IRMRC Research Report

MOTORCYCLE CRASHES INTO ROADSIDE BARRIERS
STAGE 2: CRASH MECHANICS AND INJURY CAUSATION

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Executive Summary

This report presents the results of Stage 2 of the Motorcycle Crashes into Roadside Barriers research project. Stage 1 determined the human, vehicle and environmental crash characteristics and causal factors associated with fatal motorcycle-barrier collisions in Australia and New Zealand between 2001 and 2006. Stage 2 investigates the crash mechanics and injury causation in these crashes. Stage 3 will determine survivability envelopes for different barrier systems and engineering solutions to mitigate injuries.

Motorcyclists contribute significantly to road trauma in Australia and New Zealand through the high incidence of serious injuries and fatalities. The role of roadside safety barriers in such trauma is an area of growing concern amongst motorcyclists, road authorities and road safety researchers and advocates. Roadside barriers include safety barriers positioned either at road edges or within medians, and are typically steel W beam, concrete, and wire-rope in Australia and New Zealand. This report presents a case series analysis of motorcyclists that were fatally injured following a collision with a roadside barrier during the period 2001 to 2006 in Australia and New Zealand. Aspects of the crash mechanics such as barrier and motorcycle types, crash postures, motorcyclist kinematics, pre-crash speeds, impact trajectory angles and motorcyclist kinetic energy dissipation are documented. Injury profiles and severities are detailed, and associations between injuries and crash characteristics are investigated. The implications of the results for motorcycle-barrier crash test protocols are also discussed.

Key findings in this report related to the crash mechanics and injury causation associated with fatal motorcycle-barrier collisions include:

- in 47% of cases the motorcyclist impacted the barrier in the upright posture, and in 44% of cases the motorcyclist slid into the barrier;
- the mean pre-crash speeds and impact angles were 100.8 km/h and 15.4° respectively;
- typically 30-80% of the pre-crash kinetic energy of the motorcyclist is dissipated during the contact with the barrier;
- sports motorcycle riders tended to slide into barriers, while touring motorcycle riders tended to collide with the barriers in the upright posture, which results in part from the different riding positions whilst cornering;
- the thorax body region had the highest incidence of injury and the highest incidence of maximum injury in fatal motorcycle-barrier crashes, followed by the head region;
- fatal motorcycle crashes with barriers produce a higher incidence of thorax injury, lower incidence of head/neck injury, and produce generally more severe injury outcomes than fatal motorcycle crashes in general;

- existing motorcycle-barrier crash testing protocols do not specify a thorax injury criterion, thus the high incidence of thorax injury in the present study points to a need to determine such criteria;
- the body regions injured were similar across different barrier types and crash postures, however thorax and pelvis injury had a greater association with sliding crashes than with those in the upright posture;
- an association between riding a sports motorcycle and receiving thorax injuries was determined, and in Stage 1 it was determined that a high proportion of the motorcyclists were on recreational rides in areas that provide challenging riding conditions when they collided with a barrier. It may therefore be beneficial to encourage sports motorcyclists planning a challenging recreational ride to wear (appropriate) chest protection, in addition to body abrasion and head protection;
- head injuries closely followed thorax injuries in the study, while 97% of motorcyclists were helmeted, which indicates that the crash severity exceeded the functional range of the helmets in many cases, thus efforts to improve helmet design should continue;
- the strongest association with injury severity was pre-crash speed, and a strongly linear relationship was determined between these two;
- from the variables investigated of barrier type, crash posture, impact angle and barrier post impacts, no statistically significant association between these variables and injury severity could be established;
- severe head/neck, thorax and extremity injuries, including amputations, were found amongst motorcyclists that impacted all types of barriers, however, there is no evidence in the data presented in this report that any particular barrier type is any more or less injurious for motorcyclists than another.

Funding partners and researchers

This research is funded by the following organisations;

NSW Centre for Road Safety, Road and Transport Authority (RTA)
New Zealand Transport Agency
Western Australia Road Safety Council
NSW Motor Accident Authority (MAA)
Australian Automobile Association (AAA)

The first three organisations are responsible for the roads in their respective jurisdictions. The MAA is charged with the care of road trauma victims. The AAA is a peak national body that represents the interests of motorists in Australia.

During all three phases of this project, results were reported to and discussed by the Motorcycle into Roadside Barriers Scientific Advisory Committee (MRBSAC). The following people are or have served on the MRBSAC at one time or another:

Dr. Soames Job – NSW Roads and Traffic Authority
Mr Steve Levett – (formerly NSW Centre for Road Safety, Roads and Traffic Authority)
Mr David Pratt – NSW Roads and Traffic Authority
Mr. Wal Smart – NSW Roads and Traffic Authority
Mr. Fabian Marsh – (formerly New Zealand Transport Agency)
Mr. James Cameron – Australian Automobile Association
Mr. Craig Newland – Australian Automobile Association
Mr. John Metcalfe (formerly with Australian Automobile Association)
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Researchers who have worked on this phase of the project to date are:

