BIOMECHANICAL FACTORS AND INJURY RISK IN HIGH-SEVERITY ROLLOVERS

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ABSTRACT

The number of rolls, as well as other factors, has been associated with increased injury risk in rollovers. Data from NASS-CDS from 1995-2003 were used to evaluate the biomechanical implications of vehicle kinematics during multiple rolls and to evaluate the risk of injuries to different body regions during rollovers. The data showed that the risk of injury increased with increasing number of rolls. The rate of increase in risk varied by the region of the body affected and injury severity. The increased risk was particularly great when a vehicle rolled more than two complete rolls.

Vehicle rollovers are associated with a risk of serious injury or fatality to the vehicle occupants that has been shown to increase with the number of rolls or quarter-turns [Digges and Eigen, 2003; Digges, Malliaris, and Ommaya, 1991; Hight, Siegel, and Nahum, 1972; Parenteau and Shah, 2000]. Rollover events are frequently initiated at higher speeds than other types of motor vehicle accidents, and it has been suggested that the relative harm per occupant increases dramatically with speed [Digges et al., 1991; Hight et al., 1972; Parenteau, Thomas, and Leonard, 2001]. Digges and Malliaris (1998) suggested that even for belted occupants, rollover crashes present nearly double the injury risk compared with restrained occupants in planar crashes.

Consequently, there has been considerable interest in identifying relationships between rollover severity and injury severity. However, the development of a quantitative relationship between accident and injury severity in rollover accidents is limited by the often complex and chaotic nature of rollover events for both the vehicle and its occupants. A number of independent factors influence the kinematics of a vehicle involved in a rollover event, including pre-rollover speed, pre-accident vehicle movements such as braking, steering, and skidding, vehicle geometry, and ground topology, all of which can affect the number of rolls, occupant kinematics, and injury severity [Altman, Santistevan, Hitchings et al., 2002; Hight et al., 1972; Moffatt, 1975; Parenteau, 2001]. Similarly, several factors have been associated with increased injury risk, including restraint non-use, occupant ejection, pre-incident speed, roll rate, and the number of roof-to-ground contacts [Bahling, Bundorf, Kaspzyk, et al., 1990; Digges et al., 1991; Digges, Malliaris and DeBlois, 1994; Digges et al., 1998; Digges et al., 2003; Huelke, Compton, and Studer, 1985; James, Allsop, Nordhagen et al., 1997; Orlowski, Bundorf and Moffatt, 1985;].

One factor that has been associated with increased injury risk is the number of quarter-turns experienced by the vehicle during the rollover event [Cohen et al, 1989, Digges et al., 1991; Digges et al., 2003; Moffatt, 1975; Parenteau et al., 2000]. Digges and Eigen (2003) noted that the number of quarter turns is generally related to the energy of the rollover accident, and observed that injury rates tended to increase with the number of roof impacts. Their review of the field accident data indicated that more than half of all occupants sustaining injuries with an Abbreviated Injury Score (AIS) of 3 (serious) or greater had been exposed to more than one roof impact.

To date, analyses of injury risk during rollovers have been largely limited to the investigation of rollover crash statistics, identification of occupant impact sites, and the presentation of statistical relationships between crash characteristics and measures of injury severity [Digges et al., 1991; Digges et al., 1994; Digges et al., 1998; Digges et al., 2003; Rains and Kanianthra, 1995]. Although these studies illustrate the distribution of injuries sustained in rollover accidents, little biomechanical analysis has been conducted in support of proposed injury prevention measures. While other studies have explored the biomechanical implications of occupant kinematics, injury distribution and restraint usage, the issues of injury risk and rollover severity have not been addressed [James et al., 1997; Parenteau et al., 2000]. Therefore, in the present study we asked the following question: which crash characteristics contribute biomechanically to increased injury risk in rollovers with respect to increased numbers of rolls? We also studied the risk of injuries of varying magnitudes to different body regions to assess whether the relative risks posed by more severe rollovers were greater for certain types and levels of injury.

METHODS

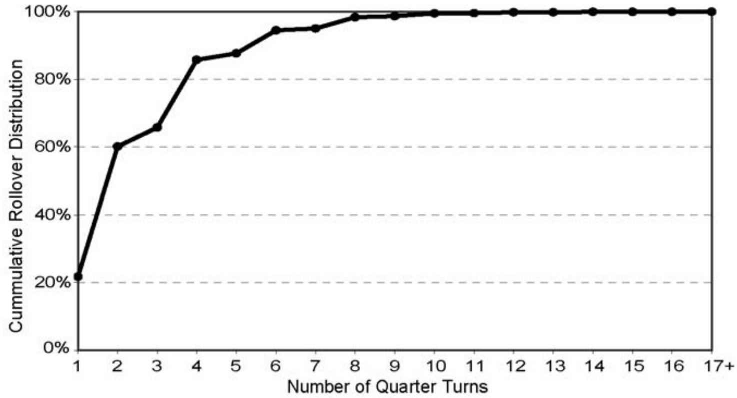
Data from rollover events involving passenger vehicles (passenger cars, SUVs, pickup trucks and vans) of model year 1990 or later recorded in NASS-CDS from 1995-2003 were obtained. Vehicles from earlier model years were excluded to minimize differences in the available safety features across the data analyzed. The analysis was restricted to years 1995 and later as in this year the number of quarter-turns definition was expanded to record values from 1 through 17, where 1 represents one quarter-turn and 16 represents four complete rolls. In the present study, the numbers of rolls were grouped into the following categories: 1, 2, 3, 4, 5-7, 8-11, and 12 or more quarter-turns. End-over-end rollovers were classified in a separate category and were not broken down by number of quarter-turns.

