CRASH DAMAGE PATTERNS ASSOCIATED WITH CHEST INJURIES IN FAR-SIDE ROLLOVERS

Kennerly Digges
Fadi Tahan
The George Washington University, National Crash Analysis Center
USA

Raphael Grzebieta
Michael Bambach
Garrett Mattos
Andrew McIntosh
University of New South Wales, Transport and Road Safety Research
Australia
Paper Number 13-0066

ABSTRACT

The NASS/CDS formed the initial basis for investigating the vehicle damage patterns associated with serious chest injuries suffered by belted occupants in far-side rollovers. MAIS 3 or 4 lung contusions were the most frequent severe chest injury. Unilateral left and right lung contusions and bilateral lung contusions were all observed in the population of injured occupants. The lung injury sources most frequently designated by the NASS investigators were the side interior and the shoulder belt. The crash tests and simulations indicated that ground impact with a lateral component produced roof and front fender damage patterns like those observed in cases with chest injuries. The observed damage patterns suggested the following as possible sources of injury causing environments for belted drivers: (1) lateral loading the roof pillars and left front fender during the third and possibly the seventh quarter-turn, and (2) rebound loading induced by the suspension system during the fourth or eight quarter-turn. Other mechanisms may also be possible in complex rollovers.

INTRODUCTION

The purpose of this study was to better understand the events in rollover crashes that are most likely to cause chest injuries among belt restrained occupants. This paper was restricted to the causes of chest injuries suffered by occupants seated on the far-side of the rollover. The data source for the investigation was NASS/CDS. The research objective was to determine the occupant to vehicle interactions that cause chest injuries. An essential and unique approach to achieve this goal was to determine vehicle damage patterns among rollovers with serious chest injuries and to reconstruct cases in order to determine the event in the crash that most likely produced the injury. A purpose of the research was to determine the requirements for a dynamic rollover test that can be used to evaluate countermeasures to reduce chest injuries.

METHODS

Rollovers frequently involve planar impacts prior to the rollover. Earlier studies have shown that these multiple crash events increase the risk of injury, when compared to a rollover without prior crash events [Digges et al 2005]. An increase in the extent of the damage from the planar impact was found to be related to an increase in injury risk. In order to study the cause of chest injuries that occur during the rollover event, only pure rollovers (without prior impacts) were considered.

Initially the NASS/CDS was examined to determine the frequency of serious (AIS 3+) injuries and the nature of the serious chest injuries. Case studies of NASS crashes with serious chest injuries sustained by belted drivers seated on the far-side of the rollover were then undertaken and damage patterns were determined. Vehicle rollover tests with dummies were examined to determine occupant motion in crashes with damage similar to that observed in the NASS cases. Computer simulations were performed to further explore factors that could contribute to chest injury.

RESULTS – NASS DATA ANALYSIS

A study of tripped single vehicle rollovers in NASS/CDS 2000-2010 examined the distribution of seriously injured belted adult occupants by injured body region [Mattos et al 2012]. The results are displayed in Figure 1. In this study, rollovers with involvement of embankments and fences were excluded. The query produced 13,387 weighted cases (124 raw).

A second CDS query identified 857,216 (n unweighted= 1676) restrained and contained occupants involved in single-vehicle pure rollover crashes between 2000 and 2009 (inclusive) [Bambach et al 2012]. These included injured and non-injured occupants of age 16 years and older.

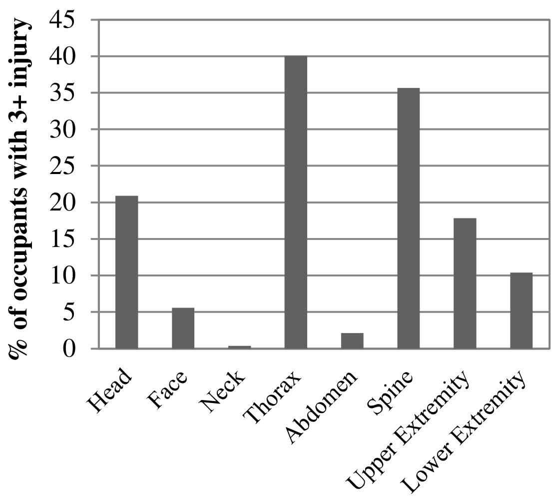

Figure 1. Distribution of occupants with serious injuries by AIS body region [Mattos et al 2012].

