THE NATURE AND SOURCE OF THE HEAD INJURIES SUSTAINED BY RESTRAINED FRONT SEAT OCCUPANTS IN FRONTAL COLLISIONS

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Introduction

Research into the biomechanics of head and neck injuries is viewed as a major step towards the introduction of more realistic injury tolerance measurement techniques. This important research also aims to identify ways in which the consequences of severe head injuries can be mitigated and the long tenn effects reduced. Practical application of an increased understanding is still some way off however and engineers and car designers are left with little guidance as to the most productive steps to take to reduce these injuries. This paper aims to provide this guidance by analysing data describing real-world crashes and the head injuries that have been sustained. The parts of the car that cause the injuries, the circumstances under which these injuries are sustained and the types of injury are discussed.

For the purpose of this analysis the head is defined as comprising the cranium, brain, face and overlying soft tissues unless otherwise stated.

There have been few studies that have examined the real-world crash conditions that result in head injuries. Viano[1] stated that real-world crash data is necessary to provide the impact situations resulting in head injury. Walficsh [2] when investigating the realism of a whole vehicle perpendicular barrier test identified the steering wheel as a major source of head injury amongst restrained drivers in frontal collisions. Bradford [3] examined head injuries in impacts all of directions. She found a similar result with UK data but also recognised contact with objects outside the car such as trees, other cars and trucks as causing more frequent severe brain injury. Thomas [4] investigated restrained drivers injuries from contact with the steering system and identified the steering wheel as a frequent cause of the face, head and torso injuries in frontal impacts. He noted that steering wheel intrusion was often associated with these injuries. The relation of intrusion to injury outcome was also stressed by Frampton [5].

Data Analysis

This paper analyses the data collected within the UK Co-operative Crash Injury Study. The data collection techniques have been described elsewhere[6 7]. The sample contains data on 1514 restrained front seat occupants in frontal crashes. The data collection methodology deliberately selects a higher proportion of the serious and fatal crashes, in order that this sample can be easily related to the accident population inverse sampling fractions are used to weight the data. The total sample of 1514 casualties represents 6988 casualties in the population while the 751 casualties with head injury in the sample represent 2985 such casualties in the population. This paper gives the results of an analysis of the weighted population estimates so as to permit easy comparison of the frequent low severity injuries with the more rare life-threatening. 105 (2%) of the 6988 casualties who were restrained in a frontal collision died and 80 (76%) of these sustained a head injury.

Frontal impacts were defined as those having a direction of force between 11 and 1 o'clock and direct contact to the front of the car.

Sources Of Injury

The sources of the head injuries sustained by the restrained drivers is shown in Table 1 which shows the sources of head injuries sustained by survivors and fatalities.

Table 1 : Causes of head injuries - survivors and fatalities

	Survivors				Fatalities	
Contact Zone	AIS 1 / 2	(%)	AIS 3+	(%)	AIS 3+	(%)
Glazing	316	(11%)	1	(2%)	7	(9%)
Pillars & roof	190	(7%)	1	(2%)	17	(21%)
Facia	149	(5%)	7	(10%)	2	(2%)
Steering Wheel	1302	(46%)	34	(51%)	25	(32%)
Exterior	44	(2%)	9	(13%)	22	(27%)
Other	162	(6%)	9	(13%)	4	(6%)
Not Known	675	(23%)	6	(9%)	3	(3%)
Total casualties	2838	(100%)	67	(100%)	80	

There were 2818 survivors who sustained AIS 1 or AIS 2 injuries. The most common cause was contact with the steering wheel which accounted for 46% of the injuries. A further 316 (11%) were caused by glazing materials and 655 (23%) were from an unidentified source. There were 67 survivors who sustained head injuries greater than AIS 3. 34 (51%) were a result of steering wheel contact while exterior objects and the facia accounted for a further 9 (13%) and 7 (10%) injured occupants respectively. The steering wheel was the most common cause of the AIS 3+ injuries of the fatalities accounting for 25 (32%) of fatalities. Exterior objects caused a further 22 (27%) of casualties and the pillar and roof another 17 (21%).