The NASS-CDS database records up to ten injury entries for each injured occupant, using a coding system based on the AIS-90 reference dictionary [AAAM, 1998]. Information such as region of the body injured, the source causing the injury, and severity of each injury is recorded. The injured body regions are classified in nine categories: head, face, neck, thorax, abdomen, spine, upper extremity, lower extremity and unspecified.

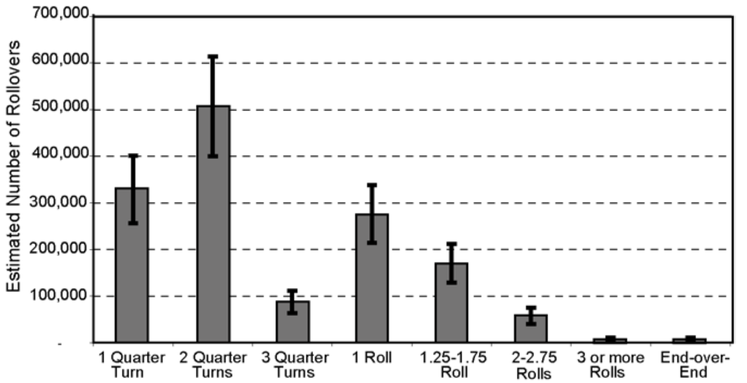
The AIS injury classifications were used to assess occupant injury severity. AIS scores range from 1 (minor) to 6 (maximum, currently untreatable). Risk of injury to each body part injured was assessed as a function of number of quarter turns. The risk of injury was evaluated in terms of an occupant sustaining at least moderate (AIS 2+) or serious injury (AIS 3+). Factors known to affect injury risk in rollovers, such as restraint use and occupant ejection were also assessed to determine if the number of quarter-turns affected the likelihood of additional injury-producing events.

RESULTS

The data from 1995-2003 consisted of 4,024 rollover vehicles, with a weighted estimate of 1.4 million vehicles involving 2.18 million occupants; 79% of these occupants were restrained. The number of rollover events decreased as the number of quarter turns increased, and the majority of all rollovers rolled for two quarter-turns or less (Figure 1).



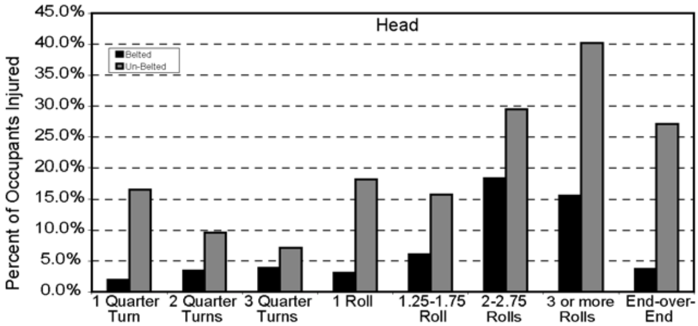
(a)



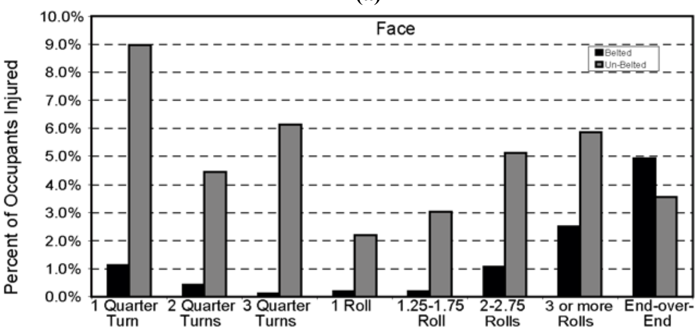
(b)

Figure. 1 – Number of weighted rollovers by (a) quarter turns and (b) broken down by categories.

The data showed that both the risk of moderate (AIS 2+) and serious (AIS 3+) injury generally increased with increasing number of quarter-turns for restrained and unrestrained occupants of passenger vehicles. Pronounced increases in injury risk were observed for occupants in rollovers consisting of two or more complete rolls, especially for unrestrained occupants. There were also trends of increasing injury risk with increasing numbers of rolls for head, thoracic, abdominal, spinal, and extremity injuries, but the rate of increase varied by body site, injury severity, and restraint use (Figures 2, 3). Occupants of rollover vehicles have the greatest risk of sustaining head and thorax injuries, followed by abdomen, spine and extremity injuries (Figure 2, 3). This holds for both AIS 2+ and AIS 3+ injury. The risk of an occupant sustaining an injury coded as a “neck” injury from a rollover accident is low (Figure 2(c), 3(c)).



