SEVERITY MEASUREMENTS FOR ROLLOVER CRASHES

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ABSTRACT

One of the confounding factors in analyzing rollover crashes and in designing countermeasures for rollovers is the lack of a standard measure of crash severity.   This paper examines NASS CDS 1997 to 2002 in order to determine rollover crash severity metrics and to recommend additional data elements to assist in determining rollover severity.

For belted occupants and unbelted ejected occupants in single vehicle crashes, the number of roof impacts is an appropriate severity indicator. Multiple vehicle rollover crashes carry higher injury risks than single vehicle crashes. The number of roof impacts and a (planar) delta-v are proposed as severity indicators for these crashes.

KEYWORDS: Rollover Accidents, Crashworthiness, Injury Severity, Occupants, Statistics

ROLLOVER CRASHES CONTINUE TO BE A GROWING CAUSE OF MOTOR VEHICLE INJURIES AND DEATHS in the United States. One of the confounding factors in analyzing rollover crashes and designing countermeasures is the lack of a standard measure of crash severity. Rollover severity factors equivalent to delta-V, used in planar crashes, are not currently available in the crash data files.

Before 1992, no extant data set captured a comprehensive rollover description. Instead, they recorded incidence. The number of quarter-turns has been suggested as a measure of rollover severity and has been estimated in many different studies. In 1998, the National Automotive Sampling System Crashworthiness Data System (NASS CDS) used this metric and quantified vehicle rollover through the third quarter-turn and aggregated four quarter-turns and greater. In 1992, NASS CDS started to describe rollover initiation type, tripping location, rollover initiation object, location of rollover initiation, and location on the vehicle where the initial principal tripping force was applied. In 1995, NASS CDS researchers began to code four complete revolutions, 16-quarter-turns, and end-over-end rollovers.   Any vehicle experiencing more than 17 quarter-turns was aggregated. With the advent of greater precision in recording quarter-turns and the pre and post rollover attributes identified, a more accurate description was available using NASS CDS.

In earlier studies of crash data, Malliaris found that pre-crash velocity was the most influential rollover crash severity parameter (Malliaris, 1991).   In a companion paper, Digges applied computer modeling to rollover crashes and found that increases in vehicle rotation rate and vertical velocity also increased rollover severity (Digges, 1991). None of these suggested parameters (pre-crash velocity, vertical velocity, and rotation rate) are readily available from after-the-fact crash investigations. However, in the future, on-board event data recorders (EDR) may make it practical to collect these added parameters in real time and store the results.

The purpose of this paper is to analyze recent NASS CDS rollover crashes .to determine relationships between crash rollover crash severity and variables that can be measured or computed using currently available crash investigation methods. The suitability of attributes that can be based on data elements currently documented in NASS CDS is the primary focus of this analysis.

Crash severity is an important factor in calculating the benefits of a countermeasure. It is desirable to have a crash severity measurement that can be related to the rate of injury. When a safety feature is introduced that reduces the risk of injury for a range of crash severities, the injury reduction for a fleet of vehicles can be calculated. For the analysis to follow, the recommended

crash severity parameters are those that predict increasing injury rate with increasing crash severity. The injury rate will be measured in terms of the number of serious and fatal injuries per 100 occupants in the exposed population.

The rollover crash is complicated by a number of confounding factors. Ejection is an intermediate outcome that increases the risk of fatality by a factor of more than 5 [Malliaris, 1987]. By paired comparison analysis of The Fatality Analysis Reporting System (FARS) data, Malliaris showed that the fatality reduction effectiveness of ejection avoidance was around 70% [Malliaris, 1987]. Kahane found that "two-thirds of the fatalities in rollovers involve occupants being ejected from the car, often in crashes with low damage" [Kahane 1989]. Deutermann confirmed Kahane's findings, reporting that in 2000, 62 percent of those occupants killed in fatal rollovers were ejected [Deutermann, 2002]. It is evident that ejection is an undesirable outcome of a rollover. A crash severity parameter that predicts increasing rate of ejection is considered to be as valid as one that predicts risk of severe injury.

In some cases, the rollover follows a planar crash. The planar crash may be with another vehicle or with a fixed object. In these planar impact crashes, the initial impact may have contributed to the injury. Consequently, crash severity metrics associated with planar crashes in addition to the rollover crash may apply. Countermeasures that are applicable to preventing ejection may not be applicable to preventing injury in the planar crash. The crash severity metric for these combined planar and rollover crashes should be different from those in which ejection is the primary risk factor. The rollover/planar class of crashes would need to be identified by an added data element in the recorded data.

The data element in NASS CDS that is most easily related to rollover severity is the number of quarter-turns that the vehicle rotates during the rollover. The number of quarter-turns is generally related to the energy of the crash. However, confounding factors, such as, vehicle geometry, vehicle deformation, and subsequent impacts can modify the number of quarter-turns. If the rollover is abruptly stopped by an impact with a fixed object such as a tree or a wall, the resulting injury may be caused by the planar impact. As in the case of the pre-rollover impacts, planar crash severity metrics may apply to this class of rollover, as well.

DATA SOURCE

The data source for this paper is NASS CDS years 1995-2002. The NASS CDS is a national sample of crashes in the United States. A condition for entry in the database is than one vehicle must be damaged sufficiently that it is towed from the crash scene. The database contains 30,000 crashes that involve 43,854 vehicles and 69,804 occupants. The NASS CDS cases are assigned a weighting factor that permits the data to be extrapolated to predict national averages. Unless otherwise noted, the information presented in this paper is based on weighted data.

