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Determination of the Significance of Roof Crush on Head and Neck Injury to Passenger Vehicle Occupants in Rollover Crashes

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ABSTRACT

A comparative study between belted rollover occupants who did and did not receive head injuries from roof contact was conducted using the National Accident Sampling System (NASS) database. The main objective was to determine if headroom reduction increases the risk of head injury. Headroom was determined for 155 belted occupants involved in rollover crashes of vehicles which were then weighted to make them representative of national estimates. Results showed that headroom was reduced more in those crashes where the occupant had head injuries than in cases where there were no head injuries. It was concluded that the risk of head injury increased with reduced headroom. Furthermore, it was observed that when the initial headroom was higher, the incidence of head injury was reduced.

INTRODUCTION

When compared to the other accident modes, rollovers have a higher risk of injuries and fatalities. While rollover accidents represent only 2.2 percent of all highway tow-away crashes, they are responsible for about 19 percent of highway fatalities[1]*. However, the risk of injury increases dramatically for unbelted occupants in rollover accidents. There were 9676 rollover accident fatalities in 1989, of which, only about 12 percent were reported to be using a seat belt or a child safety seat [2]. When examining rollover accidents using the NASS database from 1982 through 1989, it was found that about 8 percent (12,000) of serious injuries were to belted non-ejected occupants. Sixty percent of fatally injured and 48 percent of the seriously injured occupants were unbelted and ejected [3].

It is apparent that seat belts are a major injury reducing countermeasure that prevents ejection, and restrains violent occupant motion during a rollover. However, fatalities and serious injuries still occur to belted occupants. NASS database estimates that there are about 1500 seriously injured, unejected, restrained occupants in rollover accidents, annually [3]. Although higher seat belt usage reduces the risk of severe injuries in rollovers by preventing ejections, it is also increasingly important to determine the significance of roof intrusion in injury causation since occupant head injuries continue to occur in many crashes, especially in rollover accidents. It is surmised that one of the reasons for this may be roof intrusion into the passenger compartment where the occupant is seated.

There are several possible methods of reducing rollover related serious injuries and fatalities, e.g., improved window glazing, preventing doors from opening, better restraint systems, and possibly improved roof crush resistance. The first three address ejection prevention in rollover accidents, which is predominantly a problem for unbelted occupants. Restraint systems help to prevent ejection and prevent occupants from being tossed around in the vehicle compartment during a rollover crash. Improved belt restraints (e.g. belt pre-tensioners and integrated seat belts) could benefit those belted occupants by preventing them from impacting various interior components; however, they could still be injured due to excessive roof intrusion, even when they are held upright in their seats. One previous rollover accident data analysis was unable to ascertain the significance of roof intrusion on injuries in rollover accidents using the NASS

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* Numbers in [ ] indicate references at the end of the paper

data [2]. It was found in that study that while there were roof intrusion injuries, there were also injuries just as severe from other components. It was therefore concluded that overall injury severity may still not be reduced by eliminating those injuries caused by roof intrusion.

Occupant head injuries do occur from contacts against many upper interior components in rollover accidents; however, it is not clear whether roof crush increases the likelihood of head injury. A study by Bahling et al. [4] in which inverted drop tests of a vehicle with a belted dummy were conducted showed that peak neck loads occurred before the roof intruded into the passenger compartment. This suggests that neck loads are not dependent on roof intrusion, but may be more a function of the restraint system which failed to hold the dummy in the seat, and the velocity of head contact against the intruding roof. Additional tests using a rollover dolly also showed that the peak neck load on the dummy occurred prior to roof deformation. Friedman [5] has stated that reports such as these do not consider all the major factors that affect head injury (e.g. impacts where ground contact and head contact occur almost simultaneously). In addition, an analysis of rollover accident data from the NASS 1982-1983 data files by Friedman showed that the injury risk in rollover accidents increased dramatically when intrusion in the proximity of the occupant exceeds a Collision Deformation Classification (CDC) extent of 3. Furthermore, he also reported that incorporating stronger roof designs and belt pre-tensioning in a 3-D rollover simulation of a rollover accident resulted in significant reduction of neck compression loading. Another study by Digges and Klisch [6] examined 161 rollover cases from the NASS data for 1988-1989. When CDC extent values approached 4 or 5, 5 percent of non-ejected occupants were fatalities; however, when CDC extent values were 6 or 7, 20 percent of the occupants received fatal injuries. This led these researchers to conclude that there is a correlation between roof crush and fatality rate.

The purpose of this paper is to further examine the correlation between roof intrusion and head injury. In this paper, the term head injury includes injury to the head, face, or neck of an occupant involved in rollover crashes. For this analysis, interior headroom is used as a surrogate for absolute roof crush to assess the potential for head injury. This study is limited to belted, non-ejected occupants to focus on the effect of roof intrusion on head injury causation. Previous published studies examined did not investigate rollover accidents with belted occupants to assess the role of headroom reduction in increasing head injuries.

For the purposes of this paper, headroom is defined as the pre- or post-crash interior space measured vertically between the top of the occupant's head and the roof. The change in the pre-crash headroom is defined as the headroom reduction. This study tests the hypothesis that head injury is related to the intrusion into the compartment, thus reducing the initial headroom. If this hypothesis is valid, it is expected that a correlation would exist between the severity of intrusion and the potential for head injury.

INJURY CAUSATION TO BELTED OCCUPANTS IN ROLLOVER ACCIDENTS

Head injuries of belted occupants in rollover accidents may be predominantly caused by roof intrusion over a seated occupant, vertical occupant excursion (diving) and excursion velocity, or a combination of these factors. Rollover crash severity may also be indicated by all of the above parameters. As crash severity increases, it is expected that roof intrusion would increase, and forces that act against the belt restraints in rollovers would also increase. While magnitude of roof crush is coded in the NASS data, belt slack is not. Moreover, there are not any widely accepted crash severity measures used in investigating rollover accidents. This poses a problem in analyzing the data, since any correlation of increased roof intrusion to injury causation could be interpreted as due to an increase in crash severity.

