HEAD INJURIES TO NEARSIDE OCCUPANTS IN LATERAL IMPACTS: EPIDEMIOLOGICAL AND FULL-SCALE CRASH TEST ANALYSES

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ABSTRACT

The objective of this study was to conduct an analysis from the 1993-2000 NASS database and determine the occurrence of head injuries (HI) as a function of restraint use to nearside occupants in lateral impacts. Data from NCAP crash tests conducted in our vehicle crashworthiness laboratory and elsewhere were used to determine the potential for HI. The NASS analysis indicated that the risk of sustaining HI of any severity was higher without than with belt use. The risk increased by four-fold in direct side impacts (3 and 9 o'clock). Although the overall risk of sustaining a very severe HI (AIS 4-6) was low (<5%), the significant morbidity (30%) associated with these injuries necessitates further research. While the thoracic trauma index was the same between drivers and passengers (66 versus 65), the head injury criteria varied by a factor of approximately two (635 vs 374) between the two occupants in NCAP tests. Passenger head contact with interior components (roof-rail-C-pillar) was responsible for HI. A primary area of focus for side impact injury assessment and mitigation should be the struck side rear seat passenger. It may also be of value to better quantify HI metrics (e.g., rotational acceleration) by using a more biofidelic head-neck system in NCAP tests to advance injury mitigation strategies.

Key Words: Head injury, Side impact, NASS analysis, NCAP test

MOTOR VEHICLE CRASHES ACCOUNT FOR significant head injuries (HI) and fatalities due to HI (Gennarelli et al. 1989, 1984). The importance of HI in frontal impacts was emphasized in a recent study using the 1991-1998 NASS database (Pintar et al. 1999). In contrast, side impacts have received less attention except for studies using European databases (Miltner and Salwender 1995; Morris et al. 1995). The importance of HI and the means to assess and ameliorate trauma are the topic of this investigation. Specifically, this study was designed to determine the effect of restraints on nearside occupants in lateral collisions from the NASS database and to compare the potential for HI protection using data from the New Car Assessment Program (NCAP) side impact tests.

METHODS

NCAP Data: The US DOT NCAP has been in place since 1979. The NCAP started with crash testing vehicles in frontal impact mode into a fixed rigid barrier. The frontal crash test, designed according to the Federal Motor Vehicle Safety Standard (FMVSS) 208, is five mph greater in closing speed. The FMVSS 208 requires a test speed of 30 mph, and the frontal NCAP is done at 35 mph. The injury criteria are the same for the regulatory and NCAP tests. Results from the NCAP test, however, are presented as 1-5 "star rating," with five stars indicating the safest car. The NCAP was expanded in 1997 to include side impact assessment. Like the frontal program, the side NCAP is designed according to FMVSS-214. For the side impact, a 1361-kg moving deformable barrier at a crabbed angle of 27 degrees impacts a stationary vehicle on the driver's side at a closing speed of 33.5 mph. The closing speed is increased to 38.5 mph for the side NCAP test. This crabbed angle impact simulates the striking vehicle moving at 34 mph into the struck vehicle moving at 17 mph. This results in a struck vehicle delta-v ranging from approximately 18 to 25 mph, depending on the weight of the vehicle. Driver and passenger (SID) dummies on the nearside of the impact are instrumented with pelvis, spine, and rib accelerometers. There is a three-axis head accelerometer package to derive the Head Injury Criteria (HIC). The SID head and neck is based upon the Hybrid II dummy. The side impact star rating is derived from only spine and rib accelerometers. Data from the most recent NCAP crash tests are posted on the NHTSA web site. In total, 77 reports and data from side NCAP test were available for analysis. One hundred forty-five usable data points for evaluation of head accelerations were studied. Data included NCAP tests conducted in our vehicle crashworthiness laboratory.