Types of injury -survivors and fatalities

The head injuries sustained by the survivors and fatalities were classified according to the procedure suggested by Gennarelli[8]. Skeletal injuries were classified as facial bone fractures, skull fractures or a combination. Brain injuries were classified as being focal or diffuse with diffuse injuries sub-divided into minor (AIS 1 or 2) or major (AIS 3+). AIS 2 injuries represent unconsciousness for up to 1 hour for example while all focal lesions were AIS 3 or above. Although minor diffuse injuries might be considered acceptable Rutherford has found that 50% of casualties have symptoms at 6 weeks after the crash while 15% show symptoms after 1 year[9].

There were 2885 survivors in the accident population of whom 2005 (70%) sustained only soft tissue injuries. 484 (17%) sustained a fracture and 521 (18%) a brain injury while 125 sustained both together.. Table 2 shows the head injuries of the survivors. There were also 80 fatalities with a head injury, 63 sustained a fracture and 69 a brain injury. Table 3 shows their injuries. It should be noted that Table 3 systematically underestimates the incidence of diffuse injuries amongst fatalities, these injuries are typically brief unconsciousness and can not be recorded when casualties die at the scene of the accident. Similarly the identification of major diffuse injuries requires a microscopic examination of brain tissue, this is not normally performed in UK post-mortem examinations so their presence is often only indicated by the level of consciousness of fatalities who survive for a while. It is quite feasible that all fatalities recorded as receiving a focal lesion may also have an associated diffuse lesion. In addition the duration of unconsciousness of survivors is often clouded by sedation and it is often difficult to identify precisely when the casualty would have regained consciousness. The severity of a diffuse injury may therefore be only approximate.

The percentages given are of the total casualties in each group, for example Table 2 shows that 310 (64%) of the fractures of survivors involved the facial bones and were caused by steering wheel contact.

Table 2 : Head Injuries of Survivors

	Soft Tissue	Fractures			Brain Injuries			
Contact Zone	Injuries Alone	Facial #	Skull #	Face and Skull #	Minor Diffuse	Major Diffuse	Focal	Diffuse & Focal
Glazing	288 (14%)	20 (4%)		1 (0.4%)	14 (3%)		1 (0.2%)	
Pillars & roof	158 (8%)	11 (2%)	1 (0.4%)		30 (6%)			
Facia	110 (6%)	10 (2%)	1 (0.4%)	2 (0.4%)	33 (6%)	1 (0.2%)		1 (0.2%)
Steering Wheel	844 (22%)	310 (64%)	12 (2%)	11 (0.2%)	233 (45%)	15 (3%)		
Exterior	21 (1%)	17 (4%)	1 (0.3%)	1 (0.3%)	13 (2%)	4 (1%)		4 (1%)
Other	73 (4%)	40 (8%)	3 (0.6%)		49 (9%)	9 (2%)		1 (0.2%)
Not Known	513 (26%)	37 (8%)	2 (0.3%)	1 (3%)	109 (21%)	3 (1%)		3 (0.6%)
Total casualties	2005 (100%)	447 (92%)	20 (4%)	17 (4%)	481 (92%)	31 (6%)	1 (0.2%)	9 (2%)
Casualties in group	2005 (100%)	484 (100%)			521 (100%)			