The category, collision with another vehicle, frequently involves an injury producing vehicle-to-vehicle crash prior to the rollover. In such cases, crash severity measures other than those normally assigned to rollovers may be required. Some of the other categories may involve injury producing impacts with fixed objects before the rollover. However, a review of cases indicates that injury producing pre-rollover crashes are much less frequent for single vehicle crashes than multi-vehicle crashes. For this reason, the analysis to follow will be subdivided into single vehicle crashes, multi-vehicle crashes, and crashes with unknown number of vehicles. The single vehicle crashes will include all known initiation categories except multi-vehicle.

In this study of crash severity, only the front seat occupants ages 12 and older are included. This was done to reduce the bias of occupancy rate on the resulting crash severity.

The combined years 1995 to 2001 contain records of 3,871 vehicles that were involved in rollover crashes. These vehicles had 5,227 front seat occupants, age 12 years and older. This population sustained 1,309 MAIS 3+F and fatal injuries. When the NASS weighting factors are

applied, these cases are expanded to 1,535,297 vehicles with 1,945,346 front seat occupants age 12 and older with 125,768 MAIS 3+F and fatal injuries.

The distribution by vehicle type, passenger car (PC), sport utility vehicle (SUV), Van (including minivan), and pick up truck (PU), of front seat occupants aged 12 and older and front seat occupants aged 12 and older with serious injuries in rollover crashes is shown in Table 1. Occupants with serious and fatal injuries are classified as "MAIS 3+F. This category includes all survivors with MAIS 3 or greater injury, and all fatally injured regardless of their MAIS injury level. The table also shows the rate of MAIS 3+F injured to front seat occupants per 100 exposed to rollover crashes. This ratio is referred to as injury rate in Table 1 and in the Tables to follow. This ratio is an indicator of the severity of a population of crashes with regard to their ability to produce MAIS 3+F injuries. It will be used extensively in this paper to assess the relationship between crash variables and crash severity.

Table 1. Distribution of Occupants Age 12+, MAIS 3+ and Fatally Injured, Injury Rate, and Front Seat Occupancy Rate for Front Seat Occupants of Vehicles Involved in Rollover Crashes by Vehicle Class

Front Seat	PC	SUV	Van	PU
Occupants	45%	29%	6%	20%
MAIS 3+F	51%	19%	7%	23%
Injury Rate	7.4	4.3	7.5	7.1
Occupancy Rate	1.25	1.38	1.23	1.18

Table 2. Distribution of Rollover Exposed Belted and Unbelted Front Seat Occupants, MAIS 3+ and Fatal Injuries, and Injury Rate for Rollover Crashes

Exposure	No-Eject	Total Eject	Part-Eject
Belted	73.6%	0.2%	1.7%
Unbelted	18.7%	4.2%	1.6%
Total	92.3%	4.4%	3.3%
MAIS 3+F	**No-Eject**	**Total Eject**	**Part-Eject**
Belted	35.3%	0.4%	3.9%
Unbelted	23.0%	32.5%	5.0%
Total	58.3%	32.8%	8.9%
Injury Rate	**No-Eject**	**Total Eject**	**Part-Eject**
Belted	3	13	15
Unbelted	8	50	20
Total	4	48	17

It is evident from Table1 that vans constitute a very small percentage of the occupants and injuries in rollovers. Consequently, it is not possible to analyze vans with the same detail and accuracy as the other classes of vehicles. In subsequent three tables of data, van statistics are included in the totals.

Table 1 also lists the front seat occupancy rate for the vehicle classes. The front seat occupancy rate is higher for SUV's than for passenger cars. The pickup front seat occupancy rate is lower. Occupancy rate equivalency could be achieved by considering only the driver. However, several biases would result. First, front seat occupants may interact with each other during a rollover. Second, the injury risk for the driver may be different from that of the passenger, depending on the directions of roll. Both front seat occupants were included in the data to follow.

The distribution of front seat occupants exposed to rollover crashes by belt use and ejection status is shown in Table 2. Approximately 75% of the front seat occupants are belted. Total ejection is a rare occurrence, occurring 0.2% for the belted population and 4.2% for the unbelted population. However, these rare events account for about 33% of the MAIS 3+F injuries. Injury rates for totally ejected occupants are twelve times higher than for occupants who are not ejected. The data further show the effectiveness of restraints in preventing ejection. Serious injuries from total ejection among the belted population are rare, accounting for less that one half of one percent of the seriously injured occupants. Partial ejection accounts for about 9% of the seriously injured occupants. The largest fractions of the seriously injured occupants are: Belted-not ejected (35.3%), Unbelted-not ejected (23.0%) and Unbelted-totally ejected (32.8%). These three categories will be examined separately to determine crash attributes that influence the risk of severe injury.

Table 3 provides a breakout of the exposure and injury data by belted and unbelted front seat occupants in for single vehicle rollovers and rollovers after an impact with another vehicle (multi-vehicle).

Table 3. Distribution of Rollover Exposed Belted and Unbelted Front Seat Age 12+ Occupants, MAIS 3+ and Fatal Injuries, Injury Rates for Single Vehicle Rollovers, Rollovers in Multi-vehicle Crashes and All Rollover Crashes			
Belted	**Single**	**Multi**	**Total**
Exposed	61%	14%	75%
MAIS 3+F	27%	13%	40%
MAIS +F/100	2.8	5.8	3.4
Unbelted	**Single**	**Multi**	**Total**
Exposed	20%	5%	25%
MAIS 3+F	47%	13%	60%
MAIS +F/100	15.1	18.5	15.7
Combined	**Single**	**Multi**	**Total**
Exposed	81%	19%	100%
MAIS 3+F	74%	26%	100%
Injury Rate	5.9	8.8	6.4

Multi-vehicle crashes occur in only 19% of the rollovers, but account for 26% of the MAIS 3+F injured front seat occupants. These multi-impact rollovers also have higher injury rates. For multi-impact crashes, the injury rate is 1.5 times higher than for single vehicle rollovers. For restrained occupants in multi-impact rollovers, the injury rate is 2.0 times higher. These results suggest that severity measures for multi-impact rollovers should include factors in addition to the rollover attributes of the crash.

