THE NATURE OF SERIOUS INJURY IN US AND UK ROLLOVER CRASHES

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ABSTRACT

This study focused on rollover crashes in the US and UK. The rollover crash characteristics and injury distribution to belted occupants were compared for the US and UK. The UK has higher percentages of non-arrested rollovers with vehicle impact, lower percentages of arrested rollovers and non-arrested rollovers with object/topography impacts, and comparable percentages of "pure" rollovers (ground impact only), compared to the US. Both US and UK data show that rollovers are complex events. Of all seriously injured occupants in US rollovers, only 5% (with 95% confidence intervals of 3.5% to 6.7%) are belted front seat occupants with serious head/face/neck injuries, roof contact, and roof deformation coded at occupant position.

KEY WORDS: roof contact, roof deformation, head/face/neck injury, torso injury, rollover

NUMEROUS CRASH TESTS and field studies in the early 1980s and 1990s identified potentially injurious circumstances occurring to non-ejected/partially ejected occupants in rollover crashes (Orlowski et al., 1985; Bahling et al., 1990; Sakurai and Isenlo, 1991; Mackay and Tampen, 1970; Huelke and Compton, 1983). Due to the complexity of the relationships between crash factors and potential injury mechanisms in rollovers, interest in examining field data and performing vehicle tests to address rollover crash characteristics and occupant injury experience has continued through the past decade. This study examines field data on rollover crashes from the United States (US) and the United Kingdom (UK) and presents a comparison of crash characteristics and belted occupant injury experience associated with rollover crashes for the two countries.

In 2004, a study was undertaken in the US by JP Research, Inc. to develop an accurate estimate of the number of belted occupants seriously injured (focused on AIS[1] 3-6 head/face/neck injury or torso injury) in rollover crashes through contact with various injury sources, including "roof contact" (Padmanaban, 2004). The primary objective of that study was to use comprehensive statistical analyses, based on field data, to evaluate "roof contact" injury estimates published by the National Highway Traffic Safety Administration (NHTSA, 2001) and to address some key questions on accident, vehicle, and occupant factors associated with serious injuries in rollovers. This paper presents some of that study's findings. In addition, the paper provides a comparison of US and UK rollover crash characteristics and occupant injury patterns associated with rollovers. Some examples of detailed case files using US and UK rollover crash data are discussed.

BACKGROUND

In October 2001, NHTSA issued a request for comments (49 CFR Part 571; Docket No. NHTSA-1999-5572, Notice 2) seeking assistance in upgrading the requirements of Federal Motor Vehicle Safety Standard (FMVSS) 216, "Roof Crush Resistance", to reduce injuries and fatalities in passenger cars and light trucks during rollover crashes. This standard (which became effective in 1973 for US cars and 1991 for US light trucks) established strength requirements for the roof structure over the

[1] AIS and MAIS refer to the Abbreviated Injury Scale and Maximum Abbreviated Injury Scale, respectively. The AIS/MAIS scales are used in US federal crash reporting and copyrighted by the Association for the Advancement of Automotive Medicine.

front occupants of cars/light trucks with a gross vehicle weight rating (GVWR) of 6,000 pounds or less.

FMVSS 216: ROOF CRUSH RESISTANCE DOCKET. Several studies submitted to the NHTSA docket attempt to address the relationships between vehicle roof strength, roof deformation, serious injury, direction of roll, and occupant headroom using vehicle testing, biomechanical analyses, and statistical analysis of field performance of vehicles. The findings of these studies vary widely. James et al. (1995) commented on past technical literature (e.g., Felrice, 1992; Strother et al., 1984; Huelke et al., 1972; Mackay and Tampen, 1970) that showed no causal relationship between roof crush and head/neck injuries. The "Malibu" studies with belted occupants (Bahling et al., 1990) indicated that the mechanism for high neck loads in crash dummies is governed by the dummy's velocity relative to the vehicle at impact, which controls the momentum of the dummy's torso. The Malibu studies for unbelted occupants in dolly rollover tests (Orlowski et al., 1985) reported significantly higher neck assessment values compared to head, but the values were generated before significant roof crush occurred. All of these studies noted that the dummy neck loads resulted from "diving" type impacts where the head stops the torso momentum and compresses the neck, with a magnitude proportional to the impact velocity. In the recent "CRIS" (Controlled Rollover Impact System) studies (Cooper et al., 2003), rollover impacts of rollcaged and production roof cars were investigated.

