An evaluation of the risk of brain injury for real-world crashes involving occupants of passenger vehicles in ANCIS

David Logan, James Scully, Brian Fildes[1]

ABSTRACT

Brain injuries are a major cause of death and permanent disability for victims of motor vehicle crashes. The present study isolated characteristics of crashes involving passenger vehicles that were likely to result in brain injury for their occupants. The study used data from 268 seriously injured or killed occupants collected as part of the Australian National Crash In-depth Study (ANCIS). Univariate analyses were completed on a range of potential confounders in order build a multivariate logistic regression model of the risk of brain injury. Potential confounders included a wide range of variables related to the configuration of the crash, the severity of the impact, the size of the vehicles involved, the deployment of airbags, the occupant's age and sex and the level of damage to the case occupant's vehicle. The resulting model showed that the risk of brain injury was significantly dependent on the geometry of the collision partner, the speed zone in which the crash occurred, the level of intrusion into the passenger cabin and the area of the occupant's vehicle that received most of the damage. The study discusses possible countermeasures by reviewing the contact sources that resulted in brain injuries for occupants in the sample.

BACKGROUND

ANCIS has been continuously collecting real-world in-depth serious injury crash data since 2000, collecting comprehensive information on a large number of variables from relating to hospitalised vehicle occupants and their injuries, the vehicle and the crash site. The main entry criteria are:

- The occupant was hospitalised at least overnight as a result of injuries sustained in a car crash
- The vehicle in which they were travelling must have been manufactured since 1989
- The vehicle must be a car, car-derived utility, passenger 4WD ('SUV') or passenger van ('MPV')

For a full description of the study, refer to Fildes, Logan, Fitzharris, Scully & Burton (2003). In this paper, the issue of brain injury was considered. In 1991, the cost of head injuries to the occupants of cars and car derivatives in Australia was estimated at almost 40% of total injury costs ("harm") (FORS, 1992). In the US, Miller, Pindus and Douglass (1993) used the NASS database to derive a figure of 46%. It was therefore decided to examine the characteristics of brain injuries in particular to see whether any causal patterns emerged.

STATISTICAL METHOD

Univariate analyses of a number of crash-related variables were carried out to investigate their effect on the occurrence of brain injury. Then, the variables found to be significantly related were considered for inclusion in a logistic regression model. It should be noted that in the analyses that follow, the *p*-value for significance has been set at $\alpha = 0.05$. However, given that there were 34 separate tests of significance, there would be an 82.5% chance of observing one or more significant *p*-values, even if all 34 null hypotheses were true. Results significant at the $\alpha = 0.05$ level should be

[1] Monash University Accident Research Centre, Building 70 Monash University Victoria 3800. Ph: +61 3 9905 4376, Fax: +61 3 9905 4363, David.Logan@general.monash.edu.au

considered trends. The paper does, however, attempt to verify these trends from an engineering standpoint in addition to a statistical one.

RESULTS

A total of 268 vehicle occupants were available in the ANCIS database for analysis, of which 36 received a brain injury.

This study looked at brain injury only, *viz.* injuries with an AIS code (AAAM, 2001) beginning with the digits '14'. Therefore, injuries to the skull, vessels and whole area were not included. In order to be coded in this section, injuries must be verified by CT scan, MRI, surgery, x-ray, angiography or autopsy and are all of AIS3 or higher. There were only eight participants who received a head injury without also receiving a brain injury.

1 CRASH VARIABLES SIGNIFICANTLY RELATED TO BRAIN INJURY

Of the number of variables chosen from the occupant, vehicle and crash site, the variables detailed in the following sections were found to be significant at $\alpha = 0.05$ level. There was a non-significant trend toward brain injury being associated with multiple impacts rather than single, unsealed roads vs sealed roads and taller occupants compared with shorter ones. Brain injury was found to be independent of crash severity (potentially due to the lack of cases for which this variable could be calculated), road topography/curvature, vehicle body style or mass, airbag deployment, occupant age, weight, seating position and seatbelt use.

1.1 Crashes involving a rollover event

Although a trend was observed toward brain injury being more likely in a multiple impact crash (which involve rollovers around a third of the time), a significant association was observed between brain injury and rollover alone. This suggests that the trend observed for brain injuries to be more likely with multiple impacts is perhaps a consequence of the rollover events.