Table 3: Head Injuries of Fatalities

	Soft Tissue	Fractures			Brain Injuries			
Contact Zone	Injuries Alone	Facial #	Skull #	Face and Skull #	Minor Diffuse	Major Diffuse	Focal	Diffuse & Focal
Glazing	6 (24%)	3 (5%)		1 (2%)		1 (2%)	3 (5%)	
Pillars & roof	2 (6%)	6 (10%)	5 (8%)	3 (4%)		2 (3%)	7 (11%)	5 (8%)
Facia	1 (6%)		2 (3%)				2 (2%)	
Steering Wheel	3 (10%)	7 (11%)	12 (19%)	6 (9%)	1 (2%)		13 (19%)	12 (18%)
Exterior	5 (22%)	7 (12%)	8 (13%)	1 (2%)		3 (4%)	12 (18%)	1 (2%)
Other	1 (6%)	2 (3%)			1 (2%)	2 (3%)		1 (1%)
Not Known	7 (27%)						3 (4%)	
Total casualties	25 (100%)	26 (42%)	26 (42%)	11 (17%)	2 (4%)	8 (12%)	40 (59%)	19 (29%)
Casualties in group	25 (100%)	63 (100%)			69 (100%)			

Facial bone fractures alone were most commonly sustained by the survivors while skull fractures were equally divided between the survivors and the smaller number of fatalities. 447 (92%) of the survivors sustained facial bone fractures as their only head injury. In comparison there were 63 fatalities with a fracture of whom 26 (42%) sustained only facial bone fractures. 74 occupants sustained a skull fracture and 50% of these died. Focal lesions were most commonly sustained by the fatalities while diffuse injuries were most frequently reported as being sustained by the survivors although as previously noted these injuries were systematically under-reported for fatalities. There were 69 casualties who sustained a focal injury, 59 (86%) of these died, 30 at the scene of the crash.

The most common sources of injury were the steering wheel, A-pillars and roof, the facia and exterior objects.

Steering Wheel Injuries

The steering wheel was the most common injury source amongst restrained drivers, 1361 (70%) of all restrained drivers sustained their head injury from the steering wheel as did 59 (49%) of those with an AIS 3+ head injury.

The head injuries sustained from steering wheel contact are shown in Table 4. The percentages given are a proportion of the total of 1361 casualties.

Table 4 : Injuries from steering wheel contact

	No Brain Injury	Minor Diffuse Injury	Major Diffuse Injury	Focal	Focal and Diffuse
No Fracture	847 (62%)	149 (11%)	10 (0.7%)	3 (0.2%)	
Facial Bone #	234 (17%)	74 (5%)	3 (0.2%)	4 (0.3%)	2 (0.1%)
Skull #	5 (0.4%)	7 (0.5%)	4 (0.3%)		8 (0.5%)
Face & Skull #	5 (0.4%)	5 (0.3%)	2 (0.1%)	3 (0.2%)	3 (0.2%)
Total	1091 (80%)	235 (17%)	15 (1%)	13 (1%)	12 (1%)

847 drivers sustained no fracture and no brain injury, their only injury was a soft tissue injury. The most common injuries other than soft tissue injury were facial bone fractures (234 occupants - 17%), minor diffuse injury (149 occupants - 11%) and a combination of the two (74 occupants - 5%). Only 62 (4%) casualties sustained either skull fracture or more severe brain injury from a steering wheel contact.

Table 5 : Intrusion and impact severity for occupants with head injury from steering wheel contact

	Soft Tissue Only	Minor diffuse or face #	Severe brain injury or skull #
Resultant Wheel Intrusion (cm)			
0 - 10	703 (83%)	284 (62%)	28 (45%)
11 - 20	99 (12%)	123 (27%)	6 (11%)
21 +	21 (2%)	24 (5%)	22 (36%)
Not known	24 (3%)	27 (5%)	6 (9%)
Impact Severity			
Median delta-V	42 kph	48 kph	55 kph
No. below 30 kph	83 (23%)	35 (15%)	1 (4%)

Intrusion has been identified as a crucial factor when head injuries are caused by steering wheel contact . However many of the less severe brain injuries and facial bone fractures were caused at low intrusion levels. Table 5 shows the frequency with which each type of steering wheel was intruding for each group of injuries. 284 (62%) of these casualties sustained their injuries when there was less than 10 cm of residual steering wheel intrusion. A further 123 (27%) did so with between 11 and 20 cm intrusion. In comparison 28 (45%) of the 62 casualties with more severe head injury were in cars with below 10 cm of residual steering wheel intrusion. These results indicate that although intrusion increases the chance of more severe head injury other factors such as the design of the wheel are more important. Petty [10]has suggested that limiting the pressure on the face together with reducing peak accelerations might be very effective at mitigating these non-life threatening injuries.