Prof. Raphael Grzebieta – IRMRC, UNSW
Dr. Mike Bambach – Research Fellow, (formerly with IRMRC, UNSW)
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Ms Rena Friswell – Research Fellow, IRMRC, UNSW
Mr Rob Smith - motorcycle instructor and expert (now with Motorcycling Australia)

1. Project introduction

The Motorcycle Crashes into Roadside Barriers project seeks to investigate the crash characteristics, causal factors and injury mechanisms that motorcycle riders and pillions are subjected to when they impact a roadside barrier. It also seeks to determine the survivability envelop for motorcyclists crashing into each of the different barrier system types. This survivability envelop will be compared to the survivability envelope for other road users. There is currently a reasonable amount of knowledge in regards to what is a survivable crash for occupants in cars, trucks and buses that crash into different barrier systems but little credible information concerning survivability of such crashes involving motorcyclists.

Roadside barriers are typically concrete, guardrail and wire-rope. There has been a significant concern raised by motorcycle organisations in Australia and overseas regarding the use of wire rope barriers. This research project is intended to inform such public debate and policy, and propose scientifically validated solutions, in regards to the safety or otherwise of motorcycle riders and pillions impacting roadside barriers.

The project is also exploring how to reduce the injuries to motorcyclists impacting concrete, wire-rope barriers and guardrail systems. Innovative injury mitigating engineered solutions will be assessed as well as new solutions explored. In particular any solutions proposed will be assessed in regards to whether they effect a barrier's current crash and redirection characteristics for vehicles such as cars, trucks and buses. The project will also involve computer crash simulation and crash testing that, it is hoped, will demonstrate survivability outcomes for current and upgraded systems.

In summary, the project is providing the following outcomes:

a. A statistical overview of motorcycle rider/pillion passenger involvement in roadside and median barrier crashes employing NCIS data and fatality case files;

b. The causal human factors (speed, alcohol, fatigue, inexperience, bad cornering technique, etc) that lead to motorcycle/rider/pillion impacts into crash barriers and road side hazards;

c. A categorisation of typical crash scenarios that provides impact angle, speed, motorcycle and rider kinematics;

d. Reconstruction of a selected number of representative categorised cases;

e. The causal biomechanical mechanisms related to each barrier system that lead to the serious or fatal injury of the rider/pillion;

f. Rider/pillion survivability impact analysis for each barrier system, i.e. determination of the survivability envelops for different impact scenarios for varying rider configuration, speed and angle of impact and barrier type;

g. Proposed engineering design modifications to road barriers that are effective in reducing injuries to riders and pillions involved in roadside barrier crashes but will not reduce current crash safety characteristics for occupants of vehicles in cars, trucks and busses. The effectiveness of the modifications will be proven using current computer simulation and crash test technology.

The Research Report of Stage 1 provides information addressing parts 'a' to 'b' above. The present Research Report of Stage 2 addresses parts 'c' to 'e' above. Parts 'f' and 'g' will be addressed in the final stages of the project.

2. Ethics approval

Any research into humans including deceased persons requires Human Research Ethics Committee (HREC) approval. HREC approval for the research was obtained from the University of New South Wales in July 2008 whereas approval to access the National Coronial Information (NCIS) system was obtained from the Department of Justice, Victoria on 1st April 2009. Separate ethics approval was also required from the Western Australian (WA) Coroner's Court to obtain WA information. Approval for access to WA data was obtained on 29th May 2009.

The physical case files held by the Coroner's courts in Australia and New Zealand have been accessed and coded in terms of the details of the crashes that were available.

3. Background information

Motorcyclist serious injuries and fatalities significantly contribute to road trauma around the world. In 2007, Australian motorcyclists were 30 times more likely to be killed and 37 times more likely to be seriously injured than car occupants per distance travelled (DITRL, 2008). In the United States the values were 37 and 9 respectively (NHTSA, 2008), and in Great Britain 44 and 56 respectively (UK Dept. Transport, 2008). In the EU, motorcyclists were around 30 times more likely to be killed in a road crash than car occupants per distance travelled (EuroRap, 2008). A range of factors have been identified as contributing to motorcycle crashes, their severity and the severity of the motorcyclists' injury(s): speed, age, time of year, experience, alcohol, illicit drug use, time of day, conspicuity, risk taking behaviour, road side environment (poles/trees) and helmet use (Clarke et al 2006, Colburn et al 1994, Elvik 1995, Harrison and Christie 2005, Lin and Kraus 2009, NHTSA

2008, Quddus et al 2002, Rutledge and Stutts 1993, Savolainen and Mannering 2007, Shankar et al 1992, Shankar and Mannering 1996).