In investigating other planar collisions (e.g. side and frontal), crash severity is estimated by delta v, which is the change in velocity of a vehicle during the accident. It is calculated by a computer algorithm which re-constructs the crashes using vehicle stiffness estimates and static crush measurements on the vehicles involved in the accident. These delta-v estimates have been used extensively in estimating crash severity levels that correlate to serious injuries in frontal and side impact accidents. Several factors hamper the development of similar crash severity indices for rollover crashes. First, rollover accidents are non-planar, resulting in forces that act in several directions on the body of the vehicle and the occupant during the crash. Since each rollover event results in a unique vehicle trajectory, the direction and magnitude of the transferred forces to the case vehicle and occupant are different for each rollover accident. In addition, rollovers sometimes involve multiple contacts against the ground of the case vehicle, depending on the number of rolls. Vehicle moment of inertia, initial roll rate, rotational and translational accelerations, airborne height etc., contribute to the forces and energy imparted by the vehicle to the occupant and the energy dissipated in the vehicle. When these forces interact with the ground, energy is absorbed by the vehicle body, except for a small portion which is dissipated because of friction. Some kinetic energy is used up in the motion of the vehicle and the remaining is transferred to the occupant. The number of quarter turns in these crashes could serve as a surrogate for the change in vehicle kinetic energy, and therefore, could provide a crude estimate of crash severity.

Belt slack is dependent on how the occupant was wearing the belt, and on the exact dynamics of the crash. The occupant could be wearing the belt loosely before the accident, and the belt may stretch even further during the event. Moreover, it is hypothesized that inertial locking retractors may lock/unlock during the roll resulting in additional belt slack. The NASS data only provides information to indicate whether the belt was properly worn. Belt slack, and the subsequent amount of vertical excursion the occupant may have had during rollover, can not be determined; and, even if it is, the timing of when the occupant contacted the roof during the event is un-recoverable from accident data. Consequently, the occupant travel off the seat towards the roof (dive), and the velocity of head impact against the roof, during rollover crashes are unknown in the accident data. Complicating matters, it cannot be determined from available data whether the occupant hit the roof before or after the roof began deforming. Moreover, the measured roof intrusion reported in the accident data is the static deformation only, that is always less than the dynamic deformation, which depends on the roof restitution characteristics. This paper has also attempted to resolve some of the conflicts introduced by these variables in analyzing rollover accidents to understand the head injury mechanism in these crashes.

NASS DATA ANALYSIS - The NASS, and more specifically, the Crashworthiness Data System (CDS), was used to analyze rollover cases from 1988 - 1992. A subset of rollover accident cases were retrieved from the database after eliminating the cases that are affected by extraneous factors, such as ejection, multiple crash modes, and unbelted occupants. A Statistical Analysis System (SAS) program was written to retrieve the cases of interest that met the following criteria:

- Rollover accidents of at least 2 quarter turns are included so that those cases where there were roof contacts against the ground are considered.

- Only single vehicle crashes where roof contacts against the ground occurred are included; this eliminates all cases involving other crash modes (e.g. frontal and side) including fixed object crashes (trees, telephone poles, etc.).

- Occupant(s) were reported to be wearing lap and shoulder belts in the driver and/or right front passenger seating positions.

- In the data analyzed, only non-ejected occupants are considered. This eliminated occupant injuries which may have resulted from sources outside the vehicle.

- Occupants with contact injuries that did not originate from the upper interior of the vehicle are excluded.

The data analyzed consisted of 220 occupants fitting the above criteria. Since the electronic database does not record exact values of roof intrusion (except as a range), rollover quarter turns (rollovers greater than 3 quarter turns are coded as 4), and roll direction (not included in this data before 1992), the hardcopy reports were examined to obtain the necessary detailed information for the analysis. The data retrieved included information on the accident, the occupant, and the case vehicle characteristics. The data were used to create an electronic data file for the rollover cases investigated.

Unknown occupant sizes and vehicle specifications of older model year vehicles prevented determination of headroom for all the cases. Of the 220 rollover occupants considered, 32 occupant heights were unknown, and vehicle headroom information for an additional 20 occupants could not be determined with any degree of confidence. There were also 13 occupants with injuries from the roof, but not to the head. These 13 cases were excluded from the analysis. Consequently, the data set was reduced to that pertaining to 155 occupants, with complete information sufficient to make headroom comparisons.

HEADROOM DETERMINATION PROCEDURE - Roof intrusion into the occupant compartment in a rollover crash reduces the amount of space between the occupant's head and the roof. The NASS divides the front seat into three seating areas; driver, right front passenger, and middle passenger. Maximum roof intrusion in each area is recorded in the hardcopy file. Roof intrusion was over the head of each belted occupant in the rollover cases analyzed. To make headroom comparisons from the data, intrusion in the front outboard seating positions had to be obtained for each case. The following procedure was developed for determining the headroom in the vehicles involved.

First, vehicle make, model and year of each rollover case was used to find vehicle specifications from the American Automobile Manufacturers Association (AAMA) manuals. Additionally, in-house measurements, and foreign manufacturers specifications were also used. From these sources, vehicle height (h101), h-point height (hip-point of occupant from side view), and seatback angle (Figure 1) were obtained and added to the file for each case vehicle. Following this, the body dimensions for the Hybrid III dummy were obtained so that the occupant could be scaled to the correct seating heights in the vehicle. The Hybrid III standing height is 172cm. From h-point to the top of the dummy's head is 83cm, or roughly one-half (0.483) of the standing height. This fraction was assumed to be the same for heights of different occupants, since no better methods were available to determine occupant sitting heights in the case vehicles. Therefore, roughly one-half of the occupant height was used as the measurement from the h-point to the top of the head.