There is also an extensive body of literature on statistical studies of rollover crashes. A recent comprehensive statistical study based on data from 90,000 rollover accidents (Padmanaban et al., 2005) showed there was no statistically significant relationship between vehicle roof strength-to-weight ratio and likelihood of fatality or serious injury in rollovers. That study also concluded that there was no statistically significant relationship between occupant headroom and serious injury risk to belted occupants in rollovers. Some statistical studies have attempted to examine rollover crash characteristics and their influence on injury outcome. Malliaris and Deblois (1991) found that vehicle pre-crash speed is a crash severity parameter in rollovers. Digges and Eigen (2003) used the number of roof impacts and quarter turns to examine the relationship between crash severity and injury risk in rollovers. Several other studies (e.g., Najjar, 1981) have associated quarter turns to rollover crash severity.

US AND UK ROLLOVER STUDIES. Clearly, the relationships between rollovers, roof deformation, and injury outcome are not simple to pin down and will require detailed examination, including accident reconstruction and simulations to model occupant motion. Although accident reconstruction and computer modeling are beyond the scope of this study, the study reported herein is an in-depth exploration of some of the factors associated with rollover injuries in the US and UK through statistical analyses and detailed review of case files containing scene diagrams and photographs. There has been an increased interest by the safety community in both the US and UK to understand and compare the complexity of rollover events and occupant injury patterns. A recent study by Parenteau et al. (2001) analyzes US and UK data to identify factors influencing rollover occurrence and injury outcome, and Hurley and Welsh (2001) characterize UK rollover crashes to determine the influence of rollover events on injury outcome.

This paper adds to the existing body of rollover research by providing a more comprehensive discussion of rollover crashes with more recent US and UK field data.

DATA SOURCES

Real-world accident data obtained from the National Automotive Sampling System (NASS) data files (1988-2002) in the US and the Co-operative Crash Injury Study (CCIS) database (1995-2002) in the UK on tens-of-thousands of crashes involving passenger vehicles were used to perform this study. Both the NASS and CCIS data files contain information on crash type (e.g., rollover, frontal crash, etc.), injury severity, and other vehicle/occupant factors—including restraint use, number of rolls, object contacted, nature of injury (e.g., head/face/neck), injury severity, amount of roof deformation at occupant position, direction of roll, and vehicle type—which facilitated comparison of US and UK field experience.

NASS DATA. The NASS database, which is maintained by NHTSA, is a nation-wide representative sample of tow-away crashes investigated in detail by NASS teams consisting of

engineers, biomechanical experts, medical personnel, and statisticians. The NASS data files contain information on over 500 variables addressing crash/vehicle/occupant and injury factors associated with real world crashes and hence, are widely used by NHTSA and other highway safety researchers in the US to examine injury experience in rollovers. The NASS Crashworthiness Data System (NASS/CDS), used for this study, investigates about 5,000 crashes a year involving passenger cars and light trucks. Nation-wide estimates are extrapolated using a stratified sampling system to ensure the results are representative.

NASS/CDS data for the years 1988-2002 were used for statistical analyses, and NASS/CDS data from 1997-2001 were used for in-depth case review. NASS/CDS case files for the years 2002 and 2003 are available on NHTSA's website, but these use a setup that makes concurrent review of each case element—vehicle photos, scene diagrams, injury sketches, and other NASS-coded information on 150 variables—extremely difficult and, consequently, these were not included for the detailed case review. For the study period (1988-2002), NASS/CDS investigated about 11,000 light vehicle rollovers involving 19,000 occupants. Of these 19,000 occupants, about 4,300 were occupants with serious injuries (MAIS 3-6/fatal). Over 60% of seriously injured occupants were unbelted.

CCIS DATA. The CCIS database is maintained by the Transport Research Laboratory and is sponsored by a consortium of motor vehicle manufacturers and the UK Department for Transport. The database includes only passenger vehicles (primarily cars) that were less than seven years old at the time of the crash and were towed away to a garage or a vehicle dismantler. The CCIS applies a stratified sampling criterion to select crashes for further investigation. Approximately 80% of serious and fatal injury crashes, and about 10-15% of slight injury crashes (according to the UK Government's classification), are investigated. The resulting sample is biased towards more serious injuries. Some 1,500 crashes are investigated annually. For the study period (1995-2002), 844 rollover cases were investigated by CCIS.