(a)



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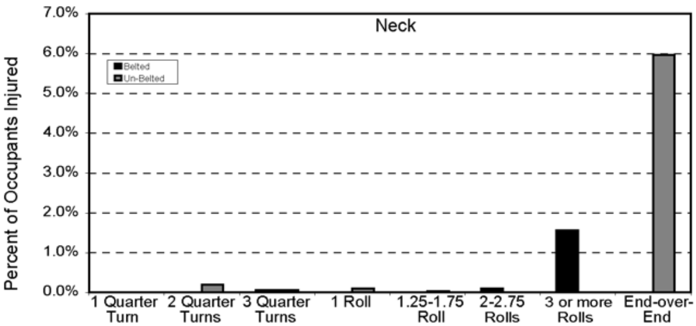
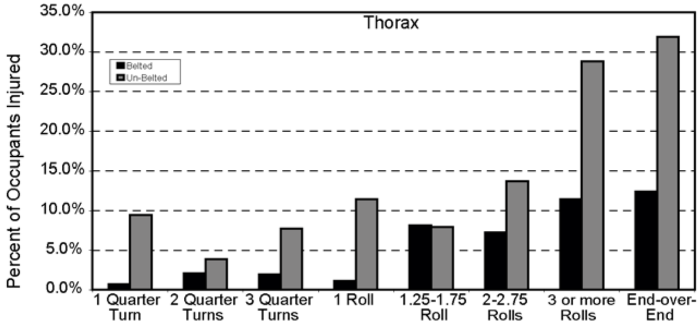
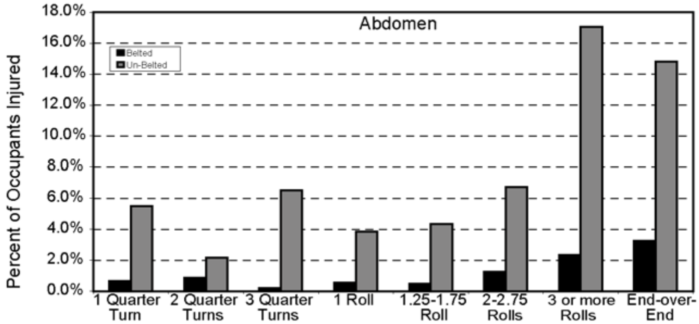


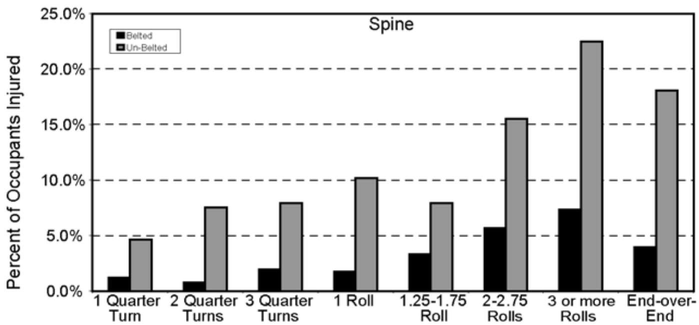
(c)


Thorax
Percent of Occupants Injured
Belted
Un-Belted
35.0%
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
1 Quarter Turn
2 Quarter Turns
3 Quarter Turns
1 Roll
1.25-1.75 Roll
2-2.75 Rolls
3 or more Rolls
End-over-End

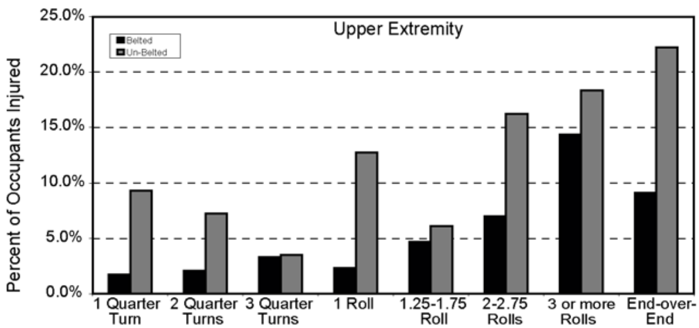
(d)


Abdomen
Percent of Occupants Injured
Belted
Un-Belted
18.0%
16.0%
14.0%
12.0%
10.0%
8.0%
6.0%
4.0%
2.0%
0.0%
1 Quarter Turn
2 Quarter Turns
3 Quarter Turns
1 Roll
1.25-1.75 Roll
2-2.75 Rolls
3 or more Rolls
End-over-End