With these measurements, an equation was developed to determine the nominal headroom (pre-crash):

$$hr = (h101 - 2.5 - H_{pt}) - (R_h\ O_{hgt})\cos\alpha$$

where,

hr = available headroom for its occupant in the case vehicle,

h101 = height of vehicle roof exterior from the ground,

H_{pt} = H-point height from the ground,

O_{hgt} = standing height of occupant,

α = seat back angle, and

R_h = Occupant's upper body length measured from h-point to the top of the head expressed as a fraction of the standing height.

In the first part of the equation, h-point height from the ground is subtracted from the vehicle height (h101) to get a measurement from the h-point to the top of the roof. An additional 2.5cm is subtracted to adjust for the distance from the vehicle top to the interior lining of the roof over the occupants head. This gives approximately the available headroom as measured from the h-point to the roof interior. This value is then adjusted to account for an occupant leaning against the seat, by subtracting a correction factor. This correction factor is calculated by multiplying the total height of the occupant by the fraction R_h multiplied by the cosine of the seatback angle α. Thus the initial headroom is calculated from the above equation for each case vehicle.

To calculate the post-crash headroom over the occupant compartment area, the amount of roof intrusion reported in the accident data was subtracted from the original roof height (h101) as obtained from the vehicle data. This value was substituted in the above equation in place of h101 to compute the post-crash headroom. If the roof intruded to a height below the top of the head, the calculated headroom is negative. In the following analysis it is assumed that the roof intrusion into the passenger compartment above the occupant seat is uniform, even though it is recognized that in real-world crashes, it may not likely be the case.

RESULTS

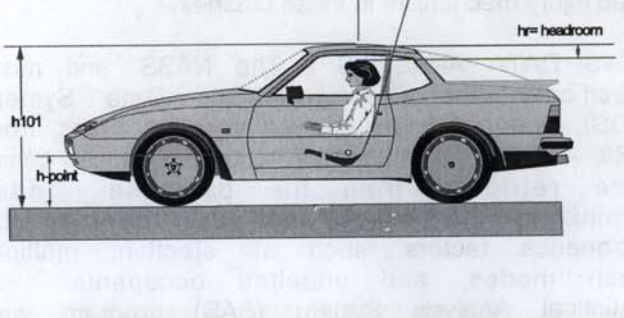

Figure 1. Side view of car with occupant showing headroom.

HEADROOM ANALYSIS - Figure 2a shows a plot of pre-crash headroom against post-crash headroom for all the rollover cases analyzed. The post-crash headroom given on the x-axis represents the space available over the head of the occupant after the crash. The numbers to the right of the zero indicate that there is space available between the roof interior and the top of the head of the occupant, while the numbers to the left indicate that the roof has collapsed to a level below the top of the occupant's head. The diagonal line passing through zero is a line of no intrusion into the compartment. Other diagonal lines to the left are lines of constant roof intrusion into the compartment.

The status of injured/uninjured for the 155 occupants are presented in Figure 2a. The data pertain to drivers and right front seat passengers. The AIS levels of the head injuries ranged from AIS 1 to AIS 6. Since there are not enough cases for breaking them down by AIS levels, the data are presented as aggregates of injured and uninjured occupants. The injured occupant group includes only occupants who received head injury from the roof. The uninjured occupant group includes those occupants with no injury from the roof. Cases on the "no intrusion" diagonal line represent occupants who had no measured roof intrusion over their head, i.e., the post-crash headroom remained the same as the pre-crash headroom.

Of the 155 occupants, 35 (9379 weighted) had head injuries while the remaining 120 (105480 weighted) did not receive any head injuries. Thirty-eight percent of the uninjured occupants are shown on the "no intrusion" line compared to only 14 percent of the injured occupants. As mentioned previously, the diagonal lines to the left of the "no intrusion" line indicate lines of increasing intrusion. The total deflection of the roof for any initial (pre-crash) headroom level is obtained by subtracting the value of the post-crash headroom as indicated by the vertical lines on the x-axis. The point of intersection of the two lines falls on the lines of constant intrusion. For example, the total deflection for a case marked as (A) in Figure 2a, where the pre-crash headroom is 5cm, and the post-crash headroom is -15cm, is 20cm (5-(-15)).

Most cases with head injury lie between 0 and 30cm roof deflection. The region labeled as (B) in Figure 2a represents those cases where the headroom was reduced to below zero. The region outside this envelope, labeled as (C) represent the area where there is some headroom available after the crash. By aggregating the cases with and without injury into these envelopes, it is easy to analyze those cases with respect to headroom reduction. On the basis of the above analysis it is observed that 17(3231) out of 35 cases of injured occupants had headroom reduction below the top of the head, while only 26(12972) out of 120 cases of the uninjured occupants had similar headroom reduction. There are no head injuries indicated when the pre-crash headroom exceeded 30cm. Most of the injuries lie in the range of -17.5 to 20cm of post-crash headroom. The above breakdown is given only for the purpose of comparison of headroom reduction for the injured and uninjured occupants. Since it is based on raw data, no meaningful conclusions can be drawn unless further analyses of weighted data are carried out and the results of the two analyses compared.