METHODOLOGY

First, data on seriously injured (AIS 3-6/fatal) occupants in US rollovers were identified. The data were broken down by restraint use, body region (head/face/neck, torso, upper extremities), and injury source ("roof contact", "ground contact", etc). Then, statistical estimates on seriously injured belted occupants with "injury source–roof contact" were derived. These injury estimates were further broken down by magnitude of roof deformation (with "roof" defined as vehicle roof, windshield header, and A/B pillars) identified at occupant seated position. Some of the key findings from this study on rollover crash characteristics and belted occupant injury outcome were then compared with UK experience.

As a companion to the statistical study, a detailed case review was performed for selected US rollover cases meeting the following study criteria:

- A rollover crash from NASS/CDS files for the years 1997-2001, in which the crash-involved vehicles were 1990 and later model cars and light trucks
- Belted front seat outboard occupants
- Non-ejected or partially ejected occupants
- Injury source identified as "roof contact"
- Injury severity (primarily AIS 3-6 head/face/neck or torso injury)
- Roof deformation coded at occupant seated position (all ranges of roof deformation were included).

One hundred and nineteen (119) US cases meeting the study criteria were available, and all were reviewed. A rollover class variable was defined to characterize rollover events using vehicle photographs, scene diagrams, and other relevant crash information. Based on detailed case reviews, the following definitions were developed to classify rollovers:

1. Arrested rolls— in which the rollover is stopped abruptly by impact with a fixed object.
2. Non-arrested rolls with object or topography impacts— in which the vehicle impacts one or more objects or terrain factors (ditch, change in grade, etc.) before, during, or after the roll, but is not abruptly stopped by the impact (e.g., Hit a tree, hit a pole, and rolled; or Vertical drop, down embankment, and rolled).
3. Non-arrested rolls with vehicle impacts— in which the vehicle impacts another vehicle

before, during, or after the roll.

4. Non-arrested rolls with ground-only impact (also called "pure" rollovers)— in which no vehicles, nor objects other than the ground, are impacted during the rollover sequence.

These definitions were then applied to the entire NASS/CDS data (1988-2002) by using the NASS/CDS variables for "rollover event sequence", "type of object contacted", "rollover initiation type", and other variables (such as single-vehicle/multiple-vehicle). All rollover crashes in the entire NASS/CDS data were classified into one of these four groups.

The UK rollovers were similarly classified, using the impact profiles, police information, and witness comments. The four classifications are:

1. Rollovers before impact (matches US classification "arrested rolls")
2. Rollovers between impacts with objects/topography; rollovers after impacts with objects/ topography (matches US classification "non-arrested rolls with object/topography impacts")
3. Rollovers impacting a vehicle before, during, or after rollover (matches US classification "non-arrested rolls with vehicle impacts")
4. "Pure" rollovers (matches US classification "non-arrested rolls with ground impacts only").

The relationships between rollover crash characteristics, magnitude of roof deformation at occupant seated position, and severity of injuries for belted occupants were also compared. These in-depth reviews and statistical analyses formed the basis for comparison of crash- and occupant-related factors associated with rollovers occurring in the US and UK.

RESULTS

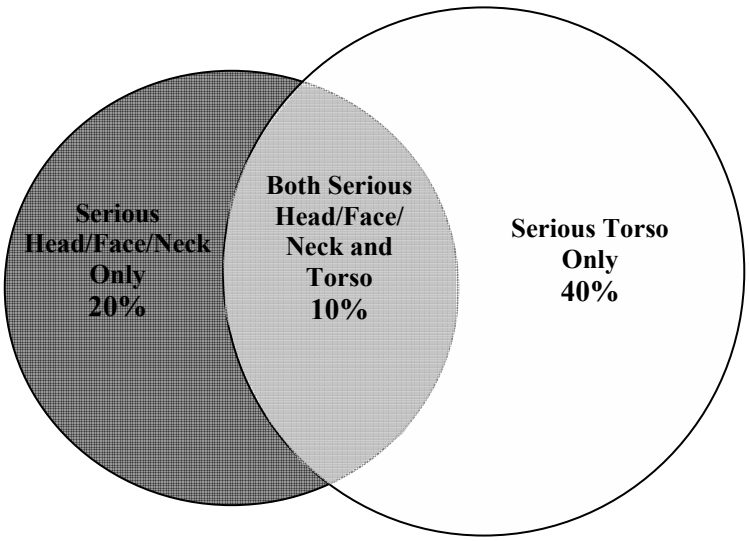
In this section, some of the key findings from the comprehensive statistical study done in the US are presented, and then some of these results are compared to UK data. Finally, discussions of results from a few detailed case reviews from the US and UK are presented.