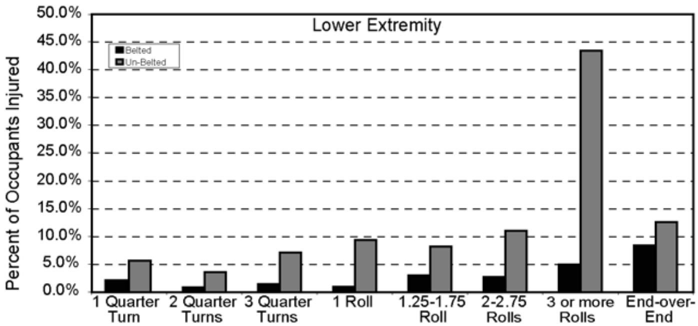
(e)


Spine
Percent of Occupants Injured
Belted
Un-Belted
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
1 Quarter Turn
2 Quarter Turns
3 Quarter Turns
1 Roll
1.25-1.75 Roll
2-2.75 Rolls
3 or more Rolls
End-over-End

(f)

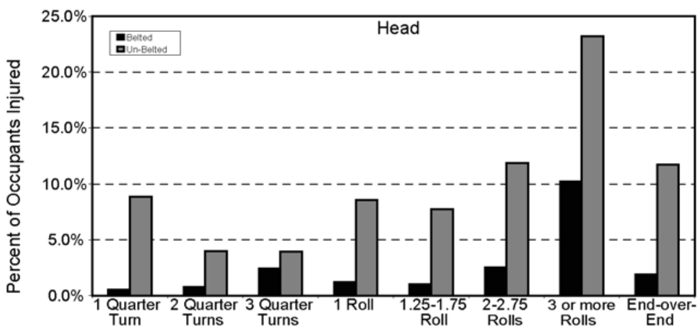

Upper Extremity
Percent of Occupants Injured
Belted
Un-Belted
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
1 Quarter Turn
2 Quarter Turns
3 Quarter Turns
1 Roll
1.25-1.75 Roll
2-2.75 Rolls
3 or more Rolls
End-over-End

(g)

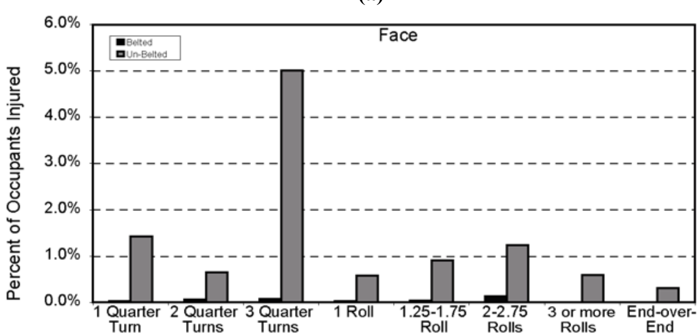


(h)

Figure. 2 – Risk of moderate injury (AIS 2+) as a function of number of rolls for different body regions.



(a)



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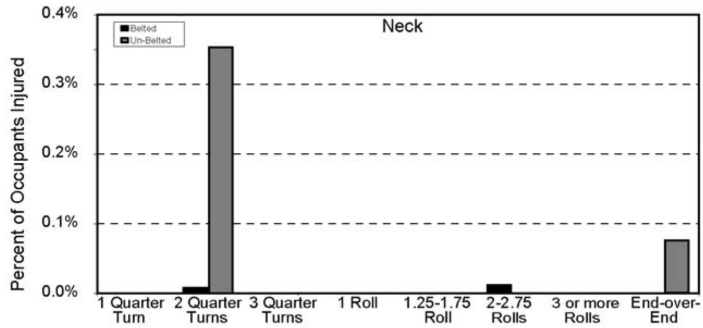
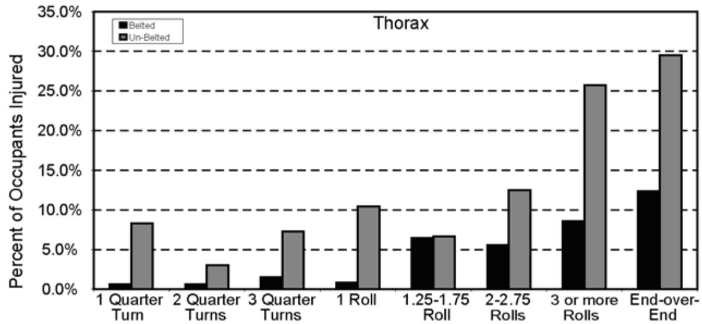
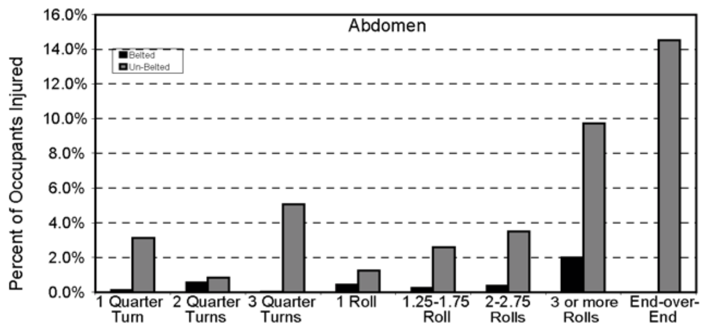

