string potentiometer data.

In Figure 16, the near side impact, from approximately 1.4 to 1.5 seconds, can be seen by a slight outward motion of the roof structure in all three data traces. After this motion, the far side of the roof strikes the ground at approximately 1.5 seconds. As described previously, tests 1 and 2 have similar data traces with differences only due to the structural

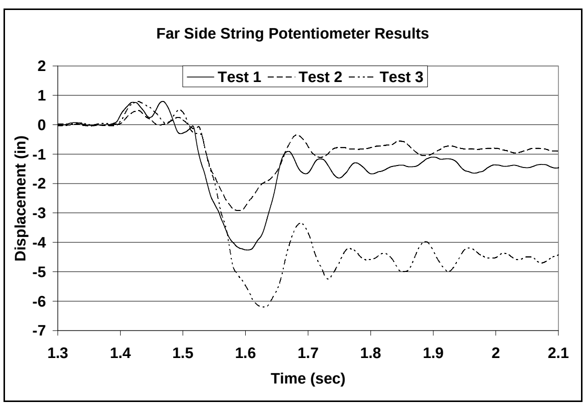

Figure 16. Driver's (Far) side string potentiometer data.

performance and tenting of the header structure. For test 1, the peak deflection is 4.25 inches with a residual deformation of 1.4 inches. For test 2, the peak deflection is 3 inches with a residual deformation of .9 inches. Test 3 has greater deformation due to a weld failure connecting the header to the roof panel. For test 3, the peak deflection is 6.2 inches with a residual deflection of 5 inches.

Accelerometers

In this analysis, we focused on the direct measurements of force and deflection. However, the system is capable of taking accelerometer data. For example, the following trace, Figure 17, is the resultant acceleration data from the three tests as measured near the CG of the vehicle.

DISCUSSION

Repeatability

The test system is very repeatable. An examination of the roadway loads illustrate that the loading environment is almost identical from test to test. The only variation is due to differences in the vehicle as shown by the differences in the string potentiometer readings and the post test appearance of the roofs. These slight variations would also be present in testing of production cars where some variation would occur due to differences in spot welds, windshield failure points, etc. However, the loading environment would be very similar from test to test and it would be hoped that the overall performance of a vehicle would not be contingent on a spot weld or the windshield failure characteristics.

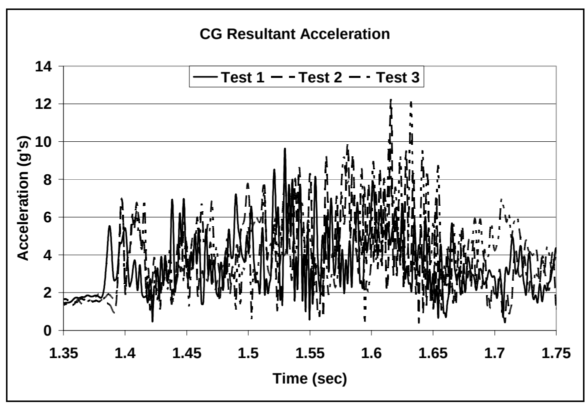

Figure 17. Resultant CG acceleration.

With the repeatability seen here, testing can be conducted at either the component or compliance level to determine the performance of the variable in question with assurance that the loading environment from test to test was consistent while isolating the damage to a particular impact or impacts as desired.

Load Cells

The lateral load cell mounting issue in these tests was corrected for future tests. The data traces in Figure 18 are the vertical and lateral load cell results for a subsequent test illustrating the performance of the system and typical data traces for a production vehicle test. In the test illustrated here, the vehicle test weight was approximately 2800 lbs. Similarly to the test bucks, the far side peak load, at approximately 1.7 seconds, is due to interaction of the top of the A-post and the roadway. Resolving the lateral load cell issue allows the direct measurement of forces during a dynamic rollover event.

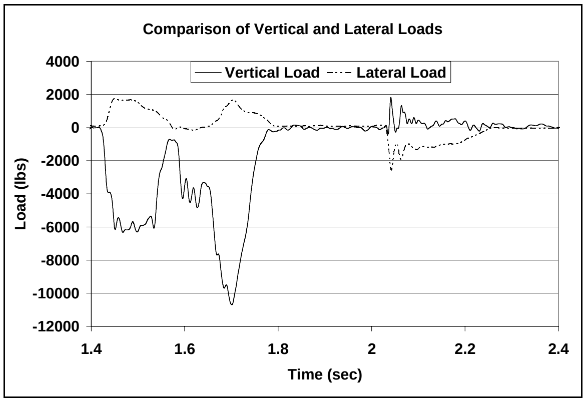

Figure 18. Comparison of vertical and lateral load cell results for a production vehicle.

CONCLUSIONS

The system has been shown to be repeatable. The majority of the parameters are fixed from test to test where the only variable is the air pressure in the system prior to testing. For these tests with identical test bucks, the roadway speed was within 5% for the three tests. The other setup parameters are either dependent upon this speed or fixed.

The loading environment on the vehicle was very consistent from test to test with only small variations, less than 10%, in the peak vertical load values seen during the roof contacts.

ACKNOWLEDGEMENTS

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SEAT INTEGRATED 3 POINT BELT WITH REVERSED GEOMETRY AND AN INBOARD TORSO SIDE-SUPPORT AIRBAG FOR IMPROVED PROTECTION IN ROLLOVER

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Paper Number 05-0204

ABSTRACT

In a rollover, the lap part of the 3-point belt certainly restrains the occupant from being fully ejected out of the vehicle, however the upper torso of the far side occupant may slip out of the shoulder belt. In this study the combination of reversed 3-point belt geometry (seat integrated), inboard torso side-support and buckle pretensioner were evaluated regarding the ability to better restrain the upper torso to the seat to prevent head-to-interior impacts.

The method of evaluation, proposed and used in this paper, was a new sled test method simulating full-scale tripped rollovers along the longitudinal axis during the initial phase of tripping, the airborne phase and the first ground impact. The roof was assumed in the tests to be able to withstand the ground impact. Since car occupants normally are seated with a certain kyfosis and may straighten and elongate their spine, standard HIII ATDs were modified with 3D-flexible lumbar spines and used in both front seat positions.

As a result, the rollover sled test method worked properly with good repeatability. While the head of the non-leading side (far-side) dummy impacted the inner roof in the standard 3-point belt configuration, the seat integrated 3-point belt with reversed geometry and buckle pretensioner showed ability to restrain the torso from moving inboard and towards the roof during the rollover tests.

INTRODUCTION

Hassan and Mackay (1995) studied the NASS-CDS in-depth database for the years 1991-1993 and found that most rollovers of Sport Utility Vehicles occur due to a trip over. Moreover, they found almost all (97%) rollovers (of the SUVs) to have rolled one turn or less. According to Parenteau and Shah (2000) who evaluated NASS-CDS data for years 1992 to 1996, the most frequent injurious rollover event for a belted occupant is a tripped rollover (along the longitudinal axis) with a far side occupant (on the non-leading side). With the same set of crash data, Viano and Parentau (2004) found that wearing seat belt reduces the risk of serious injury to the head with 50% and to the chest with 40%, head and chest injuries being the most harmful injuries in rollovers according to Fay et al (2003). Otto et al found the MAIS3+ risk reduction wearing a seatbelt to be 80% evaluating GIDAS-data for the years 1994-2000.

Although rollover crashes involve more complex occupant motion than other crash modes (Digges 1991), a shortcoming of the standard 3- point belt in rollovers is the possibility of the far side occupant to slide out of the shoulder belt (Oberfegell et al l986, Kallieris and Schmidt 1990, Bostrom and Haland 2005). According to NHTSA (2003), who are investigating countermeasures to keep occupants better secured to the seat, it is not generally clear if reinforcing the roofs alone prevents injurious head-to-inner roof contacts.

In the absence of an accepted rollover dummy, the HIII frontal crash test dummy is often used to evaluate occupant kinematics in mechanical simulations of rollovers. However, the biofidelity is in question (Viano and Parentau 2004). For example, Moffat et al (1997) found the HIII head vertical excursion during dynamic and static rollover tests to be in the magnitude of 60 mm less compared to Post Mortem Human Subjects (PMHS).

Previously, the benefits of adding an extra seat-integrated 2-point belt to the standard 3-point belt were investigated by Bostrom and Haland (2005) by means of mechanical simulations of frontal, far side and rollover crashes. They found a considerable reduction of chest deflection in frontal crash tests, head horizontal motion in far side tests and head upward motion in the rollover tests. In order to reduce the risk of injurious belt-to-neck load caused by the 2-point belt, an inflatable side support was also used in

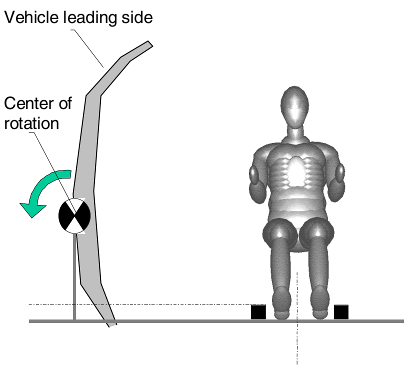


Figure 1. In a previously used sled test rollover method, the centre of rotation was fixed during the tests according to the picture.

combination with the extra belt. The rollover test set-up in this evaluation consisted of a steel construction, a platform simulating the compartment of a car able to translate laterally and rotate with a fixed rotation axis. This rotation axis, see Figure 1, was a compromise of the true rotation axis, which in a soil tripped rollover in the simplified case moves from a location around the tires of the leading side in the tripping phase to the centre of mass in the airborne phase. The ATD used was a BioSID with a modified lumbar spine (allowing an extension of the spine of 70 mm), seated in a non-leading position. The buck was accelerated with a low g-level (peak 3g), and at a speed of 36 km/h the buck was decelerated and rotated until reaching a stop at 160 degrees, which simulated a car-to-ground impact phase.

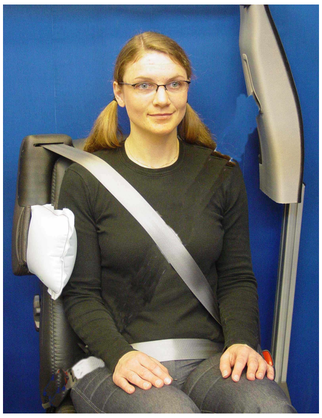
Kallieries and Schmidt (1990) evaluated the concept of a 3-point belt with reversed geometry, noting the potential beneficial effect of restraining the occupant laterally. It is tempting to believe, the beneficial features of an extra 2-point belt and an inboard side support airbag for far side occupants in rollover (Bostrom and Haland 2005) are also applicable for a seat integrated 3-p belt system with reversed belt geometry and an inboard side support airbag, see Figure 2.

The aim of this paper was threefold. Firstly, a new cost efficient tripped rollover sled test method (one ground impact) was proposed and evaluated. Secondly, 3D-flexible lumbar spring spines for HIII ATDs was proposed. Thirdly, the method and the modified dummies were used to evaluate the far-side occupant benefit of an inboard side support airbag and reversed seat integrated belt system with buckle pretensioning.

METHOD

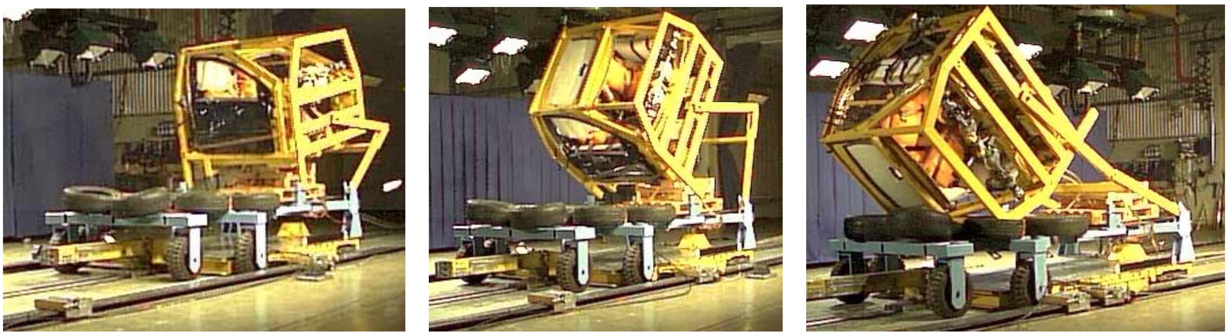
The sled test method used in this paper was designed to evaluate occupant protection in tripped rollover until first ground impact in a robust and repeatable way for most common passenger vehicle types, vehicle speeds, and tripping-accelerations. The majority of rollovers occur off-road (Viano and Parenatu 2004) and the variety of the surrounding road environments is vast. Therefore the real-life ground impact circumstances vary considerably and an occupant injury risk evaluation may be restricted to an analysis of the occupant restraint situation just before first ground impact, such as whether the shoulder belt has slipped off or not. Also, the ATD head excursion during the first ground impact may be evaluated in conjunction with a possible roof crush.

a)



b)

Figure 2. Occupant a) restrained by a 3+2 point belt and a side support airbag (as previosly described and evaluated) and b) restrained by a seat integrated belt with reversed geometry and a side support airbag.



a) b) c)

Figure 3. The sled test rig in the a) tripping phase, b) airborne phase and c) first ground impact phase.

General description

In a tripped rollover the rotational acceleration of the car equals the

Tripping torque on the car / Moment of inertia (1).

Consider a car with mass m, track width T, height of centre of mass from tripping axis H and a roll moment of inertia around centre of mass I. If the sliding or tripping acceleration of the car is a, the tripping torque is the force of the ground transmitted by the leading side wheels times the moment arm, maH initially, opposed by the torque of gravity, $mgT/2$ initially. This means a vehicle starts to roll if the sliding acceleration exceeds $T/(2H)$. That is the total mass of the car is irrelevant. This also means, if the mass-normalized moment of inertia around the tripping axis

$$(I + (T/2)^2+H^2)/m \qquad (2).$$

and the tripping acceleration (acceleration at the axis of tripping) are replicated in a mechanical simulation, the rotation and translation are replicated. Once airborne, the vehicle follows a trajectory dictated by the tripping history of rotation and translation and remains with the same rotation velocity given at the time of becoming airborne. This is the general idea behind the present rollover sled test method. The idea was first applied by Torstensson and Klasson (2003). The sled test rig consists of the following components:

1. A buck with a certain track width, T, height of centre of mass from tripping axis H and mass-normalized moment of inertia around tripping axis = $(I + (T/2)^2+H^2)/m$.
2. A pair of guiding steel pivoting arms on each sides of the buck to restrain the buck within the sled area without considerably influencing the tripping and airborne phase.
3. A buck on a wheeled carrier is fastened on the sled. As the carrier is decelerated, the buck is tripped, causing it to freely rotate. It subsequently lands on the forward area of the carrier, which has been covered by car tires.
4. A sled, which is decelerated by means of a set of brakes (see next).
5. A set of pneumatically controlled brakes, previously described by Rossey (2001) but upgraded with a mechanically controlled release function after an arbitrary distance of braking.