STATISTICAL DATA RESULTS (US DATA).

Roof Crush and Belted Occupant Injury. In the US, of all seriously injured occupants in rollovers, 5% (with 95% CI: 3.5% to 6.7%) are belted front seat occupants with AIS 3-6 head/face/neck injuries, injury source coded as "roof contact", and roof deformation coded at occupant seated position.

Rollovers and Belted Occupant Head/Face/Neck Injuries. Serious torso (abdomen, thorax, thoracic and lumbar spine, and pelvic hip) injuries are the most common type of serious belted occupant injury in rollovers. Forty percent (40%) of seriously injured belted occupants sustain serious torso injuries only, 20% sustain serious head/face/neck injuries only, and 10% sustain both serious head/face/neck injuries and serious torso injuries in rollovers. As shown in Figure 1, this overlap

Figure 1. Percentage of Belted Occupants with Serious Injury by Selected Body Regions
NASS/CDS Weighted Data, 1988-2002

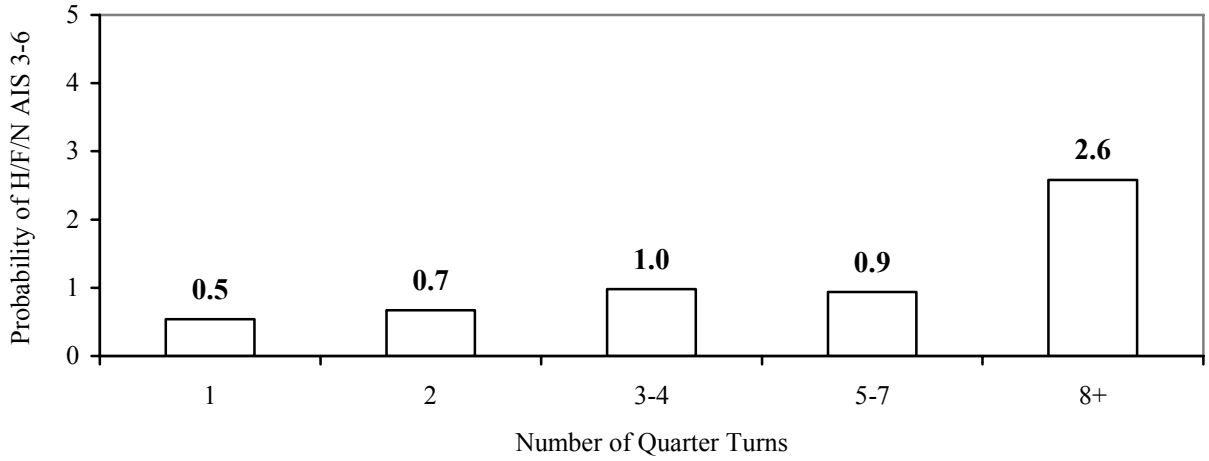


results in fully half of belted occupants sustaining serious torso injuries, and less than a third sustaining serious head/face/neck injuries in US rollovers.

Rollovers and Cervical Spinal Injuries. Less than one-half percent (0.11%, with 95% CI: 0.1% to 0.2%) of 19,000 occupants involved in rollovers sustained AIS 4-6 cervical spine injuries.

Rollover Energy/Crash Severity. While the overall energy of the rollover event may be useful to consider in assessing crash severity, it may be that the energy associated with individual roof-to-ground impacts are of greater interest in assessing potential for head/face/neck injury. This measure cannot be obtained from detailed NASS/CDS case review unless detailed accident reconstruction is done. Other variables reflecting rollover crash severity include roll distance, speed prior to roll, object(s) contacted, elevation, tripping mechanism, trip energy, and number of rolls, and a few of these variables can be developed from NASS/CDS case reviews. In particular, the NASS/CDS data include information on the number of quarter turns and object(s) contacted during roll sequence. Prior to 1995, NASS classified "number of quarter turns" into four groupings: 1 turn, 2 turns, 3 turns, and 4 or more turns. From 1995 on, more detailed coding was available for this variable and so, for this study, analysis of injury risk versus number of quarter turns was performed using NASS/CDS data for 1995-2002. Figure 2 presents the probability of serious head/face/neck injury to belted, non-ejected occupants by number of quarter turns.