The effect of roadside barriers on motorcyclist safety, the topic of the present paper, is an area of emerging concern and research. The proportion of fatal motorcycle crashes involving roadside barriers is typically small; 5.5% in the US (Gabler, 2007), 5.4% in Australasia (Jama et al, 2010) and 8-16% in Europe (EuroRap, 2008). However, barriers represent a much greater fatality risk to motorcyclists than to car occupants; 15 times in Europe (EuroRap, 2008) and 80 times for steel guardrail in the US (Gabler, 2007). Gabler (2007) determined that 12% of motorcycle-guardrail collisions were fatal, and 7.9% of motorcycle-concrete barrier collisions were fatal. The fatality risk for motorcycle-guardrail collisions was found to be 2.5 times that for motorcycle-car collisions. Selby (2006) found that of non-urban motorcycle crashes in New Zealand between 2001 and 2005, 6.4% of motorcycle-barrier crashes were fatal, which was slightly less than the fatal rate of 7.3% for crashes that did not involve a roadside object. Ouellet (1982) found that in the US, 30% of motorcyclists that impacted a guardrail received at least one AIS3+ injury. Some researchers have found that impacts with roadside barriers and other stationary objects increases the likelihood of serious injury. Savolainen and Mannering (2007) observed in the US that a collision into a guardrail reduced the likelihood of minor or no injury. Quddus et al (2002) observed a 241% and 480% increase in the probability of serious injury and fatal injury, respectively, associated with a collision with a stationary object in Singapore (relative to crashes where no collision occurs). They also recorded a decrease in the probability of a slight injury. Relative to single-vehicle accidents, injury and damage severity was found to be greatest when colliding with a stationary object.

Similar trends with regards to causal factors identified as contributing to motorcycle crashes have also been found with motorcycle-barrier crashes. The Stage 1 Research Report identified 77 fatal motorcycle-barrier crashes in Australia and New Zealand between 2001 and 2006, and the crash characteristics, environmental factors, motorcyclist demographics and causal contributing factors were discussed. Motorcyclist behaviour such as speeding and alcohol/drug use were identified as common causal factors in the predominantly single-vehicle crashes. In this report the study is extended to investigate the crash mechanics and injury profiles associated with these fatal motorcycle-barrier crashes.

With regards to crash mechanics of motorcycle-barrier crashes, Ruiz et al (2010) reported a mean collision angle with metal barriers of 13°, a mean barrier impact speed of 100km/h amongst fatal crashes, and that impacts into barriers occurred equally often in the upright posture as in the sliding posture.

Berg et al (2005) showed that in 51% of 57 barrier cases the motorcyclist impacted the barrier while driving in an upright position, 45% of the impacts occurred where the motorcycle slid on its side on the road surface before it first struck the barrier, and in the remaining 4% of the crashes the motorcycle impacted the barrier driving in an inclined position.

Quincy et al (1988) reported that in 58% of barrier crashes the motorcyclist was in the sliding posture, with the remaining 42% impacting without sliding.

Peldschus et al (2007) determined that around three quarters of collisions with fixed objects are in the upright position and typically occur at shallow angles, with 13 crashes at less than 15°, two between 15° and 30° and three between 30° and 45°.

Bryden and Fortuniewicz (1986) reported that amongst 83 barrier crashes in the US, 60% of motorcyclists were redirected, 27% were stopped in contact with the barrier, 5% went under and 5% went over.

With regards to injuries associated with motorcycle crashes, most studies report results from datasets that include all modes of motorcycle crashes (single- and multi-vehicle crashes). The MAIDS (2009) and Hurt et al (1981) studies showed that amongst motorcyclists both fatally and non-fatally injured, head and lower extremity injuries accounted for the most AIS3+ injuries, followed by thorax injuries.

Robertson et al (2002) found that amongst motorcyclists requiring hospitalisation, the most commonly injured body regions were the upper and lower extremities, followed closely by thorax injury. The number of motorcyclists that received an injury exceeded 40% for each of these three body regions.

Ankarath et al (2002) determined that amongst motorcyclists fatally and non-fatally injured, the AIS1+ injuries received most were extremity injuries (97% and 94% of motorcyclists respectively). Of the fatally injured motorcyclists, 57% received at least one AIS1+ head injury compared with 12% in the non-fatally injured group, and 32% received at least one AIS1+ thorax injury compared with 17% in the non-fatally injured group.

Moskal et al (2007) reported that amongst powered two wheel riders severely injured (AIS4+), 50% of riders received at least one AIS4+ chest injury, and 45% at least one AIS4+ head injury. Amongst the injured group (AIS1+), the incidence of upper extremity (45%) and lower extremity (63%) injury far exceeded those for chest (10%) and head (11%) injury. They also noted that the risk of head and chest injuries is greatest in the single vehicle fixed object crash mode, compared with seven other crash modes.

Kraus et al (2002) showed that amongst 548 fatally injured motorcyclists, the head sustained the most severe injury (MAIS) in 56% of cases, and the thorax in 32% of cases. Amongst non-fatally injured motorcyclists the extremities sustained the MAIS in 51% of cases, the head in 26% and the thorax in 10% of cases. Amongst the fatally injured group, 73% of motorcyclists received an AIS3+ head injury and 65% received an AIS3+ thorax injury. In the non-fatally injured group these figures were 20% and 9% respectively.

Wyatt (1999) found that amongst fatally injured motorcyclists, 64% had a head/neck injury as the MAIS, and 47% the thorax.

Sarkar et al (1995) reported that amongst fatally injured motorcyclists, for both helmeted and unhelmeted motorcyclists head injury was also the most prevalent MAIS injury.