The number of quarter turns the vehicle underwent during the single-vehicle pure rollovers experienced by the occupants are plotted in Fig. 2 [Bambach et al 2012]. The plot indicates that the majority of vehicles were either on their wheels or on their roof post-crash, as opposed to on their side. The percentages of occupants that were in vehicles that rolled 8 quarter-turns or less were 99% and 93.9%, for all occupants and seriously injured occupants, respectively. It may be noted that injury peaks occur at 4 quarter-turns and 8 quarter-turns. The 8 quarter-turn event is particularly notable because it portrays 5% of the rollovers but 18% of the serious injuries. These results suggest a more detailed investigation of crashes with 4 quarter-turns and 8 quarter-turns.

Of the belted occupants in pure rollovers, 17,368 (n unweighted= 194) received serious injury (AIS≥3) and of these seriously injured occupants 6356 (n unweighted= 64) received a serious thoracic injury (36.6%) [Bambach et al 2012].

For some occupants, more than one chest injury was recorded. Of the occupants that received serious thoracic injury, the proportions of AIS3, AIS4, AIS5 and AIS6 injuries were 61%, 34%, 3% and 2%, respectively. The total number of weighted injuries was 35,788.

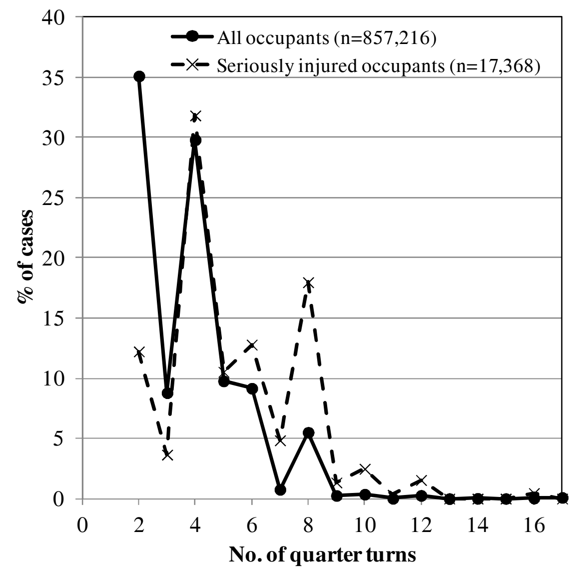

Figure 2. Number of quarter-turns experienced by restrained and contained occupants in single vehicle contained rollover crashes [Bambach et al 2012].

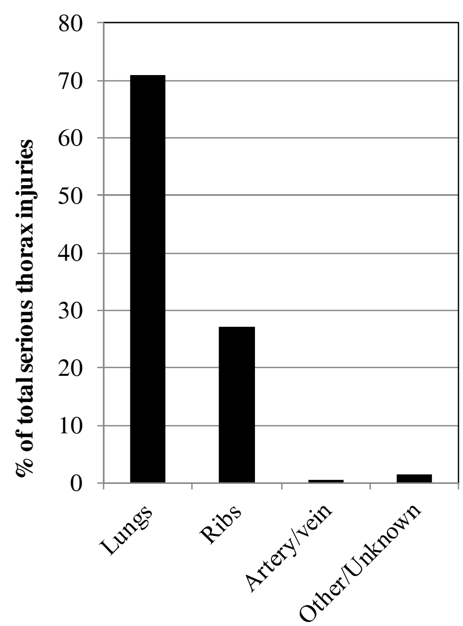

Figure 3. Distribution of serious chest injuries by organ/bone injured [Bambach et al 2012].