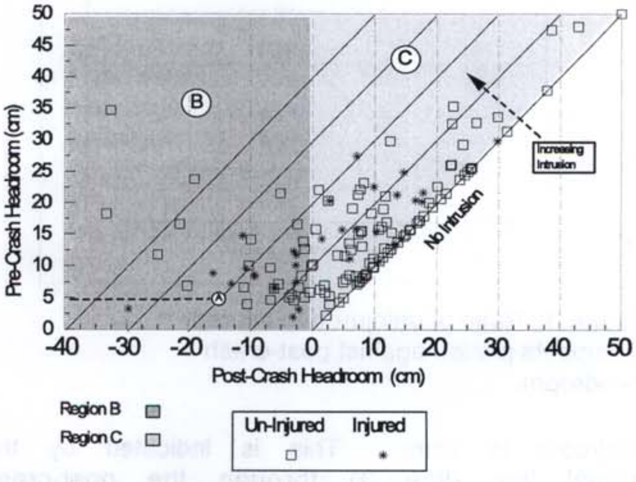

Figure 2a. Plot of pre-crash headroom vs. Post-crash headroom.

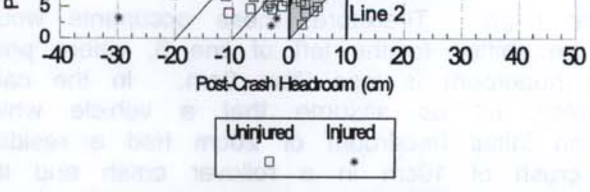

Figure 2b. Shift of headroom due to dynamic effects.

EFFECT OF DYNAMIC ROOF INTRUSION - In order to illustrate the dynamic effect on the potential for head injury in rollover crashes, Figure 2a has been re-plotted showing a hypothetical case where the initial headroom is below 20cm. This is given in Figure 2b. The three diagonal lines shown are lines of constant roof intrusion levels of 0cm, 10cm, and 20cm.

The intersection of the line indicating 20cm pre-crash headroom with the 20cm constant intrusion line shows that the post-crash headroom is 0cm. This is indicated by the vertical line (line 3) through the post-crash headroom of 0cm on the x-axis. All the cases to the left of line 3 and below line 1 have post-crash headroom below the top of the head. The cases in the shaded region bounded by lines 1, 2 and 3 and the 0cm diagonal line are occupants with up to 20cm pre-crash headroom and between 0 and 10cm of post-crash headroom. If an additional 10cm of intrusion due to dynamic deflection of the roof and the relative displacement of the occupant towards the roof due to belt slack and other factors are added, the occupants in the shaded region would experience headroom reduction to below the top of the head. Therefore, these occupants would then be shifted to the left of line 3, where post-crash headroom is less than 0cm. In the case illustrated, let us assume that a vehicle which had an initial headroom of 20cm had a residual roof crush of 10cm in a rollover crash and the dynamic roof deflection in the same case is an additional 10cm, thus resulting in a total headroom reduction of 20cm.

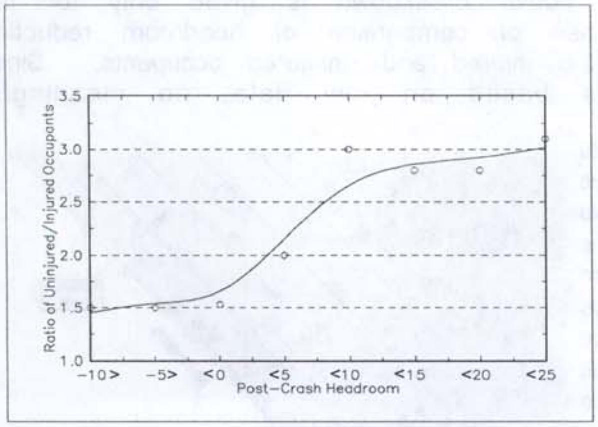

Figure 3. Ratio of uninjured to injured occupants plotted against post-crash headroom.

For the above hypothetical case, the total count of uninjured and injured occupants with headroom reduction below the head by the static roof deflection measurement was 40(24020 weighted). When the dynamic effects are included, the total count with headroom reduction below the head is 85(49027 weighted), over double the original number. The number of injured occupants increased from 17(3530) to 21(5079), while the number of uninjured increased from 23(20490) to 64(43948). It appears that dynamic roof deflection, for this specific case, increases the number of uninjured occupants with headroom reduction below the head significantly more than the injured occupants. If it can be assumed that cases with headroom reduction below the head have a high probability of receiving a head injury, dynamic headroom reduction up to 10cm does not appear to cause more head injuries, in this particular case of occupants.

The above discussion and the absolute number of injured and uninjured occupants are given only to illustrate that the dynamic roof crush and the relative displacement of the occupant with respect to the roof are important parameters that need to be accounted for in evaluating the head injury potential in rollover crashes. The numbers are in no way meant to be used to calculate the rate of increase of head injuries per unit dynamic headroom reduction or any such analysis.

RATIO OF UNINJURED TO INJURED OCCUPANT CASES - The number of uninjured and injured occupants up to a specific post-crash headroom level were counted and the ratio of the uninjured to injured occupants computed. A plot of the ratio of uninjured to injured occupants against available post-crash headroom less than a specific level is given in Figure 3. When the post-crash headroom is below zero, the ratio is almost a constant. As the headroom increases up to about 15cm, this ratio increases rapidly, indicating that the number of uninjured is appreciably higher. The ratio increases from about 1.5 at 0cm to almost 3.0 when the post-crash headroom is up to 20cm. Thus, the number of uninjured occupants almost doubles in relation to the number of injured occupants when the post-crash headroom increases from <0 to <20cm. Between <20 to <25cm post-crash headroom, the curve is approximately level at a ratio of almost 3.0 because most of the cases analyzed have post-crash headroom below 25cm. The number of uninjured occupants count is most affected for post-crash headroom from <0 to <20cm.