Although HIC is not considered to be the best measure of head injury possible a value of 1000 is frequently taken as representing the onset of severe brain injury or skull fracture. Only 62 (4%) of cases can be considered to have exceeded this limit since they sustained injuries of this severity. This group, although small, cannot be considered insignificant since 25 (41%) of these 62 casualties died representing 31% of the total of 80 fatalities in the population.

Table 5 also shows the median delta-V for each group of injuries. The median value of delta-V for severe brain injury or skull fracture is 55 kph while that for minor diffuse and facial bone fracture is 48 kph.

The most effective technique to mitigate head injuries from the steering wheel is probably to avoid contact. This might be done by increasing the stiffness of the seatbelts however a consequence might well be an increase in torso injury especially amongst older people. Given that contact will occur at some impact severity then the use of padding could reduce head injury severity. This analysis has shown that any padding should be tuned so that severe brain injury or skull fractures are avoided in impacts equivalent to a 55 kph impact and also so that facial bone fractures and minor diffuse injury are reduced under the conditions of at least a 48 kph crash.

Airbags have been suggested as a means of reducing face injuries from the steering wheel. One design option for an airbag is to use a small facebag that can be triggered in higher delta-V crashes, 30 kph is often suggested. This has the advantage that the sensors can be set to a level that minimises false triggering. Table 5 shows that 23% of all soft tissue injuries and 15% of minor diffuse injuries or face fractures from steering wheel contact take place below this speed. Under these conditions an airbag sensor set to a high delta-V trigger will not inflate and the driver may still contact the steering wheel. It is possible that a steering wheel with an uninflated airbag will be stiffer than one optimised for face contact. Car design therefore needs to ensure that airbag installation in cars does not increase face and head injuries at low impact severities. Other analyses [11] of real-world crash data have shown that head and face injuries represent only 30% of the economic cost of steering wheel injuries with over 60% resulting from chest and abdomen injuries. The most effective type of airbag will reduce both head and torso injuries under European conditions of seat location and restraint use.

Glazing Injuries

There were 324 casualties who sustained their most severe head injury from glazing materials - either unbroken glass or flying glass from a broken window. Altogether 437 injuries were sustained and 404 (92%) were soft tissue injuries. Since the importance of this injury source is partly dependant on the number of injuries sustained by each occupant Table 6 shows the source of injuries on an injury basis rather than an occupant basis.

Table 3 shows 7 instances of skull fracture or severe brain injury resulting from contact with glazing materials. Inspection of these cases revealed that all contacted a laminated windscreen that was supported by a truck in an underrun collision. Although the contact was technically with the windscreen the predominant causation factor was the truck. These cases have not been included in Table 6.

There were a total of 437 injuries sustained from contact with unsupported glazing materials. 404 (92%) were AIS 1 lacerations, abrasions or contusions. There were 11 facial bone fractures and 9 corneal abrasions and other AIS 1 eye injuries. There were also 13 casualties with minor diffuse brain injury.

174 (40%) of the injuries were sustained from contact with a laminated glass windscreen while 44 (10%) were from a toughened glass screen. A further 75 (17%) were a consequence of striking the side door glass in oblique impacts and there were 136 (31%) injuries from flying glass.

Table 6: Glazing material injuries and type of glass.