It may be concluded from these studies that amongst motorcycle crashes in all crash modes, extremity injuries predominate in crashes with less serious injury outcomes, whereas head/neck and thorax injuries predominate in crashes with more serious and fatal outcomes. As many as one third to two thirds of fatally injured motorcyclists may receive a serious thorax injury, and one third to one half may have the most severe injury as a thorax injury. Around one half to three quarters may receive a serious head injury, while a similar proportion may receive a head injury as the most severe. The results of these studies are summarised in Table 1.

	Crash mode+	Helmet use	Sample size	Severity	Head/neck	Thorax	Extremity
Ankarath et al (2002)	All	81%	74	AIS 1+	57%	32%	97%
Kraus et al (2002)	All	--	548	AIS 3+	74%	65%	39%
Kraus et al (2002)	All	--	548	MAIS	56%	32%	4%
Wyatt et al (1999)	All	98%	59	MAIS	64%	47%	5%
Sarkar et al (1995)	All	100%	37	MAIS	54%	49%	22%
Sarkar et al (1995)	All	0%	127	MAIS	76%	32%	9%
Present study	Barrier only	97%	77	AIS 3+	51%	81%	45%
Present study	Barrier only	97%	77	MAIS	41%	50%	11%

+ The crash mode "All" indicates all single- and multi- vehicle crashes

Table 1: Percentage of fatally injured motorcyclists with injury to the head/neck, thorax and extremities

Few studies have reported on injuries specifically associated with motorcycle-barrier crashes. The MAIDS (2009) study examined injuries occurring only amongst motorcyclists that collided with a roadside barrier, where 60 injuries were detailed. However, the number of motorcyclists amongst whom the injuries occurred were not provided, and the thorax region was excluded from the results, thus the data are inconclusive. Peldschus et al (2007) reported injury profiles from a European study of motorcycle collisions with roadside infrastructure (COST 327), however the project only included crashes where a head/neck injury or impact occurred and was therefore biased towards such injuries. It did show, however, that thorax injuries occurred in more than 50% of motorcycle collisions involving road infrastructure and barriers (where the motorcyclist received head/neck injury or impact). The injury risk of guardrail posts and metal barrier edges to motorcyclists were also highlighted.

In this report, the Stage 1 study is extended to investigate the crash mechanics and injury profiles associated with the 78 fatal motorcycle-barrier crashes that occurred in Australia and New Zealand between the years 2001 and 2006 (note: one additional case has been added since Stage 1 was completed). Barrier types, crash postures, pre-crash speeds, impact trajectory angles and motorcyclist kinematics are determined. The AIS3+ injuries are detailed, some of the more severe injuries are discussed, injury severities are determined and comparisons of injuries with crash mechanics are made. Finally, some statistical relationships are determined and conclusions are drawn, particularly with reference to motorcycle-barrier crash testing protocols.

4. Data methods and results

4.1 Coronial data from Australian jurisdictions

This case series study is predominantly based on the information contained in the Australian National Coroners Information System (NCIS). The NCIS is an internet-based data storage and retrieval system that contains coronial cases from all Australian states dating from the middle of 2000. The NCIS database includes all reportable deaths which include roadway fatalities. Variables coded in the NCIS include demographic information about the person, object involved and the place of death. Each death record in the NCIS should also have attached to it an initial police, autopsy and toxicology report. Each case usually reports the cause of death as recorded by the investigating coroner. Further detailed information is typically available where an inquest was held to establish the cause of death. However, not all NCIS cases have these additional documents available on-line. In these instances, the original paper case files must be requested through the individual coroners' courts and not all paper case files contain all the documents.

4.2 Case identification in Australian jurisdictions

As the first step in identifying motorcycle-barrier crashes in the NCIS database, the initial query was designed as follows:

1) All jurisdictions were searched;
2) Employment field was left blank;
3) Time field was left blank;
4) Query object was chosen as a mechanism;
5) The mechanism that caused the death was defined as blunt force;
6) Level 2 of the mechanism was defined as a transport injury event;
7) Level 3 of the mechanism was defined as motorcyclist/motorcycle rider;
8) The vehicle details were defined as two wheeled motor vehicle;
9) The vehicle was further defined as a motorcycle.

The output from the database contained the particulars of the deceased such as the sex, age, date of birth and date of death. An output of up to three levels of the medical cause of death, location and the crash vehicle counterpart was requested.

4.3 Case identification in New Zealand

Data on motorcycle crashes in New Zealand were obtained from the Crash Analysis System (CAS) of the New Zealand Transport Agency. CAS is an internet-based database of all vehicle crashes that are reported to the police in New Zealand. Once the cases involving or potentially involving a roadside barrier were identified using the text descriptions in the database, the police briefs of these cases were requested from the New Zealand Coroner through the New Zealand Transport Agency.

4.4 Data extraction

In this study roadside barriers included safety barriers positioned either at road edges or within medians. Once the cases potentially involving roadside safety barriers were identified in the NCIS, a request was made to the coroner in each state in Australia for permission to view the police reports. The level of detail included in the police briefs prepared for the coroners varied within and between states but was usually of sufficient quality to enable a basic reconstruction of the crash events. The following information was extracted with regards to the present study of injury causation; autopsy report, type of barrier, pre-crash speed, impact angle, contacts with barrier posts, crash posture (sliding or upright) and type of motorcycle (sports, touring or off-road).