When the headroom initially available is reduced to zero, the headroom reduction is considered to be 100 percent. When the post-crash headroom is negative, the reduction in headroom is considered >100 percent. When the post-crash headroom is between 0 and initial (pre-crash) headroom, the reduction is considered to be <100 percent. Figure 4 is a further comparison of the ratio of uninjured to injured occupants plotted against percent headroom reduction above a specific level. The percent headroom reduction is computed as the difference in the pre- and post-crash headroom divided by the pre-crash headroom. At a headroom reduction of >0 percent, the ratio includes all occupants in vehicles with roof intrusion. The graph shows a downward trend of the ratio of uninjured to injured occupants as the percent headroom reduction increases. For >0 to >200 percent headroom reduction, the ratio of uninjured to injured occupants decreases from about 3.3 to 0.9. This corresponds to almost a four times increase in the number of injured cases compared to the uninjured cases. The highest rate of change in this ratio occurs between >0 and >100 percent headroom reduction indicating a predominant effect on susceptibility to injury as the percent headroom is reduced in this range. One-hundred percent headroom reduction occurs when the roof intrudes to the top of the occupant's head. At 100 percent headroom reduction, the ratio of uninjured to injured occupants is 1.6, and at 0 percent headroom reduction, it is 3.3. This shows that as headroom reduction decreases from >100 to >0 percent, the number of uninjured occupants, compared to injured occupants is more than double.

WEIGHTED DATA COMPARISONS - The accidents in the NASS database are skewed towards accidents with severe damage and injuries. Consequently, weighting factors are used for each accident to develop national estimates of the total number of cases from the unweighted sample. Sampling errors are not accounted for in the analysis in this paper. However, care was taken to keep the data sets large enough so as to draw general conclusions from the analysis. All the results presented are from the database created using the constraints discussed in the NASS DATA ANALYSIS section.

To ascertain the significance of roof crush in causing head injuries, four upper interior components including the roof were examined as injury sources for the group of accidents selected in this study. These components included the roof, side rail, front header, and A-pillar. Recorded injuries included fractures, brain hemorrhages, neck sprains, and skin abrasions and cuts, to the head, face, and neck. Figure 5 illustrates the distribution of head injury due to component contacts in the above data set. Roof contacts were responsible for about 75 percent of head, face, and neck injuries for these occupants over the five years of NASS data, with a total estimated count of 13,943. The roof and side rail together represent over 88 percent of the injuries due to contact against the selected components. Consequently, roof contact is considered to be responsible for most of the head injuries when they occur. However, there were over 150,000 other occupants that did not receive any head injuries in similar rollover accidents.

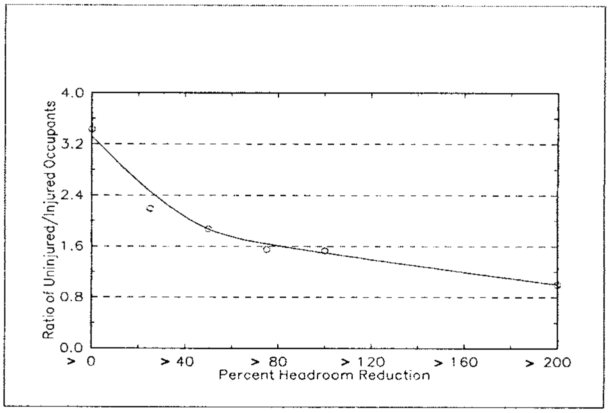

Figure 4. Ratio of uninjured to injured occupants plotted against percent headroom reduction.

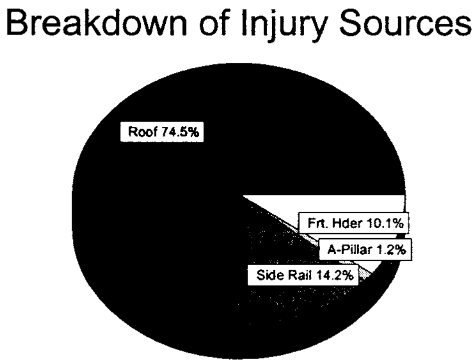

Figure 5. Injury distribution from contacts against interior components (NASS 1988-1992 database).

Percent headroom reduction gives a clear indication of the effect of roof intrusion on head injury causation as shown in Figure 6. In this figure, percent headroom reduction is shown for both injured and uninjured occupants. About 63 percent of the uninjured occupants had headroom reduction between 0 and 30 percent, while only about 27 percent of injured occupants had similar headroom reduction. On the other hand, for injured occupants, about 48 percent of them had a headroom reduction greater than 70 percent compared to only about 23 percent for the uninjured occupants. Therefore, it is apparent that headroom reduction over 70 percent increases the risk of head injury from roof contact considerably. As stated previously, to determine possible causes of head injury, further analysis of this data could only be conducted if belt slack, and dynamic roof intrusion information were known.

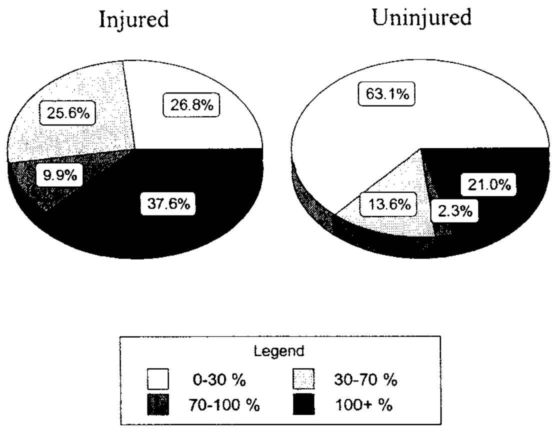

Figure 6. Comparison of percent headroom reduction for injured and un-injured occupants.