See Figure 3 for views from the three phases of tripping, airborne and first ground impact. If the sled is still moving at the start of the airborne phase, higher sled speeds do not alter the simulation outcome as the deceleration of the sled is not dependent on the pre-roll sled speed (in contrast to some real-life situations). That is, with the possibility of releasing the brakes (see description 5. above), the pre-roll speed of the sled is less relevant. See Figure 4 for 45 km/h pre-roll speed rollover simulations with two deceleration levels, with and without release of the brakes during the tripping phase, giving different rotation accelerations and rotation speeds. In the following sub-sections the buck, pulse, ATDs, restraint systems, and evaluation parameters for the present test series are described.

Table 1.
Rig details.

	W/o dummies	With dummies
Track width [m]	1.71	1.71
Mass [kg]	790	946
Moment of inertia around COG [kgm^2]	342	398
Normalized moment of inertia [m^2]	0.43	0.42
Height of dummy hip point (to tripping axis) [m]	-	0.60
Height of COG (to tripping axis) [m]	0.64	0.64

Buck

The buck used was a frame of a SUV type of vehicle. The buck was reinforced externally, keeping the normalized moment of inertia (Equation 2), the track width and the height of the COG above an assumed tripping axis, same as the original vehicle. See Table 1 for values of these entities for the buck with and without two front seat HIII 50th% occupants firmly attached to the seats with belts.

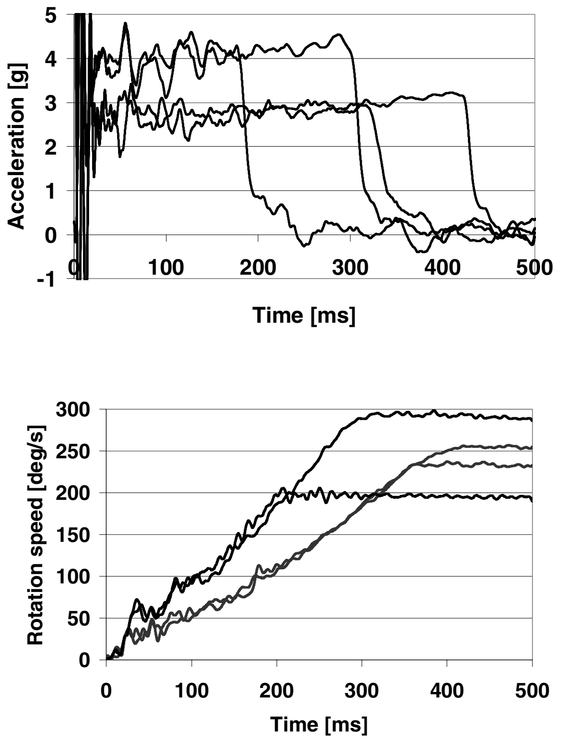


Figure 4. Four examples of tripping pulses and the resulting rotational speeds. Two pulses of 3g and two of 4g were and were not released during the tripping phase. The pre-roll speed was 45 km/h.

Pulse

The pulse chosen in the present evaluation, 45 km/h impact speed and a tripping acceleration of 3g, was replicated from in house full-scale soil-tripped rollovers resulting in one roof impact.

Dummies

Two HIII 50th% ATDs were positioned in the front seats, and positioned according to OEM specifications. The upper arms of the dummies were removed to prevent obstruction of the film view of the head. The ATDs, were modified with 3D-flexible lumbar spines, see Figure 5. The modification was performed by replacing the rubber interface between the lumbar spine end plates by a steel spring-coil with shearing and

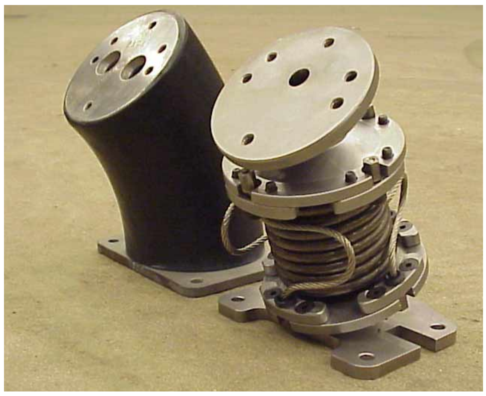


Figure 5. The original and the modified HIII lumbar spine. The rubber was replaced with a spring coil and the four wires limits the elongation to 60 mm.

Table 2.
Test matrix.

Test	Belt	Retractor pretensioner	Buckle pretensioner	SSA*	IC**
1	Standard	Yes	-	-	Yes
2	Standard	Yes	-	-	Yes
3	Standard	Yes	-	-	Yes
4	Reversed	-	Yes	Yes	Yes
5	Reversed	-	Yes	Yes	Yes
6	Reversed	-	Yes	Yes	Yes

*only for non-leading side occupant **only for leading side occupant

elongating features of 10 N/mm. The elongation was restricted to 60 mm by four wires. The elongation characteristics were chosen based on simple estimations. First, straightening of the lumbar lordosis and thoracic kyfosis of a normally seated occupant was estimated to be associated to 30 mm of elongation without much force. Secondly, according to Brown et al (2002) the lumbar joints may each elongate about 6 mm within the physiological range with an elasticity of about 20 N/mm. Therefore the modified lumbar spine, simulating both the possibilities of lumbar elongation as well the overall spine straightening, within the physiological range, was designed to elongate 60 mm with 10 N/mm. This is in accordance with the observed spine elongation of up to 3 inches of astronauts in gravity-free space (NASA 2005) and the observed elongation differences between HIII and PMHS subjected for both static and dynamic rollover tests (Moffat et al 1997). Also, the shearing and elongation characteristics implemented in a modified lumbar spring spine of the BioSID have been shown to enable replication of PMHS kinematics in a far side crash simulation (Fildes et al 2005).

Restraint system

According to the aim of this paper, tests were performed both with standard geometry 3-point belts as well as reversed geometry seat-integrated 3-point belts. In the reference tests, front seat seat belts with retractor pretensioners were used. In the reversed case no retractor was used. Instead, the belts were statically secured and buckle pretensioners were triggered, see Table 2 for the complete test matrix. In order to prevent harmful belt-to-neck interactions in the case of reversed belt geometry, the upper belt guides were oriented vertically and an inboard side support airbag, SSA, was installed in the non-leading (far-side) seat. The SSA consisted of a non-ventilated 3 litre bag, a production gas generator (for a near (outboard) side airbag) and a bracket mounted at the inboard

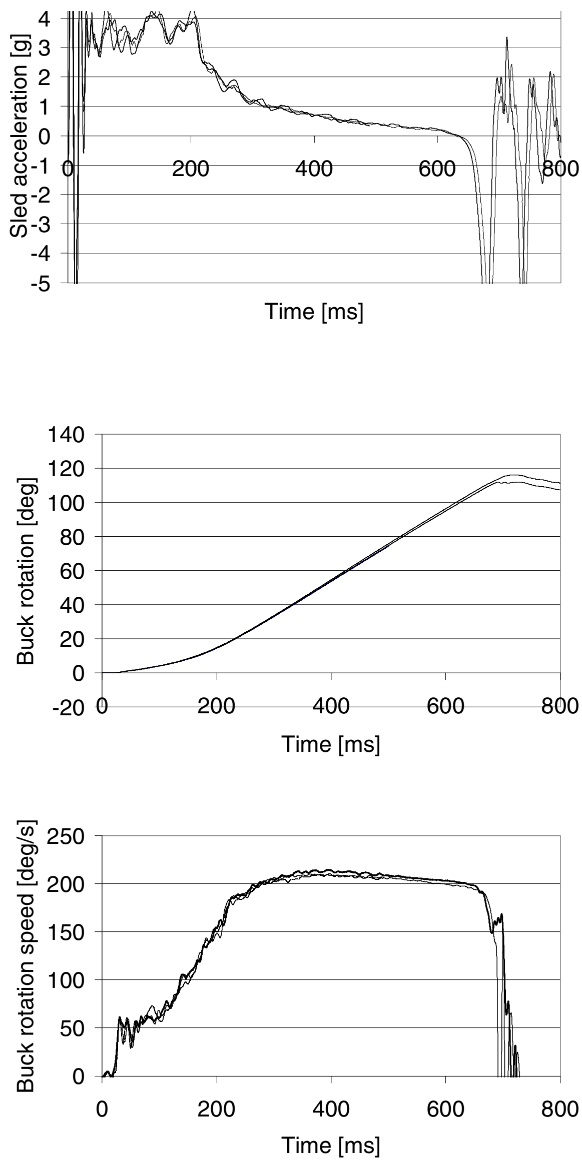


Figure 6 – The sled deceleration, buck rotational speed and rotation for the three reference tests versus time for the first 800 ms. In Test 1, the data was captured only the first 500 ms.

side of the seat frame, see Figure 2. The seats were reinforced standard seats. In all tests, standard inflatable head curtain airbags (IC) were installed on the leading side. The triggering time for all pretensioners, side support airbags and curtains was 140 ms corresponding to a roll angle and roll angle speed of 7 degrees and 100 deg/sec respectively.

Evaluation parameters

Throughout this paper, all coordinate systems and filter classifications used are according to SAEJ211 standard. Two high-speed cameras were mounted on the buck in front of each ATD. Two film analysis markers were placed 130 mm apart on the dummy faces. The markers were tracked using TEMA software, giving the motion in the buck y-z plane of these two markers. With a Faro-arm device, the interior and head of the dummy surfaces were pre-measured in the dummy motion plane.

Head acceleration and upper neck load were measured in both dummies. The lower neck load was measured in the non-leading side dummy in order to evaluate the belt-to-neck interaction in the reversed geometry test.

RESULTS

The sled x-acceleration and buck y-acceleration and the buck rotational speed time histories for the three reference tests are shown in Figure 6. In Figure 7, the y-z plane trajectory of the head upper marker in the three reference tests is shown. According to the buck and dummy head motion visualized in Figure 6 and 7, the repeatability of the method was good.

Table 3 .
Nij and HIC values for all tests (except Test 1 where the data were captured only the first 500 ms).

Test	HIC36	Nij
1	Data loss	Data loss
2	415	1.13 (NCF)
3	572	0.45 (NCF)
4	65	0.22 (NTE)
5	32	0.24 (NTE)
6	29	0.20 (NTE)

In all reference tests the non-leading side dummy's upper torso slipped out of the shoulder belt in the tripping phase after about 170 ms corresponding to a buck rotation of 13 degrees. The belt pretensioner, triggered after 140 ms, acted on the ATD, which at that time, already had moved in the in-board direction. Thereafter, at about 350 ms after the start of the roll, the ATD moved in the out-board direction. At ground impact the dummy was only restrained by the lap part of the belt. In addition, a considerable belt slack was introduced when the dummy initially moved inboards, a slack which was not reduced by the pretensioner due to too the late deployment time. In all the three reference tests (Tests 1-3), the ATD head hit the inner roof at the event of ground impact. The maximum upper neck loads occurred in Test 2 where the Nij value was 1.1 (Table 3), mainly due to 6.6 kN of compression force when the head and neck was compressed between a moving torso and a grounded roof. On the other hand, in all reversed belt geometry tests, the shoulder belt did not slip off the shoulder and therefore restrained the dummy from moving too far towards the roof in the ground impact phase. See Figure 8 for inboard and outboard views for both belt geometries at 120, 200, 500 and 1000 ms. Furthermore, for the reversed geometry, the shoulder belt interacted with the dummy neck with the flat side. Although there exists no established tolerance levels, the lower neck loads (Fy) was considered to be low (<1 kN) indicating a harmless belt-to-neck interaction. See Table 3 for all Nij and HIC values.

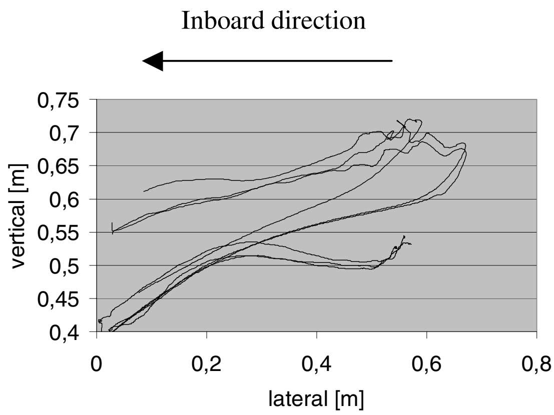


Figure 7 - The first 850 ms motion in the y-z plane of the head upper marker for the three reference tests. The head first moved inboard and downwards and thereafter outboard and upward.