Injuries were coded according to the Abbreviated Injury Scale (AIS) (AAAM, 2005) from the autopsy reports, and only AIS3+ injuries were coded. The injury producing the maximum AIS score (MAIS) was determined, as were injury severity scores (ISS) calculated as per AAAM (2005). The three most severely injured body regions have their maximum AIS score squared and added together to produce the ISS score.

4.5 Statistical analysis

Logistic regression was used to provide odds ratios and 95% confidence intervals. Statistical significance was measured at the level $p < 0.05$.

4.6 Data results

In total 1462 cases of a roadside fatality involving a motorcycle were identified to have occurred in Australia and New Zealand. Of these, 78 were positively identified as involving a roadside safety barrier. A further 38 cases could not be categorised due to insufficient information in the NCIS. Of the 78 coronial files collected, 72 contained police reports, 56 contained mechanical inspections, 77 contained autopsy reports and 74 contained toxicology reports. The police reports contained a varying amount of information, however as per police procedure for fatal crashes in most cases police crash team investigators were in attendance at the crash scene. Such investigators are typically trained and experienced in crash scene investigation.

In 66 case files scene photographs were included, in 62 cases measurements of the crash scene were documented (skid/scrape mark lengths, location of impact points, resting positions of motorcycle and motorcyclist and any parts thereof, etc), in 54 cases the pre-crash speed of the motorcycle was estimated and in 14 cases scene diagrams produced from a surveying instrument were included (Figure 1). Many cases also included witness accounts and statements from police attending the scene.

It was noted in the Stage 1 report that the majority of motorcyclists crashed while on a recreational ride, and it was common for motorcyclists to ride with others, thus there was a significant amount of useful information provided in witness statements as to the circumstances of the crash. The pre-crash speeds were determined by the crash scene investigators and typically relied on varying combinations of calculations based on scene measurements, analysis of the scene, witness statements and in some cases ride-throughs at the scene by experienced motorcyclists. Where speed ranges were provided, the minimum value has been conservatively used in this study.

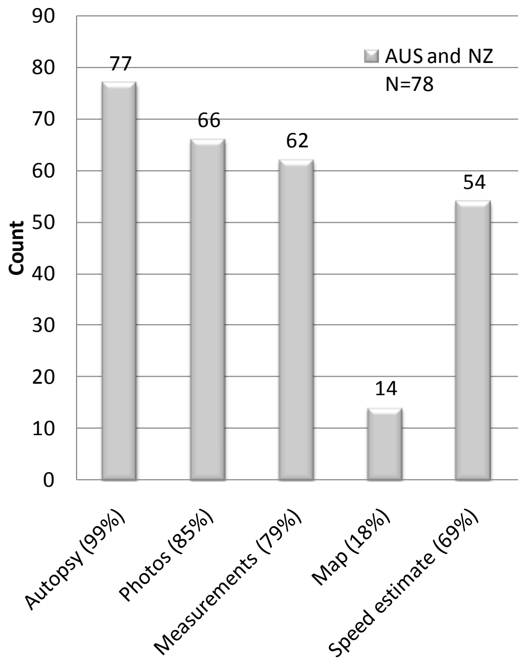


Figure 1: Information that was available in the coronial files from Australia and New Zealand

Amongst the 78 case files there were seven cases where the motorcyclist was definitely injured by a secondary non-barrier object only. Of these, three went clear over the barrier without contact, one was thrown beside the barrier into a culvert and three were re-directed by a concrete barrier and were injured by secondary non-barrier objects. These cases have been included in the crash mechanics analyses following. However, due to the injuries being received only as a result of a non-barrier contact, they were excluded from the injury analyses following. There were an additional 12 cases where the motorcyclist contacted with a secondary non-barrier object. Of these, four motorcyclists had confirmed barrier contacts and eight could neither be confirmed nor discounted. All 12 cases have been included in both the crash mechanics and injury analyses following. In the remaining 59 cases the motorcyclist did not contact a secondary non-barrier object.

The rigid upright posts of some barrier systems have been previously noted to be particularly harmful to motorcyclists (Ouellet, 1982, Peldschus et al, 2007). Thus in the present study the involvement of posts was documented. Post impacts were determined in the files from the on-scene crash investigators reports of markings, and in some cases were additionally complimented by witness statements. Such markings include one or more of: blood/human tissue on posts; helmet scrape marks on posts; clothing material caught on posts; imprints left in helmets matching post markings; or motorcyclist position when found. It should be noted that cases in which a post impact was not documented does not necessarily infer such an impact did not occur, since a specific investigation of the occurrence of a post impact was not a required procedure of the crash investigation.