Further analysis of the average intrusion measurements for the weighted data set is given in Table 1. Average post-crash headroom was 4.6cm for injured occupants, and 10.7cm for the uninjured. Thus the average post-crash headroom for uninjured occupants is 2.3 times higher than that for injured occupants. Furthermore, the percent of headroom reduction for injured occupants was about 69 percent, compared to just 31 percent for uninjured occupants, while the average pre-crash headroom was only 6.7 percent higher for the uninjured occupants than the injured occupants.

Average rollover as measured by quarter turns was 3.20 for the vehicles with occupant injury, and 3.31 for those with no injury. Thus, there was only a slight (3 percent) difference in average quarter turns between the cases with and without injury. Consequently, it is concluded that the group of injured and uninjured occupants were exposed, on the average, to the same crash severity in these accidents, where crash severity is assessed in terms of quarter turns. While rollover quarter turns are not always accepted as a measure of crash severity, the resulting averages do indicate that the rollover cases compared in this study had relatively low crash severity. The cases analyzed only averaged about 3 quarter turns, which probably does not cause very violent motion of occupants, especially when belted. This would mean that the velocities imparted to the occupant are not likely to be high when compared to more severe rollover accidents. In fact, over 50 percent of the accidents in these cases were 2 quarter-turn rollovers. Without the high velocities and forces imposed, the occupant is less likely to have large forces transferred to the head due to the violent motion of the vehicle. Belt slack may still be an important parameter that needs further investigation, but this study used only cases where seat belt use was coded as "Belt Properly Worn", and it was assumed that belt "slack" was about the same in all cases, irrespective of whether the occupant was injured or uninjured.

It does not appear that belt slack alone would explain the differences seen in the status of injuries and its relationship to post-crash headroom between injured and uninjured occupants. Differences seen between these two groups show that roof intrusion into the compartment is a likely contributor to causing head injuries. The post-crash headroom for cases where the occupant was not injured was over 2 times higher than the post-crash headroom for injured occupants.

Table 1. Average rollover quarter turns, pre-crush headroom, and post-crush headroom for weighted vehicle and occupant cases.

	Avg. Vehicle 1/4 Turns	Avg. Pre-Crash Headroom (cm)	Avg. Post-Crush Headroom (cm)	% Headroom Reduction
Injured Cases	3.20	14.6	4.6	69
Uninjured Cases	3.31	15.6	10.7	31

Table 2 breaks down the distribution of injured and un-injured occupants further by headroom reduction. Average pre-crash headroom was

19.1cm for injured occupants, and 17.5cm for uninjured occupants when the headroom reduction was <100 percent. At the same time, average post-crash headroom for these two sets of data are different, with the uninjured occupants having a post-crash headroom about 3cm higher than in the case of occupants with injuries. This indicates that the average headroom reduction for the injured occupants was 7.5cm, whereas the same for uninjured occupants was only 2.4cm. A number of factors may be responsible for this difference. First, as seen from Figure 4, the shift from uninjured to injured occurs at a faster rate when the headroom reduction is <100 percent. The second possibility is that in these cases where there are head injuries, the dynamic effect (occupant dive and dynamic roof collapse) may be more predominant than in the uninjured cases. The average percent headroom reduction of injured occupants was 39 percent, while percent headroom reduction of uninjured occupants was only about 14 percent, or about a third of that for the injured occupants.

For occupants who had headroom reduction ≥100 percent, the pre-crash headroom was much less for injured and uninjured occupants. Pre-crash headroom was 7.1 cm for injured occupants and 8.4 cm for uninjured occupants. While both had a substantial percentage of headroom reduction - 200 percent for injured and 169 percent for the uninjured - the percentage of uninjured who had headroom reduction ≥100 percent was smaller when compared to the injured occupants. Only 21 percent of uninjured occupants had headroom reduction ≥100 percent, compared to 38 percent of injured occupants. The uninjured cases with headroom reduction ≥100 percent averaged 2.6 quarter-turn rolls and the injured averaged 4.1 quarter-turn rolls, a 58 percent increase. These additional quarter-turns may cause higher forces imparted to the occupant to cause vertical excursion and roof contact with the head.

Table 2 also showed that if you sum up the number of occupants under the injured and uninjured columns, the total number of injured occupants (9379) was much smaller than the number of uninjured (105480). This could be partly due to the effectiveness of seatbelts in preventing injuries in the rollover cases analyzed.

Table 2. Average rollover quarter turns, pre-crush headroom, and post-crush headroom.

	Injured		Uninjured	
	Headroom Reduction ≥100%	Headroom Reduction <100%	Headroom Reduction ≥100%	Headroom Reduction <100%
No. of Vehicles	3231	5794	12972	70888
Avg. 1/4Turns	4.1	2.7	2.6	3.5
Avg. Pre-Crash Headroom (cm)	7.1	19.1	8.4	17.5
Avg. Post-Crash Headroom (cm)	-7.1	11.6	-5.8	15.1
% Headroom Reduction	200	39	169	14
No. of Occupants	3530	5849	22099	83381
% Distribution of Occupants	38	62	21	79
Raw Count	17	18	26	94