Buck | Standard geometry | Reversed geometry

140 ms

200 ms

500 ms

700 ms

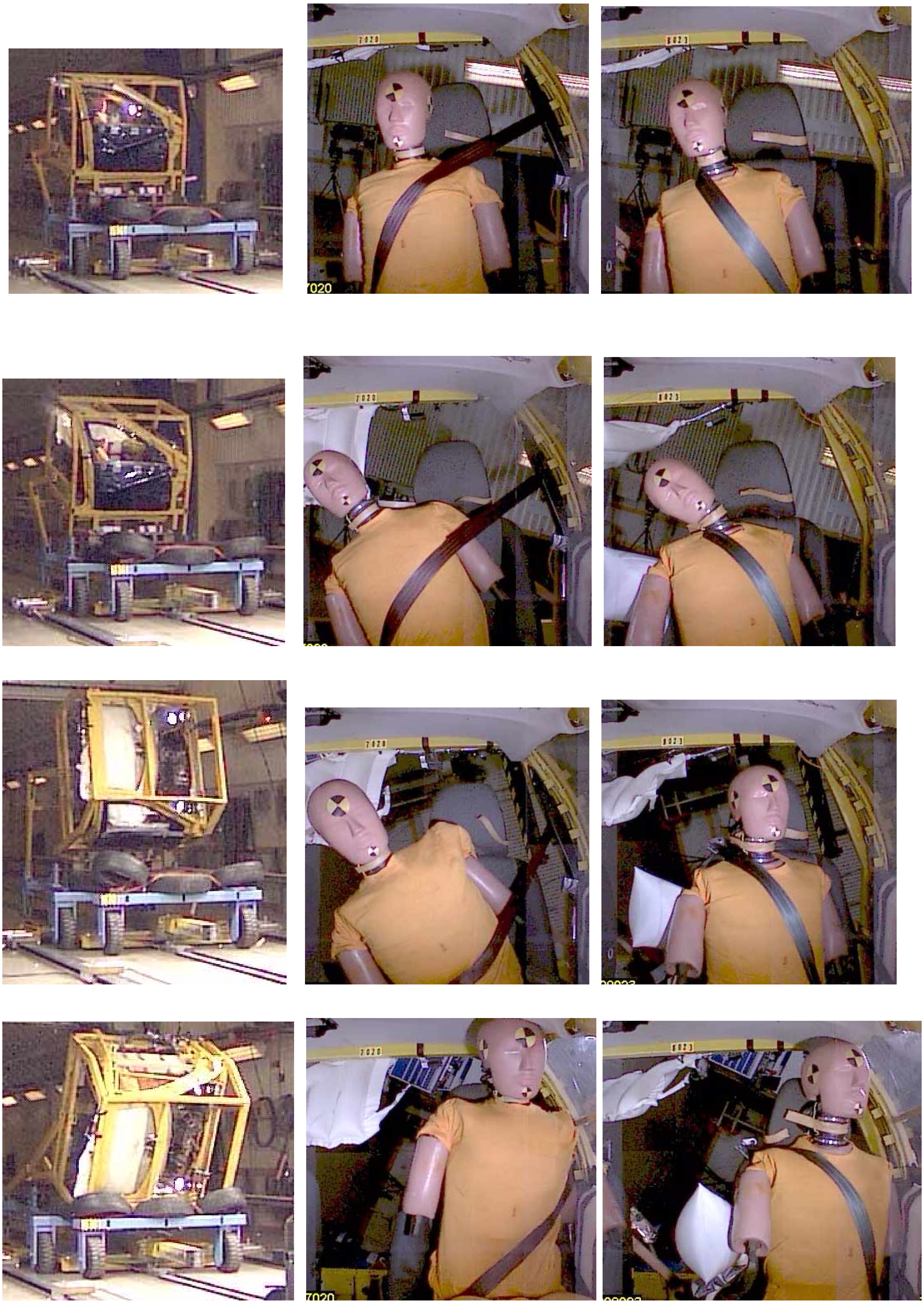


Figure 7. Outboard and inboard non-leading occupant views for standard and reversed belt geometry at 140, 200, 500 and 700 ms .

DISCUSSION

The method used in this paper was designed to simulate tripped rollover until the first ground impact. As the speed and tripping acceleration may be varied, the method includes the possibilities of simulation of most types of soil and curb type of tripped rollovers and therefore most types of real-life rollovers. The present benefit analysis was limited to an analysis of the observation of the belt staying on the shoulder or not and the consequent head excursion towards a roof that did not intrude. Also, a limitation was the chosen pulse, 45 km/h and 3g, a replication of what is believed to be a typical tripped rollover with one roof impact. According to Digges and Eigen (2003) the number of roof impacts is an appropriate severity indicator for belted occupants, two or more impacts covering the majority of rollovers causing AIS3+ injuries. Therefore, according to Digges and Eigen the present pulse may be considered representing a rollover with a rather low severity (although their study involved all types of cars). Therefore, the shortcomings of the standard belt found in this paper would probably not improve while the benefits of the evaluated countermeasures do not necessarily apply to cars with extensive roof crush. This needs to be further evaluated.

The spring lumbar spine modification to the HIII ATD improved both the lateral and upward motion of the ATD during the rollover simulations. It is the authors' belief that the modification had a great impact on the results and conclusions of this paper, and that this was an important step towards more human-like rollover simulations of occupant motion.

To obtain a low belt-to-neck load an inboard side support airbag was included in the reversed belt configuration in order to off-load the belt for occupant inboard movement. Also, the upper belt guide was aligning the belt vertically in order to promote a flat belt alignment to the neck. Regarding the offload effect, the torso side support airbag has in previous far side impact tests (Bostrom and Haland 2005) shown its ability to keep the occupant (driver) within the seat with standard geometry belts, for a lateral acceleration of 10g, both in 90 degree (3 a'clock) as well as 60 degree (2 a 'clock) tests. While there are accepted limits on the loads and moments applied to the neck for evaluating vertebral bone and ligament injuries, there are no currently accepted load limits for evaluating direct interaction of a torso belt with the soft tissues of the neck. Nevertheless, the direct belt loading to the neck caused by the reversed belt measured by the lower neck load cell was considered by the authors to be low (<1 kN).

Introducing a torso side support airbag on the inboard side of the seat, and reversing the belt geometry, may have implications in out-of-positions and crash circumstances not evaluated in this paper. The side support airbag may need to be tuned for these out-of-positions. Further tests need also to be performed to evaluate the impact of reversing the belt in frontal and near side crashes. Nevertheless, the deployment time of this small bag with relatively high pressure (2 bar) can be as long as 30–40 ms, which is a good prerequisite for a benign out-of-position performance.

Regarding the leading side occupant, the inflatable curtain successfully protected the head for both belt configurations; see Figure 9 for inboard views

Figure 9 - Inboard views at the event of ground impact for the leading side occupant for both belt geometries. No side window was present.

at the event of ground impact

Although the aim of this paper was to evaluate the benefits in rollover, far side tests were performed with reversed belt geometry and the side support airbag. Not so surprisingly, the results resembled the results for an extra 2-point belt evaluated by Bostrom and Haland (2005). The inboard belt restrained the occupant from moving inboard and the side support airbag off-loaded the belt-to-neck loading, thus indicating also a benefit in far side crashes.

The proposed countermeasure evaluated in this paper may be optimized to provide even better protection for the far-side occupant in rollover crashes. For example, a decreased triggering time of the SSA and the buckle pretensioner would reduce the initial lateral motion of the occupant and thereby reduce the remaining belt slack after the belt pretensioning. A reduced belt slack would decrease the occupant upward motion even further.

SUMMARY

A series of tests with spine modified HIII dummies and a new sled test method for tripped rollover (along the longitudinal axis) until first ground impact was performed. The benefit of a seat integrated, buckle pretensioned, 3-point belt with reversed geometry and an inflatable inboard torso side support was evaluated. The repeatability of the method in terms of the buck and ATD motion (kinematics) was concluded to be good. The spine modifications did withstand the test series and enabled an elongation of the ATD's back during vertical tension. Reversing the geometry of a 3-point seat belt showed improvement of the shoulder belts ability to restrain the torso of a non-leading side occupant in a tripped rollover without causing harmful belt-to-neck loading.

ACKNOWLEDGEMENT

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REQUIRED AIRBAG CHARACTERISTICS FOR OCCUPANT RETENTION IN ROLLOVER CRASHES

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Paper Number 05-0226

ABSTRACT

Evaluating performance of occupant retention countermeasures at the side windows through full-scale crash tests are typically expensive and yield inconclusive results. The results are inconclusive due to the non-repeatable nature of this testing. Another approach utilizes guided impact testing that propels an attached headform into a window to evaluate performances of these safety systems. This may provide some procedural value in generating repeatable results with limited objectives.

The capability to limit the guided impact headform displacement relative to a vehicle's exterior window plane is assumed to represent reduced risk of occupant ejection. However, it is not known what ejection risk is represented for a given headform excursion.

This study characterized headform excursions in guided impact testing for a given window airbag design with a range of restraint capabilities. Not surprising, disparities in the headform excursions were observed depending on the impact location of the impact on the airbag. System level evaluation of the airbag design in a rollover environment was conducted to determine which restraint capabilities represented a reduced risk of occupant ejection.

A correlated computer model of NHTSA's Dynamic Rollover Fixture (DRF) was used to identify the restraint characteristics for the airbags in which occupant ejection occurred as well as those where occupant retention was achieved in order to establish a relationship to headform excursion. However, the relationship for a given headform excursion to ejection risk was not apparent due to disparity in the headform excursion results.

Review of simulations in the DRF showed that as the occupant interacted with the airbag, occupant moved from the region of the airbag where excursions were the lowest, towards the region of the airbag where headform excursion was greatest. The dummy moved forward until it "pocketed" in the un-inflated front zone of the airbag or until it escaped out of the zone with the highest allowable excursion.

BACKGROUND

The fatality rate for an ejected vehicle occupant is three times as great compared to occupants who remain inside of the vehicle. More than 5,000 ejected fatalities are through front side windows with over 2,000 of these from partial ejections. For that reason reducing occupant ejections through side windows offers the potential for significant safety benefits [1].

The National Highway Traffic Safety Administration (NHTSA) has been conducting research for several years on ejection mitigation, which includes evaluations of a guided impactor test to characterize occupant ejection potential as a possible approach to addressing occupant ejection through the side window. A guided impactor is a device with a headform attached to the end of a shaft and is propelled linearly at a potential countermeasure, as shown in figure 1. The impactor device can measure the headform distance traveled when impacting the countermeasure. Guided impact testing has shown to be an excellent method in measuring excursion.

Figure 1. Guided impactor used by NHTSA

NHTSA has applied ejection mitigation research towards characterization of window airbag systems that deploy down from the roofline above the door to protect occupants in side crashes. Some of these airbag systems have shown capability to significantly limit the headform excursion of the guided impactor.

However, it is not clear on what basis an excursion criterion could be established for evaluating performance of countermeasures to mitigate occupant ejection. It has been observed, for example, that the deflection of the airbag may create additional potential for ejection as shown in figure 2.

Figure 2. Opening created by guided impactor

The fundamental question one could ask, as it relates to guided impact testing, is what is an appropriate metric to mitigate occupant ejection.

Meaningful energy levels, locations and limits for excursion testing have not been agreed upon. NHTSA is evaluating 4 impact locations points around the perimeter of the window as depicted in figure 3 [2]. Another impact location being considered by industry is located at the centroid of the window.

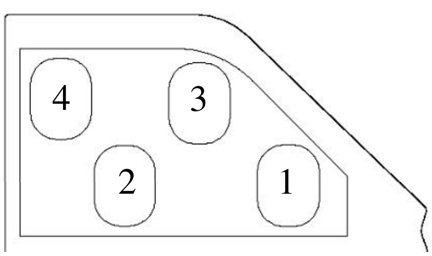

Figure 3. NHTSA's impact positions

The perimeter locations attempt to address not only the likely impact points of the occupant's head during a rollover, but also critical locations where other parts of the body may try to escape with some significant energy associated with them. Impact energy levels of the guided impact testing ranged from 150J to 400J, based on analysis of velocities of unbelted occupants during a rollover [3]. Occupants to window velocities ranging from 15-24kph have been shown in rollover tests.

Part of the challenge with creating a universal metric at a component level is that rollover scenarios are wide ranging. Of course, there is also the challenge of creating a test in a static environment that can provide insight into a system level response.

It has been observed, while guided impact testing can assess the capability of a system to contain a headform at a given location, the airbag countermeasure reacts to the impact and alters the area of designed coverage. This deflection may also alter how an occupant reacts with the airbag. It may be possible for an occupant to migrate towards areas of an airbag design that may not mitigate ejection effectively.

The changes in coverage can also affect partial ejection for a given system. When an occupant loads a system, it most often moves outboard and towards the roof, leaving a gap at the top of the beltline. This gap is typically in a critical area where partial ejection can occur. Partial ejection is usually associated with non-fatal injuries, but at numbers higher than those with full ejections [4].

GUIDED IMPACT CHARACTERIZATION

The airbag system used in this study was designed for a mid-size SUV and met all requirements for primary impact performance (FMVSS 201/ 214, IIHS) as well as offering extended inflated duration for rollover protection. Coverage of the subject airbag design for all seated occupants is shown in figure 4.

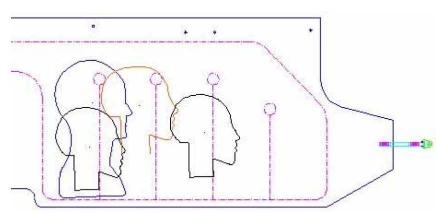

Figure 4. CAD coverage of airbag designed for study

The guided impact testing used an 18kg (40lb) HIII headform. The head was oriented with the front of the head facing forward and the side of the head adjacent to the impacting surface of the airbag. The initial impact location of the testing was position 3 as identified by the NHTSA impact positions. This position was chosen as it potentially represented a challenge for window airbag designs due to the vehicle geometry. The impact energy was 183J, which represents a headform impactor-to-window velocity of 16kph.

Figure 5 shows the guided impact test setup with the airbag in the deployed position. The amount of excursion outside of the vehicle plane was measured using a potentiometer zeroed when the headform contacts the inside surface of the window plane. All deflection values listed are measured from the window plane.

Figure 5. Guided impact test setup with headform impacting the airbag at position 3

The pressure for the airbag design was varied for a series of guided impact tests. The pressure was varied to characterize a range of headform excursions for this study. Note that the specific pressure needed is dependent on the airbag design and the geometry, for this reason specific pressure values will not be listed, and the airbags at varying pressures will be listed by letter.

Results of the guided impact testing for this setup demonstrated retention characteristic of the airbag design to limit the headform excursion at 183J for a given pressure [5].

Computer Modeling

Data from the guided impact testing was correlated to a MADYMO model of the airbag design for additional analysis. Figure 6 shows the excursion test data with the 183J headform impacting at position 3 compared to the correlated MADYMO results of an airbag variant.