The distribution of thoracic injuries by organ/bone injured is shown in Figure 3. It is evident that the lung and rib injuries are predominant.

Figure 4 shows that lung contusions were the principle lung injury with unilateral more frequent than bilateral. In Figure 4, the populations of lung injuries and rib injuries each add to 100%.

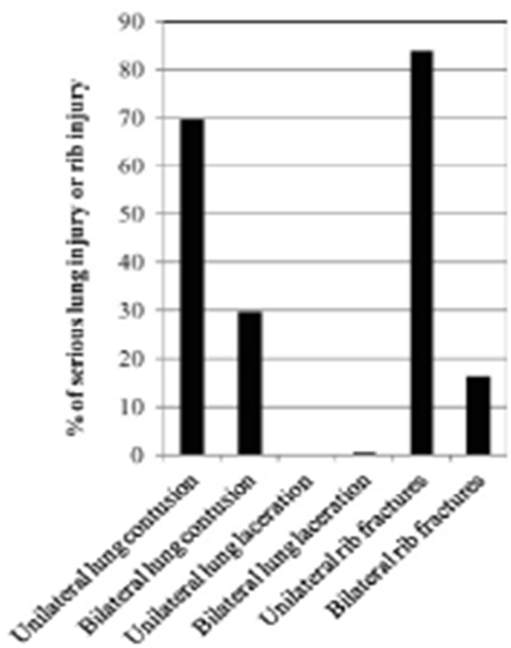

Figure 4. Distribution of serious chest injuries by aspect of the injury [Bambach et al 2012].

The distribution of serious lung injuries suffered by occupants in far-side rollovers is displayed in Table 1. The unweighted number of cases for this distribution was 48.

Table 1.
Distribution of serious lung contusions in among belted occupants in far-side rollovers (NASS 2000-2009 unweighted data)

Lung Injury Type	Percentage
Unilateral -door side	42%
Unilateral -console side	19%
Bilateral	40%

RESULTS – CASE STUDIES

The approach to develop a better understanding of chest injury causes involved a case review of NASS rollovers with AIS 3+ thoracic injuries. The review examined the damage pattern of the rollover cases to determine the direction and sequence of the crash forces that might contribute to the injury. In order to improve the chance of accurately analyzing the cases, it was desirable to select cases in which the chest injury was the most serious injury and it was not caused by confounding factors such as interactions with other occupants in the vehicle.

The selection criteria for cases of far-side belted occupants with AIS 3+ chest injuries to be examined were filtered by the following criteria:

- Passenger car, pickup or SUV
- A single vehicle without other crashes before, during or after the rollover
- Driver only or with right front passenger with no or minor injuries not related to driver injury
- Right side leading rollover (Driver on the far-side of the rollover)

Sixteen cases met the initial criteria. Upon examining the cases, additional criteria were needed to exclude cases that were not possible to reconstruct. Two cases were so severe that the damage to the vehicle was so extensive that crash forces could not be determined. Occupants in five of the cases sustained more severe roof contact brain injuries than their thorax injuries. One case did not document the damage to the vehicle.

These eight cases were removed and the damage patterns of the remaining eight cases were analyzed.

Table 2.
Vehicles and rollover severity of selected cases with serious chest injuries

Case Nr.	PSU	NASS Case	1/4 Turn	MY	Model
1	48	248K	4	1996	Explorer
2	41	176K	4	1994	Explorer
3	74	86A	6	2002	Explorer
4	12	135J	6	2006	G6
5	48	114J	7	2006	Tacoma
6	48	180J	8	2001	Rodeo
7	48	5J	8	2002	Montero
8	78	45C	9	2002	Malibu

A list of the eight cases and significant characteristics is included in Table 2. It is interesting to note that half of the cases were on their wheels at the completion of their rollover.

For the eight cases under study, Table 3 displays the injuring contact, the type of chest injury and the vehicle damage that was used to define the force direction during the rollover. The injuring contact in the table is based on the NASS documentation.