Figure 2. Probability of Belted, Non-Ejected Occupants with AIS 3-6 Head/Face/Neck Injury, by Number of Quarter Turns
NASS/CDS Weighted Data, 1995-2002



As seen in Figure 2, the severity of injury generally increases with number of rolls, but additional factors have to be considered to understand injury consequences. A rollover with fixed object contacted (tree/pole) could have different injury consequences compared to a rollover with no object contacted.

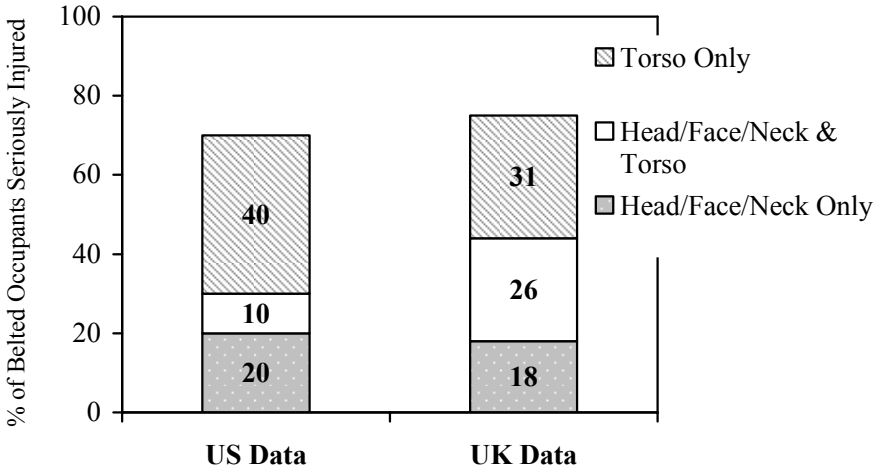
COMPARISON RESULTS FOR US AND UK DATA. The following sections present comparisons of results from the statistical study and the NASS/CDS detailed case review.

Statistical Data Comparison. In the US, about 3% of all crashes are rollovers and 9% of all tow-away crashes investigated by NASS/CDS are rollovers, while in the UK this percentage is higher, with 14% of all tow-away crashes investigated by CCIS being rollovers. This is a slight increase from past studies that have shown 10-12% of UK crashes are rollovers (Mackay et al., 1991; Parenteau et al., 2001). In addition, 15% of US rollovers are more than one complete roll, while in the UK the number is 20% (Mackay et al., 1991). About 85% of US rollover crashes are single-vehicle rollovers, while in the UK, the corresponding rate is 69%. Other differences between US and UK rollover crash statistics are discussed below.

Rollover Injuries. In the US, 20% of belted, seriously injured, rollover occupants sustain head/face/neck injuries only, 40% sustain torso injuries only, and an additional 10% sustain both head/face/neck and torso injuries. Hence, about 30% of seriously injured belted occupants in US