Neck
Belted
Un-Belted
Percent of Occupants Injured
0.4%
0.3%
0.2%
0.1%
0.0%
1 Quarter Turn
2 Quarter Turns
3 Quarter Turns
1 Roll
1.25-1.75 Roll
2-2.75 Rolls
3 or more Rolls
End-over-End

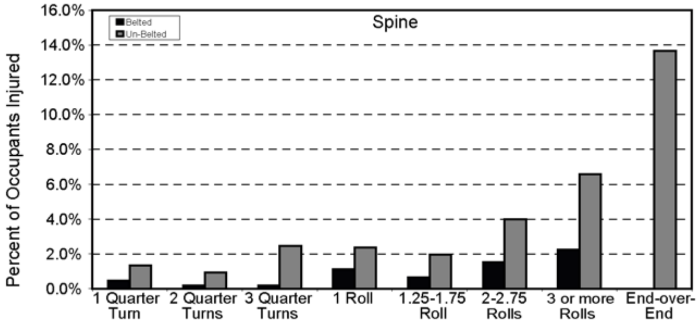
(c)


Thorax
Belted
Un-Belted
Percent of Occupants Injured
35.0%
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
1 Quarter Turn
2 Quarter Turns
3 Quarter Turns
1 Roll
1.25-1.75 Roll
2-2.75 Rolls
3 or more Rolls
End-over-End

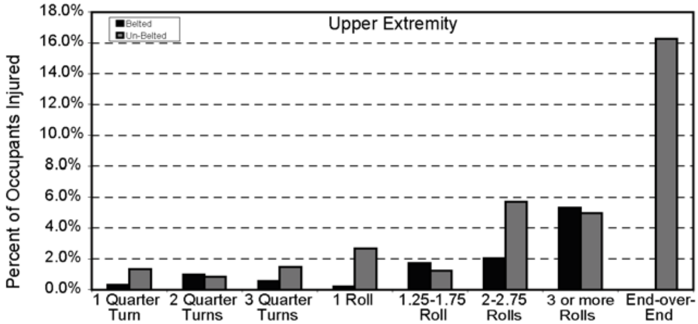
(d)


Abdomen
Belted
Un-Belted
Percent of Occupants Injured
16.0%
14.0%
12.0%
10.0%
8.0%
6.0%
4.0%
2.0%
0.0%
1 Quarter Turn
2 Quarter Turns
3 Quarter Turns
1 Roll
1.25-1.75 Roll
2-2.75 Rolls
3 or more Rolls
End-over-End

(e)



(f)



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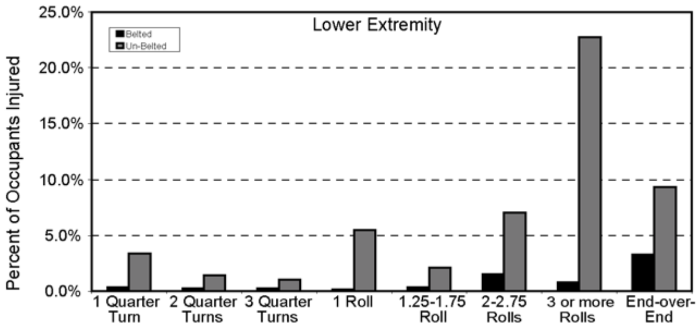


(h)

Figure. 3 – Risk of serious injury (AIS 3+) as a function of number of rolls for different body regions.

DISCUSSION

Rollovers are complex, chaotic events, and the occupant kinematics and potential injury mechanisms are similarly complex. The associated increases in injury severity with increases in number of quarter-turns may have several causes, including more frequent and more severe impacts with interior vehicle surfaces, increased opportunities for ejection, and more severe ground impacts for ejected occupants. Additionally, occupants in rollovers with a high number of quarter-turns are more likely to sustain multiple injuries.

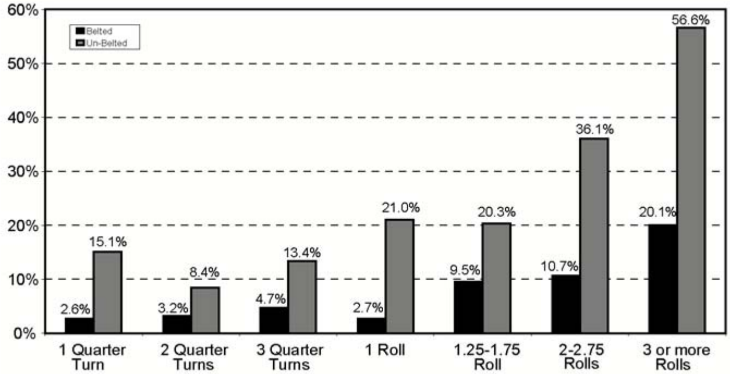
Factors that increase rollover severity, such as increased pre-incident speed and increased roll rate, are often associated with an increased number of quarter-turns. For example, as the velocity of a vehicle at the initiation of rollover increases, the roll distance increases approximately proportionally, as greater energy must be dissipated prior to the vehicle coming to rest [Altman et al., 2002; Moffatt, 1975]. These increases in roll distance are typically associated with greater numbers of vehicle-to-ground impacts and thus increased opportunities for occupant injury. The translational speed of the vehicle is typically highest at trip and gradually diminishes, suggesting that injury risk may be highest early in the rollover event. However, Moffatt *(*1975) recognized that the rotational velocity may increase or decrease throughout the rollover, depending on a number of environmental factors, including vehicle geometry and topography at the rollover site.