Table 1: Distribution and expected counts of brain injury occurrence for crashes involving a rollover event compared with those not involving a rollover event.

Impact Type		Brain Injury		Total
		No	Yes	
No rollover	Count	204	26	230
	Expected	199	31	230
Rollover	Count	28	10	38
	Expected	33	5	38
Total	Count	232	36	268

$\chi^2(1) = 6.3$, $p = 0.02$. 'Expected' counts have been rounded to nearest integer.

1.2 Location on vehicle of most significant damage

The CDC code is a seven-digit identifier of vehicle damage, covering the principal direction of force, damage location, type and extent. The area of the vehicle for which the highest damage extent is recorded was tested for an association with occurrence of brain injury. Where the damage extent was equally high in two or more regions, the vehicle was classified as having 'multiple' regions of most significant damage. Fisher's Exact Test showed a significant ($p = 0.04$) relationship between the two variables.

Table 2: Distribution and expected counts of brain injury occurrence by the area of most significant damage.

Area of most significant damage		Brain Injury		Total
		No	Yes	
Front	Count	115	9	124
	Expected	107	17	124
Right	Count	54	13	67
	Expected	58	9	67
Rear	Count	10	0	10
	Expected	9	1	10
Left	Count	28	8	36
	Expected	31	5	36
Roof	Count	9	2	11
	Expected	10	2	11
Underside	Count	1	0	1
	Expected	1	0	1
Multiple	Count	15	4	19
	Expected	16	3	19
Total	Count	232	36	268

$FET = 12.1$, $p = 0.04$. 'Expected' counts have been rounded to nearest integer.

The increased likelihood of brain injury in side impacts makes sense, so the trend was further investigated by categorising the lateral impact cases into struck (or near) side and non-struck (far) side. Brain injury was more likely in both near and far side impacts, as shown in Table 3.

Table 3: Distribution and expected counts of brain injury occurrence by impact type.

Impact type		Brain Injury		Total
		No	Yes	
Neither (not side impact)	Count	148	13	161
	Expected	139	22	161
Near (struck) side	Count	63	14	77
	Expected	67	10	77
Far (non-struck) side	Count	16	5	21
	Expected	18	3	21
Near and far sides	Count	5	4	9
	Expected	8	1	9
Total	Count	232	36	268

$FET = 13.8$, $p = 0.002$. 'Expected' counts have been rounded to nearest integer.

1.3 Principal collision partner

Due to the possibility of vehicles having multiple collision partners, only the collision partner for the most severe impact was analysed. The impact to be considered was selected using the final digit of the CDC vehicle damage code, representing damage extent. Vehicles involved in collisions with larger vehicles, such as trucks, buses or semitrailers experienced more than the expected number of brain injury cases, as were those vehicles which impacted narrow, rigid objects such as trees, poles or posts.

Table 4: Distribution and expected counts of brain injury occurrence by principal collision partner.

Principal Collision Partner		**Brain Injury**		**Total**
		No	**Yes**	
Car/Utility/4WD	Count	102	6	108
	Expected	94	15	108
Tree/pole/post	Count	71	19	90
	Expected	78	12	90
Truck/bus/semi-trailer/campervan	Count	20	6	26
	Expected	23	4	26
Other object	Count	10	0	10
	Expected	9	1	10
Rollover	Count	4	2	6
	Expected	5	1	6
Crash barrier/wall	Count	5	1	6
	Expected	5	1	6
Other vehicle	Count	6	0	6
	Expected	5	1	6
Motorcycle	Count	2	0	2
	Expected	2	0	2
Animal	Count	0	1	1
	Expected	1	0	1
Multiple objects*	Count	1	0	1
	Expected	1	0	1
Unknown	Count	11	1	12
	Expected	10	2	12
Total	Count	232	36	268

$FET = 13.8$, $p = 0.002$. 'Expected' counts have been rounded to nearest integer. * Multiple impacts to the same region with a single CDC code.

1.4 Principal direction of force (PDoF)

As used in the previous section, the most severe impact also yielded a PDoF, representing the angle relative to the vehicle at which crash forces were exerted. The first two digits of the CDC damage code were used, resolving the PDoF into 30 degree (clock face) increments with '12' signifying a PDoF from the front, '03' a right-side impact and so on. It would be expected that this variable would exhibit similar patterns to the 'Area of Most Significant Damage' (See Table 2), albeit with better resolution. In Table 5 the PDoF values have been grouped symmetrically.