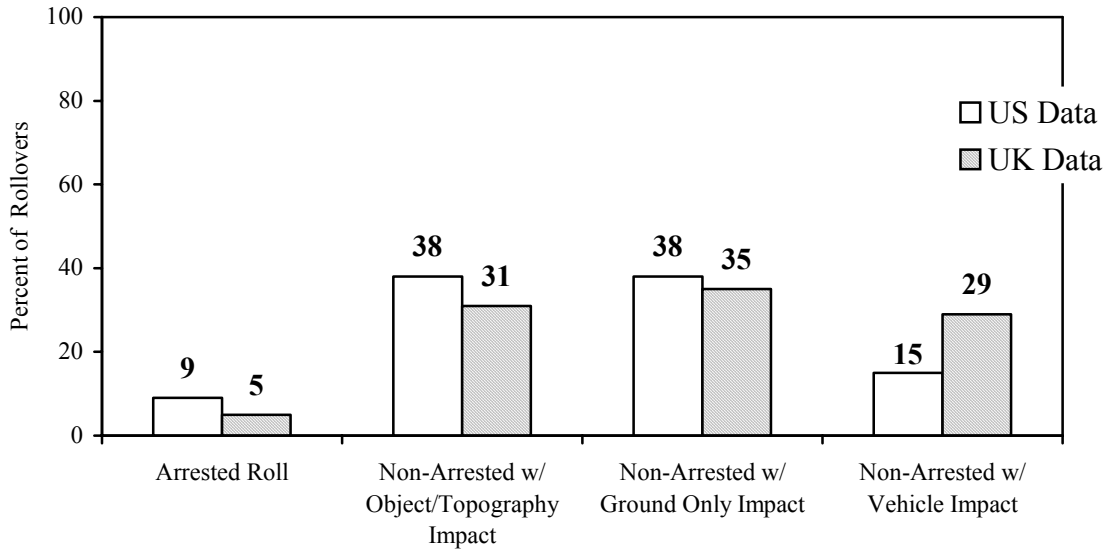
rollovers sustain head/face/neck injuries. As shown in Figure 3, 18% of belted, seriously injured, rollover occupants in UK sustain head/face/neck-only and 31% sustain torso-only injuries. In addition, 26% sustain both serious head/face/neck *and* torso injuries. The UK data show a much higher proportion of serious head/face/neck and torso combined, compared to US (26% versus 10%). About 44% of belted occupants in the CCIS rollover data sustain serious head/face/neck injuries and about 57% sustain serious torso injuries. These differences are due to sampling design differences between the two data files, in that the CCIS database is biased towards the police categories of fatal and serious, with only about 5% of the sample selected having the equivalent of AIS 1 level injuries.

Figure 3. Percentage of Belted Occupants with Serious Injury by Selected Body Regions
NASS/CDS Weighted Data, 1988-2002; CCIS Data, 1995-2002



Rollover Characterization. Figure 4 presents the distribution of US (all NASS investigated) and UK (CCIS investigated) rollovers by rollover crash characteristics.

Figure 4. Distribution of Rollover Characteristics (US and UK)
NASS/CDS Weighted Data, 1988-2002; CCIS Data, 1995-2002



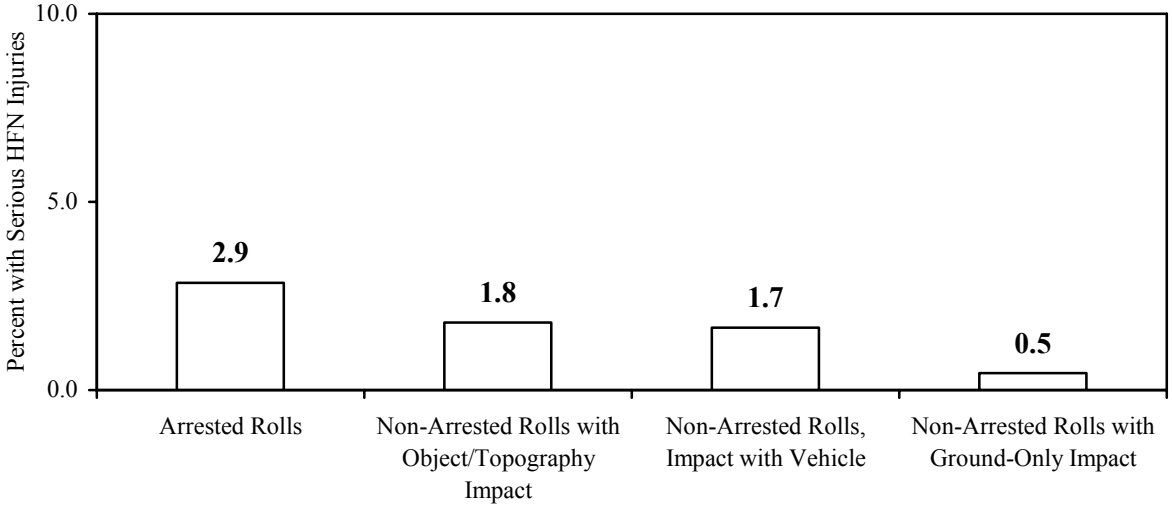
The results show that the US has slightly higher percentages of arrested rolls (9% US versus 5% UK); higher percentages of non-arrested rolls with object/topography impacts (38% US versus 31% UK), and comparable percentages of non-arrested rollovers with ground-only impact (38% US versus

35% UK). In contrast, the UK has a much higher percentage of non-arrested rollovers impacting vehicles (15% US versus 29% UK).