Another observation from Table 3 is the large difference in injury rates between restrained and unrestrained. The injury rate for the unrestrained is approximately 5 times higher than for the restrained. These results further illustrate the need to examine rollover severity for restrained and unrestrained separately.

Tables 4 and 5 show data on populations of belted and unbelted front seat occupants, respectively. The tables provide distributions of non-ejected totally ejected and partially ejected occupants in single and multi-vehicle rollovers.

Table 4. Distribution of Belted Front Seat Occupants by Ejection Status, MAIS 3+F Injuries, Injury Rates for Single Vehicle Rollovers, Rollovers in Multi-vehicle Crashes and All Rollovers			
No Ejection	**Single**	**Multi**	**Total**
Exposed	79.4%	17.8%	97.2%
MAIS 3+F	59.5%	29.2%	88.7%
Injury Rate	2.5	5.5	3.1
Part-Ejection	**Single**	**Multi**	**Total**
Exposed	1.4%	0.8%	2.3%
MAIS 3+F	7.3%	2.4%	9.8%
Injury Rate	17.2	10.0	14.6

Table 5. Distribution of Unbelted Front Seat Occupants by Ejection Status, MAIS 3+F Injuries and Injury Rates for Single Vehicle Rollovers, Rollovers in Multi-vehicle Crashes and All Rollovers			
No Ejection	**Single**	**Multi**	**Total**
Exposed	60.8%	14.8%	75.6%
MAIS 3+F	26.5%	11.4%	38.0%
Injury Rate	6.9	12.2	7.9
Partial-Eject	**Single**	**Multi**	**Total**
Exposed	5.5%	1.0%	6.5%
MAIS 3+F	6.0%	2.2%	8.2%
Injury Rate	17.2	34.4	19.9
Total Ejected	**Single**	**Multi**	**Total**
Exposed	14.7%	2.4%	17.1%
MAIS 3+F	45.6%	7.9%	53.5%
Injury Rate	49.0	53.0	49.6

Table 4 shows data for belted occupants. The data for totally ejected occupants is very sparse and the resulting injury rates are unreliable. For the No-ejection category, the higher injury rates for the Multi-vehicle category suggest a separation from the Single vehicle rollovers.

Table 5 shows data for unbelted occupants. When compared to Single rollovers, Multi-vehicle rollovers almost double the injury rates for the 'No ejection' and 'Partial ejection' categories. The injury risk for totally ejected occupants is about 50% for both single and multi-vehicle rollovers. This result suggests that in considering factors that influence injury rate, unrestrained totally ejected occupants should be examined as a separate category. It also suggests a separation of Multi-vehicle and Single rollovers.

ROLLOVER CHARACTERISTICS BY VEHICLE CLASS

Table 1 shows that vans contribute 6% of the exposure and 7% of the MAIS 3+F injuries among the relevant occupants. Figure 1 provides a comparison of the frequency of rollovers by number of

quarter-turns for the four classes of vehicles. The small population of vans appear to exhibit different characteristics from the other three classes of vehicles. The other vehicles have peak frequencies at 2, 4, and 6 quarter-turns. The vans exhibit a decreasing frequency trend with the number of quarter-turns.

Figures 2 and 3 show the exposure and number of MAIS 3+F injuries by number of quarter-turns for relevant occupants in vans. Figure 2 shows that MAIS 3+F injuries in van rollovers with more than 5 quarter-turns are rare.
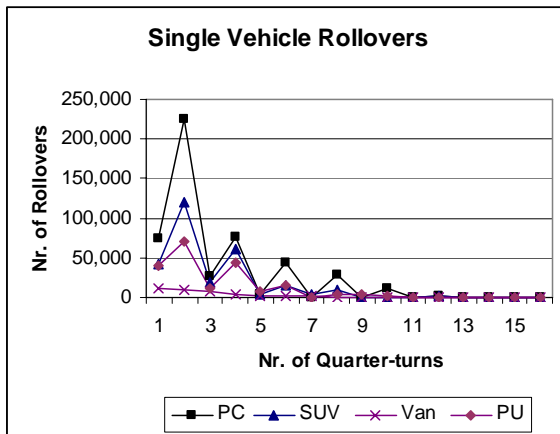
Figure 1. Number of Quarter-turns for Different Classes of Vehicles in Single Vehicle Rollovers

Figure 2. Number of Quarter-turns for Vans Involved in Single Vehicle Rollovers

Figure 3 shows that the rollover, which is terminated with the van on its roof, exhibits the largest number of MAIS 3+F injuries. Because vans exhibit rollover characteristics that differ from other vehicle types, vans have been excluded in the analysis to follow.
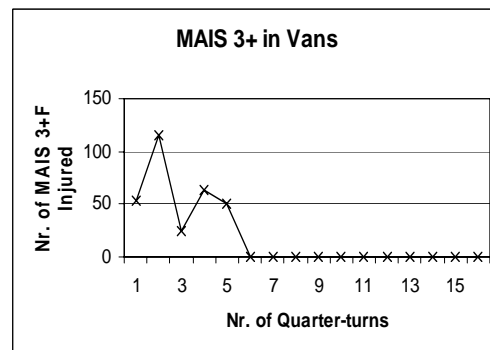