The vehicle kinematics in a rollover have been described as consisting of a trip phase, one or more airborne phases, and one or more ground impact phases [Bahling et al., 1990; Moffatt, 1975]. During the trip phase, the occupants continue to move in the vehicle's initial direction. Occupant motion relative to the vehicle depends upon restraint usage, contact with interior vehicle structures, and the occupant's position in the vehicle. Occupant kinematics also differ by seating position, as outboard passengers, moving along a larger radius, have more energy to dissipate than inboard passengers and are exposed to greater injury potential [Moffatt, 1975; Parenteau et al., 2000].

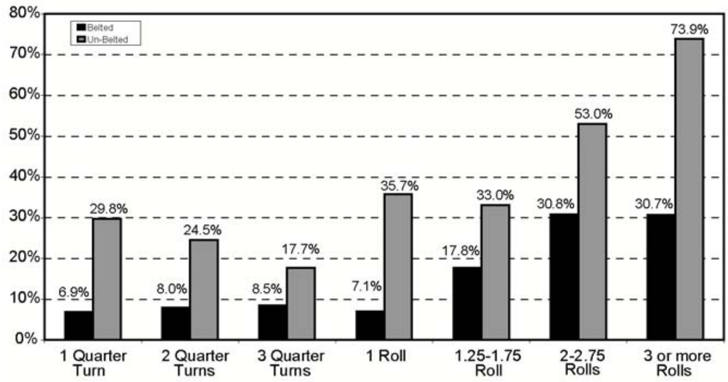
In high-energy rollovers the trip is followed by an airborne phase, during which the occupant tends to move away from the vehicle's center of gravity until motion is stopped by contact against interior vehicle surfaces, the restraint system, if used, or by ejection from the vehicle. It has been suggested that the upward movement of the occupant relative to the vehicle during airborne phases may be minimized by the seatbelt [Parenteau et al., 2000]. However, studies have demonstrated that even a properly restrained occupant will experience several inches of excursion due to the compliance of the restraint, changes in restraint geometry during the rollover, and compliance of the soft tissues of the body [Bahling et al., 1990; Moffatt, Cooper, and Croteau, 1997; Moffatt, Hare, and Lewis, 2003].

During vehicle-to-ground impacts, the occupants tend to move towards the point of ground contact at their pre-impact velocity [Howard, Hatsell, and Raddin, 1999; Parenteau et al., 2000]. This motion continues until stopped by contact with vehicle structures, including the restraint system, if used, other occupants or cargo, the ground, or by ejection from the vehicle. Higher pre-impact speeds will increase the risk of injury during occupant contacts. As the number of vehicle-to-ground impacts increase, occupants are exposed to an increasing likelihood of sustaining injuries due to these impacts via contact with interior structures, the ground, or through complete or partial ejection from the vehicle. The peak decelerations of the vehicle during vehicle-to-ground impacts are also significantly higher than the average vehicle deceleration in a rollover event and may expose the occupant to substantial injury risk [Howard et al., 1999; Cooperrider, Thomas, and Hammoud, 1990; Moffatt, 1975; Orlowski et al., 1985].

One factor that is not related to rollover severity, but does significantly influence rollover-related injury potential is restraint usage. Our study showed that restraint use was associated with an overall reduction in injury risk at all numbers of quarter-turns (Figure 4). Restraint use was also associated with a reduced risk of injury to all body regions (Figures 2, 3), although the relative benefit of restraint use tended to decrease for some body regions at high numbers of quarter-turns, likely indicative of the high-energy nature of these events. Similar to the findings of Digges et al. (2003), we also found that for unrestrained occupants, risk of moderate and serious injury was relatively high in rollovers consisting of only one quarter-turn, compared with rollovers of four quarter-turns or less. Further research into the vehicle and occupant kinematics of these events and their effect on injury risk is warranted.



(a)



(b)

Figure. 4 – Comparison of the risk of injury to restrained and unrestrained occupants as a function of number of rolls for (a) serious injury (AIS 3+) and (b) moderate injury (AIS 2+)

While no relationship has been identified between restraint status and the number of rolls, higher percentages of occupants tend to be unrestrained as the rollover severity increases (Figure 5). As discussed above, an increase in number of rolls is typically related to higher energy rollovers and can be related to higher initial travel speeds. Both non-use of the restraint system and higher travel speeds have been associated with risky driving behavior [Preusser, Lund, Williams, et al., 1988]. Further research into possible relationships between driver behaviors and rollover severity is also warranted.