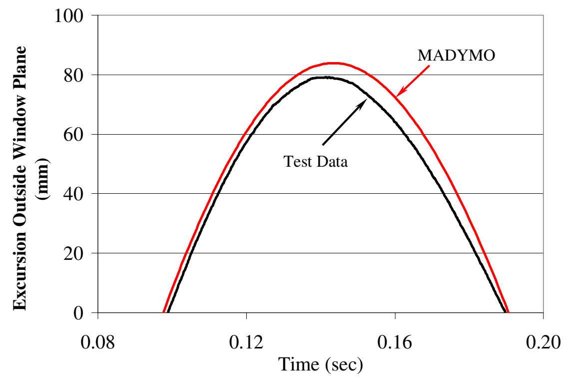

Figure 6. Comparison of headform excursion outside the window plane (MADYMO model versus test data)

The correlated model was used to simulate a range of airbag pressures in the guided impact test in order to assess their headform excursion. Variations of the retention characteristics were based on a range of pressure expected in the system during a late-term event such as rollover. The excursions for the range of airbags in the guided impact test are shown in figure 7.

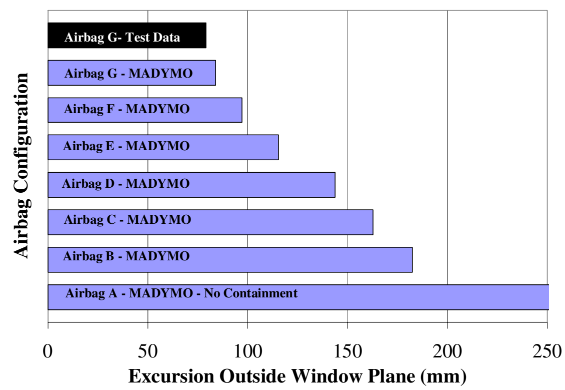

Figure 7. Excursion of airbag design in the guided impact test condition at position 3 for various pressures

When impacting at position 3 with 183J, this range of airbags showed performance ranging from the headform traveling only 85mm outside of the vehicle plane to the headform pushing though the airbag with little resistance and traveling to the end of its stroke. An end view of the maximum headform excursion of two of these systems tested is shown in figure 8.

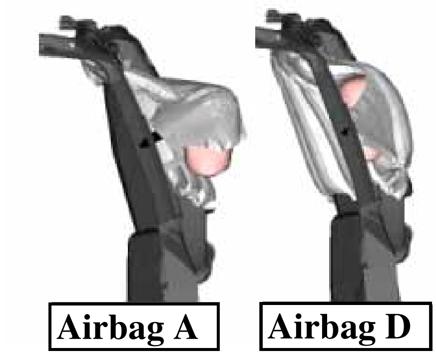

Figure 8. Comparison of headform excursion outside the window plane (airbag A versus airbag D) tested at position 3

ROLLOVER EVALUATION

The Dynamic Rollover Fixture (DRF), a NHTSA research tool for evaluating countermeasures in rollover, was used for the rollover evaluation in this study due to its demonstrated capability to eject a dummy repeatability [6].

The DRF (shown in figure 9) can achieve roll rates of 360 degrees per second as well as occupant to window velocities ranging from 15-30kph, all within the range of real-world scenarios [7].

Courtesy of NHTSA

Figure 9. Dynamic Rollover Fixture (DRF)

The test that was used for this study had a maximum roll rate of 360 degrees per second. Based on analysis conducted by NHTSA with at this roll rate with the unbelted 5^{th} percentile female dummy in this position, occupant to window velocity would be approximated at 15kph [8]. This roughly approximates the velocity seen in the guided impact testing. The DRF fixture is a key element to this analysis. There is a great deal of data on various rollover scenarios and which are most prevalent [9].

A MADYMO model was created using the roll rate and kinematic response of the DRF testing with an unbelted 5^{th} percentile female dummy. This occupant was selected because there was a fairly large data set of tests on the DRF from which to correlate the model. The smaller dummy and lower impact point would likely present challenges for the system. The vehicle geometry of the roof rail in the MADYMO simulation was modified to represent the mid-size SUV that the airbag was designed for.

Figure 10. DRF test with unbelted 5^{th} percentile female dummy versus MADYMO simulation

Once the model was created and validated, as illustrated in figure 10, a comparison was made between the impact location used in the guided impact tests (position 3) and the impact location of the unbelted occupant in the DRF test condition. Figure 11 shows a comparison of position 3 used for guided impact testing and the location where the head contacts initially in the DRF test condition.

Figure 11. Impact Locations - Guided Impact Test Versus DRF

The location of impact seen in the DRF testing was considerably aft (~300mm) of the position 3 used for the analysis. Therefore it was necessary to simulate additional guided impact testing at a position corresponding to the point where the unbelted occupant would load the airbag system in the DRF test condition. This will be referred to as the DRF position, corresponding approximately to position 4 in figure 3. The comparison of the simulations is shown in figure 12.

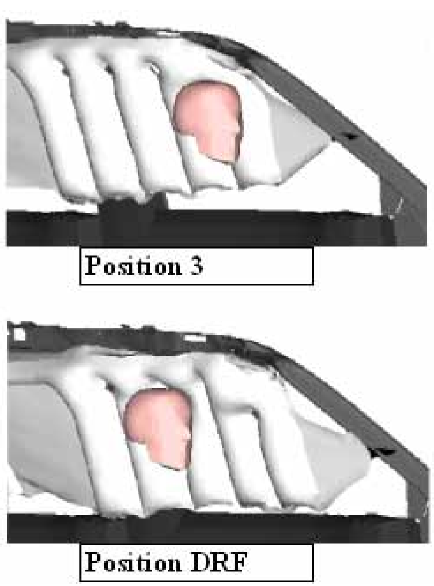

Figure 12. Simulation Impact Locations – Position 3 Versus DRF

The guided impact test series was repeated with the impact location based on that seen in the DRF analysis. The results are shown in figure 13.

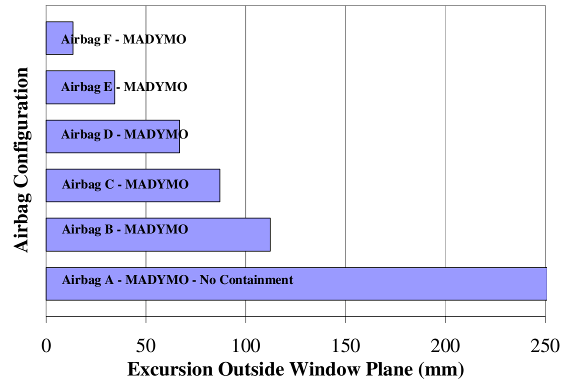

Figure 13. Performance of different airbag designs in the guided impact test condition at the DRF position

The trend of the excursion was the same, but the magnitudes of excursion were much less. The next step in the investigation was to evaluate an unbelted 5th percentile female occupant in the DRF test.

RESULTS

The results of the two sets of excursion testing (position 3 and DRF) as well as the DRF response are shown below in Table 1. The third column indicates which airbag variations contained the occupant and which did not.

Table 1. Performance of different airbag designs in the guided impact test conditions and the DRF test

	Impact Position 3	Impact Position DRF	DRF Test
	Excursion (mm)	Excursion (mm)	Containment (Y/N)
Airbag A	Not contained	Not contained	No
Airbag B	183	112	No
Airbag C	163	87	No
Airbag D	144	67	Yes
Airbag E	115	34	Yes
Airbag F	97	14	Yes

The results of the DRF testing subsequently focused attention on airbags C and D. Additional scrutiny was given to airbags C and D due to the fact that with a very small change in the airbag characteristics, one system did not contain the occupant in the DRF test (C), while the other did (D). The guided impact results for airbags C and D have substantially different excursion values based on their impact locations. These discrepant results make it difficult to define an allowable excursion criterion. Figure 14 shows the occupant response in the DRF test.

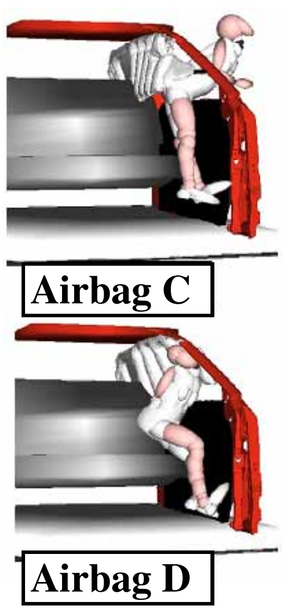

Figure 14. Performance of airbags C and D in the DRF test with an unbelted occupant

A comparison of airbag C and D shows approximately 20mm of difference in their response in the guided impact test, regardless of impact position. Their respective excursions are shown in figures 15 and 16.

Figure 15. Performance of airbags C and D in the guided impact test at position 3

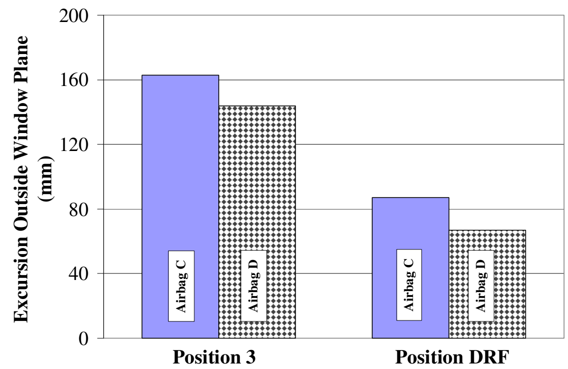

Figure 16. Performance of airbags C and D in the guided impact test at position 3 and position DRF

DISCUSSION

It was observed in analysis of DRF simulations that the occupant moves in the forward direction as it loads the countermeasure (regardless of the airbag variant). This is relevant to the guided impact testing in that the occupant moves from a position with a lower excursion (position DRF, 13mm to 112mm) to a position with a higher excursion (position 3, 97mm to 182mm).

This response consistently shows the unbelted occupant taking the "path of least resistance", out of the vehicle in some cases. With the seat and b-pillar limiting the occupant's movement in the aft direction, and the airbag at the DRF position limiting it in the outboard direction, the dummy moves forward (there are also kinematic contributions such as the mass of the inboard arm swinging forward). The dummy moves forward either until it "pockets" in the un-inflated front zone of the airbag (approximately at position 3) or until it escapes out of the zone with the highest allowable excursion.

The forward motion simulated in the DRF model is illustrated in figure 17 and this forward motion is consistent with different countermeasures [3].

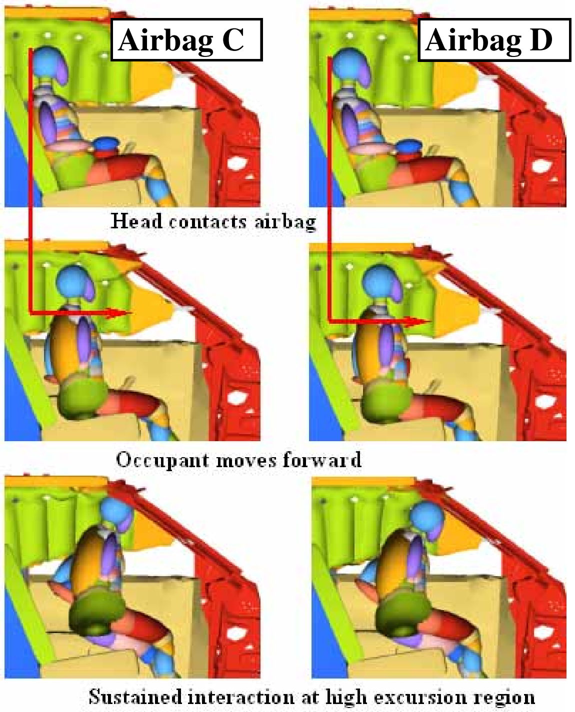

Figure 17. Forward movement during DRF test of airbags C and D

This phenomenon should affect guided impact strategy. Regardless of the guided impact response of the airbag at the point of initial impact, if there exists a region of the airbag with little or no retention properties, an unbelted occupant will move toward that area. If this area is sufficiently large, the occupant may eject in spite of whatever retention is offered in other areas of the airbag.

Additional study on the effect of a single region of the rollover system that offers comparatively less resistance to excursion than other regions and its effect on the overall ejection mitigation performance will be conducted.

CONCLUSIONS

This study analyzed headform excursions for a given window airbag design and varied restraint characteristics to achieve a range of headform excursions in guided impact tests. This study then attempted to find threshold values for excursion in guided impact testing that would either result in occupant ejection or occupant retention in a given rollover environment.

There appears to be at most a qualitative relationship between guided impact head excursion results and risk of ejection, within the limits of this study.

Consequently, use of guided impact testing at a single location, as a means to quantify and inexpensively evaluate curtain designs with regards to ejection mitigation is limited.

The excursion values in the guided impact tests, along with the DRF analysis, do appear to offer insight into the retention performance of a system during the rollover event. The movement forward of the occupant from an area of greater stiffness (lower excursion values) to one of less stiffness (greater excursion values) indicates a phenomenon that should affect the occupant retention strategy of airbag design.

RECOMMENDATIONS

Until some guided impact test standard is developed it is recommended that caution be used in predicting occupant ejection risk using guided impact test results.

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ROOFBAG-A CONCEPT STUDY TO PROVIDE ENHANCED PROTECTION FOR HEAD AND NECK IN CASE OF ROLLOVER

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ABSTRACT

The purpose of this conceptual study is to address the increasing number of fatalities and severe injuries in vehicle rollovers. A restraint concept for reducing Head and Neck loading by hard contact with the roof of the car has been developed to reduce and/or mitigate these injuries.

The human neck is capable of sustaining higher loads when it is in flexion (e.g. the head is bent forward). Therefore, moving the occupant's head to a bent forward position using a slowly deploying airbag is proposed.

The Roofbag concept includes a slide chamber and support chamber. Together, they form a multi-chamber airbag which is mounted at the top of the seat back. The inflator has an extremely slow onset, causing the airbag to deploy in about 250ms. When the slide chamber is inflated, it positions itself behind and above the occupant's head. The support chamber pushes the slide chamber forward, causing the occupant's head to bend forward.

Three advantages for this concept have been identified: the occupant's neck can sustain higher bending loads when positioned in flexion; a cushion is positioned between the occupant's head and the roof; the survival space between the head and the roof is increased.

A series of rollover tests (SAEJ2114, Curb Trip) using HIII dummies were performed to understand and demonstrate the benefits of this concept. The results show a significant reduction in head and neck injuries when the Roofbag concept is employed. Out-of-position tests show low-to-medium level loadings.

Further potential benefit could possibly result from expanding the Roofbag concept to other applications, such as head protection for convertibles or neck protection during rear impact.