	Source of glazing injury					
	Windscreen					
Injury Type	Toughened	Laminated	Unknown	Side door glass	Flying glass	Total Injuries
Soft Tissue Injuries	44	153	4	73	130	404
Facial Bone Fractures		7				11
Eye Injuries		3			6	9
Minor Diffuse Injuries		11		2		13
Total	44	174	4	75	136	437

A contusion will nonnally heal rapidly with no long tenn scarring while lacerations may result in some disfigurement. 19 (43%) of the 44 surface injuries sustained from a toughened glass windscreen were lacerations compared with 102 (67%) of the injuries from contact with laminated glass. The higher likelihood of contusions resulting from contact with a toughened glass windscreen is likely to be a consequence of casualties contacting the windscreen in small cars in low speed crashes. In these circumstances the windscreen may not be broken by frame distortion. At higher impact speeds the windscreen is more likely to be broken and lacerations will be sustained from flying glass.

Other frequent sources of lacerations were the side window glass (48%) and flying glass (69%). Flying glass comes from a window that has been broken before occupant contact nonnally following distortion of the frame. Inevitably it will be toughened glass as laminated glass is designed to remain bonded to the interlayer, additionally there were no cases of laminated side glass fitted to any of the cars in the crash sample. Toughened glass was therefore the cause of 142 (57%) of the 247 lacerations from identified glazing types.

There were 5164 vehicles involved in frontal collisions including all those that did not carry a restrained front seat occupant with a head injury, 4961 had an identified windscreen type. 668 (13%) of these were fitted with a toughened glass screen while 4321 (87%) were fitted with a laminated glass windscreen. The ratio of toughened windscreens to laminated windscreens was therefore 668:4321 = 0.15:1. Amongst the causes of soft tissue injuries the ratio of toughened:laminated windscreens was 44:153=0.29:1. When the other glazing sources were included, both of which were toughened, the ratio became 44+73+130:400=0.62:1 . Toughened windscreens and toughened glass are therefore overrepresented as a cause of soft tissue injuries amongst the population of restrained front seat occupants with head injuries.

Minor diffuse injury was only seen when contacting a laminated windscreen. The defonnability of the interlayer can result in the longer duration decelerations to cause this inertial-type of injury. Crash severities great enough to potentially result in high speed head contacts onto toughened windscreens probably also resulted in sufficient vehicle crush to break the glass prior to contact. Therefore no diffuse injuries were observed resulting from a toughened windscreen.

Pillar and Roof Injuries

There were 211 casualties with a head injury sustained from contact with the A-pillar or roof, these casualties represented 5% of all those with a head injury. This number is likely to underestimate the contribution of A-pillar and roof contacts to all head injuries in all impact directions as many such contacts will occur in impacts to the side of the car. The direction of force on 38 (31%) of drivers who contacted the zone was 1 o'clock, the remainder were at 12 o'clock. In many cases there was a significant degree of rotation of the car so that, although the car saw a purely longitudinal force, the driver moved in an oblique direction. The conditions are therefore similar to those in many partial overlap frontal collisions. Table 7 shows the nature of the injuries sustained. The percentages given are of the total of 211 casualties with a head injury from a pillar or roof contact.

Table 7 : Head injuries from pillar and roof contacts

	No Brain Injury	Minor Diffuse Injury	Major Diffuse Injury	Focal	Focal and Diffuse
No Fracture	157 (75%)	23 (11%)		2 (1%)	2 (1%)
Facial Bone #	9 (4%)	6 (3%)	2 (1%)	1 (0.5%)	
Skull #		1 (0.5%)		3 (1%)	2 (1%)
Face & Skull #				2 (1%)	1 (0.5%)
Total	166 (79%)	30 (15%)	2 (1%)	8 (4%)	5 (3%)

157 (75%) of all casualties with head injuries from contact with the A-pillar or roof sustained only minor soft tissue injuries. A further 38 (18%) sustained either minor diffuse injury, facial bone fracture or both. 16 (8%) sustained more severe brain injury or skull fracture, 15 of these sustained focal lesions and 15 occupants died.