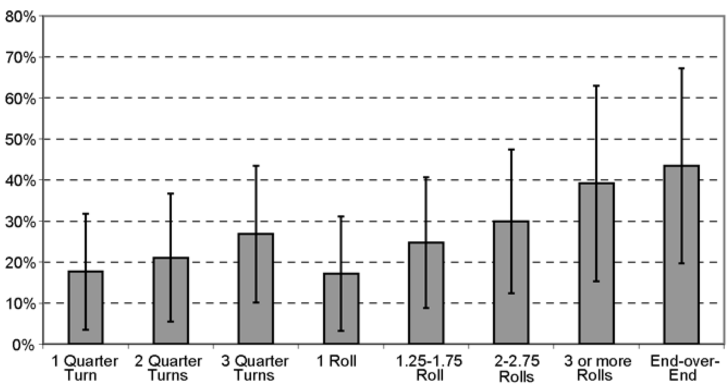


Figure. 5 – Percentage of unrestrained occupants as a function of number of rolls. Error bars represent the 95% confidence intervals.

Restraint use reduces injury risk in rollovers, primarily by reducing the risk of occupant ejection [Bahling et al, 1990; Parenteau et al., 2000; Digges et al., 1994; Huelke, Lawson, Scott et al., 1977]. The risk of full and partial ejection for unrestrained occupants is significantly higher than for restrained occupants, and the risk of ejection generally increased with the number of quarter turns experienced for both restrained and unrestrained occupants (Figure 6). The data also shows that both restrained and unrestrained occupants who are ejected (either partially or completely) tend to have an increased risk of injury in rollovers with higher numbers of quarter-turns (Figure 7), which may be a result of the higher energy and increased number of ground contacts in these events.

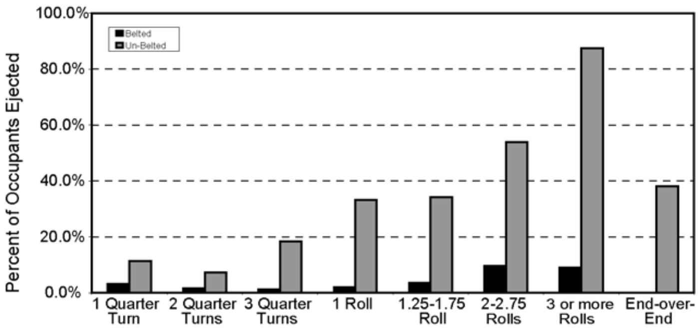


Figure. 6 – Combined risk of full and partial ejection as a function of number of rolls

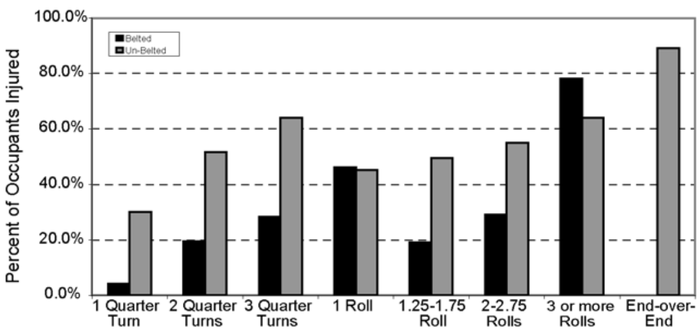


Figure. 7 – Risk of serious or greater injury (AIS 3+) for ejected occupants as a function of number of rolls

In the present study, the body regions exposed to the greatest risk of serious injury (AIS 3+) for both restrained and unrestrained occupants were the head and thorax. However, it is notable that the risk of serious injury for restrained occupants was less than 5% for the thorax in rollovers consisting of less than five quarter-turns, and in rollovers consisting of less than three complete rolls for head injuries. Restrained occupants also generally had less than 5% risk of moderate injuries (AIS 2+) for the face, abdomen, and lower extremities, while the risk of moderate spinal and upper extremity injuries did not exceed 5% until at least two rolls had been completed. In contrast, the unrestrained occupant has a greater than 5% risk of serious head and thorax injury at the first quarter roll, and more than 20% risk for three or more complete rolls. However, the risk of serious extremity injuries exceeded 5% only after two rolls, while the serious abdominal and spinal injuries exceeded this level only after completing at least three rolls. Generally, unrestrained occupants were exposed to several times greater risk of facial injury compared to restrained occupants, although the overall risk of moderate facial injury was less than 10%, and risk of serious facial injury was less than 5%.