Table 5: Distribution and expected counts of brain injury occurrence by Principal Direction of Force of most severe impact.

Principal Direction of Force		Brain Injury		Total
		No	Yes	
12	Count	78	6	84
	Expected	73	11	84
01 or 11	Count	54	10	64
	Expected	55	9	64
02 or 10	Count	36	5	41
	Expected	36	6	41
03 or 09	Count	33	6	39
	Expected	34	5	39
04 or 08	Count	4	3	7
	Expected	6	1	7
05 or 07	Count	11	2	13
	Expected	11	2	13
06	Count	7	0	7
	Expected	6	1	7
Rollover	Count	4	3	7
	Expected	6	1	7
Unknown	Count	5	1	6
	Expected	5	1	6
Total	Count	232	36	268

$FET = 15.6$, $p = 0.04$. 'Expected' counts have been rounded to nearest integer.

1.5 Speed zone

Due mainly to the limitations of the crash reconstruction software, Equivalent Barrier Speed (EBS) could only be calculated for 79% of the cases. Perhaps partly for this reason, a significant relationship between brain injury occurrence and EBS was measured, although there was a trend toward higher values of EBS for brain injury cases. The speed zone in which the vehicle was travelling could be considered a proxy for crash severity and was available in 259 of the 268 cases. Where a crash site inspection was not carried out (in the case of the more distant crashes from the team bases), the occupant's recollection was instead used, as this and the observed speed limit were found to be highly correlated. A greater than expected number of brain injury cases were observed in speed zones of 90 km/h and above, while fewer than expected were found in 50 and 60 km/h zones.

Table 6: Distribution and expected counts of brain injury occurrence by speed limit at crash location.

Speed Zone		Brain Injury		Total
		No	Yes	
40	Count	1	0	1
	Expected	1	0	1
50	Count	21	0	21
	Expected	18	3	21
60	Count	69	5	74
	Expected	64	10	74
70	Count	16	3	19
	Expected	17	3	19
80	Count	37	6	43
	Expected	37	6	43
90	Count	3	2	5
	Expected	4	1	5
100	Count	72	15	87
	Expected	76	11	87
110	Count	6	3	9
	Expected	8	1	9
Total	Count	225	34	259

$FET = 14.5$, $p = 0.03$. 'Expected' counts have been rounded to nearest integer.

1.6 Intersection type

Perhaps unexpectedly, fewer than expected brain injury cases were observed at all intersection types, while the converse was true for mid-block crashes. The logistic regression model will reveal whether these trends still exist once confounders have been taken into account.

Table 7: Distribution and expected counts of brain injury occurrence by speed limit at crash location.

Intersection Type		Brain Injury		Total
		No	Yes	
Mid-block	Count	128	27	155
	Expected	135	20	155
3-leg intersection	Count	39	2	41
	Expected	36	5	41
4-leg intersection	Count	30	1	31
	Expected	27	4	31
Multi-leg intersection	Count	8	0	8
	Expected	7	1	8
Roundabout	Count	8	0	8
	Expected	7	1	8
N/A	Count	1	1	2
	Expected	2	0	2
Unknown	Count	0	1	1
	Expected	1	0	1
Total	Count	214	32	246

$FET = 15.4$, $p = 0.01$. 'Expected' counts have been rounded to nearest integer.

1.7 Crash site location (rural vs urban)

At the time of crash site inspection, a generic land use is assigned for area around the site; 'urban', 'rural' or 'mixed'. This variable was available in all but 15 of the 268 cases. There is a strongly significant ($p = 0.01$) relationship with brain injury occurrence, with brain injury being more likely in rural and mixed use environments.

Table 8: Distribution and expected counts of brain injury occurrence by land use at crash location.

Land Use		Brain Injury		Total
		No	Yes	
Urban	Count	120	10	130
	Expected	113	17	130
Rural	Count	92	16	108
	Expected	94	14	108
Mixed	Count	7	6	13
	Expected	11	2	13
Unknown	Count	1	1	2
	Expected	2	0	2
Total	Count	220	33	253

$FET = 15.6$, $p = 0.001$. 'Expected' counts have been rounded to nearest integer.