5. Crash mechanics results

The Stage 1 report details and discusses the human, vehicle and environmental crash factors associated with the fatal motorcycle-barrier collisions reported in the present report. Of particular note were the findings that 97% of the motorcyclists were wearing a helmet prior to the crash, 86% of crashes were single vehicle run-off crashes, 80% occurred on a corner, 92% of motorcyclists were male with a mean age of 34.2 years, 72% were less than 40 years and 81% of motorcyclists died at the crash scene. In this section the barrier and motorcycle types, crash postures, motorcyclist kinematics, pre-crash speeds and impact trajectory angles are detailed.

5.1 Barrier and motorcycle types

In Australia and New Zealand the main barrier types installed are steel W beam barriers with steel C-section or timber posts (commonly referred to as guardrails in the US), followed by concrete and wire rope (steel cable) barriers. Amongst motorcyclists fatally injured in barrier crashes, 77% involved W beams, 10% involved concrete barriers, 8% involved wire rope barriers and 5% involved other barriers. Other barriers include timber and tubular steel post and beam barriers. The

Stage 1 report noted that the barrier types involved in fatal crashes reflect the exposure of motorcyclists to such barriers on Australian and New Zealand roadways.

The type of motorcycle that was being ridden was typically provided in the case files, and were classified by a motorcycling expert into the general categories of sports, touring and off-road motorcycles. Sports motorcycles are of the type typically ridden with the body leaning forward on the motorcycle, and are designed to be leant over to the inside of a corner. The touring category includes cruiser, chopper and touring motorcycles and are of the type ridden with the body relatively upright, and are not designed to be leant over as significantly as sports motorcycles when cornering. Off-road motorcycles include dirt motorcycles and enduro motorcycles. In the 78 cases the majority of motorcycles were sports motorcycles (51), followed by touring motorcycles (17) and off-road motorcycles (3), with insufficient information to classify the motorcycle in seven cases.

5.2 Crash postures

The crash postures in which motorcyclists collided with the barriers were classified into the three categories of upright (37 cases), sliding (34 cases) or ejected (5 cases). In two cases the crash posture could not be determined. In the sliding crash posture the motorcycle falls to the roadway, and the motorcyclist and motorcycle slide along the road surface and into the barrier. Witness reports often comment on the fact that the motorcyclist and the motorcycle are separated prior to contacting the barrier in this posture, however a reliable criterion to establish separation could not be established from the case files. The sliding crash posture may be further categorised in some cases into cases of low-siding or high-siding. Low-siding involves the motorcycle falling to the roadway on the side of the motorcycle that is on the inside of the corner. High-siding involves the motorcycle flipping over from the inside of the corner to contact the roadway on the outside side of the motorcycle. Evidence of the motorcycle low- or high- siding could be determined in 23 of the sliding cases, from the skid and scrape marks on the roadway and/or damage to the motorcycle.

In the upright crash posture the motorcyclist collides with the barrier in the upright position and seated on the motorcycle. The motorcycle is typically redirected along the barrier. Due to the impact trajectory angle of the motorcycle relative to the barrier, momentum causes the upper body of the motorcyclist to want to continue over the barrier. This momentum caused the motorcyclist to be ejected over the barrier upon impact in nine cases. In 20 cases this momentum and the redirection of the motorcycle along the barrier resulted in the motorcyclist scraping/tumbling/skidding along the top of the barrier. After scraping along the top of the barrier for some distance the motorcyclist was ejected from the barrier, and in 15 of the 20 cases this occurred as a result of the motorcyclist impacting with a barrier post. It could not be determined from the case files to what extent the motorcyclist remained in contact with the motorcycle during the process of scraping along the top of the barrier. Some crash tests in the upright posture have shown crash test dummies (ATDs) may separate from the motorcycle during this process (Berg et al, 2005, Peldschus et al, 2007). In eight cases it could not be determined if the motorcyclist had scraped along the top of the barrier.

In the ejected crash mode the motorcycle came into contact with the gutter (three cases) or an object (two cases), and the motorcycle rapidly decelerated ejecting the motorcyclist forwards from the motorcycle and into the barrier. The crash postures are summarised in Figure 2, along with the motorcyclist kinematics and the occurrence of motorcyclist impacts with barrier posts. The crash postures relative to the barrier types are shown in Figure 3. It is noted that in none of the eight cases where a fatality resulted from a collision with a concrete barrier did the motorcyclist impact in the sliding crash posture.

5.3 Motorcyclist kinematics

The response of the motorcyclist as a result of the collision with the barrier may be classified into five categories: the motorcyclist went over the barrier (Over); the motorcyclist went under the barrier (Under); the motorcyclist stopped within 3m of the impact with the barrier without going over or under the barrier (Stopped); the motorcyclist was redirected for more than 3m from the impact point and came to rest adjacent to the barrier (Adjacent); or the motorcyclist was redirected for more than 3m from the impact point and came to rest in the lane(s) of the roadway (Redirected). The case counts of stopped, adjacent, over, redirected and under were 22, 20, 17, 11 and one respectively, and unknown in eight cases (Figure 4). The motorcyclist kinematics relative to the crash posture are shown in Figure 2. The distance of 3m was used in the classifications since the crash scene investigators tended not to measure the distance unless it exceeded this value (approximately).