Figure 3. Number of Quarter-turns for MAIS 3+F Injured Occupants in Vans Involved in Single Vehicle Rollovers

SEVERITY FACTORS – BELTED, NOT EJECTED OCCUPANTS

The single vehicle rollovers with belted, not-ejected occupants constitute about 60% of the exposed population, but only 23% of the MAIS 3+Fatal injuries. Since only a single vehicle is involved, these crashes are less frequently influenced by injury producing pre-rollover events. Consequently, these crashes are more likely to provide insight into how rollover crash variables influence injury severity. One of the most commonly proposed rollover crash severity variables is the number of quarter-turns. This variable is generally related to the energy of the crash. In addition, it provides an indication of the duration of exposure of the occupant to the rollover event. However, it does not provide an indication of the severity of the impacts with the ground or the consequence of the resulting vehicle intrusion. It also does not provide a direct indication of the severity of the linear acceleration that produced the rollover.

Table 6 shows the number of quarter-turns vs. the percentage of relevant involved occupants and of relevant exposed occupants with MAIS 3+F injuries. The table shows both weighted and

unweighted data. The weighted totals are 1,157,781 occupants and 28,402 with MAIS 3+F injuries. The unweighted totals are 1,757 occupants and 196 with MAIS 3+F injuries. The end over end rollovers were removed from the totals when the percentages for the lateral rollovers were calculated. The exclusion, of the end-over-end rollover, was attributed to their unique form of initiation, vehicle crash dynamic heterogeneity, and low frequency. There were 31 occupants exposed to end-over-end rollovers. Eight received MAIS 3+F injuries.

    The weighted data from Table 6 indicates that 48% of the MAIS 3+F injuries to relevant belted occupants involve rollovers with more than one roof impact. The unweighted data contains an over sampling of low severity events. In the unweighted data, approximately 23% of the relevant occupants with MAIS 3+F injuries are exposed to more than one roof impact.

Table 6. Distribution of Not Ejected Front Seat Belted Occupants with MAIS 3+F Injuries by Number Quarter-turns for Single Vehicle Rollovers				
Single Vehicle Belted – Unejected				
Qtr. Turn	Weighted		Unweighted	
	Exposed	MAIS3+F	Exposed	MAIS 3+F
1	13.8%	7.0%	14.3%	13.7%
2	44.4%	24.0%	30.2%	28.4%
3	5.5%	11.8%	6.4%	7.8%
4	19.6%	5.7%	21.7%	16.2%
5	1.2%	3.1%	4.1%	4.4%
6	8.3%	38.8%	12.1%	14.7%
7	0.7%	1.2%	1.1%	1.0%
8	4.8%	3.0%	5.6%	5.4%
9	0.3%	0.2%	0.8%	0.5%
10	0.9%	3.2%	1.5%	3.9%
11	0.0%	0.0%	0.1%	0.0%
12	0.3%	1.1%	1.3%	2.9%
13	0.0%	0.0%	0.0%	0.0%
14	0.1%	0.3%	0.4%	0.5%
15	0.0%	0.0%	0.0%	0.0%
16	0.0%	0.4%	0.2%	0.5%
>16	0.1%	0.0%	0.2%	0.0%
End	0.4%	3.8%	1.7%	3.9%

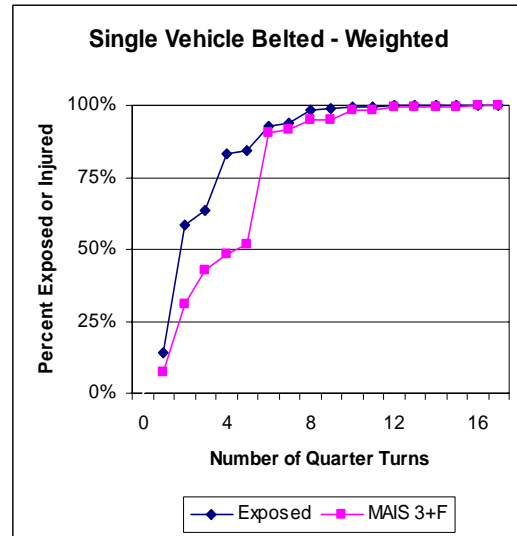**Single Vehicle Belted - Weighted**

Figure 4. Number of Quarter-turns in Single Vehicle Rollovers for Not Ejected Front Seat Belted Occupants Ages 12+ and Not Ejected Front Seat Belted Occupants Ages 12+ with MAIS 3+F Injuries

    Figure 4 shows the occupant exposure and resulting MAIS 3+F injured not-ejected front seat occupants by number of quarter-turns. The number of quarter-turns were numbered 1 to 16 and >16. End-over-end rollovers were excluded from these charts to maintain vehicle crash dynamic homogeneity inherent to the lateral rollover crashes.

    For the belted occupants, the MAIS 3+F injured lags the occupant exposure at low numbers of quarter- turns. This lag occurs in both weighted and unweighted data. However, it is more pronounced in the weighted data. The weighted data show a steep increase in injuries for rollovers that terminate at the second roof impact.

    A breakout of the distribution of injuries and injury rates is shown in Figures 5 and 6. These data are presented in terms of number of roof impacts. Zero roof impacts corresponds to one quarter-turn. One roof impact corresponds to 2 through 5 quarter-turns. Two impacts corresponds to 6 through 10 quarter-turns. Eleven or more quarter-turns are designated as 3+ roof impacts. The figures show both the weighted and the unweighted data.