An additional damage pattern that was noted on 5 of the 8 cases was upward damage of the roof at the center or on the near-side of the rollover. This roof tenting suggested a lateral force component on the roof during the rollover.

Table 3.
Occupant contacts, injuries and vehicle damage that defined the roll motion for cases in the study

Case Nr.	Occupant Contact	AIS Injury	Vehicle Damage
1	Belt	4 Bilateral Lung	Side Left Fender
2	Left Interior	4 Bilateral Lung	Top/side Left Fender
3	Belt	4 Bilateral Lung	Lower Left Rear
4	Left Interior	4 Bilateral Lung	Side Left Fender/Wheel
5	Belt	3 Right Lung	Top/side Left Fender
6	Left Interior	3 Left Lung	Top/side Left Fender
7	Seat Back	3 Right Lung	Rear C-pillars
8	Left Interior	4 Bilateral Lung	Side Left Fender/Wheel

The four cases that were upright at the termination of rollover exhibited some similarities in their damage patterns. These four cases are: 1, 2, 5 and 6. To truncate the presentation of results, the reconstruction was focused on these cases and they are addressed in this paper. These four cases are summarized in the subsections to follow.

Case 1 - 2006 41 176

Case 2006 41 176 was a 1996 Ford Explorer that rolled 4 quarter-turns, passenger side leading. The vehicle is shown in Figure 5. There were three occupants, two of which suffered no injuries. The driver was a belted 38 year old male. There was no air bag deployment.

While negotiating a turn, the Explorer departed left, steered right and crossed the highway. The vehicle departed right and rolled on the grass shoulder.

The 38 year old male driver sustained an AIS 4 bilateral lung contusion and AIS 3 bilateral rib fractures, all attributed to the safety belt. He also had 4 AIS 1 skin abrasions to the chest and abdomen and an AIS 1 heart contusion attributed to the belt. There was an AIS 1 right back skin abrasion attributed to the seat. There were 2 AIS 1 lower extremity skin injuries caused by the knee bolster and 2 AIS 1 facial injuries caused by the roof side rail and flying glass.

Figure 5. Case 1 – Ford Explorer – 4 quarter-turns.

Case 2- 2005 48 248

Case 2005 48 248 was another Explorer with more extensive roof damage. This 1994 model, shown in Figure 6, was subjected to a 4 quarter-turn trip-over, passenger side leading. There was no air bag deployment.

Figure 6. Case 2 – Ford Explorer – 4 quarter-turns.

In addition to the 54 year old male belted driver, the Explorer in Case 2005-48-248 contained a 52 year old female right front passenger who sustained a single AIS 1 skin abrasion to the arm.

The vehicle departed the roadway to the right and rolled along the shoulder and in the roadway.

The 54 year old male driver sustained an AIS 4 bilateral lung contusion attributed to the left interior. Also coded were 2 AIS 3 left arm fractures attributed to the roof, an AIS 2 head injury attributed to the roof and one AIS 1 skin abrasion of the abdomen attributed to the belt. There were no AIS 1 or 2 level injuries from left interior.

Case 5- 2004 48 5

Figure 7. Case 5 — Isuzu Rodeo - 8 quarter-turns.

Case 2004-48-5 involved the 2001 Isuzu Rodeo shown in Figure 7. This vehicle was subjected to an 8 quarter-turn trip-over, passenger side leading. The sole driver was a 26 year old female. She was belted and the air bag did not deploy.

A non-contact vehicle, in lane two, changed lanes to its right into the Rodeo's travel lane. To avoid a collision the Rodeo departed the right road edge. The right wheels descended a negative slope (-8/122), and the driver steered left to correct. The front wheels went left and the rear wheels went down the slope. The Rodeo tripped and rolled eight quarter-turns. The vehicle came to rest from the rollover on its wheels in lane one facing southeast. The vehicle's engine was still running and in gear and it began moving forward into the median.