NASS Data: A subset of the NASS-CDS database was abstracted from 1993-2000 to include numerous variables. A head injury (HI) was defined as present if there was an AIS score for the head (skeletal or internal tissue) greater than zero. Scalp and external injuries were excluded. If multiple AIS head injuries were present, only the highest was used for analysis. This was noted as the maximum head injury AIS (max AIS HI). Nearside occupants were studied who were more than 16 years of age and whose restraint use was known. For this study, "unbelted" meant that the occupant had no seat belt use. Because of the very small number of side airbag deployments with no belt use, crashes in which no belt was used but had an airbag deployment were included in the unbelted category. Most (of these) were frontal airbags since, during the years of this study, there were few side airbag deployments, and the NASS database could not describe side airbag deployment. Occupants were considered "belted" if belt restraints were used irrespective of airbag deployment status. Delta-V's were collapsed into 10 km/h categories from 0 – 90 km/h with principal direction of force (PDOF) of 8, 9, or 10 o'clock for left side and of 2, 3, or 4 o'clock for right side occupants. Both front and rear passengers were included. Ejections and rollovers were excluded. Raw and weighted frequencies of head injuries were obtained as a function of AIS 1990 rating, restraint use, and delta-v. Relative percentages and weighted numbers are presented in the paper. Unless stated otherwise, all numbers refer to the weighted data.

RESULTS: NASS Analysis

1. <u>Overall Composition and Influence of PDOF on Risk of HI of Any Severity</u>

The entire side impact data set (for the years 1993 to 2000 inclusive, Table 1) consisted of 1,296,336 nearside occupants. Of these, 1,208,262 (93.2%) incurred no HI

(AIS=0), and 88,074 (6.8%) had a HI of AIS severity one to six (AIS>0). These nearside occupants were subdivided into those involved in a crash in which the PDOF was directly from the side (3 or 9 o'clock for right and left side occupants) and those in which the crash was slightly frontward (PDOF 2 or 10 o'clock for right and left side occupants) or rearward (PDOF 4 or 8 o'clock for right and left side occupants). Frontward crashes (55.6%) were substantially more frequent than direct side (37.9%) or rearward (6.5%) crashes. The risk of incurring any HI was slightly more for frontward (7.4%) than if the PDOF was directly from the side (6.1%) or rearward (6.0%). These differences did not seem to be associated with different rates of belt use because they were very similar in frontward, direct side, and rearward crashes (88.4%, 89.3%, 87.2% respectively).

Table 1: Summary of Side Impact Data

Direction	AIS = 0	AIS > 0	Total	HI (%)	Occurrence (%)
Frontward	667,237	53,179	720,416	7.4	56.6
Direct side	461,570	29,807	491,377	6.1	37.9
Rearward	79,455	5,088	84,453	6.0	6.5
Total	1,208,262	88,074	1,296,336	6.8	100.0

2. <u>Influence of Seat Belt Restraint Use</u>

Table 2 demonstrates that the risk of sustaining HI of any severity was almost double if no seat belts were used (6.2 versus 11.5%). This difference was absent in the frontward side crashes, similar in the rearward side crashes, but was very significant in the direct side crashes. The incidence of HI was more than four-fold greater if seat belts were not used (18.5% versus 4.6%). Thus, seatbelt has a protective effect in side crashes.

Table 2: Head Injury as a Function of Restraint Use

Direction	Unbelted				Belted			
	AIS = 0	AIS > 0	Total	HI (%)	AIS = 0	AIS > 0	Total	HI (%)
Frontward	77,130	6,434	83,564	7.7	590,107	46,745	636,852	7.3
Direct side	43,012	9,736	52,748	18.5	418,558	20,071	438,629	4.6
Rearward	10,072	748	10,820	6.9	69,383	4,340	73,723	5.9
Total	130,214	16,918	147,132	11.5	1,078,048	71,156	1,149,204	6.2

3. <u>Influence of Side Impact Direction on Severity of HI When HI did Occur</u>

Although the overall risk of incurring an HI was slightly less in a direct side crash, if HI did occur, it was more likely to be serious. Thus, the risk of a serious HI (AIS 3+ = AIS 3-6) was greater in direct side crashes (20.3% versus 17.4%), less in frontward (16.2%), and least in rearward (13.1%) side crashes. These minor directional differences were ranked the same for those belted (19.1% side, 14.8% front, 14.0% rear) but not for unbelted occupants. Table 3 shows that if a HI occurred to an unbelted occupant, the chances of sustaining an AIS 3+ head injury were substantially increased compared to a belt-restrained occupant. Frontward side impact has the greatest risk (nearly double, from 14.8% belted to 26.8% unbelted). The risk of serious HI is only slightly higher for direct side impact (19.1% versus 22.7%), and the risk drops for the unbelted rearward configuration, perhaps because of few cases in the NASS dataset.