INTRODUCTION

For many years Rollover has been a growing issue. According to DOT HS 809438 [3] occupant fatalities in SUV rollovers increased dramatically nearly doubling from 1991 to 2000. For comparison the rollover fatalities in passenger cars decreased and for Pick-Up Trucks and Vans it stayed constant.

Rollover – A New Challenge in Safety

When comparing Rollover with frontal or side impact accidents we find significant differences in the following parameters:

Timing; the main injuries in a side or front impact occur at about 30 ms up to 100 ms. In a rollover the time window for injuries occurs at a time later than 500 ms after the rollover is unavoidable. Hence, the rollover event is at least a ten times slower event than a front or side impact.

Multi-Directional Kinematics; in Rollovers the motion of the occupant is multi-directional and continuing for up to 5 seconds. Hence, injury contacts are much less predictable which makes it difficult to provide appropriate protection devices. Fay and Sferco [6] show that rollovers in Europe often occur in multi impact crashes as the later event. This indicates that at the time of a rollover the seating position of the occupant is already undefined.

Human Reaction; a rollover is a comparatively slow event which allows the occupants to react to the upcoming event. According to the DOT HS 809438 report [3] about 33% to 50% of the drivers attempted to avoid the rollover by a steering maneuver which is a volitional action. There is also a natural subliminal muscle tonus which starts to activate muscle action 100 ms to 200 ms after the occupant experiences quick movements [18]. Together it shows clearly that the rollover event causes human reactions – volitionally or subliminally.

Together this explains why standard safety devices for frontal and side impact are not effective for rollover.

Rollover Types, Roof Crush and Injuries; Bedewi et al [1] show that 57% of rollovers are initiated by the ground. The second most frequent initiation sources are fixed objects at 13% and contact with another vehicle accounts only for 8%. It can be assumed that ground as initiation source results in most cases in trip-over type rollovers. This is also confirmed by Eigen [5] where single vehicle trip-over accounts for 71% of rollovers. The number of quarter turns is a significant measure which correlates in many cases with injuries. One quarter turns are less frequent – they account for about 14% to 22% for all categories of vehicles [1]. Two, three or four quarter turns are most common, with an occurrence rate of 40% to 58% [1]. The remaining cases have five and more quarter turns. Hence, it can be concluded that most rollovers have at least one roof-to-ground contact. Furthermore, Bedewi et al [1] looked into the maximum roof deformation as an indicator for head-roof associated injuries. It is shown that 37% of Head-Roof AIS3+ injuries correlate with a roof deformation of 30cm up to 45cm. Another 20% of Head-Roof AIS3+ injuries correlate with a roof deformation of 15cm up to 29cm. For comparison the FMVSS 216 regulates a maximum deformation of 12.7cm (5 inches). For belted occupants roof contact is the most common injury source: passenger car 31%, pick-up 52%, SUV 33% and van 24% [1].

Non-Ejection Injuries: Digges and Eigen [2] analyzed the different categories for rollover MAIS 3+ occupants. They found the three most dominant fractions: Belted-non-ejected (35.3%), Unbelted-non-ejected (23%) and Unbelted-totally-ejected (32.5). The other categories are 5% or less. As commonly known, the unbelted driving condition is the most dangerous - not only for rollover. To cope with the ejection issue the NHTSA [4] has done extensive ejection mitigation studies which target establishing a future safety standard. It will require a reasonable level of containment for an occupant in a rollover. Therefore, in this paper we focus on injuries of non-ejected occupants. Obviously, seat belts are very effective to avoid ejection, but they also have limitations when head-to-roof contact must be avoided. As rollovers can be such chaotic events, it can be assumed that head-to-roof contact occurs mainly because of two reasons: Firstly because of roof intrusion and secondly because the shoulder belt is slipping off and then passing the gained belt slack to the pelvis belt and hence, allowing extra movability towards the roof.

INJURY MECHANISM IN A ROLLOVER

Impact Location; Literature is packed with statistical interpretation of rollover accidents and the resulting injuries.

Head, face and neck injuries represent a significant part of rollover related AIS3+ injuries.

For these body regions, literature states that the most important injury source is the roof [9] including the roof rail.

So, there is an exigent need for an additional protection system that provides enhanced performance to protect the head, face and neck region in case of a rollover.

Biomechanics; From the biomechanical point of view, the head-neck portion is a quite complex mechanism. It includes vertebral bodies connected multi-muscularly to each other, blood vessels, intervertebral disks and the spinal cord. The head rests on top of the spine. For the head's rotation, mainly the articulation between the 2 upper vertebrae Atlas (C I) and Axis (C II) is responsible. It allows humans a physiological rotation of ±45° around the yaw axis.

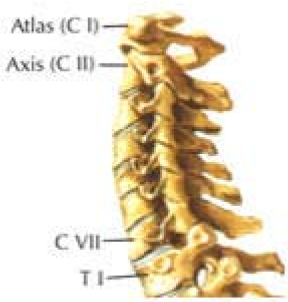

Figure 1. Cervical spine
Netter: „Atlas of human anatomy"[14].

The complete cervical spine and the atlanto-occipital junction are responsible for flexion/extension (pitch) and lateral bend (roll) as shown in Figure 2. They allow flexion of 40°, extension of -75° and a lateral bend of ±75° [22]. These multi-directional degrees of freedom and the wide ranges of physiological mobility require a fragile constitution which can be disadvantageous in the case of a rollover.

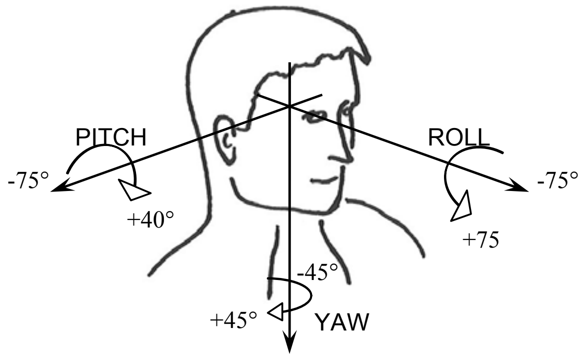

Figure 2. Axes defining physiological motions.

Injuries and Injury Mechanisms; Injuries of the cervical spine are typically caused by exceeding spinal motion limits or force limits. In case of an accident, high forces induced by the vehicle's kinematics and by the inertia of the torso and head effect serious damages. Typical injuries of the cervical spine during a rollover are mainly caused by bending, compression, tension, torque and shear of the upper spine. The injuries express themselves in wedge fractures, burst fractures and dislocations [11 and 13].

Head injuries of restrained occupants are typically caused by high velocity contacts of the head to interior parts, mainly the roof and roof rail. No matter if the roof is crushed or not and independent from the restraint use, the head's injuries are a great fraction of the injury distribution. Typical head injuries are fractures of the skullcap or serious damages of the brain, e.g. epidural hematomae.
The high risk of spinal cord and brain injuries and the consequences that arise out of these injuries like paralyzation or death is what makes rollover injuries so dangerous and expensive for the entire society.
Head-roof contact, being the main cause of head and neck injuries [9], occurs when the occupant moves out of its seat towards the roof or roof rail.
When being turned upside down, the force of the entire body mass is imposed on the head-neck complex in a mainly axial direction.
The injury mechanisms of the spine have been simulated in cadaver tests of the upper spine and head region.
Nightingale, Myers and McElhaney et al [16, 13] describe test methods for analyzing injuries of the upper spine of cadavers. A head-spine test specimen, connected to a simulated torso mass of 16 kg, is dropped from a height of 0.53m. Objective of the analyses is the influence of varying underground properties and angles.

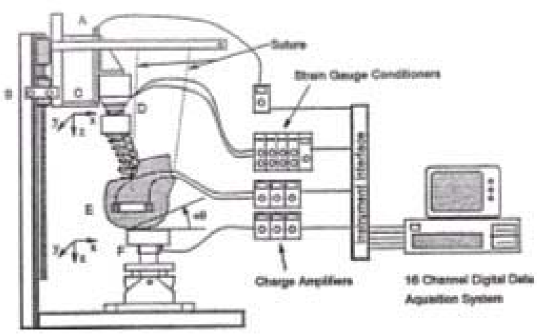

Figure 3. The dynamics of head and neck impact Myers, Nightingale: IRCOBI 1997 [13].

It has shown to be advantageous if axial and vertical loads are induced to the spine in a pitched head position (posterior head impact).
It has also shown that a soft padded surface, being able to deform upon the load of the head, can be disadvantageous under certain circumstances. It can deform, thus build a pocket that will trap the head and hinder it from flexing out of the force path.

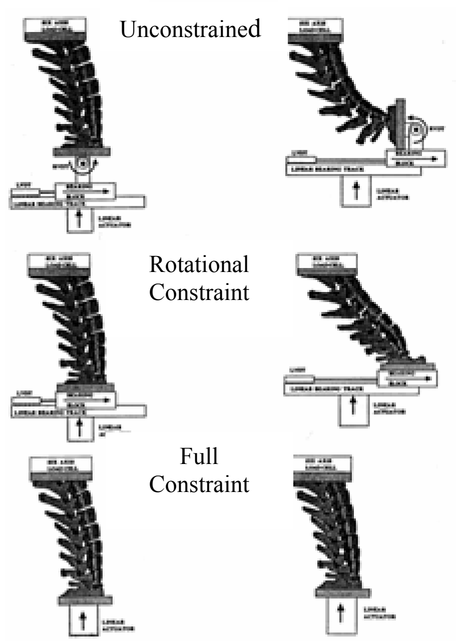

Figure 4. End condition on cervical spine McElhaney and Myers et al: SAE 912915 [11].

In "The influence of end condition on human cervical spine injury mechanism" [15], Myers and McElhaney et al. examine axial loads on the human spine.
Figure 4 shows the motion patterns of loaded cadaveric cervical spines in the above mentioned study upon different constraint types of the neck.
The axial loads and moments on the spine decrease from the fully constrained to the unconstrained type.
The unconstrained type shows how the spine reacts to an axial force if the head has the possibility to give way and flex out of the force path. The higher the constrictions on the degrees of freedom are, the higher the risk of injury.
Spinal injuries can be prevented or mitigated by reducing the compression force acting on the neck.
The unconstrained resulting motion is desirable for the upper spine in case of a rollover event.
The movement pattern is similar to the natural or physiological protection position, if it is possible for the occupant to react in a timely manner (Figure 4).
Occupants, when realizing a dangerous situation, will actively increase the head-to-roof clearance by flexing the head-neck complex as shown in Figure 4 [8].

Figure 5. Restrained occupant in a 180° roll Friedman: SAE 980212 [7].

Pocketing is an effect that leads to undesired constraints in the head's linear and rotational movability and should thus be avoided.
Pocketing can be caused by a vertical excursion of the occupant towards a soft roof liner structure. The head, being axially loaded by the neck and the effective torso mass, will dive into the soft roof liner material, thus deforming it and building a form-closed connection which reduces the head's capability to escape linear forces and rotational moments.

Roof Crush or roof intrusion worsens the situation. Injuries caused by compression forces of restrained occupants in rollovers appear to result also from an intruding roof that decreases the head-roof clearance.

The collapsing roof can also form a pocket around the head which results in an undesired motion pattern [7].

Padding on the roof during a head-roof contact has a significantly positive effect on the head injury values. Nightingale et al. [16] show that padded surfaces have a direct influence on the forces acting on the head. But padding also can be disadvantageous. By introducing padding materials, the risk of "pocketing" the head is increased as well.

The challenge is to get padding without generating a pocketing effect.

Figure 5 illustrates an occupant in a 180° roll. The differences in head-roof distance in the bent and unbent head-neck complex are apparent. On the left side, there is a high risk for injuries due to little roof clearance, axial load of the spine and only little space for padding. Since the forces of the torso weight will be transmitted to the roof nearly perpendicularly, there is also a high risk of "pocketing". On the right side, a greater head-to-roof clearance is apparent, also a posterior initiation of forces and space for padding elements. In case of rollover, the position of the right occupant is advantageous.

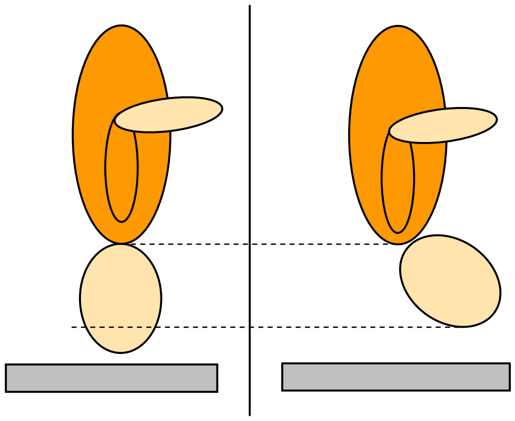

Figure 6. Increasing head-roof clearance by flexion of the neck at a 180° roll.

Summarizing the causes for head-neck injuries in a rollover event, it can be said that not only avoiding some of the mentioned dangerous conditions, but avoiding all of them must be the goal.

- Avoiding cervical injuries by not transmitting the load vertically and axially to the upper spine [17].
- Increasing the head-roof clearance by neck flexion has substantial potential for injury reduction.
- Introduction of padding in the area of head-roof contact to reduce head injuries, thus to reduce forces in axial direction, but without creating the pocketing effect.

All points together have been realized in a newly developed airbag that has high potential to reduce serious injuries of the head-neck complex in the case of a rollover event significantly.

ROOFBAG CONCEPT

The Roofbag is a multi-functional rollover protection system. It has been designed to mitigate / avoid the large fraction of head, face and upper spine injuries which in the field represent a significant part of rollover related AIS3+ injuries.

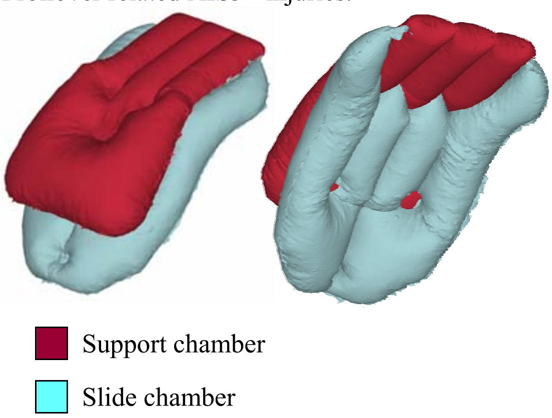

Figure 7. Roofbag simulation model.