The noted differences in injury risk for restrained versus unrestrained occupants are strongly related to occupant motion during the rollover. The restrained occupant in a rollover will interact with a limited set of vehicle interior surfaces using specific body regions, depending on the direction of the roll, the rotational velocity, the nature of the vehicle-to-ground impacts, and the occupant's seating position within the vehicle. For example, Digges et al. (1994) noted that the percentage of injuries sustained through roof, roof rail, and header contacts is higher for restrained occupants than for the unrestrained occupant, indicative of the restrained occupant remaining in close proximity to these structures throughout the rollover event. Conversely, as long as the unrestrained occupant remains within the accident vehicle, their motion during vehicle-to-ground impacts is not limited by the restraint system and will continue until stopped by more forceful contact with other structures, which may be distant from the occupant's initial position. Also, as discussed earlier, the unrestrained occupant is at greater risk of being ejected from the vehicle and sustaining injuries due to the ejection.

The relatively high risk of head injury, compared with other regions, observed for both restrained and unrestrained occupants has been noted by other researchers, including Mackay and Tampan (1970), who suggested that seatbelts were not effective in reducing head injuries in rollover accidents, and Huelke et al. (1977), who reported that lap/shoulder belts generally reduced the incidence of significant injuries to all parts of the body in rollover accidents, with the exception of the head. Reported neck injuries were generally low for all occupant groups. This may be due in part to the Abbreviated Injury Score coding methodology, where moderate and severe neck injuries refer primarily to vascular and muscular injuries and do not include the spine. Such injuries typically are a result of tensile loading of the neck causing avulsion-type injuries or from direct contact or penetrating injury to the neck, injury mechanisms not typically seen during rollovers. Cervical spine injuries, which can occur during rollovers as a result of inertial loading of the neck by the still-moving torso during roof-to-ground impacts, are classified as spinal injuries and not as neck injuries.

The data also show that end-over-end rollovers are associated with a relatively high risk of injury, compared with “barrel roll” rollovers, a finding that has also been noted by other researchers [Hight et al., 1972; Robinette and Fay, 1993]. The increase in vehicle center of gravity height necessary for the vehicle clearance in an end-over-end rollover increases the drop height experienced by occupants during these events. Additionally, the kinematics of an end-over-end event are such that occupants seated on both sides of the vehicle can experience similar kinematics. However, as end-over-end rollovers are not broken down by the number of quarter turns in the NASS-CDS database, the analysis of injury risk for this rollover modality is limited.

Once an occupant is in the process of being ejected, the mechanisms by which injuries are sustained are markedly changed. During ejection, compression of the body between the vehicle and the ground can cause crushing injuries. Additionally, motion of the partially-ejected body relative to the rolling vehicle in concert with ground contacts can cause “whip-like” contact against the vehicle’s exterior surfaces. Following complete ejection, the occupant is exposed to a range of potentially injurious forces, including ground impact forces and frictional forces from roadway and ground surfaces. In the event that an ejected occupant lands ahead in the path of the rolling vehicle, the opportunity for further crush injuries arises.

As noted previously, the field accident data demonstrate that as the number of quarter turns in a rollover increases, the risk of ejection increases (Figure 6). Additionally, the risk of injury to an ejected occupant tends to increase for both restrained and unrestrained occupants with increasing number of quarter turns (Figure 7). In a rollover with a high number of rolls, the increased number of vehicle-to-ground contacts, the increased total duration of the rollover event, and increased severity of vehicle-to-ground contacts due to increased overall energy of the rollover all increase the likelihood of ejection.

Increased vehicle translational speed relative to the ground and increases in roll rate often seen in rollovers with higher number of quarter-turns indicate that an ejected occupant will likely have an increased velocity relative to the ground, which tends to increase the severity of the occupant’s subsequent ground contact. For partially ejected occupants, increased severity of vehicle-to-ground contacts can increase the force with which the occupant is “flung” against the vehicle’s exterior surface during these contacts. Our findings agree with those of Huelke et al. (1985), who suggested that although ejection tends to be associated with the more severe crashes, the incidence of more severe injuries might be at least "partially attributable to the severity of the crash, rather than the ejection event itself."

There are several limitations to this study. One limitation that applies to all field accident studies of rollover events is that rollovers are difficult to generalize due to their complex nature. For example, rollovers consisting of the same number of quarter-turns may have different initial travel speeds and roll rates, as well as different numbers, locations, and severities of ground contacts, which can affect injury potential to the occupants. Other limitations include a lack of specific quarter-turn data in rollovers of more than four quarter-turns in pre-1995 NASS entries, resulting in the exclusion of these data, and the exclusion from specific analyses of NASS-CDS cases with missing data on relevant variables. NASS-CDS data also do not include data on number of rolls for end-over-end rollovers.

CONCLUSIONS

While rollovers with a high number of rolls occur infrequently, rollovers with an increased number of quarter-turns are associated with increases in injury severity. The increased risk is particularly great when a vehicle rolls more than two complete rolls. Increases in number of rolls can also increase the risk of other vehicle events that increase injury risk, such as ejection and the severity of vehicle-to-ground contacts. The rate of increase in risk varies by the region of the body affected and the severity of the injury. Additionally, the rate of increase in risk to different regions of the body as well as the distribution of injury risk is significantly affected by restraint usage.

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