Fortunately, as shown in Figure 1, the overall risk of sustaining a very severe HI (AIS 4+) is rather low. Nonetheless, the risk is three times greater for unbelted than belted nearside occupants (1.4% versus 0.5%). There is a difference for each gradation of side impact, but the largest difference, i.e., the greatest degree of belt protection, is for direct side crashes (0.5% incidence of AIS 4+ compared to 1.8% if unbelted).

Table 3: HIC Occurrence in Unbelted Occupants

Direction	AIS = 1-2	AIS =3+	Total	% AIS 3+
Frontward	4,711	1,723	6,434	26.8
Direct side	7,524	2,212	9,736	22.7
Rearward	692	56	748	7.5
Total	12,927	3,991	16,918	23.6

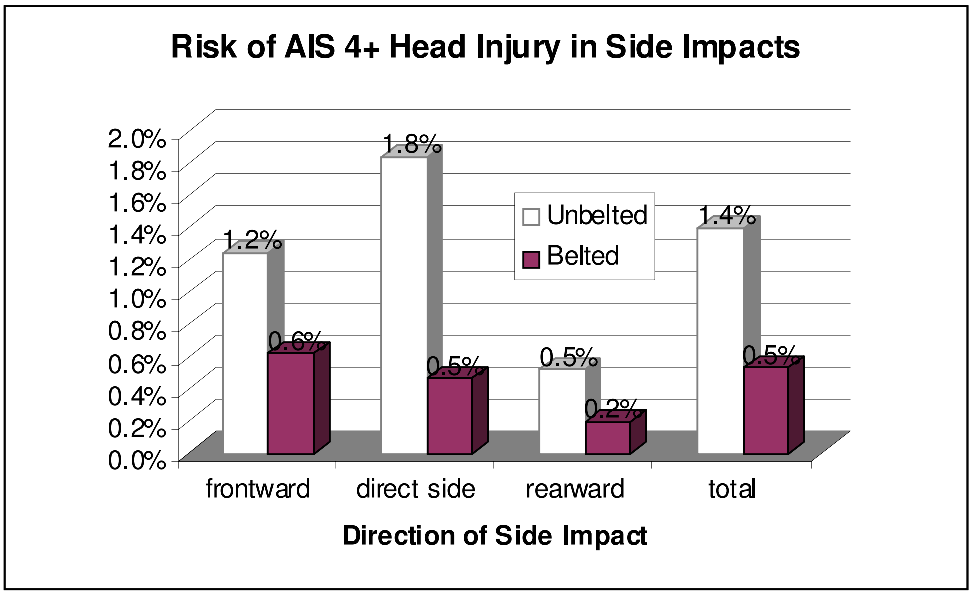
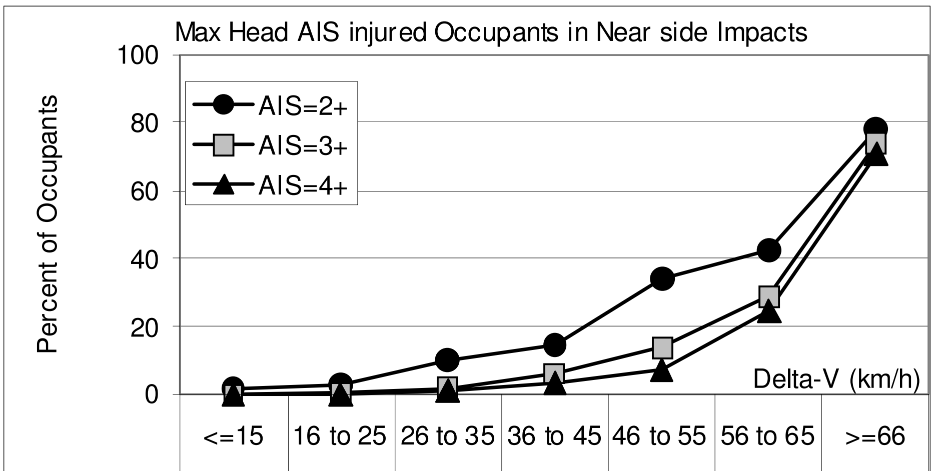


Figure 1: HI risk of AIS 4 and greater as a function of direction of side impact.