Roofbag Cushion: The Roofbag cushion consists of two airtight chambers: A slide chamber which is directly connected to the inflator and will be filled by the inflator upon ignition of the airbag system.
A support chamber, which is attached to and riding on the slide chamber.

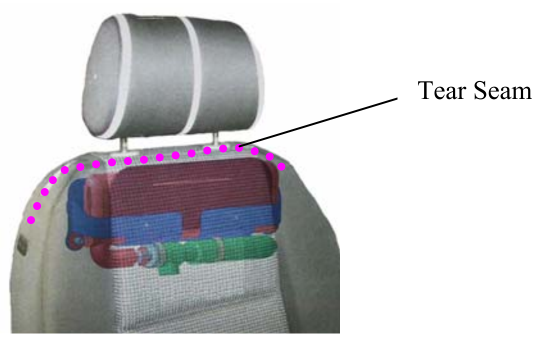

Figure 8. Roofbag assembly in seat (illustration).

Roofbag Package: The Roofbag package is mounted in the upper portion of the seat backrest. It is directly attached to the seat frame. Being deployed, it will open a tear seam applied to the seat back cover.
With its soft housing it can be implemented without disturbing the comfort function of the seat. It can be adapted to seats with an active head rest.

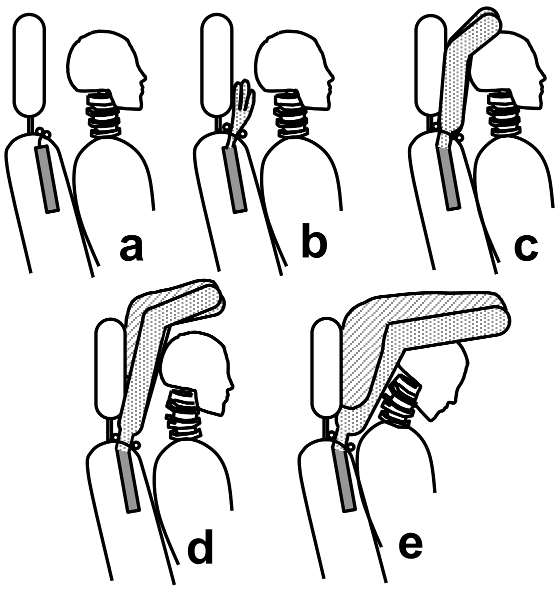

Figure 9. Roofbag function (illustration).

Roofbag Function: Different from known airbag systems, the Roofbag is designed to actively move the occupant into a "rollover-protected" position.
Upon detection of an upcoming unavoidable rollover event, the Roofbag will deploy. The slow onset inflator will open the tear seam, and deploy the slide chamber. The slide chamber (Figure 9b) with its side arms will span up the uninflated support chamber and guide it through the gap between head and head rest (Figure 9c).
The support chamber is inflated through venting ports between slide- and support chamber.

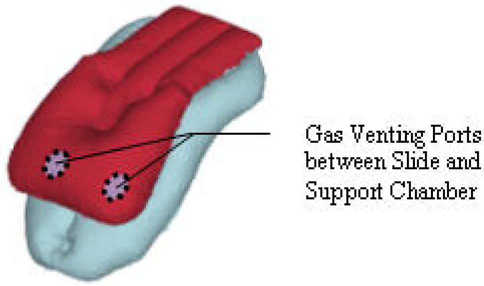

Figure 10. Gas venting ports (illustration).

Compared to the slide chamber, the support chamber is filled with a time delay.
Inflating slowly between the head rest and the slide chamber, the support chamber gently presses the occupants head into a "rollover-protected" position (Figure 9d + e).

Benefits of the "Rollover-Protected" Position:
To mitigate rollover injuries effectively, the Roofbag's rollover protection concept is threefold:

The Roofbag transforms unfavorable axial neck and spine loads into posterior loads, thus allowing the head and neck portion to escape the critical axial load path by flexing in its natural degree of freedom.
The Roofbag increases the survival space between head and roof.
The Roofbag supplies sufficient padding between head and roof structure, reducing head injuries caused by direct head-roof contact without trapping the head (pocketing effect).

Enclosing the head-neck portion from above, the Roofbag will additionally help to protect the occupants head against lateral movement.

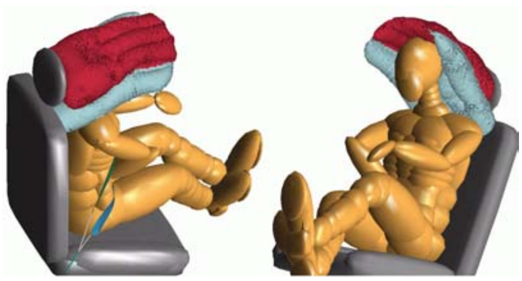

Figure 11. Roofbag CAE function testing.

Roofbag Deployment: Compared to other state-of-the-art side airbag systems, the Roofbag has a very low onset inflator and subsequently deploys slowly.
Its nominal time to position the cushion and also the occupant is about 400 ms [Figure 12 and 13].

This will allow deploying an airbag in the sensitive head-neck region without endangering an in position or out-of-position occupant.

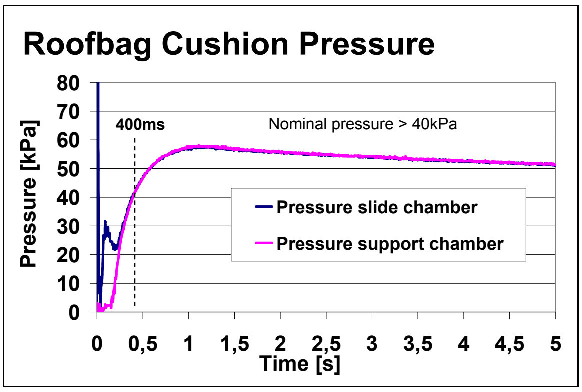

Figure 12. Roofbag RT cushion deployment pressure.

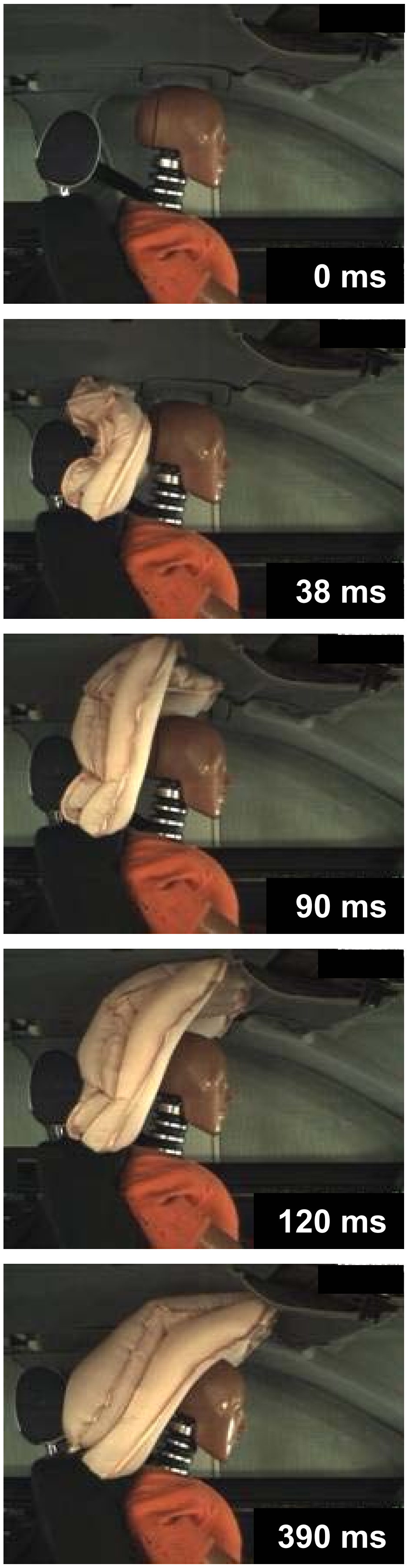

Figure 13. Roofbag deployment (50% Hybrid III).

Dummy Neck vs. Human Neck:
A 50 % Hybrid III dummy was used for development tests. The Hybrid III dummy, being a standard in rollover testing, has a stiffer neck compared to the human neck.
The Roofbag's flexing effect is not as visible when used with a Hybrid III dummy.
The Roofbag is far more effective in flexing a human occupants head and neck portion into a "rollover-protected" position.

Figure 14/15. Comparison human / dummy response.

Collaboration with other Restraints:
The Roofbag has been developed to collaborate with other occupant restraint systems.

In combination with rollover-optimized seat belts and curtain airbags, it will effectively protect the occupants head against roof and roof rail impacts and to a certain extent also against lateral head movement.

For unrestrained occupants, a benefit can be expected for rollovers, when the occupant is still in the protection area of the cushion.
Since in later rollover phases the occupant's position is likely to change drastically, an additional benefit for unrestrained occupants is uncertain.

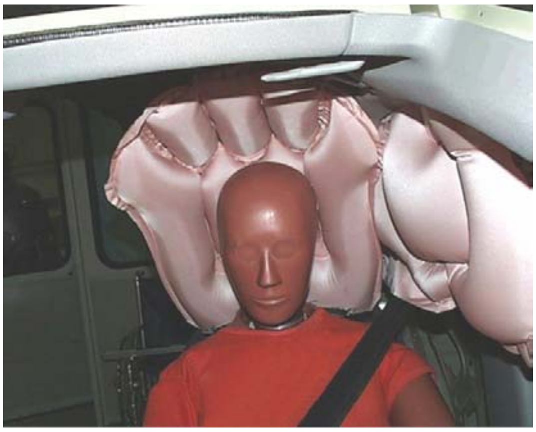

Figure 16. Combination of rollover relevant restraints.

TEST RESULTS

Pendulum Test Results

Several tests were conducted to check the performance of the developed system.
First a falling pendulum test was designed to be adequate for a first evaluation system. The aim was to simulate the kinematics between the dummy head and the intrusion of the roof.
A falling pendulum is mounted to a rigid wall and a linear guided drop plate is raised to a certain height.

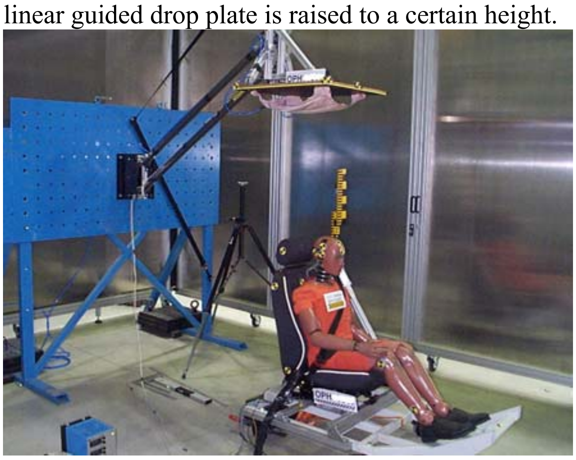

Figure 17. Fall pendulum test setup with dummy Hybrid III 50%.

The pendulum energy as result of the drop height and the mass of the drop plate was defined considering to the assumptions of the investigations by B. Myers [13]. The mass of the drop plate was defined as effective torso mass at 16 kg, the resulting energy was adjusted by the drop height and ranges up to 110 Joule.

First, a baseline test without a protection system was conducted. The pendulum performance tests were conducted with an unfolded cushion that was filled with compressed air. In parallel, the deployment behavior and the cushion folding were developed. The ideal pressure was detected by a series of pretests (see chapter roofbag concept) and defined as a target pressure of about 50 kPa.

For all following tests the Hybrid III 50% dummy was used. This dummy is regulated in the FMVSS208 rollover test and most popular in other papers and publications for rollover evaluation.

The energy of the pendulum was defined by 110 Joule (mass= 16 kg, v=4.7 m/s). The most important resulting dummy loads are shown in table 1.

Table 1.
Results of Baseline Test without Roofbag.

Dummy Load	Value
Axial compressive Neck Force	-7.6 kN
Flexion Bending Moment	28.4 Nm
Extension Bending Moment	-34.1 Nm
HIC_{15}	191
NIJ	1.3

As expected and seen in table 1 the body regions of interest were the head and the neck of the dummy.
The Injury-Assessment Reference Values for Hybrid III-Type adult Dummies (IARV) by Mertz [12] have been suggested as guidelines for assessing injury potentials associated with measurements made with Hybrid III-type 50% adult dummy. Additionally, the Neck Injury Criteria [23] (NIJ) was regarded as the limit for the neck loads. The relevant limits for the test are shown in table 2.

Table 2.
IARV Dummy Limits according to Mertz [12].

Dummy Load	Limits
Axial compressive Neck Force	-4.0 kN
Flexion Bending Moment	190 Nm
Extension Bending Moment	-57 Nm
HIC_{15}	1000
NIJ	1.0

Especially the neck compression force with -7.6 kN is nearly two times higher than the limit of -4.0 kN. The NIJ is exceeding the limit.
Several pendulum tests were done to improve and to show the performance of the system.

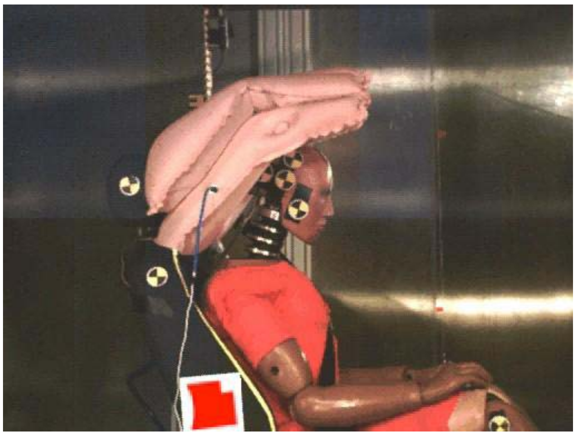

Figure 18. Fall pendulum test setup with dummy Hybrid III 50% and deployed roofbag before test.

