Injuries in Rollovers by Crash Severity

Kennerly Digges
Ana Maria Eigen

The National Crash Analysis Center,
The George Washington University
The National Highway Traffic Safety Administration
USA
Paper Number 07-0236

ABSTRACT

Earlier studies by the authors have examined factors that contribute to rollover crash severity. These factors include: (1) belt use, (2) the number of quarter-turns aggregated according to number of vehicle inversions, and (3) the damage severity from planar impacts with fixed and non-fixed objects that occur before or during the rollover. Further research indicated that rollovers with severe damage from planar impacts should be analyzed separately from other rollovers since the injury rates for these crashes is 2 to 3 times greater than equivalent crashes with less severe damage.

This paper separates rollovers into two categories, based on the presence or absence of severe damage from a planar crash. The research then examines the distribution of MAIS 3+ injuries and harm by body region and contact for belted and unbelted adult occupants in each rollover category. The rollover categories are further examined by ejection status, roll direction and number of vehicle inversions. Ejection paths are examined for the partially and totally ejected occupants.

Based on the analysis, the magnitude of the opportunities for injury and harm reduction through safety enhancements such as air curtains and safety belts designed for rollover protection is examined.

INTRODUCTION

Prior to 1995, NASS did not code the number of quarter-turns beyond four. This also included crashes where rollover was the most severe event. Earlier analysis showed clearly that rollovers with 4+ quarter-turns carried a higher injury rate than rollovers with fewer quarter-turns. Beginning in 1995, the NASS coding was expanded to enumerate the number of quarter-turns up to 16. Rollover extent of damage was also measured and categorized in three severity levels – minor, moderate, and severe. Unlike the extent of damage classified via the Collision Deformation Classification, a reserved phrase and variable name in NASS CDS, this study examines total delta-v and estimated delta-v, as given for the most severe event. For planar crashes, for which a delta-v can be calculated by measurements taken at the crash scene, the numeric or total delta-v is considered. In cases where the algorithm parameters are exceeded, an qualitative or quantitative delta-v is reported as the estimated delta-v. The algorithm fails in extreme or complex planar engagements and rollover crashes. The enumeration of up to 16 quarter-turns in NASS has provided a much more detailed characterization of the rollover. However, it has complicated the analysis because it has created smaller cells with varying amounts of data. Some lower numbers of quarter-turns carry higher injury rates than subsequent numbers of quarter-turns. It is desirable to aggregate the quarter-turn cells in a way that produces injury risks that generally increase with number of quarter-turns. It is also desirable to identify the factors other than quarter-turns that contribute to injury risk.

In an earlier study, crash factors that increased the risk of MAIS 3+ injuries in rollovers were examined [Digges 2006]. The earlier study found that the number of times the vehicle roof faces the ground (number of vehicle inversions) was a statistically significant factor that predicted increased injury risk for single vehicle rollovers. The analysis also examined the extent of damage to vehicle as added severity metric for rollovers that are preceded by or interrupted by impacts with fixed and non-fixed objects. Vehicle damage was measured and categorized in three severity levels – minor, moderate, and severe. Rollovers were also coded into four classes – (1) rollover as a single event, (2) rollover as the 1st event of multiple harmful events, (3) rollover preceded by impact with a non-fixed object and (4) rollover preceded by impact with a fixed object. It was found that the number of vehicle inversions was a good severity metric for rollovers with fixed and non-fixed object impacts so long as cases with severe damage from the object impacts were excluded. The inclusion of the rollovers with minor and moderate damage from fixed object impacts with pure rollovers permits the application of the number of vehicle inversions as a severity metric to about 80% of the rollovers with belted front seat occupants and MAIS 3+ injuries. The remaining 20% are rollovers with severe damage with fixed or non-fixed objects and the planar impact may have contributed to the injury severity. In an earlier study, new NASS codes were used to examine crash factors that increased the risk of MAIS 3+ injuries [Digges 2003]. That study used NASS/CDS (Crashworthiness Data System) 1995-2001 data. The variables added in 1995 permitted a more robust examination of how planar damage and number of quarter-turns may influence the risk of injury. These rollovers may require countermeasures to protect against both the planar impact and the rollover.