Notwithstanding the differences between the direct, frontward, and rearward direction of impact, more robust analyses can be done by combining the three into “side impact” crashes. This analysis probably has more validity, given the difficulty of precisely assigning a crash to one of the three directions. The larger numbers also provide additional confidence for comparison, which is otherwise difficult with three smaller datasets. The number of minor (AIS=1-2) head injuries is greatest at crash delta-v’s less than 35 km/h; whereas more severe (AIS=3+) head injuries occur most frequently between 26 and 45 km/h (Table 4). The percentage of AIS=3+ head injuries precipitously increases with a higher delta-v such that between 36 and 55 km/h almost 40% of the head injuries are severe (AIS=3+). There is a general increase in head injury risk for increasing delta-v crashes such that at delta-v’s greater than 56 km/h there is a 30% or greater risk of severe (AIS=3+) head injuries (Figure 2). The cumulative probability of sustaining HI as a function of injury severity (AIS) and delta-v is shown (Figure 3).

Table 4: Effect of Crash Delta-v on Head Injury, Combined Data

Delta-v (km/h)	AIS=1-2	AIS=3+	Total	%AIS=3+
<=15	14800	246	15046	1.6
16 to 25	18592	1281	19873	6.4
26 to 35	15021	2869	17890	16.0
36 to 45	3845	2532	6377	39.7
46 to 55	1908	1080	2988	36.1
56 to 65	218	459	677	67.8
>=66	57	1040	1097	94.8



	<=15	16 to 25	26 to 35	36 to 45	46 to 55	56 to 65	>=66
AIS=2+	1.621	2.865	10.059	14.511	33.780	42.632	78.245
AIS=3+	0.040	0.266	1.979	6.360	13.777	28.904	74.180
AIS=4+	0.026	0.165	0.915	3.439	7.131	24.559	70.685

Figure 2: HI risk for all nearside occupants (combined direction data) as a function of delta-v.

RESULTS: NCAP Analysis

Of the 77 examined side NCAP tests, 145 possible occupant data sets were included in the analyses. Although the star rating for the vehicles is based on TTI, test reports include data for the Head Injury Criteria (HIC). There were 138 usable HIC data points from driver and rear seat passenger SID dummies. The HIC is calculated from the resultant acceleration of a three-axis accelerometer package placed at the center of gravity of the dummy head. In general, the HIC values for the rear passenger dummy (mean = 635) were higher than the driver dummy (mean = 374), although the average TTIs were virtually identical (driver = 66, passenger = 65). There was also a greater linear correlation between the thoracic injury measure, TTI, and the HIC for drivers (correlation coefficient of 0.61) than for passengers (correlation coefficient of 0.33) (Figure 4). In examining some NCAP film data, rear seat passenger dummies with relatively high values for HIC demonstrated a consistent head strike to the C-pillar of the vehicle (Figure 5).

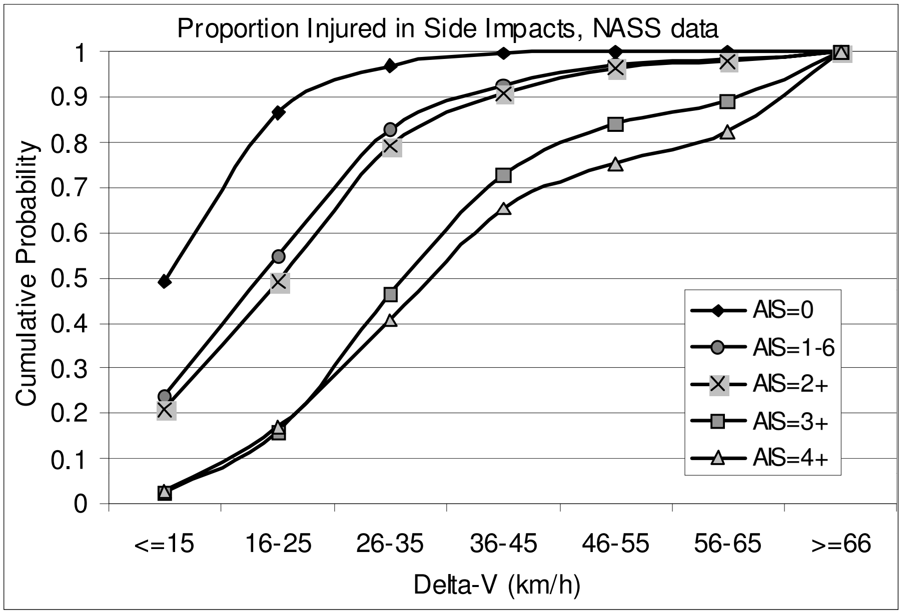


Figure 3: Cumulative probability of sustaining HI as a function of AIS and crash delta-v.