The results of the tests are shown in table 3. The pendulum tests have shown that the roofbag is able to reduce the critical axial neck compression force from -7.6 kN to an uncritical -1.25 kN. The flexion neck moment is reduced from 28.4 Nm to 11.3 Nm. The extension neck moment virtually stays the same and has to be observed for further tests, also considering the limit of -57 Nm. Beside the axial neck compression force there is also an impressive improvement regarding the HIC (191 w/o roofbag, ≈0 with roofbag) and the NIJ reduction (1.3 w/o roofbag, 0.3 with roofbag).
The dummy sensor curves are listed in the Appendix (see Appendix Figure A1 for neck loads and Figure A2 for resultant head acceleration).

Table 3.
Results of Performance Pendulum Test with and without Roofbag.

Dummy Load	Limits	Baseline	With Roofbag
Axial compr. Neck Force	-4.0 kN	-7.6 kN	-1.25 kN
Flexion Moment	190 Nm	28.4 Nm	11.3 Nm
Extension Moment	-57 Nm	-34.1 Nm	-37.9 Nm
HIC_{15}	1000	191	≈ 0
NIJ	1.0	1.3	0.3

Rollover Test Results

Two standard rollover crash tests according to the FMVSS208 have been confirmed with 2 Hybrid III 50% dummies in the front seat row (driver and passenger side).

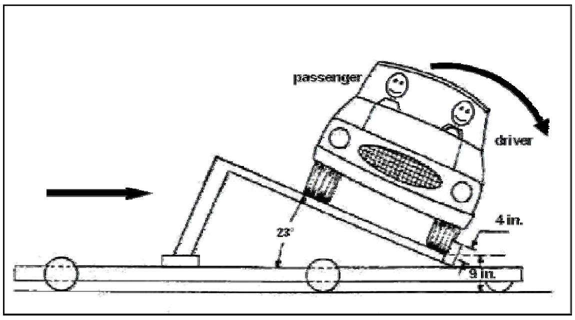

Figure 19. Rollover test setup according to FMVSS208.

The vehicle was a current popular European passenger car. The first car was equipped without additional safety devices; the second car was equipped with the roofbag system. During the rollover all dummy signals were recorded to document the dummy loads and the performance of the roofbag.
Figure 20 shows the dummy on the driver side with the deployed roofbag module in test position.

Figure 20. H III 50% dummy on driver side with deployed roofbag in test position.

Table 4 shows the dummy loads on the driver side, table 5 shows the results on the passenger side dummy in relation to the limits.

Table 4.
Dummy Loads on the Driver Side.

Driver Position			
Dummy Load	**Limits**	**Baseline**	**With Roofbag**
Axial compr. Neck Force	-4.0 kN	-2.4 kN	-0.85 kN
Flexion Moment	190 Nm	8.4 Nm	12.1 Nm
Extension Moment	-57 Nm	-9.1 Nm	-18.1 Nm
HIC_{36}	1000	27.4	20
NIJ	1.0	0.4	0.26

Table 5.
Dummy Loads on the Passenger Side.

Passenger Position			
Dummy Load	**Limits**	**Baseline**	**With Roofbag**
Axial compr. Neck Force	-4.0 kN	-12.0 kN	-0.80 kN
Flexion Moment	190 Nm	53.2 Nm	20.1 Nm
Extension Moment	-57 Nm	-12.7 Nm	-19.4 Nm
HIC_{36}	1000	102	72
NIJ	1.0	2.07	0.27

A comparison of the different results on each individual value shows the tendency that the dummy loads on the passenger side are higher compared to the values on the driver side. The reason is the rotation of the vehicle during the rollover. The driver is on the "near side " to the ground and below the axis of rotation of the vehicle; the passenger is so called " far side" and has much more energy of rotation during the first roll. The performance of the roofbag as seen in the pendulum tests is confirmed by the results in table 4 and table 5.
The most impressive reduction is seen on the passenger side. The compression neck force reduces from -12.0 kN (w/o roofbag) to 0.8 kN (with roofbag) and the reduction of the NIJ from 2.07 to 0.27(with roofbag). The other dummy loads cannot be improved in a clear way, but those values are not critical. The reduction of the compression neck force and the NIJ is the result of the changed kinematics of the dummy. The reason for this change of kinematics is the influence of the roofbag that forces the dummy into the rollover protected position.
The passenger dummy sensor curves are listed in the Appendix (see Appendix Figure B1 for neck loads and Figure B2 for resultant head acceleration).

Out-of-position Tests

Another important point beside the performance during a crash is the low aggressiveness in out-of-position situations. Out-of-position tests are defined for frontal airbags [24] and side airbags [10]. New test positions were designed, in accordance with the known out-of-position setups. The following dummies were chosen to be important: Hybrid III 5% female, Hybrid III 6 year old dummy, Hybrid III 3 year old dummy.
Table 6 shows the defined dummy positions.

Table 6.
Out-of-position Dummy Positions.

Dummy	Position
Hybrid III 5% Female	Sleeping Position
Hybrid III 6 year Child	Rearward facing kneeling on Seat
	Forward facing on Cube
Hybrid III 3 year Child	Forehead on Tear Seam
	Forward facing on Booster Cube

The positions were defined to produce the worst possible interaction between dummy and roofbag module. Nevertheless the positions should not be too unrealistic; all tests were conducted with head rest in the seat back and with one type of seat.
Limit values for the head, neck and thorax were defined, to have a guideline and to assess the results. The limits for the relevant dummies were taken from the TWG [10] limits for side airbags. Those relevant limits are shown in table C1 and C2 in the Appendix. The TWG [10] distinguishes between reference values, which are established and significant and the research values, which have to be considered for further developments and have a biomechanical and scientific basis. For the Roofbag study, all values were taken to be equivalently important.
Figure 21 and Figure 22 show typical newly defined testing positions.

Figure 21. Out-of-position configuration "sleeping female" for Hybrid III female dummy.

Figure 22. Out-of-position configuration "forehead on tear seam" for Hybrid III 3 year old child dummy.

The results of the tests are shown in table C3 in the Appendix, in each case the 5 highest values were presented as percentage of the limit values (table C1 and table C2 in the Appendix). All tests showed acceptable injury risks for dummies out-of position.
Only one of the conducted tests has a maximum dummy load above 40% relative to the limit, which is the position rearward kneeling on booster (see Figure 23).

Figure 23. Out-of-position configuration "rearward kneeling on booster" for Hybrid III 6 year old child dummy.

As seen in table C3 (Appendix) there were two dummy loads above 40%, the highest load is the extension moment in the lower neck with 74% followed by the NIJ with 70%. Both loads are directly induced by the deploying roofbag, the cushion strikes directly to the dummy head with a load path into the direction of the center of gravity of the head. The booster used in this configuration caused highest loads on the head, so higher loads in variations of this position were not expected, in other words, this seems to be the worst case. Nearly all test positions can be rated as uncritical. Nevertheless there are parameters like, the finish of the tear seam and the cover fabric of the back rest which can directly influence the out-of-position performance. Thus the out-of-position performance should be checked continuously in parallel with the further development or, while changing the vehicle surrounding.

DISCUSSION

Seatbelt Use vs. Head-to-Roof Contact

Among other topics NHTSA has declared Rollover and also seatbelt use as top priority. Increasing seatbelt use will reduce injuries for frontal and side impacts and also for rollover. For rollover the most important benefit will be a huge reduction in ejections. But even if seatbelts were to be used by 100% of all vehicle occupants there would still be a considerable number of injuries [2]. Up-to-date seatbelts are equipped with pretensioners and energy absorbing devices which are designed for frontal impact performance. In case of a rollover the pretensioner will reduce the belt slack and hence the mobility of the occupant towards the roof will be limited. Despite up-to-date seatbelts there is still a risk for head-to-roof contact. First, we have to consider that in the chaotic event of a rollover the occupant may slip out of the shoulder belt and hence gain additional mobility towards the roof. Second, there are considerable numbers of vehicles that experience a large roof intrusion during a rollover which causes a high injury risk regardless of seatbelt use. Together it can be seen that head-to-roof contacts can not be avoided in a rollover. Therefore, we need safety devices for rollovers which provide safety beyond seatbelts. The target is to avoid Head-to-Roof contact. The roofbag concept has shown its capability to do so.

Ejection Mitigation vs. Head-to-Roof Contact

Injury field statistics show that in many cases occupants were not belted when experiencing a rollover. Subsequently many of those occupants were ejected from the vehicle and seriously injured. Currently, the injuries caused by total or partial ejection outnumber the other injuries. Hence ejection must be avoided. NHTSA and industry are putting high priority on pursuing advanced restraints which prevent ejection through the side window. Only after such advanced ejection mitigation restraints are introduced to the fleet should we think about the second priority which is to avoid head-to-roof contact. As seen from the shown test results a concept like the roofbag will be highly beneficial.

Dummy (HIII vs. ESII)

Throughout the roofbag concept study the Hybrid III dummies were used (50%; 5%; 6year old and 3 year old). However it can be argued that this is not a suitable dummy for Rollover testing. The ESII dummy or WorldSID would have been a better choice for lateral injuries. A RID (Rear Impact Dummy) could have been a better predictor when it comes to neck and spine injuries. To enlarge the testing program to those additional dummies the time and finance budget would have been multiplied several times. Therefore, it was decided to focus on an evaluation program around the Hybrid III family. The results provided show the high potential of the roofbag concept. If we were to consider a mass production close application of the roofbag concept, the roofbag will need further detailed evaluation and possibly more optimization.

Restraint Performance beyond Rollover

All evaluations which were done were focused on rollover protection. When deployed - the roofbag is located between the head rest of the seat and the head of an occupant. This makes the roofbag concept a potential candidate to reduce rear impact induced injuries. At a timing of approx. 40 ms the roofbag fills already the gap between the head rest and the occupants head. At this timing the pressure inside the roofbag is above 20 kPa. It is yet to be evaluated how effective the roofbag concept could be used in case of a rear impact situation. If we can define a positive balance between rear impact vs. rollover and cost vs. benefit - then the roofbag concept will earn additional credit points for implementation.

CONCLUSIONS

The roofbag concept is a brand new idea on how to reduce head and neck injuries which are caused by head-to-roof contacts. From biomechanics we learn how to bring the occupant into the best "rollover-protected" position (i.e. bending the occupants head and neck actively forward). Deployment tests and pendulum tests show the basic performance and benefit. The pendulum tests show the following drastic injury reductions (100% are equal to limit value):

- Axial compression neck forces were reduced by 158%
- Neck Flexion Moment were reduce by 9%
- HIC was reduced to from 191 to ≈ 0
- NIJ was reduced by 100%

FMVSS 208 rollover tests were conducted to evaluate the dynamic performance. Different benefit values could be achieved for driver and passenger occupants. For the driver (near-side seating position) the following was achieved:

- Axial compression neck forces were reduced by 38%
- The flexion moment was increased from 8.4 Nm to 12.1 Nm. This increase is not critical at all since the limit is set at 190 Nm.
- The extension moment was increased from -9.1 Nm to -18.1 Nm. Again this is not critical as the limit is set at -57 Nm.
- The HIC was reduced from 27.4 to 20

- NIC was reduced by 14% to a uncritical 0.26

The benefit for the passenger side occupant (far-side seating position) was more significant. This was not a surprising result as this seating position usually experiences higher rotational forces. The following was achieved:

- Axial compression neck forces were reduced by 280%
- The flexion moment was reduced by 17%
- The extension moment was increased from -12.7 Nm to -19.4 Nm. This is not critical as the limit is set at -57 Nm.
- The HIC was reduced from 102 to 72
- NIC was reduced by 180% to a uncritical 0.27

Finally tests were done to evaluate the potential risks for in or out-of-position seating situations. These evaluations show no significant injury risk for dummies in-position and acceptable injury risks for dummies out-of-position.

In summary the effective use of the roofbag concept was shown in various conditions. Further efforts will be needed to reduce serious and fatal injuries in case of rollovers. Also efforts will be beneficial which direct to technologies and consumer education to avoid rollovers as a whole.

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APPENDIX

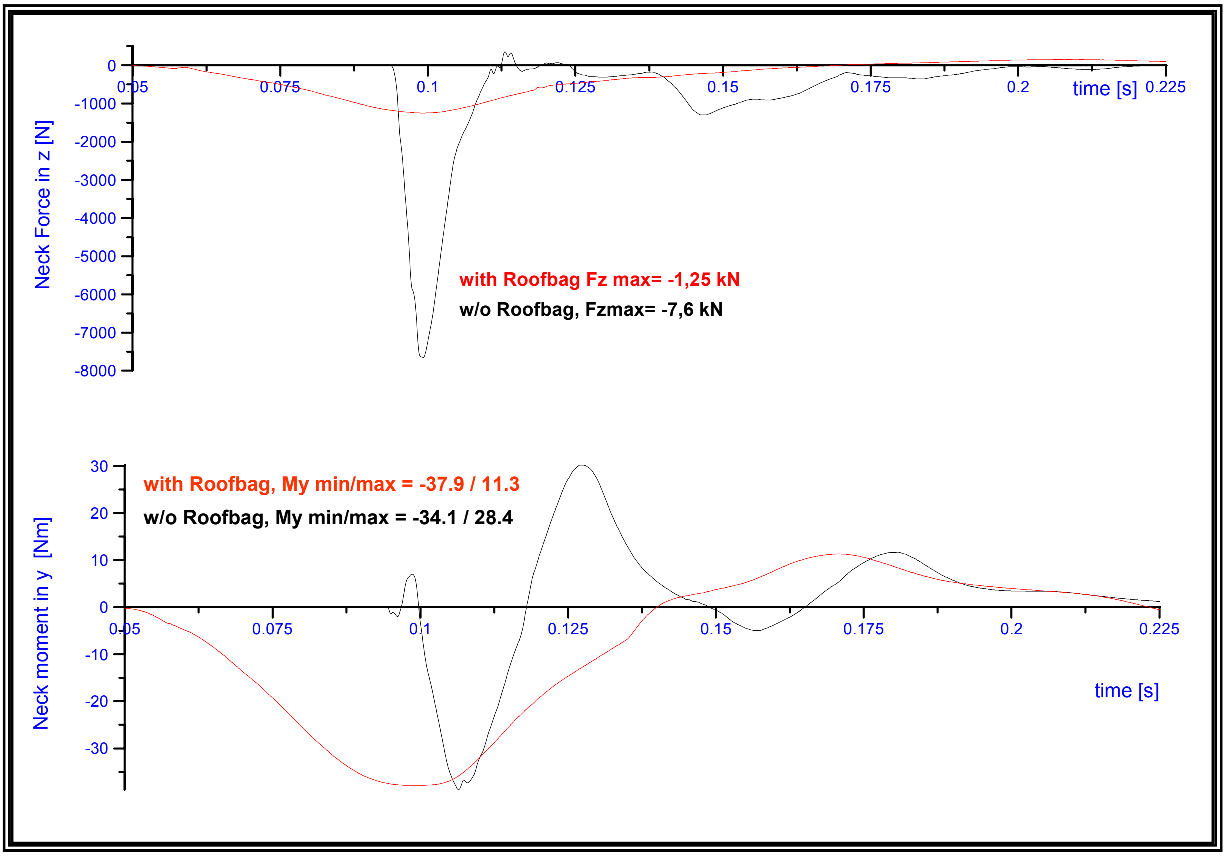

Figure A1. Comparison of neck force and neck moment in pendulum tests with and without roofbag.