The driver sustained an AIS 3 unilateral left lung contusion and an AIS 1 chest skin contusion attributed to the left interior. There were 2 other AIS 1 leg injuries attributed to the knee bolster. The roof was the contact for AIS 1injuries to the head, cervical spine and upper extremity.

Case 6- **2002 48 180**

Figure 8 shows a 2002 Mitsubishi Montero that was subjected to a trip over with 8 quarter-turns, passenger side leading. The driver was a 23 year old male. He was belted and the air bag did not deploy.

Figure 8. Case 6 –Mitsubishi Montero - 8 quarter-turns.

There was also a right front passenger with unknown age, gender but with no injuries.

2002 Mitsubishi Montero, was travelling west on a four lane, dry, level (-0.016 slope) interstate highway divided by a grassy median. There was a very slight curve to the right. The vehicle went off the left side of the roadway, came back onto the road and crossed both travel lanes. When the vehicle reached the right side shoulder it began to rollover. After rolling eight quarter-turns, the Montero came to final rest partially on the shoulder and partially on the grassy roadside.

The driver sustained a right lung contusion, AIS 3, attributed to the seat, back. He also had an AIS 2 cervical vertebral fracture caused by the roof. There were four AIS 1 facial and scalp lacerations attributed to the roof.

RESULTS - ROLLOVER TEST

A rollover test of a Ford Expedition conducted by Transportation Research Center for Vehicle Research and Test Center (VRTC) (NHTSA test number 6960), was analyzed to determine occupant motion during an 8 quarter-turn rollover. The damaged vehicle is shown in Figure 9. This test was a soil tripped rollover crash that was conducted to investigate the dynamics of belted occupants during rollover crashes. The Expedition was translated laterally on a test cart at 48.8 km/h (30.3 mph). It was released with its roll axis perpendicular to the direction of the soil trip area. The vehicle contained a belted Hybrid III dummy on the far-side of the rollover. Videos were available showing the dummy motion and the external vehicle position during the rollover.

The three videos from the rollover test were superimposed and synchronized in order to examine the driver dummy motion at various times of the rollover. Critical conditions showing dummy motion that could contribute to chest injury are shown in Figures 10, 11 and 12. The dummy motion is shown in the left side of the figures. The top right graphic is from the downstream high speed video and the lower right graphic shows the real time video.

Figure 9. Damaged Ford Exposition after a rollover test with 8 quarter-turns.

Figure 10. Dummy and vehicle position during the third quarter-turn.

Figure 11. Dummy and vehicle position prior to completion of the eighth quarter-turn.

*Figure 12***.** Dummy and vehicle position during the completion of the eighth quarter-turn.

DISCUSSION

Analysis of the videos from the Expedition rollover tests indicate that for an 8 quarter-turn rollover there were at least two opportunities for far-side belted occupants to incur serious chest injuries. The first occurred during the third quarter-turn and the second at the eighth quarter-turn.

The damage patterns for the 4 quarter-turn cases analyzed (cases 1 and 2) and the 8 quarter-turn case (case 6) all display lateral damage to the left front fender. This damage and the tenting of the roof suggest that lateral forces were applied to the vehicle during the third quarter-turn. Computer simulation of 4 quarter-turn cases confirmed this hypothesis [Tahan et al 2013]. The computer simulations further indicated that the dummy impacts the center console during the fourth (final) quarter-turn. This impact was induced by the rebound of the suspension system. Damage to the left front fender in cases 1, 2 and 5 suggest that there was an off-axis roll component or a wobble in the rollover. Simulation indicated that increases in the wobble increase the severity of the occupant impacts to the door and to the center console.

The 8 quarter-turn rollover test of the Expedition showed similar opportunities for chest injuries to those discussed above. Figure 10 shows the dummy impacting vehicle side during the third quarter-turn. In this test, an air curtain protects against head injury. A less severe impact with the door was noted at the seventh quarter-turn. The driver in case 5 sustained a left lung contusion attributed to the left interior, suggesting that the injury occurred during the third quarter turn.