The earlier study found that the number of times the vehicle roof faces the ground (number of vehicle inversions) was a statistically significant factor that predicted increased injury risk for belted occupants in single vehicle rollovers and in rollovers with impacts with fixed and non-fixed objects where only minor and moderate damage occurs.

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 2005. 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 and right front passengers. It was found that the higher occupancy rates of vans and SUV's tended to bias the results when all rear seat occupants were included [Digges 2003]. Earlier work has shown that belted and unbelted occupants should not be combined when attempting to characterize rollover crash severity [Digges 2003]. In the present study, only belted occupants were considered. Occupants less than 12 years old were excluded from the study because of complications that could be introduced by the presence of a variety of supplemental restraint systems not provided by the OEM.

Quarter Turn Codification

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 owing to its severe nature and varying crash dynamics requires an individual severity metric and is not examined in detail. 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

Two types of data queries were run for the analysis. First, all applicable front seat occupants involved in single vehicle rollovers were disaggregated. In this run all damage levels were included but impacts with fixed and non-fixed objects were excluded. Second, all remaining rollover types were disaggregated and the cases with severe planar damage were excluded. The data runs provided the distribution of crashes and injured occupants by MAIS, Fatality, and Injured Body Regions. The results are presented in the sections to follow.

Definition of MAIS 3+F and Harm

The MAIS 3+F populations were determined by separating the fatally injured from the survivors. All the fatalities were that added to the survivor data at the MAIS 6 level. The Harm was then calculated using the procedures reported by Malliaris. The Harm weighting factors based on the costs in Appendix E of DOT HS 809 203, February 2001. Several modifications were introduced. MAIS 1 injuries were excluded from the MAIS 2+ Harm calculation. Both MAIS 1 and 2 injuries were excluded from the MAIS 3+ Harm calculation. In this analysis, fatally injured occupants reported to have sustained MAIS 1 or 2, minor or moderate, injuries were not included. There occurrence is rare and generally related to the absence of an autopsy report.

Analysis Variables

The analysis variables were created using existing NASS CDS variables and attributes. These included groupings for the total delta-v, injury source associated with the maximum injury per body region, and consideration of the sequence of the rollover with respect to the crash events.

The delta-v groupings have been used in previous publications and are based upon total delta-v, and where unavailable estimated delta-v. The delta-v has been categorized as minor moderate, severe. The delta-v is related to the most event in the crash. This is either a calculated or estimated planar delta-v or and an estimated delta-v. In the case of rollover crashes, delta-v is used very loosely and synonymous with crash severity. This is an accepted meaning of delta-v but in the planar sense it involves some sense of change in velocity. The estimated planar delta-v is generally associated with the researcher-assessed delta-v based upon experience. This can take on a numeric, as well as a qualitative value.

The sequence of the rollover and its severity was reported in Digges, 2006. This disaggregation considered rollover as a single event crash; otherwise called pure rollover. Multiple event crashes during which the rollover occurred subsequent to the first event. Consideration was also given to whether rollover occurred pursuant to a fixed, nonfixed contact, or mixed fixed and nonfixed contacts.

Table 1: Rollover Type and Severity Inclusion

Rollover Type	Severity (Extent of Damage)	Injury Severity
Pure Rollover	All	All
Other Rollover	Minor, Moderate	All

The injury source groupings associate occupant contacts to injuries sustained, per Table 2. These groupings are reflective of gross vehicle locations and include: upper vehicle, mid vehicle, safety belt and airbag systems, ground and other vehicle contact, other contacts. The upper vehicle includes roof, headers, windows, frames, and pillars. The mid vehicle consists of side interior, dash board, and steering wheel. The safety belt and airbag systems account for any constituent of the active or passive restraint system exclusive of the knee bolster. Finally, the other grouping considers any contact not listed previously.