It has been suggested that head protection from contact with the upper parts of the interior of the car should be required and the NHTSA has issued a Notice of Proposed Rulemaking. This rule would require padding to cover the A-pillar, roof, side header rail and B-pillar. It should be noted that levels of seatbelt use are lower in the US than in the UK accident sample although full-size airbags might give some benefit in oblique impacts. Fan [12] and Monk [13] have recently explored means of reducing these head injuries and have recommended the use of padding and an impact to measure pillar stiffness. The analysis of the real-world data has shown that the most common types of injury resulting from roof and A-pillar contact are soft tissue injuries followed by minor diffuse injuries or facial bone fractures. Prevention of these severe injuries could alter the outcome of the casualties who died. The UK accident data shows that other important factors such as intrusion and support occur that are not considered in the proposed regulation. The contacts were classified according to whether they were intruding and also whether there was a supporting part of the striking object immediately behind the contact zone. The results are shown in Table 8.

In many vehicles the normal head position of the driver is remote from the A-pillar and it is only when the pillar intrudes and moves towards the driver that a contact becomes possible. Table 8 shows that even when only soft tissue injuries are sustained intrusion is frequent at 53% but only 16 (10%) of drivers struck a pillar or roof that was supported by the striking object. When minor diffuse or facial bone fractures are sustained intrusion is more frequent but only 11 (27%) of contacts were supported. The most severe injuries were all associated with intruding contacts and 13 (87%) of these were supported. A supported pillar or roof is likely to be in contact with a tall object and the accident data indicates that these are frequently trees or trucks[14]. These objects are also often relatively undeformable and the resulting crashes frequently have a high impact severity, the head contact velocity can therefore be high.

The above analysis indicates that upper interior protection can potentially provide a valuable reduction in the head injuries of fatalities. It also indicates that this will only happen if the test procedure takes account of the higher contact velocities that cause these injuries in real-world collisions. Further modelling or experimental work is required to estimate the contact velocities.

Table 8 : Intrusion and support of roof and A-pillar contacts

	Soft Tissue Only	Minor diffuse or face #	Severe brain injury or skull #
% of contacts intruding	83 (53%)	34 (82%)	16 (100%)
% of contacts intruding and supported	16 (10%)	11 (27%)	13 (87%)

Facia Injuries

159 (5%) of casualties with a head injury sustained their injury from contact with the facia and 144 (91%) of these were front seat passengers. 8 (5%) casualties, of whom 6 were front seat passengers, sustained AIS 3+ head injuries. 151 (95%) sustained a face injury while only 42 (26%) sustained a head injury. The injuries of the 144 front seat passengers are shown in Table 9.

Table 9 : Injuries resulting from facia contact.

	No Brain Injury	Minor Diffuse Injury	Major Diffuse Injury	Focal	Focal and Diffuse
No Fracture	110 (76%)	21 (15%)			1 (0.7%)
Facial Bone #	6 (4%)	2 (2%)	1 (0.7%)		
Skull #	1 (0.7%)			2 (1%)	
Face & Skull #					
Total	117 (81%)	23 (16%)	1 (0.7%)	2 (2%)	1 (0.7%)

110 (76%) of the occupants sustained soft tissue injuries alone. A further 29 (21%) involved facial bone fracture or minor diffuse injury while only 5 (3%) sustained the most severe head injuries. 2 of the 5 with severe injuries died and these 2 represented 2% of the total fatalities with head injuries.

Table 10 shows the frequency of intrusion and the median delta-V for the three groups of casualties - soft tissue injuries alone, minor diffuse injury or facial bone fracture and severe brain injury or skull fracture.