The US and UK rollover data on "ground-only impacts" were further examined to determine the average number of quarter turns for vehicles not impacted by other objects or vehicles. In the US, the average number of quarter turns involved in "pure" rollovers (ground-only impact) is four for passenger cars and three for light trucks. In the UK the average number of quarter turns for "pure" rollovers is four, which may reflect differences in the makeup of UK vehicle fleet (which primarily includes passenger cars).

Serious Injury Risk by Rollover Characteristics. The US NASS/CDS data and UK CCIS data were examined to determine the serious head/face/neck injury risk to belted occupants by rollover characteristics. Due to small sample sizes, results for UK data are not presented. For US data, as seen in Figure 5, the serious injury risk to belted occupants is higher for arrested rolls compared to any class of non-arrested rolls (i.e., rollovers with ground-only, object/topography, or vehicle impacts). The data show that, for belted occupants, the serious head/face/neck injury risk is lowest in rollovers with ground-only impacts. However, these findings do not address injury causation or crash severity factors such as speed prior to roll, roll energy, or roll distance. The confidence intervals on the Figure 5 results for US data are given in parentheses for each as follows: arrested rolls (1.2 to 4.5), non-arrested rolls with object/topography impact (0.7 to 2.9), non-arrested rolls, impact with vehicle (0.9 to 2.5), non-arrested rolls with ground-only impact (0.3 to 0.6).

Figure 5. Serious Head/Face/Neck Injury (AIS 3-6) Risk, by Rollover Type (US)
Belted Occupants. NASS/CDS Weighted Data, 1988-2002



Detailed Case Review Comparisons.

Some Example US Cases. This section presents two rollover cases reviewed as part of a study of 119 NASS/CDS cases (with 124 occupants). A thorough examination of photographs, scene diagrams, injury contact pictures, and all the available information in NASS/CDS for several such cases confirms that rollovers are complex events involving numerous factors associated with crash severity and occupant injury severity. The two cases presented here are examples of variability in occupant injury outcome, in severity and in type, for vehicles that sustain approximately the same magnitude of vertical roof deformation at each occupant position. The first case is a passenger car with severe roof deformation and second case is a sport utility vehicle with minor vertical roof deformation. These cases also demonstrate that magnitude of deformation is not a predictor of injury outcome. Both situations highlighted here—of rollovers with severe roof deformation/no injury to belted occupant as well as those with minor roof deformation/severe injury to belted occupants—were seen numerous times.

The case shown in Figure 6 involved a vehicle that rolled over two quarter turns and did not hit any objects during the roll; i.e., a "pure" rollover. There was vertical roof deformation of 30-46 cm

(12-18 in.) over both occupants; however, while the belted driver (160 cm [5 ft., 3 in.]) sustained serious head/face/neck injury (AIS 5), the belted right front passenger (180 cm [5 ft., 11 in.]) sustained only minor injury (AIS 1). It is interesting to note that the roof deformation over the non-injured passenger is visibly more severe than over the injured driver.

Figure 6. US Case No. 1997-12-173J

Another case (Figure 7) involved a sport utility vehicle in an off-road pure rollover (no object contacted) with six quarter turns. The unbelted driver (175 cm [5 ft., 9 in.]) sustained serious torso injury (AIS 3) and the belted passenger (160 cm [5 ft., 3 in.]) sustained serious head/face/neck injuries (AIS 3), even though the vertical roof deformation at both occupants' positions was minor (3-8 cm [1-3 in.]).

Figure 7. US Case No. 2000-43-007J

*Example UK Case***.** A case from the CCIS files highlights the facts that rollover crash characteristics and crash severity influence injury outcome, and that simple measures alone, such as number of quarter turns, may not be enough for determining injury outcome in a rollover. This case is an example of an arrested roll influencing injury outcome in a rollover with only one quarter turn.