Figures 11 and 12 show how the dummy moves rapidly from the exterior of the vehicle (Figure 11) to the interior (Figure 12) in less than 200 milliseconds. This motion occurs rapidly during the rebound of the suspension system. In the Expedition test vehicle, the center console was removed and consequently the dummy head excursion shown in Figure 12 may be greater than in the unmodified vehicle. The chest injury induced by this upper body motion could originate from the seat belt that crosses the lower chest. In real world rollovers the driver's right side chest injury could also be caused by impact with the center console, the seat back or other objects or passengers located to the right of the driver.

The vehicle in case 6 sustained lateral damage to the left front fender and the left rear upper quadrant. This damage pattern suggests a more extreme wobble than existed in the other cases. The driver in case 6 sustained a right lung contusion attributed to the seat back. Based on the motion shown in Figures 11 and 12, it is probable that this injury occurred during the eighth quarter-turn. It is also possible that in case 6, a rearward component from the upper quadrant impact may have increased the severity of occupant interaction with the vehicle.

Other injury mechanisms may exist in rollovers, especially those with added complexity and those that do not terminate on the vehicle's wheels.

The vehicles analyzed in this study were all SUV's. Further analysis of passenger cars and pickups will be required to determine the extent to which the observations from the SUV's can be broadly applied.

CONCLUSIONS

Chest injuries are a major source of harm to belted occupants in rollovers. The approach of reconstructing rollovers with chest injuries provides a basis for understanding these injuries and for developing rollover test procedures and countermeasures.

For NASS belted occupants with serious chest injuries incurred during exposure to far-side rollovers, lung contusions are the most frequent chest injury.

For serious lung contusions that occurred in NASS rollovers involving 4 or 8 quarter-turns, at least two opportunities for the injuries were evident. Based on NASS vehicle damage patterns and analysis of simulation and crash test data, the most probable opportunities were during the third quarter-turn and the final quarter-turn.

The crash tests and simulations indicated that ground impact with a lateral component produced roof and front fender damage patterns like those observed in NASS cases with chest injuries.

The observed damage patterns suggested the following as possible sources of injury causing environments for belted drivers: (1) lateral loading the roof pillars and left front fender during the third and possibly the seventh quarter-turn, and (2) rebound loading induced by the suspension system during the fourth or eight quarter-turn. Other mechanisms may also be possible in complex rollovers.

ACKNOWLEDGMENT

The authors would like to thank the Australian federal government's Australian Research Council for providing funds to carry out this research through the Linkage Projects grants scheme (No: LP110100069). The authors would also like to thank the industry partners for providing funding, namely, the New South Wales state government's Centre for Road Safety at Transport for New South Wales, the Victorian state government's 3rd party insurer Transport Accident Commission (TAC), the West Australian (WA) state government's Office of Road Safety at Main Roads WA, the mining company BHP Billiton Ltd, and the US Center for Injury Research (CFIR).

REFERENCES

Bambach, M.R., Grzebieta, R.H., and McIntosh, A.S, 2012; Thoracic injuries to contained and restrained occupants in single-vehicle pure rollover crashes. Accident Analysis and Prevention, 2012

Digges, K.H., Eigen, A.M., Dahdah, S., 2005; Injury patterns in rollovers by crash severity. Paper no. 355. In: Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 2005.

Mattos, G.H., Grzebieta, R.H., Bambach, M.R and McIntosh, A.S. 2012; Head injuries to restrained occupants in single-vehicle pure rollover crashes. Traffic Injury Prevention, 2012.

Tahan, F.J., Digges, K.H., Reichert R., Kan, C.D., Grzebieta, R.H. 2013; Assessing vehicle damage patterns with chest injuries in far-side rollovers, NCAC 2013-R-001 Report submitted to Transportation and Road Safety (TARS) Research University of New South Wales (UNSW), Sydney, Australia.