    Figure 6 shows that for this belted population, the injury rates generally increase with number of roof impacts. For the weighted data, the increase is particularly large when the number of roof impacts exceeds one. As shown in Table 6, a large fraction of the MAIS 3+F injuries occur in

rollovers that terminate at the second roof impact. For the weighted data, the fraction is 38.8%. For unweighted data, the fraction is 14.7%.
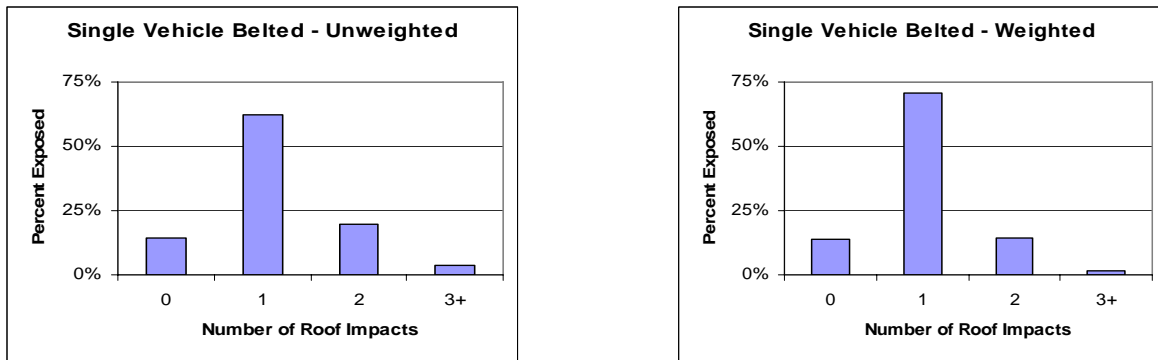

Figure 5. Distribution of Belted Not Ejected Front Seat Age 12+ Occupants with MAIS 3+F Injuries in Single Vehicle Rollovers by Number of Roof Impacts Unweighted and Weighted)
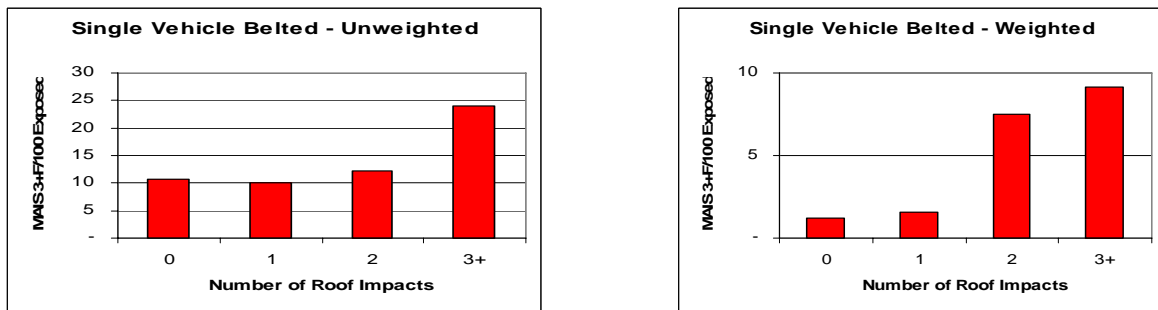

Figure 6. Injury Rate per 100 Exposed for Belted Not Ejected Front Seat Age 12+ Occupants with MAIS 3+F Injuries by number of Roof Impacts (Unweighted and Weighted)

The injury rate distribution shown in Figure 6 suggests that the number of roof impacts may be an appropriate injury severity indicator for this population. A separation between one roof impact and more than one roof impact is a suggested indicator for injury severity. Figure 5 shows that a small number of rollovers involve three or more roof impacts and this population constitutes about 5% of the MAIS 3+F injured. The data in Figure 6 indicates that these events carry the highest risk of injury. This is particularly true for the unweighted data.

CRASH SEVERITY FOR UNBELTED, EJECTED OCCUPANTS

Total ejection of an occupant is an undesirable intermediate outcome of a rollover. Risk of death and severe injury is unacceptably high for occupant ejections. Once ejection occurs, the existing safety features are defeated, and serious injury is highly probable but almost random consequence. Because of the undesirability of ejection, the analysis to follow will include all ejections, not only those with MAIS 3+F injuries.

Table 7. Distribution of Ejected Front Seat Unbelted Occupants and Ejected Occupants by Number Quarter-turns for Single Vehicle Rollovers				
Single Vehicle Unbelted				
Qtr. Turn	**Weighted**		**Unweighted**	
	Exposed	Ejected	Exposed	Ejected
1	17.4%	5.3%	12.8%	4.2%
2	33.3%	7.6%	27.9%	14.2%
3	8.1%	5.4%	6.0%	5.9%
4	17.7%	32.9%	21.6%	23.8%
5	2.1%	4.1%	3.9%	5.5%
6	12.4%	19.8%	13.2%	18.1%
7	1.4%	2.0%	1.8%	3.1%
8	4.7%	11.9%	7.2%	13.5%
9	0.1%	0.4%	0.5%	1.0%
10	1.4%	4.2%	2.0%	3.1%
11	0.0%	0.1%	0.1%	0.2%
12	0.8%	4.2%	2.1%	4.9%
13	0.1%	0.4%	0.1%	0.3%
14	0.2%	0.9%	0.5%	0.8%
15	0.0%	0.1%	0.1%	0.2%
16	0.0%	0.0%	0.1%	0.2%
>16	0.1%	0.7%	0.4%	1.0%
End	1.6%	5.4%	3.0%	3.8%
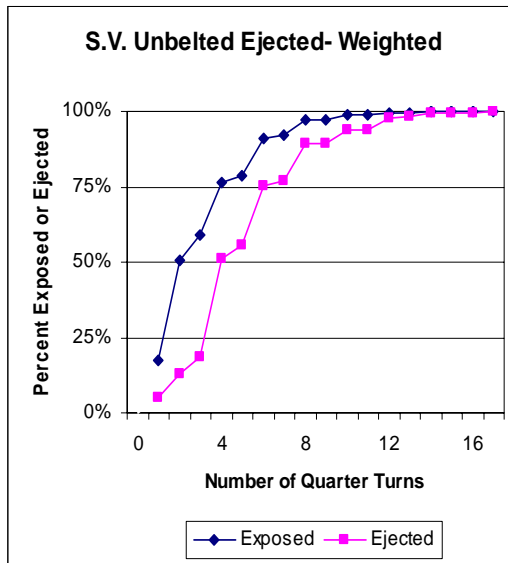
Figure 7. Number of Quarter-turns in Single Vehicle Rollovers for Unbelted Front Seat Age 12+ Occupants and Ejected Unbelted Front Seat Age 12+ Occupants