1.8 Vehicle – struck side intrusion level

Three types of intrusion were investigated: frontal, struck side and roof. Only side and roof intrusions were found to be significantly associated with brain injury occurrence. Of the 36 brain injury cases, 21 were in vehicles where a side impact occurred, compared with an expected value of 13.

Table 9: Distribution and expected counts of brain injury occurrence by presence of side impact intrusion.

Presence of struck side intrusion		Brain Injury		Total
		No	Yes	
No	Count	155	15	170
	Expected	147	23	170
Yes	Count	76	21	97
	Expected	84	13	97
Unknown	Count	1	0	1
	Expected	1	0	1
Total	Count	232	36	268

$FET = 9.0$, $p = 0.009$. 'Expected' counts have been rounded to nearest integer.

The height at which struck side intrusion occurred was also investigated, with intrusions at cant rail, mid-window and base of window found to be significantly related to occurrence of brain injury ($t = -2.4, df = 24.8, p = 0.03$, $t = -2.3, df = 25.2, p = 0.03$, $t = -1.8, df = 94, p = 0.04$ respectively)

1.9 Vehicle – roof intrusion level

Of the 36 brain injury cases, 11 were involved in crashes where some roof intrusion occurred. This was significantly more than the expected number of cases.

Table 10: Distribution and expected counts of brain injury occurrence by presence of roof intrusion.

Presence of roof intrusion		Brain Injury		Total
		No	Yes	
No	Count	203	25	228
	Expected	197	31	228
Yes	Count	29	11	40
	Expected	35	5	40
Total	Count	232	36	268

$\chi^2(1) = 8.0$, $p = 0.005$. 'Expected' counts have been rounded to nearest integer.

1.10 Occupant gender

A significantly greater number of males than expected suffered brain injury, as can be seen in Table 11 below.

Table 11: Distribution and expected counts of brain injury occurrence by occupant gender.

Gender		Brain Injury		Total
		No	Yes	
Male	Count	115	25	140
	Expected	121	19	140
Female	Count	117	11	128
	Expected	111	17	128
Total	Count	232	36	268

$\chi^2(1) = 4.9$, $p = 0.03$. 'Expected' counts have been rounded to nearest integer.

2 LOGISTIC REGRESSION ANALYSIS

As there were only 36 brain injury cases in the dataset, it was decided that the model should adjust for no more than four covariates and therefore the criteria for the inclusion of variables needed to be quite strict. The first criterion was that the relevant chi-square or *t*-test demonstrated a significant relationship with brain injury at $\alpha = 0.05$ level. Consequently, the variables detailed in the previous section were selected for inclusion in the model. Some of the variables were simplified by merging individual values into categories. For example, speed zones were grouped into '40-60', '70-90' and '100-110' km/h.

After adjusting for confounding variables, six significant relationships remained and are shown in Table 12 below. Note that the variable reflecting the occurrence of a struck-side collision was also significant, but was not included in the model as it compromised the fit of the variable representing side door intrusion level without providing additional information.

Table 12: Significant Adjusted Odds Ratios (with Confidence Intervals) of receiving a brain injury for the occupant of a motor vehicle crash in ANCIS.

Characteristic	Adjusted OR	95% Confidence Interval	
Occupant in non-struck (far) side crash?	6.4	2.1	19
Collision partner heavy vehicle (compared with car/car derivative)	6.6	1.6	27
Collision partner tree, pole or post	3.0	1.0	8.6
Crash occurred in 70-90 km/h zone compared with 40-60 km/h zone	3.0	0.9	9.9
Crash occurred in 100-110 km/h zone compared with 40-60 km/h zone	5.5	1.7	18
Side intrusion level at upper door of 100mm	1.4	1.1	1.7

Odds ratios presented to two significant figures.

3 CONTACT SOURCES

For each of the in-depth cases collected in ANCIS, the data collection team assigns a contact source to each injury sustained by the vehicle occupant. With expertise in injury causation, biomechanics, crash and occupant kinematics, the crash circumstances are used to approximate the motion of the occupant during the crash and the expected outcome is correlated with evidence found from the injuries, in the vehicle interior and at the crash site. Injury causation is coded in accordance with the NASS system and entered into the database. The results in this section are based upon the 36 occupants, receiving 82 AIS3+ injuries. Consequently, given the small quantity of data to date and wide variety of contact sources, only fairly broad indications of the source of brain injuries can be identified.