Table 10 : Intrusion and delta-V for head injuries from the facia

	Soft Tissue Only	Minor diffuse or face #	Severe brain injury or skull #
% of contacts intruding	18 (16%)	15 (52%)	4 (80%)
Median delta-V	51 kph	55 kph	65 kph

The injuries sustained when a facia does not intrude are mainly facial bone fractures and soft tissue injuries. Brain stem injuries, skull fractures and periods of unconsciousness above 6 hours were also observed and these injuries can occur at low intrusion levels. Front seat passengers have greater flexibility over the fore/aft position of their seat than drivers. The distance between many front seat passengers and the facia is often large which means that higher levels of impact severity are required before a contact occurs. A higher delta-V will result in greater forward movement together with increased intrusion. The crashes where head injuries were sustained from the facia tended to be the more severe crashes. The median delta-V for the group who contacted the facia was 57 kph compared to 43 kph for all those with a head injury from any source. Casualties who only sustained soft tissue injuries had a median delta-V of 51 kph while it was 65 kph for the small number with severe brain injury or skull fracture

The performance of the facia to head impact is determined in Europe by ECE regulation 21 and in the US by the similar FMVSS 201. Both regulations require a limit of 80 g for 3 ms when a head form is used under conditions similar to a 50 kph frontal collision. This analysis of real-world accident data has shown these crash conditions frequently only result in soft tissue injuries when occupants are restrained. If the severe head injuries are to be reduced then the test requirements should be evaluated under the conditions of a 65 kph collision. This more severe requirement would only have the potential to mitigate the head injuries of a small proportion of fatalities and the cost-effectiveness would be low.

Exterior Objects

Previous analyses of the causes of head injuries have identified objects outside the car as being a major cause of severe head injury [3]. Table 1 shows that 30 (39%) of the 75 occupants with exterior contacts resulted in AIS 3+ injuries. Other analyses have shown that intrusion is a causal factor in head injuries separate from impact severity [15]. Contacts with exterior objects and intruding structures are more difficult for car designers to mitigate so it is useful to assess the relative incidence of these injuries in a representative accident sample. Objects exterior to the car play a significant role especially where more severe injuries are sustained. This most commonly occurs when the car underruns a truck and can result in occupants hitting the truck with their head or hitting a part of the car that is supported by the truck. The countermeasures necessary to mitigate these injuries involve lowering the bumper heights of trucks and improving compatibility. A study carried out by Thomas [16] suggested that 30% of all car occupant fatalities that collide with the front of trucks could be prevented. The remaining fatalities may not be preventable with current technologies.

The injuries resulting from contact with an exterior object were more severe compared with head injuries from other sources. Table 11 compares injuries from interior and exterior contact, with and without support. The percentages given are row percentages.

Table 11 : Intrusion, exterior objects and head injuries.

	Head Injury Severity			
Intrusion	AIS 1	AIS 2	AIS 3+	Row Total
Interior contact, No intrusion,	1591 (82%)	325 (17%)	30 (2%)	1946 (100%)
Interior contact, Unsupported intrusion	582 (68%)	215 (25%)	61 (8%)	858 (100%)
Interior contact, Supported intrusion	47 (44%)	36 (34%)	24 (23%)	107 (100%)
Exterior Contacts	26 (35%)	18 (24%)	30 (40%)	74 (100%)
Total casualties	2246 (75%)	594 (20%)	145 (5%)	2985

Interior contacts were the least severe, 1591 (82%) were AIS 1 and only 30 (2%) were AIS 3+. Intrusion caused these injuries to be slightly more severe with 582 (65%) being AIS 1 and 61 (8%) AIS 3+. Contact with a supported, intruding interior object caused 24 (23%) to be AIS 3+. Contact with exterior objects resulted in the most severe injuries with only 26 (35%) injuries being AIS 1 and with 30 (40%) of injuries being AIS 3+.

The impact severity where exterior contacts occurred were typically more severe than for interior contacts. The median delta-V for all casualties with an interior contact was 44 kph while it was 76 kph for all exterior contacts.

The nature of the injuries caused by interior contacts and by exterior contacts are shown in Tables 12 and 13.