The distributions of unbelted front seat occupants and totally ejected unbelted front seat occupants in single vehicle rollovers is shown in Table 7 as a function of the number of quarter-turns.

The table shows both weighted and unweighted data. The weighted totals are 364,329 unbelted exposed relevant unbelted occupants with 66,239 of them were ejected. The unweighted totals are 1,604 unbelted occupants with 613 ejected. The end-over-end rollovers were removed from the totals, owing to their unique nature, when the percentages for the lateral rollovers were calculated. There were 48 occupants exposed to end-over-end rollovers of which 23 were ejected.

The cumulative weighted data, based on Table 7 is plotted in Figure 7. The both weighted and unweighted data show increased risk of ejection at 4 and 6 and 8 quarter-turns. Groupings of quarter-turns by roof impact showed an increased risk of ejection that was statistically significant. Groupings of quarter-turns by number of wheel impacts did not result in statistically significant increases in injury risk.

The distribution of unbelted relevant occupants is shown in Figure 8. The data is presented in terms of number of roof impacts. The figure shows both the weighted and the unweighted data. The weighted data show that 21% the unbelted occupants are exposed to more than one roof impact. For the unweighted data, the fraction is 28%. However, the percentage ejected with more than one roof impact is much higher. The weighted data from Table 7 shows that 45% the ejected unbelted occupants are exposed to more than one roof impact. For the unweighted data, the fraction is 46%.

Figure 9 shows the ejection rate for unbelted occupants vs. the number of roof impacts. Both the weighted and unweighted data show increasing rate of ejection with increasing number of roof impacts.
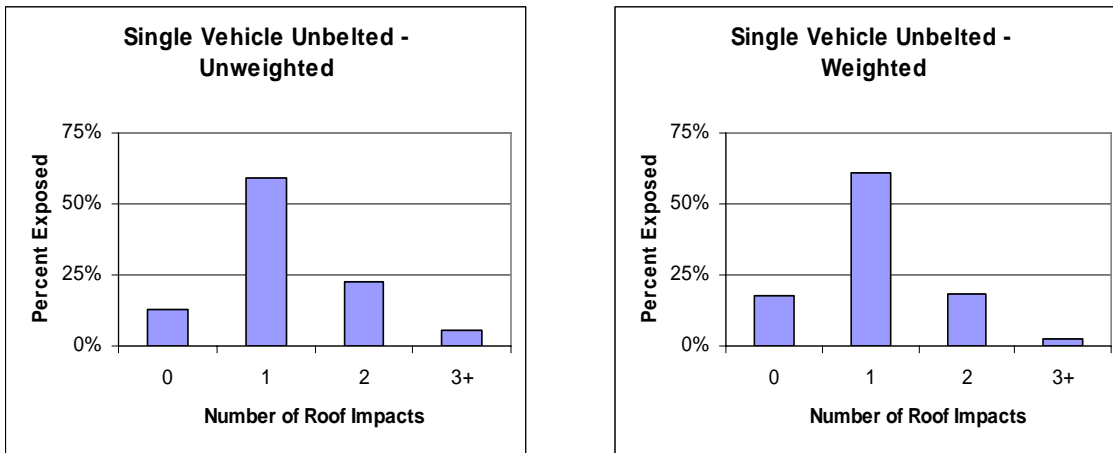
Figure 8. Distribution of Unbelted Front Seat Age 12+ Occupants in Single Vehicle Rollovers by Number of Roof Impacts (Weighted and Unweighted)
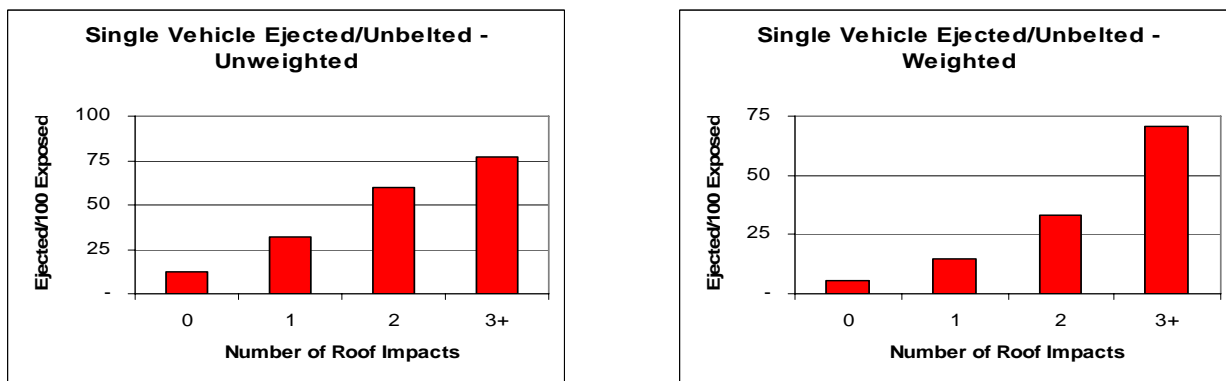

Figure 9. Unbelted Ejected Front Seat Age 12+ Occupants in Single Vehicle Rollovers per 100 exposed by Number of Roof Impacts (Weighted and Unweighted)

STATISTICAL SIGNIFICANCE

Several relationships, within each population of interest, were subjected to chi-square tests. The significance testing allowed relationships to be accepted or to be potentially attributed to chance. A 95 percent confidence interval was established with acceptable p-values falling below 0.05. The tested relationships included number of roof impacts and number of wheel impacts.