Of the 17 motorcyclists that went over the barrier: 16 crashed into the barrier in the upright posture and one was ejected clear over the barrier; 11 contacted the barrier prior to going over (of these six contacted a secondary non-barrier object); three did not contact the barrier prior to going over (all three contacted a secondary non-barrier object); and three may/may not have contacted the barrier prior to going over (of these two contacted a secondary non-barrier object).

Further details of the motorcyclist kinematics were determined from those cases in which measurements were taken of the crash scene and are summarised in Table 2. The mean distance the motorcyclist travelled from the impact point with the barrier was 21.8m (SD = 23.4m) in all crash postures. Amongst motorcyclists that impacted the barrier in the sliding crash posture this was 12.7m (SD = 20.6m) and in the upright posture 26.3m (SD = 20.4m). This results from the momentum retained by motorcyclists in the upright posture as they scrape/tumble/skid along the top of the barrier. The mean distance motorcyclists scraped along the top of the barrier in the upright posture was 13.9m (SD = 12.4m). Given that W beam posts are typically spaced 2m apart, this presents multiple opportunities for the motorcyclist to impact with a post, resulting in the high incidence noted in this crash posture (15 from 20 in Figure 2). The mean distance motorcyclists slid on the roadway prior to impacting the barrier in the sliding crash posture was 28.9m (SD = 13.8m).

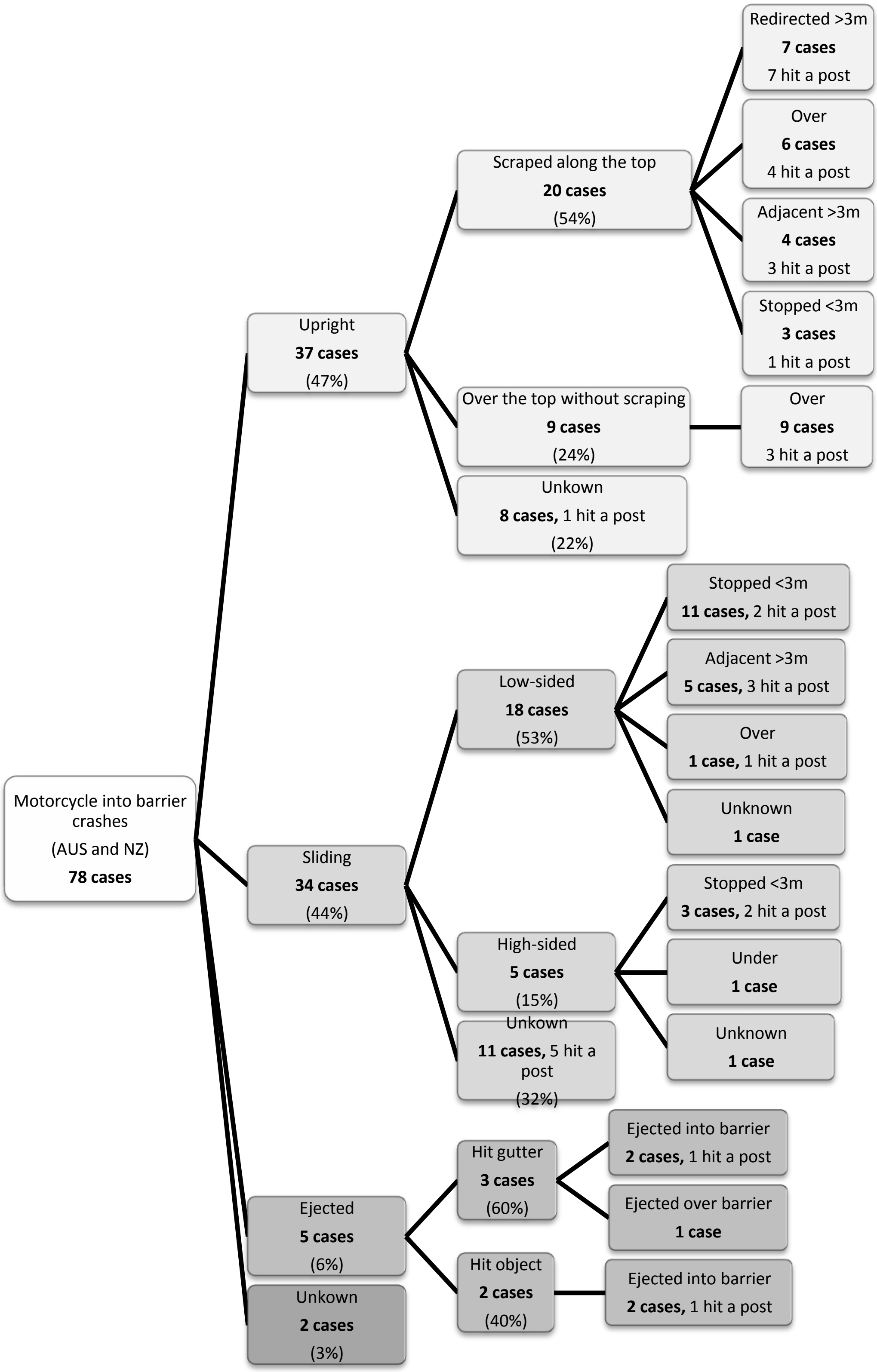
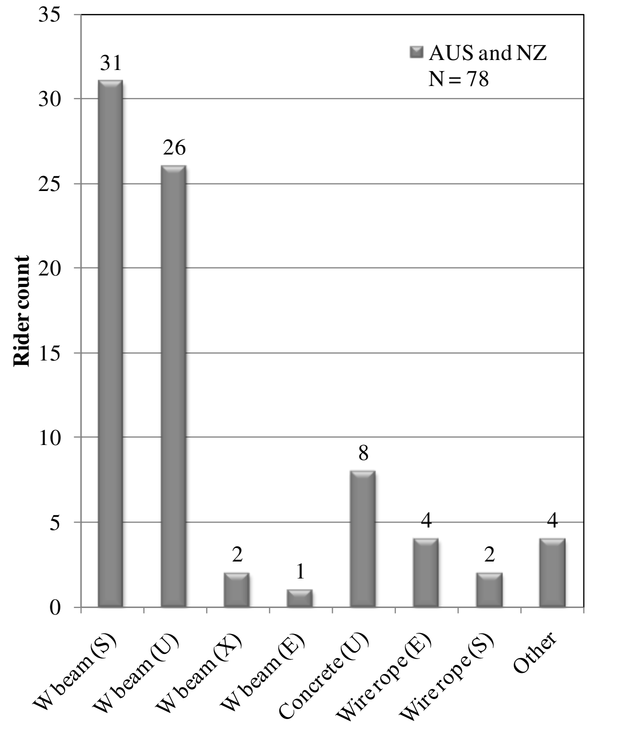