Table 12 : Nature of Surface and Skeletal Injuries

Nature of Surface and Skeletal Injuries	Interior Contacts	Exterior Contacts
Soft Tissue Only	1653 (79%)	40 (53%)
Facial Bone Fracture	374 (18%)	25 (32%)
Skull Fracture	35 (2%)	9 (12%)
Face and Skull Fracture	24 (1%)	2 (3%)
Total	2085	77

Table 13 : Nature of brain injuries

Brain Injuries	Interior Contacts	Exterior Contacts
No brain injury	1697 (81%)	41 (53%)
Minor Diffuse	323 (16%)	13 (17%)
Major Diffuse	20 (1%)	7 (9%)
Focal	26 (1%)	12 (16%)
Focal & Diffuse	18 (1%)	5 (6%)
Total	2085	77

Tables 12 and 13 show that exterior contacts result in greater proportions of the more severe brain injuries and fractures. 1653 (79%) of head contacts with interior structures only resulted in soft tissue injuries compared with 40 (53%) of exterior contacts. Both facial bone fractures and skull fractures were more frequent when exterior objects were contacted. Similarly exterior contacts resulted in higher proportions of AIS 3+ diffuse injuries and focal lesions.

In line with Table 1 exterior objects did not cause a large portion of the more severe injuries in frontal impacts. Exterior objects resulted in only 27 (6%) of the 425 facial bone fractures and 11 (16%) of the 70 skull fractures. 17 (28%) of the 61 focal lesions were a result of exterior contact in comparison with 20 (6%) of the 363 diffuse injuries.

A recent analysis of the causes of head injuries in side impacts [17] reveals that exterior objects are the most frequent cause of AIS 3+ head injuries and also focal injuries and skull fractures. Similar results from this analysis have revealed that the circumstances that result in head contact with exterior objects in frontal impacts result in the most severe injuries. However exterior objects only cause 31 (21%) of AIS 3+ injuries in frontal impacts so the influence on casualty totals is low. Contacts with exterior objects are not the limiting factor in frontal impact protection that they are in side impact protection as they result in a smaller proportion of the life-threatening injuries.

The real-world injury data does not demonstrate that the interiors of cars have too much padding. High numbers of diffuse injuries are sometimes taken to indicate that car design now encourages rotational head injuries. Table 13 shows that 44 (72%) of all focal lesions are a result of interior contact while Tables 2 and 3 show that 59 (86%) of focal injuries are sustained by fatalities. These injuries can be mitigated by appropriate padding to car interiors. However this analysis has also shown that life-threatening injuries are caused at higher impact severities than other injuries and there is therefore the need to develop suitable padding materials. The objective should be to reduce the AIS 3+ injuries at high impact severities while also reducing the minor diffuse injuries and facial bone fractures that are sustained at lower speeds.

Conclusions

- Facial bone fractures and diffuse injuries are most commonly identified amongst survivors while focal injuries are most common amongst fatally injured occupants.
- 23% of all head injuries from steering wheel contact occur at speeds below 30 kph - a level which is frequently the trigger level for Eurobags.
- The design of steering wheels needs to prevent skull fracture and brain injury under high impact severities as well as facial bone fractures at lower severity impacts. Steering wheel intrusion should be minimised under high severity impact conditions.
- The use of laminated windscreens still causes fewer soft tissue injuries than toughened glass even when car occupants are restrained.
- The high levels of seatbelt use in European vehicles suggest that the requirements for upper interior protection are different form those in the US. The pillars and roof should mitigate severe diffuse and focal injuries when the pillar is intruding and supported by an exterior object.
- Head contact with exterior objects in frontal impacts is not quite the limiting factor in occupant protection that it is in side impacts. Although the resulting head injuries are often severe they cause only 27% of the AIS 3+ injuries of fatalities.
- 68% of all AIS 3+ head injuries were sustained from contacting a part of the car interior that was unsupported although intrusion was frequent. The reduction of intrusion levels that will increase the available ride-down space will benefit many occupants who sustain head injuries.

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