3.1 Frontal crashes

In frontal crashes, nine of the 22 injuries (41%) were attributed to 'Rear Surface of Other Vehicle', with no rollover occurring in any of these crash events. This is most likely to be as a result of an underrun impact with a geometrically incompatible vehicle such as a truck, whether it be a rear impact crash into a stationary tray truck or a head on crash with a moving vehicle. In these types of impacts, the stiff structures of the occupant's vehicle pass beneath the larger collision partner, with relatively little deceleration occurring until the vehicle impacts the undercarriage of the truck. By this time, the truck may have overridden the case vehicle to the point where it begins to penetrate the windscreen, making contact with the occupant's head, resulting in both brain and facial injuries. It is worth noting that these injuries are the result of perhaps only one or two crashes, but are worth noting due to their quite severe outcomes. Eight of the remaining 13 injuries were assigned to the windscreen or steering wheel, most likely in vehicles without airbags or with unbelted occupants.

3.2 Struck side crashes – external contact points

'Other Vehicle/Object' was the assigned contact source for 13 injuries (16%), the greatest single number for any of the contact sources. Where this contact source was assigned, in the majority of cases the area of most significant damage to the vehicle was the right-hand side and it was a struck-side impact. Of this subset, rollover did not occur 80% of the time and therefore it is reasonable to assume that the injuries were caused by the occupant's head striking the intruding bullet vehicle.

3.3 Struck side crashes – internal contact points

There was a strong association between right side, struck side impacts and the adjacent occupant contact points, including A-pillar, window (plus frame and sill), B-pillar and other struck side interior surfaces. Rollover was relatively uncommon for this crash type/contact subset. In all, the aforementioned contact points were assigned to around 24% of the brain injuries.

3.4 Rollover crashes

The final injury-to-contact source association that could be observed was the roof, accompanied by roof perimeter contacts such as the header and rails. Where the roof or surrounds was the assigned brain injury contact (16 of 82 injuries), a rollover event was present three quarters of the time. These injuries most likely result from a combination of deformation to the roof and occupant displacement out of the seat (toward the roof) during a rollover event.

POTENTIAL COUNTERMEASURES

In struck side impact crashes, there is very little space between the occupant and the side of the vehicle to allow the unrestrained head to move under the influence of crash forces without it impacting something. Therefore, the most effective countermeasures appear to be head-protecting airbags, including seat-mounted head/thorax bags and curtain airbags. The latter, in particular, are designed to remain inflated for a relatively long period of time in order to provide protection in long duration rollover events. In rollover, it is important to both minimise roof intrusion with appropriately strong roof structures, as well as to keep the occupant firmly in the seat, perhaps by firing belt pretensioners as is common in frontal impacts. Finally, with regard to frontal impacts with underrun, arguably the most practical countermeasure would be to ensure better geometric compatibility between vehicles. This is achieved by ensuring that higher vehicles have sufficient structure at lower levels in order to effectively 'engage' with passenger car frontal structures, preventing the massive intrusions that are characteristic of this crash type.

The importance of speed is also demonstrated by this study, with the risk of brain injury increasing significantly for 70-90 and 100-110 km/h speed zones compared with those crashes occurring in 40-60 km/h speed zones.

CONCLUSION

A number of variables were investigated within the ANCIS database of 268 real-world crashes to determine whether they had a significant effect on the occurrence of brain injury. The latter was defined as AIS codes beginning with '14' and represented injuries only to the brain itself (thereby excluding skull fractures). Chi-square and *t*-tests were carried out to identify those variables that were significantly related and a logistic regression model developed to adjust for confounders. It was found that brain injury was around six times more likely to occur in a non-struck (far) side crash than in other crash types. Similarly brain injury was nearly seven times more likely for those occupants involved in a collision with a heavy vehicle compared with those colliding with a car or car derivative. Not surprisingly, impacts with narrow objects such as trees, poles and posts were three times more likely to result in a brain injury. Brain injury risk also was found to vary strongly with speed, with a brain injury outcome three times more likely for crashes in 70-90 km/h speed zones compared with 40-60 km/h and 5.5 times more likely in 100-110 km/h zones.

The primary areas for countermeasure development would appear to be in better side impact avoidance and protection, particularly with heavy vehicles, and also in minimising impact severity through lower speeds.

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