Table 2: Injury Contact Categories

Injury Contact Categories	Description
Upper Vehicle	Window Sills and above, inclusive of frame and glazing
Mid Vehicle	Instrument Panel, Interior Hardware, Steering Assembly
Safety Belt and Airbag System	Active and Passive Restraint System, inclusive of components and hardware
Ground, Vehicle Exterior, Other Vehicle	Any exterior occupant contact, generally associated with some degree of ejection
Other Contact	Any other contact not mentioned in the previous categories.

RESULTS: DATA ANALYSIS

Table 3 shows the distribution of Exposed and MAIS 3+F injuries for relevant belted population in NASS/CDS 1995-2005. The relevant population is all outboard front seat occupants age 12 and older. In this table, we consider only the relevant belted population involved in rollover without planar impacts and the relevant belted population exposed to rollovers with minor or moderate damage from planar impacts. The raw NASS/CDS contains 4,669 belted relevant occupants exposed to rollover and 701 relevant occupants with MAIS 3+ injuries. The weighted numbers are 2,180,113 exposed relevant occupants and 73,340 MAIS 3+F injured occupants. The columns in Table 1 show the number of vehicle inversions. One quarter turn is represented by “0 Inv”. Two to five quarter-turns are included in “1 Inv” and so on. End-over-end rollovers are represented by “EOE”. The “% of All” column shows the percent of the total for the sum of the rows. About 33% of MAIS 3+F injuries in this population occur in single vehicle rollovers without planar impact. The remaining 67% are rollovers with planar impact and minor or moderate damage. Rollovers with planar impact are considered a different class of and severe damage and have been excluded from this analysis.

The “3+ Risk” row in Table 1 the MAIS 3+F injury rates per 100 relevant occupants exposed to the crash environment as defined by the same column. The “3+ Risk” in the % of All column is the average risk for the population in the row.

Table 3. Distributions of Exposed Occupants, Harm, MAIS 3+F and MAIS 3+F Injury Risk for Rollover Populations

Single Vehicle Rollover, No Planar Impact - All Damage Severity							
Population	0 Inv	1 Inv	2 Inv	3+ Inv	EOE	Unk	% of All
2+Harm	1%	36%	41%	13%	1%	9%	28%
3+ Harm	1%	33%	45%	11%	1%	9%	29%
MAIS 3+F	0.2%	23%	66%	6%	2%	3%	33%
Exposed	8%	72%	14%	1%	0.1%	5%	27%
M3+ Risk	0.11	1.01	11.30	14.35	48.74	3.35	2.71
Rollover with Planar Impact - Minor and Moderate Damage							
Population	0 Inv	1 Inv	2 Inv	3+ Inv	EOE	Unk	% of All
2+Harm	14%	50%	22%	7%	1%	6%	72%
3+ Harm	14%	48%	24%	7%	1%	6%	71%
MAIS 3+F	8%	48%	32%	5%	2%	6%	67%
Exposed	18%	67%	11%	1%	0.2%	3%	73%
M3+ Risk	1.29	2.02	7.98	14.51	18.38	5.78	2.83
Rollover with No Planar Impact + With Planar Impact - Minor and Moderate Damage							
Population	0 Inv	1 Inv	2 Inv	3+ Inv	EOE	Unk	% of All
2+Harm	11%	46%	27%	8%	1%	7%	100%
3+ Harm	10%	44%	30%	8%	1%	7%	100%
MAIS 3+F	6%	41%	40%	6%	2%	6%	100%
Exposed	15%	68%	12%	1%	0.2%	3%	100%
M3+ Risk	1.09	1.68	9.19	14.44	23.50	4.72	2.79

Several observations may be made from the data. First, a substantial fraction of the MAIS 3+F injuries (72%) in single vehicle rollovers without planar impact involve crashes with more than one vehicle inversion. In the cases of rollovers with planar impacts, only 43% of the MAIS 3+F injuries occur in crashes with more than one inversion.

Second, the injury risk for 0 inversions is much higher for rollovers with minor and moderate planar damage than it is for pure rollovers. Earlier papers have noted that this is partially due to the vulnerability of the vehicle to a roof impact with a fixed or non-fixed object when the rollover is interrupted at one quarter-turn. A more precise benefits analysis should separate out these cases.