Another comparison was made to examine if the incidence of injury is affected by initial headroom below and above 12.7cm, as measured from the roof interior. The 12.7cm threshold was chosen because, this is the upper limit of roof crush established in Federal Motor Vehicle Safety Standard (FMVSS) No. 216, "Roof Crush Resistance". Currently, FMVSS No. 216 sets the limits of roof deflection to be no more than 12.7cm when loaded to 1½ times the vehicle weight (22.2 kN limit for passenger cars only) by a 183cm x 76cm load plate on the leading edge of the roof [7]. This roof crush is measured from the outside of the vehicle. The intrusion into the compartment headroom of the occupant may depend on the structural stiffness of the roof, and the initial headroom of the vehicle. Figure 7 shows the distribution of cases with headroom reduction ≥ and <100 percent and pre-crash headroom ≥ and <12.7cm. In Table 2, 38 percent of the injured occupants had headroom reduction ≥100 percent; however, in Figure 7 it is shown that of that 38 percent, 82 percent had pre-crash headroom less than 12.7cm. Also, while only 21 percent of uninjured occupants had headroom reduction ≥100 percent considering all cases, 38 percent of those have similar headroom reduction when the pre-crash headroom was less than 12.7cm. For the injured cases, it would appear that when pre-crash headroom is less than 12.7cm, a high percentage (82%) of cases have headroom reduction below the head. The percentage for both injured and uninjured cases with headroom reduction exceeding 100 percent when the pre-crash headroom was greater than 12.7 cm, is very low, i.e. 1 percent for cases with injury, and 6 percent for cases without injury. It is noted that there are only a few cases when pre-crash headroom is >12.7cm and the headroom reduction is ≥100 percent. If the pre-crash headroom is greater than 12.7cm, the risk of headroom intrusion below the head is very low. On the other hand, when the pre-crash headroom is less than 12.7cm, the risk of head injury from headroom reduction, and thus roof contact, increases significantly.

LTV'S AND PASSENGER CARS - Table 3 gives the results of rollover, and headroom comparisons between light trucks, vans, and multi-purpose vehicles (LTV's), and passenger cars. LTV's are involved in over 38 percent of all the rollover accidents in this study, even though the 1991 Polk Registration data show that LTV's comprise only about 28 percent of the fleet. Several factors involving rollover susceptibility and other vehicle use factors probably may be responsible for the higher involvement of LTV's in rollover accidents.

About 6 percent of LTV occupants in this database had head injuries in rollover accidents. In comparison, the risk of receiving a head injury in passenger car rollovers is almost 10 percent as seen from this data. LTV roofs are generally stronger and higher, giving more headroom to the occupant than in passenger cars; consequently, if it is assumed that headroom reduction is important in causing injury, it is conceivable that LTV's would have a lower percentage of injuries in rollover crashes since their initial headroom is much higher. The data on post- and pre-crash headroom in LTV's and passengers supports this hypothesis. In this data, the average pre-crash headroom for LTV's was about 44 percent higher than in passenger cars. Headroom reduction (pre-crash minus post-crash headroom) for injured occupants averaged 12.8cm for LTV's in comparison to 8.9cm for passenger cars. Headroom reduction for uninjured occupants averaged 6.9cm and 3.5cm for LTV's and passenger cars, respectively. Due to the high initial headroom in LTV's, it takes more roof deflection including the dynamic effect of roof collapse and vertical occupant excursion, to have head injury from roof contact.

Table 3. Comparison of LTV and Passenger Car rollover data for NASS 1988-1992.

Vehicle Type		Injured	Uninjured
LTV's	# Occupants	2605	41406
	% Distribution	5.9	94.1
	Raw Count	10	48
	Pre-Crash Headroom (cm)	19	21.4
	Post-Crash Headroom (cm)	6.2	14.5
	% Headroom Reduction	67	32
	Avg. 1/4 Turns	3.1	4.1
Passenger Cars	# Occupants	6774	64074
	% Distribution	9.6	90.4
	Raw Count	25	72
	Pre-Crash Headroom (cm)	12.8	11.8
	Post-Crash Headroom (cm)	3.9	8.3
	% Headroom Reduction	69	30
	Avg. 1/4 Turns	3.2	2.6

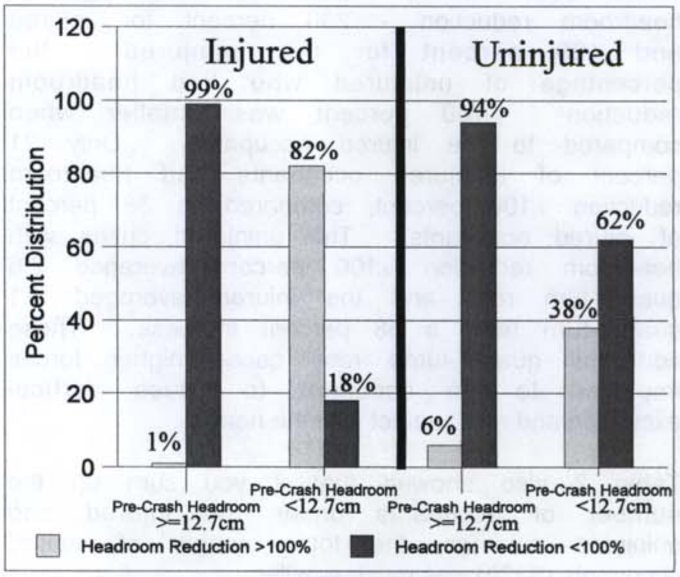

Figure 7. Distribution of cases when pre-crash headroom is more or less than 12.7cm.

The average percent headroom reductions for LTV's and passenger cars were almost the same for injured occupants at 67 percent for LTV's, and 69 percent for passenger cars. However, the percent headroom reduction for uninjured occupants in passenger cars and LTV's was about half that for injured occupants. Even though the average pre-crash headroom for LTV's and passenger cars are quite different, the average percent headroom reduction is almost the same. This suggests that to sustain an injury in an LTV, the absolute headroom reduction must be more than in passenger cars, which confirms the notion that the initial headroom of LTV's are higher than passenger cars. However, the dynamic effects of the passenger car and LTV's may be different due to the usually stiffer roofs of LTV's, which could cause the percent headroom reduction to be nearly the same.