To evaluate the NCAP dataset using the results from the NASS dataset for nearside occupants in side impact, the appropriate delta-v range in the NASS data must be chosen to match the delta-v's in the NCAP test. The NCAP data resulted in crash delta-v's for the struck vehicle from approximately 30 km/h for larger cars to about 40 km/h for smaller cars. Examining the NASS data in these delta-v ranges results in a risk for AIS=4+ head injuries up to 3.4% (Figure 2). The probability of AIS=4+ head injuries is correlated to HIC in the FMVSS (Figure 6). Using the exponential probability equation provided by the NHTSA for frontal impact, a 3.4% probability of AIS=4+ head injury results in a corresponding HIC value of approximately 500. This method was adopted because of the lack of a HIC-based curve for side impact. Application of this HIC value to the NCAP dataset (Figure 6) indicates that almost half of the dummy occupants sustained higher HIC values. Clearly, more than half of the passenger dummies sustained HIC values in excess of 500. In addition, even for five-star vehicles, 35% of passenger occupants sustained HIC values in excess of 500. Acknowledging that the star rating is based only on TTI and because of the poor overall correlation between TTI and HIC (R-squared = 0.17), the poor correlation between star rating and HIC was not a surprise. This is especially true for passenger occupants (Figure 7, R-squared = 0.03).

DISCUSSION

As indicated in the Introduction, few studies have addressed the prevalence of head injuries in side impacts. Gennarelli and co-workers discussed the directional dependence of brain trauma using laboratory studies and the use of rotational acceleration for brain injury tolerance (Gennarelli et al. 1987; Meaney et al. 1984). Epidemiological analysis from a U.K. database found that in lateral impacts 23% of all head injuries belonged to the

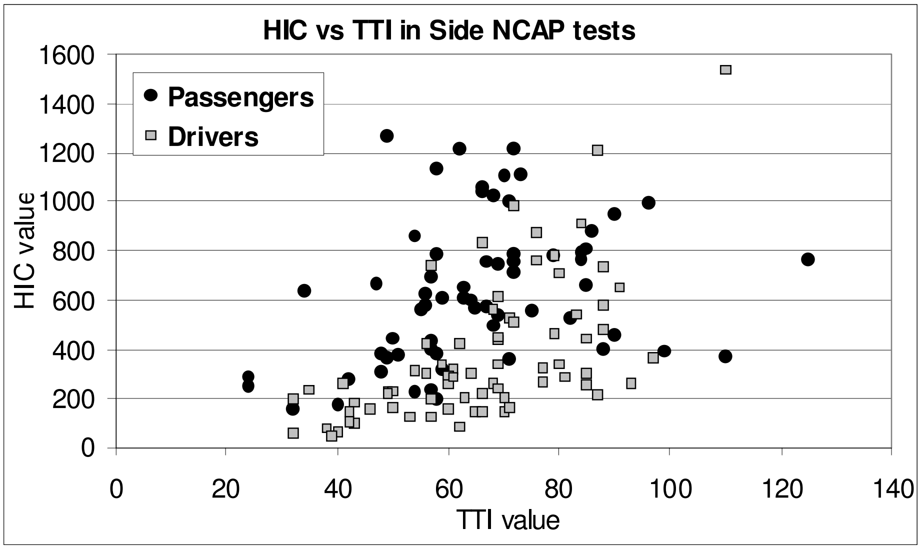


Figure 4: Passenger and driver dummy response for HIC and TTI from side NCAP tests. Note the preponderance of greater HIC values in the passenger population.

AIS=4-6 category (Morris et al. 1993). Contact within the interior structures of the vehicle, such as the B/C pillars, was determined to be a source of head impact and the ensuing head injury. Diffuse brain injuries were determined to be secondary to head contact with the interior (than exterior) component of the vehicle. Based on these findings, the authors alluded to the potential benefits of head injury countermeasures such as side airbags.