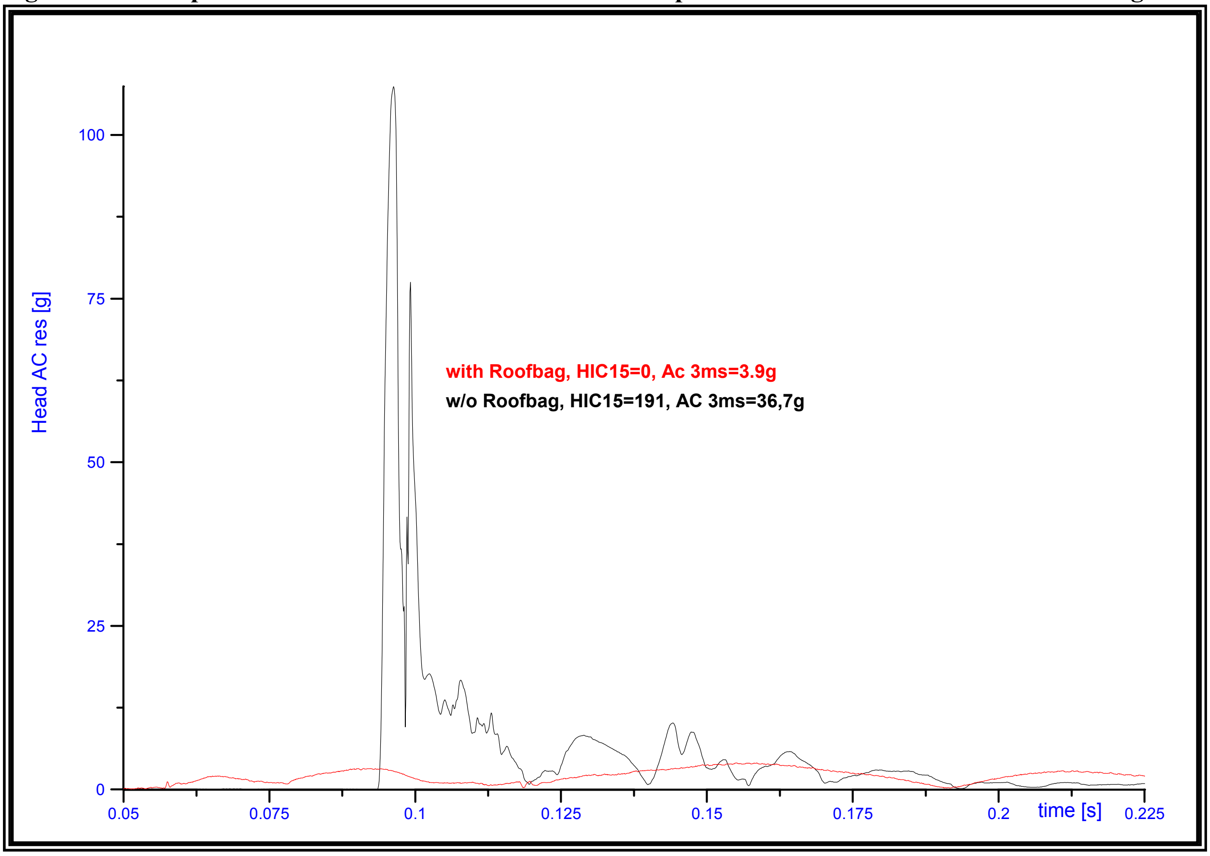

Figure A2. Comparison of resultant head acceleration in pendulum tests with and without roofbag.

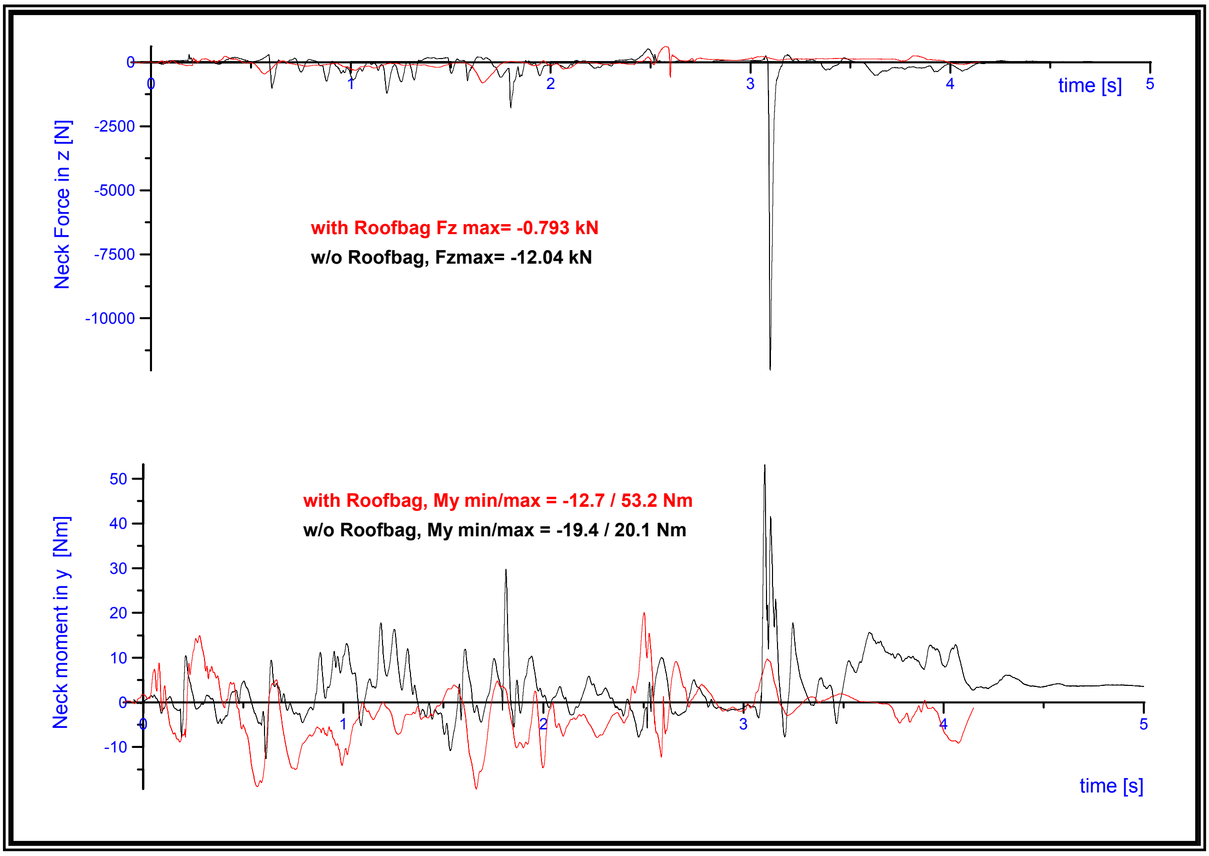

Figure B1. Comparison of neck force and neck moment in FMVSS208 rollover test with and without roofbag, passenger side.

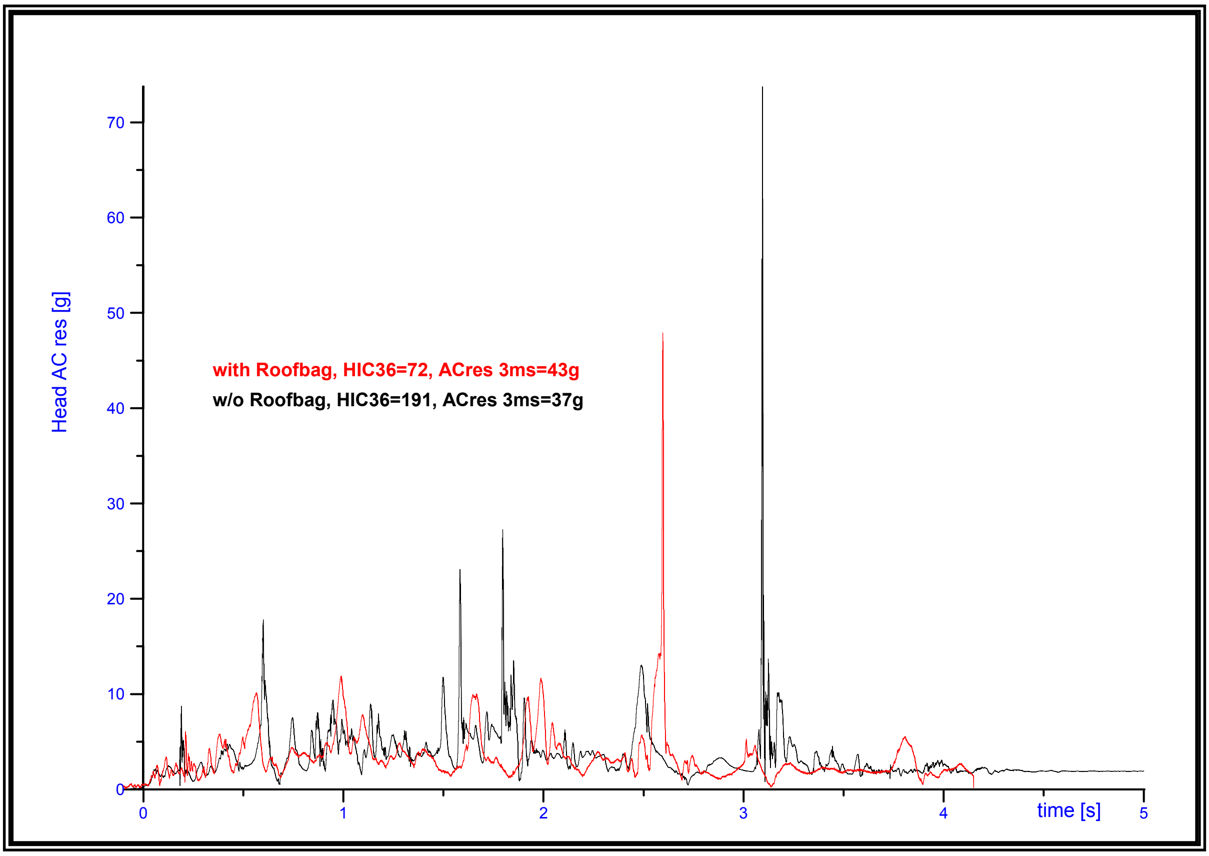

Figure B2. Comparison of resultant head acceleration in FMVSS208 rollover test with and without roofbag, passenger side.

Table C1.
Dummy Injury Reference Values for Out-of-position Testing [54].

Dummy Injury Reference Values for Out-of-Position Testing of Side Airbags			
	Dummy		
Body Region/Injury Measure	**Hybrid III 3-Year-Old Child**	**Hybrid III 6-Year-Old Child**	**Hybrid III Small Female**
Head			
15 ms HIC	570	723	779
Upper Neck			
N_{ij}	1	1	1
Intercepts			
F_T (N)	2120	2800	3880
F_C (N)	2120	2800	3880
M_F (Nm)	68	93	155
M_E (Nm)	27	37	61
Tension (N)	1130	1490	2070
Compression (N)	1380	1820	2520
Thorax			
Deflection (mm)	36	40	—
Deflection rate (m/s)	8.0	8.5	—

Table C2.
Dummy Injury Research Values for Neck and Thorax for Out-of-position Testing [54].

Dummy Injury Research Values for Out-of-Position Testing of Side Airbags			
	Dummy		
Body Region/Injury Measure	**Hybrid III 3-Year-Old Child**	**Hybrid III 6-Year-Old Child**	**Hybrid III Small Female**
Upper Neck			
Lateral moment (Nm)	30	42	67
Twist moment (Nm)	17	24	39
Lower Neck			
Flexion moment (Nm)	83	119	190
Extension moment (Nm)	34	48	77
Lateral moment (Nm)	60	84	134
Twist moment (Nm)	17	24	39
Tension (N)	1130	1490	2070
Compression (N)	1380	1820	2520
Thorax			
Spine acceleration (max g, 3 ms)	55	60	—

Table C3.
Relevant Results of the Out-of-position Tests.

picture	dummy	position	belted	remarks	max percentage of limit values	comment
	HIII 3 year old child	forward facing, on booster cube high	no	neck in front of head rest	extension moment low. neck 37% upper neck NIJ 27% thorax spine 01 (max ac 3ms) 25% upper neck twist moment 20% thorax chest04 (max ac 3ms) 18%	injury values are on a low level
	HIII 3 year old child	rearward facing,kneeing on booster (forehead on tear seam)	no	face touching back rest over cushion outlet	upper neck NIJ 28% lower neck extension moment 27% thorax spine 01 (max ac 3ms) 15% upper neck compression 12% thorax chest04 (max ac 3ms) 11%	injury values are on a low level
	HIII 6 year old child	rearward kneeing on booster, arms on head rest	no	face touching back rest over cushion outlet	lower neck extension moment 74% upper neck NIJ 70% upper neck tension 32% lower neck tension 28% lower neck twist moment 26%	direct deployment into dummies face, injury values are on an acceptable level considering the seating position
	HIII 6 year old child	forward facing, on booster cube	no	neck close to cushion outlet	lower neck extension moment 33% upper neck twist moment 27% lower neck twist moment 26% upper neck NIJ 24% lower neck flexion moment 21%	injury values are on a low level
	HIII 5% female	angle of backrest +60°	no	lying on back rest, neck close to cushion outlet	upper neck extension moment 26% upper neck NIJ 14% upper neck flexion moment 8% upper neck compression 5% upper neck tension 4%	injury values are on a low level