Average post-crash headroom for injured occupants did not have roof intrusion to a level below the occupants head. The post-crash headroom of injured occupants averaged 6.2cm for LTV's and 3.9cm for passenger cars. Thus, dynamic roof intrusion, and the vertical occupant excursion may also be contributing to head injuries. However, when comparing the uninjured occupants in LTV's and passenger cars, the post-crash headroom was 14.5cm and 8.3cm, respectively. Therefore, while vertical excursion and dynamic effects are in all probability adding to the total headroom reduction in some accidents, it is obvious when comparing the injured and uninjured groups that measured static headroom reduction is a parameter that correlates well with the risk of head injury.

Interestingly, the average quarter turns for the LTV's with uninjured occupants averaged a full quarter turn more than for the LTV's with head injured occupants. This trend was just the opposite for the passenger cars, with 3.2 average quarter turns for injured occupants, and 2.6 average quarter turns for uninjured occupants. It is possible that the higher headroom in the LTV's may have made the influence of the number of quarter turns less significant in causing head injuries. It may also be indicative of the fact that LTV's as a group are more susceptible to increased roll rate than passenger cars where the center-of-gravity of the cars, in general, are lower than that of LTV's.

INJURY DISTRIBUTION - Table 4 shows the AIS levels for the injuries and their distribution by percent headroom reduction. Only 36 percent of all head injuries, AIS 1+, had headroom reduction >100 percent. On the other hand, 65 percent of all serious injuries, AIS3+, had similar headroom reduction. In general, as the injury severity increases, the percentage of headroom reduction increases.

Table 4. Head injuries from roof contact by AIS level and by associated headroom reduction from NASS 1988-1992 data.

Injury Severity	Total Head Injuries	Head Injuries with Headroom Reduction ≥100%	Percent of Injuries with Headroom Reduction≥100%
AIS 1+	12042	4374	36
AIS 2+	2613	788	30
AIS 3+	201	131	65

SUMMARY AND CONCLUSIONS

The NASS database was used to examine rollover accidents and head injuries to belted occupants. Using AAMA specifications and other specifications of vehicles, the occupant height, and vehicle roof intrusion measurements for the NASS cases analyzed, headroom in case vehicles were determined before the crash (pre-crash), and after the crash(post-crash). With this information, comparative analyses were conducted to determine the factors that are likely to cause head injuries in rollover crashes. Unweighted data were used to study the trends in head injury causation by headroom reduction and roof contacts. Analyses were also conducted with weighting factors to make national estimates of the data. Conclusions based on results from these analyses, are enumerated below:

1. The risk of a head injury increases as the headroom is reduced. The following results of weighted data lead to this conclusion:

- Headroom reduction over 70 percent increases the risk of head injury from roof contact substantially.

- Average pre-crash headroom is a significant factor in determining the risk of headroom intrusion below the head. Since risk of head injury increases with post-crash headroom below the head, pre-crash headroom must also be considered as an important indicator of the risk to head injury.

- The percentage of injured occupants with post-crash headroom below the top of the head was 1.8 times (2.2 unweighted) the percentage of uninjured occupants.

- Average percent headroom reduction of injured occupants was more than twice that of uninjured occupants. At the same time, the injured and uninjured cases each averaged the same number of quarter-turn rolls.

2. Analyses of the raw data also showed trends where the risk of head injury increased with higher headroom reduction. Results found were:

    - The percentage of uninjured occupants with no roof intrusion was over three times that of the percentage of injured occupants.

    - The ratio of uninjured to injured occupants is reduced by about 50 percent as post-crash headroom decreases from <20 to <0cm.

    - The ratio of uninjured to injured cases with any headroom reduction (>0 percent) is over double that for cases with headroom reduction greater than 100 percent. The ratio declines exponentially as headroom reduction increases. When the level of headroom reduction is greater than 200 percent, the ratio decreased to less than one-third the ratio for cases with headroom reduction over 0 percent.

3. A hypothetical analysis was conducted to examine the effects of adding dynamic roof intrusion and vertical occupant excursion to the residual headroom reduction. Even though dynamic effects did not significantly increase the number of injured occupants for the case analyzed, it is necessary to take into consideration the dynamic effects when assessing the potential for head injury due to roof contacts.

4. Average quarter-turns among the groups of injured and uninjured cases were quite low. Consequently, high vehicle velocity and resulting occupant motion may not be a factor in comparing injury potential in low severity rollover crashes. Differences in headroom reduction were not necessarily due to differing crash severities among the two groups.

5. Belted occupants in LTV's appear to be less susceptible to head injury because of the generally higher and stronger roofs in these vehicles.

6. As the severity of the injury increases, the percentage of cases with headroom reduction below the top of the head increases.

It was noted, that vertical excursion of the occupant off the seat also increases the potential for head contacts, especially for those injured occupants who did not have significant headroom reduction, but still suffered a head injury. Belt slack is a factor, however the results of the passenger car and LTV comparison suggest that if the initial headroom is appreciably higher, injury still could occur once the headroom is reduced to below a certain level. When pre-crash headroom below 12.7cm was examined, it was found that all but 18 percent of the cases with injury had headroom reduction below the top of the head. Conversely, the same examination of uninjured occupants showed that 62 percent did not have headroom intrusion. This suggests that even if belt slack is causing the occupant to come vertically off the seat, it must be acting in conjunction with headroom reduction to cause injury. It is, therefore, important in further research to determine which injuries resulted from intrusion into the available headroom, which occurred as a result of the occupant "diving" into the roof, and which are caused by a combination of the above two factors. Better classification of the injury causation could be developed with more information on the belt restraint system.

This study shows that future research should consider the impact of roof intrusion into the compartment. To improve rollover crashworthiness of vehicles, headroom reduction and the belt system should be evaluated simultaneously to upgrade occupant protection. As more occupants use belt restraints and, belt pre-tensioners, integrated seat belts, web grabbers, etc., become more prevalent, the importance of headroom reduction is likely to move toward the forefront for rollover protection.

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