The strength of the relationship for occupant outcome, ejection status, and crash configuration was tested for each of the relevant populations. The occupant outcome was a dichotomous variable indicating serious injury or not. Ejection status considered four outcomes: unejected, completely ejected, partially ejected, and ejection of unknown degree. The crash configuration considered the number of vehicles involved in a crash: The single vehicle involved one vehicle. The multiple vehicle involved two or more vehicles. The results of these tests follow for belted unejected relevant occupants and unbelted ejected occupants.

For Belted Unejected Relevant Occupants, the testing returned significant results for the seriously injured occupants and total occupants in single vehicle crashes. Insignificant results were recorded for the other occupants, those sustaining low severity injuries or remaining uninjured.

For Unbelted Ejected Occupants, significant results were returned. This was deemed noteworthy because the data clearly favored the use of roof impact as a severity indicator for

ejection rate. The data supported limited disaggregation, but the number of wheel contacts was not found to be significant.

MULTIPLE AND FIXED OBJECT IMPACTS – BELTED

Table 3 shows that the injury rate for belted occupants in multi-vehicle crashes prior to rollover is approximately twice as high as for single vehicle rollovers. It is evident that a planar crash prior to rollover could contribute to the injuries received by the occupants. An additional severity metric to account for the planar crash severity is needed to account for the injury risk added by the planar crash.

In many cases, the planar crash is minor. It may contribute to causing the rollover. However, the injuries are produced during the rollover. These crashes are expected to cause only minor damage to the vehicle that rolls over. As the planar damage increases, the risk of injury during the planar crash is expected to increase. The severe planar impact may produce most of the injuries prior to the rollover.

In NASS CDS rollover cases that involve a planar crash, there are two elements to indicate the severity of the planar crash. One is the estimated severity of the planar crash. This variable has three levels – minor, moderate and severe. A second element provides for a calculated delta-V, based on the absorbed energy determined from the damage measurements. These measurements provide input to the WINSMASH algorithm used by NASS investigators to calculate delta-V. The algorithm is insufficiently robust to process damage for measurements pursuant to rollover or severe sideswipe events. If a rollover event has been identified as the most severe crash event, a qualitative severity estimate would be assigned.

In this study, multiple impact crashes were segmented by crash severity and number of roof impacts. In the event of multiple planar impacts, the event of highest severity was the one for which the calculated or estimated delta-v was highest. The calculated delta-v's were grouped in ranges according to the estimated delta-v ranges. The quantitative delta-v was selected over the qualitative delta-v if both were available for a given case. For this analysis, the numeric ranges of calculated delta-v were: less than 25 kmph, greater than 24 and less than 55 kmph, and greater than 54 kmph. The estimated, qualitative, measurements were made based upon the crash investigator's experience. The data was collected over the years 1995 through 2002 to obtain an adequate sample size for interpretation. The relevant crash configurations included multi-vehicle and fixed object impacts prior to rollover. Only properly belted occupants were included.

Table 8 shows the weighted and unweighted distributions of exposed relevant occupants, and MAIS 3+F injuries for multiple vehicle and fixed object rollover crashes for the years 1995-2002. This, weighted, group consisted of 406,727 relevant occupants with 35,807 MAIS 3+F injuries. The data show the distributions for the combined measured delta-v and the estimated severity.

Figures 10, 11 and 12 show the occupant exposure, MAIS 3+F injuries and MAIS 3+F injuries per 100 exposed for the relevant crashes and populations. The dependent variables are plotted against number of roof impacts and planar crash severity. The injury risk data plotted in Figure 12 shows that for Low and Med damage the risk increase with number of roof impacts. Further, the number of roof impacts appears to be more influential than the extent of damage. In the lowest damage category, the planar contact may have been incidental. However, for the severe damage, where delta-V is estimated at greater than 55 kph, the planar injury appears to overwhelm the rollover injury. This suggests that planar severity metrics may be useful in conjunction with number of roof impacts provided the delta-V is less than 55 kph or the planar damage is not "severe".

It should be noted from Figure 10 that there are only 1.3% of the crashes that fall into the 0 roof impacts, High damage category. Consequently, the abnormally high risk for this cell may be caused by a small sample.