Although the incidence of AIS 4-6 HI in side impacts in the NASS database was found to be 3.4% (Figure 2), the implications are significant from a clinical perspective. For example, during an evaluation of data from trauma centers in the United States, Gennarelli et al. determined that mortality rates range from 28 to 32% for AIS 4-6 HI patients (Gennarelli et al. 1994). Consequently, amelioration of these types of HI not only decreases the societal economic burden and improves side impact protection, but also enhances clinical outcomes.

In a similar vein, although the incidence of HI was reported using European databases, the analysis was limited to front seat occupants (Miltner and Salwender 1995; Morris et al. 1995). In contrast, the present analysis included the rear seat occupant because NCAP tests were conducted with two struck side (driver and passenger) anthropomorphic dummies. This facilitated a comparison of TTI and HIC between the driver and passenger. While the thoracic indices were similar between the two dummies (driver TTI = 66, passenger TTI = 65), significant differences were found in HIC (driver HIC = 374, passenger HIC = 635). Furthermore, kinematic analysis revealed contact (Figure 5) between the passenger dummy and interior component(s) of the vehicle, in particular, the roof rail-C pillar region. These results clearly demonstrate a need for the protection of the rear seat occupant in nearside impacts. As discussed later, tools are available to further

Figure 5: Image frames from onboard high-speed film of a passenger dummy in a NCAP test conducted in our vehicle crashworthiness laboratory. The top frame is prior to impact; middle frame is during impact wherein a head strike to the C-pillar can be seen; bottom frame demonstrates the head strike mark (arrow) as the dummy moves away. occupant

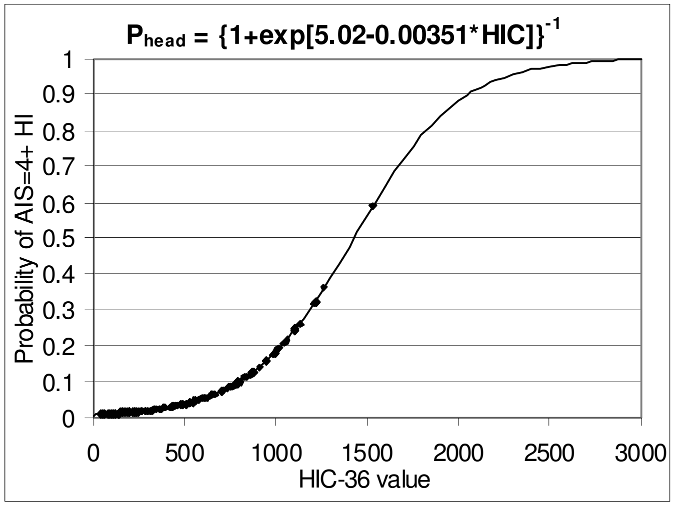


Figure 6: The probability curve used by NHTSA to define AIS 4 and greater HI in frontal impact. The dots on the lower end of the curve represent data points of occupant responses from the side NCAP tests.

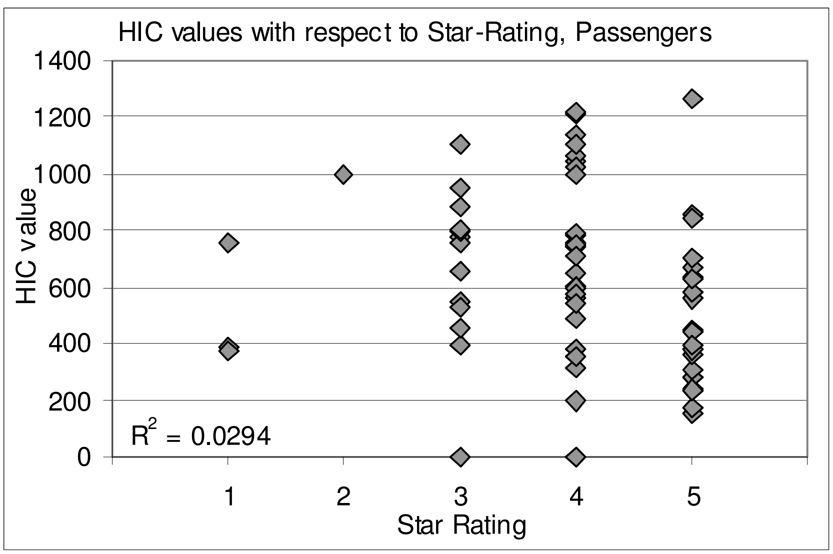


Figure 7: Head injury criteria for passenger dummies in side NCAP tests. Note the poor correlation between star rating and HIC.

quantify biomechanical variables (e.g., rotational acceleration) that may be of value to assess and achieve lateral impact protection for the struck side rear seat occupant.