The vehicle shown in Figure 8 was traveling along an "A" class road when it lost control and left the road on the nearside and rolled one quarter turn onto its offside (nearside roll). It then slid into a tree, with the roof making direct contact. The roof intrusion was estimated to be 61 cm (24 in.) on the driver side and 43 cm (17 in.) on the front passenger side. There were two male occupants (both aged 35 years old) in the car, and both were wearing seat belts. The driver received fatal injuries. He received injuries to the organs of the head (AIS 4), thorax (AIS 4), and abdomen (AIS 3). The front seat passenger also received fatal injuries. He received injuries of AIS 5 severity to the skull and the brain.

Figure 8. UK Case

Both the US and UK case studies highlighted here, whether taken together or as individual studies, show that rollovers are complex events and that there is a high degree of variability in the crash characteristics and injury outcome of these events.

DISCUSSION

The NASS/CDS data indicate that, of seriously injured occupants in rollovers, about 5% (with 95% CI: 3.5% to 6.7%) sustain serious head/face/neck injuries and have roof contact and roof deformation coded at occupant position. This finding, particularly in light of NHTSA's focus on roof contact and magnitude of roof deformation, deserves serious attention and study.

Additionally, the comparisons between the UK and US rollover crashes reveal not only similarities (such as that, in both countries, arrested rolls make up the smallest class of rollovers, followed by non-arrested rolls with vehicle impacts) but some intriguing differences (such as the fact that, while non-arrested rolls with vehicle impacts is the second most common class of rollovers, it represents a much larger percentage of rollovers in the UK than in the US).

For belted occupants with serious injuries in US and UK rollovers, torso injuries are more frequent than head/face/neck injuries. However, the UK (CCIS) data shows a much higher percentage of combined head/face/neck and torso injuries (26%) compared to results for US NASS/CDS data (10%) and a higher percentage of belted occupants with serious head/face/neck injuries (44% for UK versus 30% for US).

In both the US and the UK, the percentage of rollovers with ground-only impacts is the about same (between 35% and 38%). The UK has a much higher percentage of non-arrested rollovers with vehicle impacts, compared to the US, and the US has a higher percentage of non-arrested rollovers with impacting object/topography and slightly higher percentage of arrested rollovers. In the US, serious head/face/neck injury risk to belted occupants in "pure rollovers" is much lower than for occupants in arrested rolls or in non-arrested rolls with object/topography/vehicle impacts. However, these findings do not address injury causation or other crash severity factors.

Detailed case review of US and UK rollover cases reveals that injury outcomes are products of the detailed circumstances unique to each case, a finding that underlines that rollover events are complex and that likelihood of serious injury appears to be associated with more than one crash-related factor.

The UK data are not 100% compatible with the US data; neither are the two fleets identical in vehicle composition. In addition, the sample sizes in CCIS data and NASS/CDS data are small for cervical spine associated injuries in rollovers. Necessarily, these facts to some degree limit the comparisons between UK and US experience, and the results have to be interpreted with caution. However, the data are extremely comprehensive, allowing the study to provide a larger understanding of rollover crash experience in the real world.

What is clear from these studies is that the current parameters used for describing the characteristics of rollover accidents, in the databases available, are inadequate in terms of providing specific causal relationships for the mechanisms of injury to occupants. Serious injuries arise when loads applied to specific body regions exceed the individual's tolerance levels. Those loads come from structures where the localized contact velocities are high. Those localized contact velocities may arise from specific high energy impacts due to the nature of a particular rollover. Those impacts may or may not lead to deformation of the bodyshell of the vehicle, but there is no simple causal relationship. Until further detailed descriptions of such accidents are collected through improved recording and reconstruction techniques, there will always be uncertainty as to the relationships between structural deformation and injury outcome.

ACKNOWLEDGEMENTS

This paper uses accident data from the United Kingdom Co-operative Crash Injury Study. CCIS is managed by TRL Limited, on behalf of the Department for Transport (Vehicle Standards and Engineering Division) who fund the project with Autoliv, DaimlerChrysler, Ford Motor Company, LAB, Nissan Motor Company, Toyota Motor Europe, and Visteon. The CCIS data were collected by teams from the Birmingham Automotive Safety Centre of the University of Birmingham; the Vehicle Safety Research Centre at Loughborough University; and the Vehicle & Operator Services Agency of the Department for Transport. Further information on CCIS can be found at http://www.ukccis.org

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