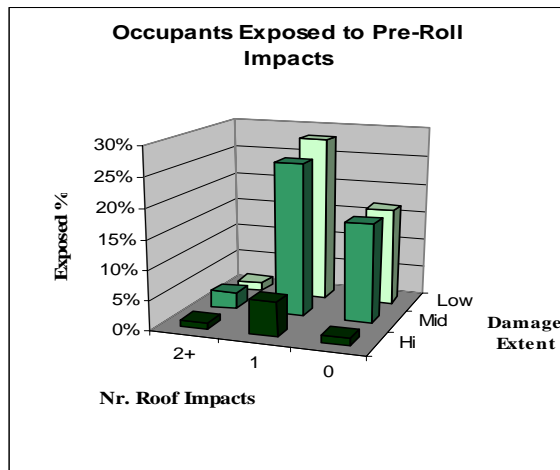| Table 8. Unejected Restrained Front Seat Occupants, AGE GE 12 Involved in Fixed Object and Multiple Vehicle Impacts prior to Rollover by Number of Roof Impacts and Planar Damage Severity				
	All Relevant Occupants			
	Roof Impacts			
Delta-v	**Zero**	**One**	**Two Plus**	**Total**
Low	16.7%	28.1%	1.5%	46.3%
Mid	16.8%	25.9%	2.8%	45.5%
Hi	1.3%	5.8%	1.1%	8.2%
Total	34.8%	59.8%	5.5%	100%
	Crashes with MAIS 3+F Occupant			
	Roof Impacts			
Delta-v	**Zero**	**One**	**Two Plus**	**Total**
Low	3.5%	24.1%	2.7%	30.3%
Mid	9.5%	25.3%	5.9%	40.7%
Hi	7.4%	14.4%	7.3%	29.1%
Total	20.4%	63.8%	15.8%	100%

Figure 10. Percent of Unejected Restrained Front Seat Occupants, AGE GE 12 Involved in Fixed Object and Multiple Vehicle Impacts prior to Rollover by Number of Roof Impacts and Damage Severity
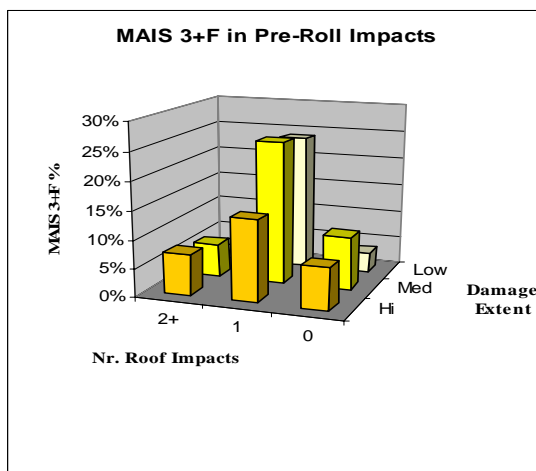

Figure 11. Percent of Unejected Restrained Front Seat Occupants with MAIS 3+F Injuries, AGE GE 12, Involved in Fixed Object and Multiple Vehicle Impacts prior to Rollover by Number of Roof Impacts and Damage Severity
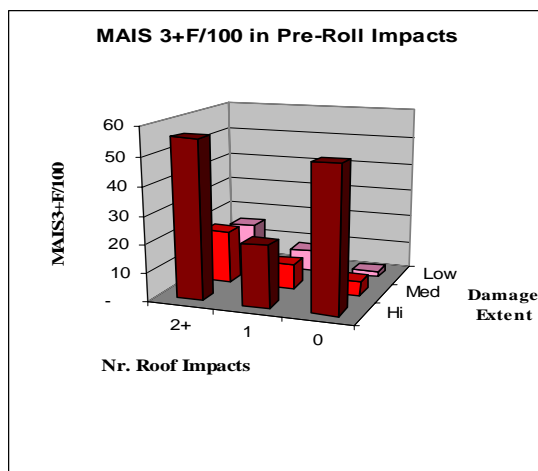

Figure 12. MAIS 3+F Injuries per 100 Exposed Unejected Restrained Front Seat Occupants, AGE GE 12, Involved in Fixed Object and Multiple Vehicle Impacts prior to Rollover by Number of Roof Impacts and Damage Severity

CONCLUSIONS

For not ejected belted occupants in single vehicle crashes, the number of roof impacts is an appropriate severity indicator. The relationship between injury risk and number of roof impacts was found to be statistically significant.

For crashes with another vehicle or fixed object prior to rollover, the injury risks are higher than for single vehicle crashes. Impacts with a fixed object such as a tree or wall prior to rollover also carry higher risks. Consequently, additional severity measures are required.

For vehicles with planar impact prior to rollover, the extent of planar damage, separated by Low, Medium and High was found to be an additional severity metric. Low damage corresponded to a delta-V of less than 25 kph. High damage corresponded to a delta-V of greater than 55 kph. For

the high damage population, the planar damage risk appears to overwhelm the rollover risk. For lesser amounts of planar damage, the combination of damage extent and number of roof impacts appear to be reasonable crash severity measures.

For unbelted ejected occupants in single vehicle rollovers, the ejection risk generally increases with the number of quarter-turns. However, number of roof impacts provides a more uniform relationship between crash severity and injury risk that was found to be statistically significant. Each additional roof contact increases the ejection risk by a factor of about 2.3.

It was found useful to separate the belted and unbelted in the analysis. Ejection plays a major role in causing injuries to the unbelted, but not to the belted. Consequently, different factors may influence the risk.

Vans appear to have different rollover characteristics from other classes of vehicles. Van rollovers are more likely to end on the side and less likely to end on the roof. Rollovers and injuries in crashes with more than one roof impact are rare. These vehicles constitute only 6% of the rollovers. Consequently, there is only limited data on their characteristics.

For the passenger cars, pickups and SUV's, a large fraction of the injuries are sustained by exposure to more than one roof impact. For the relevant restrained occupants, 48% of the MAIS 3+F injured were exposed to two or more roof impacts, based on weighted data. For the relevant ejected occupants, 45% were exposed to more than one roof impact.

Continued studies are needed as additional data becomes available. The factors that influence injury risk for the following populations need further study: restrained-partially-ejected, unrestrained-not-ejected, planar crashes prior to rollover with high damage.

ACKNOWLEDGEMENT

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