The main objective of the current analysis was to evaluate head injuries and head injury risk in nearside impact crashes. The NASS database is a sampling of real-world crashes. It provides national estimates of the occurrence of injury by appropriately weighting the sampled raw data. Full-scale vehicle crash tests annually conducted by the NCAP provide crashworthiness data in a controlled environment. Ideally, NCAP results should be a reflection of real-world events. The NCAP does not currently use HIC as part of the crashworthiness assessment. When this program was originally proposed, few interventional strategies were available to protect the head in side impact. Today, the side airbag has become a very feasible method of head protection in lateral crashes. The current analysis of the NCAP crash data clearly indicates that head protection could be improved, particularly for the rear seat passenger in a nearside impact.

The limitations of using the NASS database are acknowledged. It has been criticized that the belt restraint use reported in the NASS database may be overstated due to its origination from case police reports. Criteria for a crash incident to be sampled into the NASS database depend on unique guidelines established for each sampling center. The first sampling filter examines type and model year of vehicle, tow status of vehicle, severity of police-reported injuries, and disposition of injured persons. Only vehicle types that are not medium/heavy trucks and late-model (current production to previous three years) vehicles are sampled. Crashes involving most severely injured victims (including fatalities) and transported directly from the scene for treatment are also a priority in the sample. The second filter gives priority to crashes with at least one overnight-hospitalized victim. The sampling, therefore, gives priority to more severe injuries.

The lack of a rigid NCAP testing protocol also adds to the limitations in this data set. The moving barrier (i.e., bullet vehicle) was modeled after a medium-sized car (1361 kg) with bumper heights and height to upper hood edge obtained from average passenger cars and light trucks in 1987. The prediction was that the average weight of vehicles would decline in the future. With the popularity of SUV's, these predictions need alteration. Many SUV's have significantly higher ride heights that may adversely influence the HI risk to the nearside occupant when, as the striking vehicle, the front grill of the penetrating SUV provides a boundary condition for head impact.

While the HIC is the only approved and federally adopted injury criteria, other variables such as the rotational acceleration have been suggested as candidates for brain injury assessment (Meaney et al. 1994). Because NCAP utilizes the SID with a Hybrid II head-neck system (in the majority of cases), lack of instrumentation and biofidelity requirements limit data collection to only three triaxial linear accelerations. Consequently, other mechanisms of injury cannot be evaluated using this protocol. Becuase it is possible to replace the Hybrid II head-neck system with the Hybrid III in the SID torso, modifications can be done to obtain additional data that may be of value for further analyze head injury in lateral impacts.

Because an evaluation of head injury risk in the vehicle crash environment is done with anthropomorphic test devices (dummies), the biofidelity of the head-neck structure is essential for an accurate evaluation of head motion. If the neck structure is too stiff, for example, the head may not translate to a location where impact could occur. Conversely, the head may impact a location that a living human occupant may have a very low probability of contact. Differences exist in dummy head neck design. For example, the

SID neck is made out of a cylinder of solid rubber. In contrast, the neck of the Hybrid III dummy, designed for frontal impact, consists of a series of aluminum plates between rubber pucks. The neck of the THOR dummy consists of smaller rubber pucks between aluminum plates and has cables to simulate the stabilizing action of muscles. The WorldSID neck has rubber pucks and aluminum plates and nodding joints at the two ends of the neck to allow for more lateral head translation. Head kinematics in side impact will be different due to different features in neck design. In contrast, direct impact to chest structures of these different dummy designs may not affect the thoracic kinematics. From this viewpoint, head injury metrics (e.g., head motion) may be more susceptible to dummy biofidelity than a chest injury metric (TTI). Stricter guidelines for head-neck biofidelity in dummies are helpful for HI assessment and mitigation in side impacts.

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