Third, the injury rate for one vehicle inversion is generally higher for the crashes with planar impacts, suggesting that the planar crash may contribute to the injury. However, when examining the influence of vehicle inversion on injury rate, the differences are small in comparison.

Table 4 shows the similar data to Table 3, but with the injuries disaggregated by body region. In Table 4 the two rollover groupings in Table 1 are combined.

Table 4. Distributions of Harm, MAIS 3+F and MAIS 3+F Injury Risk by Injured Body Region with Rollovers with Severe Damage from Planar Impacts and End-over-end Rollovers Excluded

Head, Face, Neck & Spine Injuries						
Population	0 Inv	1 Inv	2 Inv	3+ Inv	Unk	Ave Risk
2+Harm	8%	50%	23%	12%	6%	
3+ Harm	6%	48%	26%	13%	7%	
MAIS 3+F	6%	54%	30%	3%	8%	
Exposed	15%	68%	12%	1%	3%	
M3+ Risk	0.31	0.66	1.78	5.44	1.61	0.83
Chest & Abdomen Injuries						
Population	0 Inv	1 Inv	2 Inv	3+ Inv	Unk	Ave Risk
2+Harm	13%	43%	28%	8%	6%	
3+ Harm	13%	40%	30%	9%	7%	
MAIS 3+F	6%	35%	43%	5%	7%	
Exposed	15%	68%	12%	1%	3%	
M3+ Risk	0.41	0.48	3.36	4.79	1.91	0.94
Pelvic, Upper & Lower Extremity Injuries						
Population	0 Inv	1 Inv	2 Inv	3+ Inv	Unk	Ave Risk
2+Harm	20%	50%	18%	7%	4%	
3+ Harm	19%	48%	19%	8%	4%	
MAIS 3+F	10%	65%	16%	5%	3%	
Exposed	15%	68%	12%	1%	3%	
M3+ Risk	0.63	0.65	1.01	3.96	0.79	0.74

The distribution of MAIS 3+ injuries by body region for the population in Table 2 is shown in Table 5.

Table 5. Percentage of MAIS 3+F Injured by Body Region in Rollovers with Severe Damage from Planar Impacts and End-over-end Rollovers Excluded

Body Region	MAIS 3+F	MAIS 3+F Harm
Head, Face, Neck, Spine	33%	37%
Chest, Abdomen	37%	32%
Pelvic, Upper and Lower Extreminity	30%	32%

DISCUSSION

Tables 1 and 2 both show an increasing injury rate for increases in number of vehicle inversions. For planar impact rollovers with minor and moderate damage the 0 and 1 vehicle inversions carry a higher injury risk than the single vehicle rollovers. The planar impact may contribute to the injuries in some of these cases. However, the differences are small in comparison with risk increase when 2 or more vehicle inversions occur. Earlier research found that for the selected population of rollovers, there was a statistically significant relationship between the number of vehicle inversions and the risk of MAIS 3+ injury.

Table 3 indicates that the chest/abdomen has the largest fraction of MAIS 3+ injuries, but the Head Grouping has the largest fraction of MAIS 3+F Harm. This indicates that when Head injuries occur they are at a higher severity than chest injuries.

Table 2, shows the injury distribution by injured body regions. For both the Head Group and the Chest Group, about 39% of the MAIS 3+ Harm occurs after 2 or more vehicle inversions. For the Pelvic and Extremities Group, only 21% of the MAIS 3+ Harm occurs at the higher rollover severity. The injury risk for all body regions increases with number of inversions.

REFERENCES

Digges, K., and Eigen, A., “Crash Attributes that Influence the Severity of Rollovers”, Paper 231, Proceedings of the ESV Conference, May, 2003.

NHTSA, “1995-1997 National Automotive Sampling System/Crashworthiness Data System” NHTSA, DoT HS 809 203, Page 152, Feb 2001

Digges, K., and Eigen, A., “Classification of Rollover According to Crash Severity,” 50th Proceedings of the Association for the Advancement of Automotive Medicine”, p141-154, October 2006.