Figure 2: Summary of crash postures, motorcyclist kinematics and post impacts for the 78 motorcycle-barrier crashes



U = upright posture S = sliding posture E = ejected X = unknown

Figure 3: Summary of barrier types and crash postures

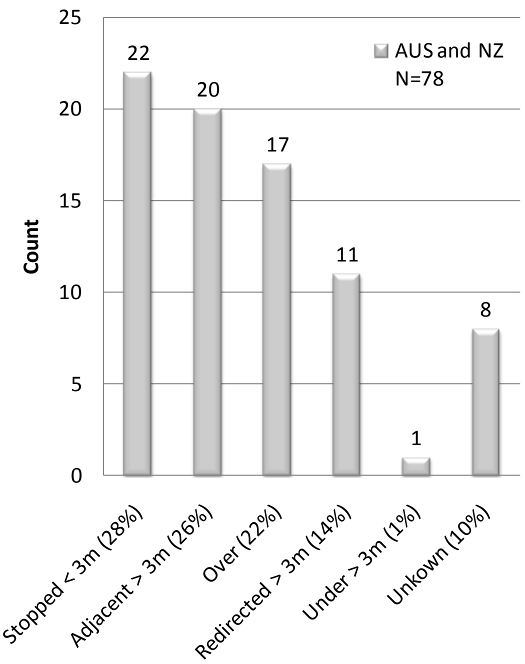


Figure 4: Basic result of the 78 motorcycle-barrier crashes

	Mean	Count	Range
Total distance motorcyclist travels after first impact – all postures (m)	21.8	62	0 - 100
Total distance motorcyclist travels after first impact - Upright posture (m)	26.3	34	2 - 82
Total distance motorcyclist travels after first impact - Sliding posture (m)	12.7	27	0 - 95
Distance motorcyclist scrapes along the top of the barrier (Upright posture) (m)	13.9	20	2 - 40
Distance motorcyclist slides before barrier impact (Sliding posture) (m)	28.9	26	9 - 56
Impact trajectory angle – all postures	15.4°	52	5 - 33
Impact trajectory angle - Upright posture	15.4°	26	5 - 33
Impact trajectory angle - Sliding posture	15.9°	24	5 - 32
Impact trajectory angle - motorcyclist redirected adjacent >3m	11.6°	14	
Impact trajectory angle - motorcyclist redirected into roadway>3m	10.6°	7	
Impact trajectory angle - motorcyclist stops <3m	16.7°	13	
Impact trajectory angle - motorcyclist goes over	19.7°	16	

Table 2: Summary of motorcyclist kinematics from cases where scene measurements were provided in the case files

5.4 Impact angle

Impact trajectory angles were determined with excellent accuracy from the 14 cases in which scene diagrams produced from a surveying instrument were included. In another 38 cases the impact angles were determined with reasonable accuracy from scene measurements. The mean impact angle in all crash postures was 15.4° (SD = 8.6°), and the mean impact angles for the sliding and upright crash postures were approximately the same (Table 2). Motorcyclists that went over the barrier tended to have impacted the barrier at angles larger than the mean. Motorcyclists that were redirected tended to have impacted the barrier at angles shallower than the mean, and both results are to be expected when one considers the momentum of the motorcyclist.

5.5 Pre-crash speed

The pre-crash speed was estimated in 54 cases. The speeds varied between 60km/h and 200km/h, with a mean of 100.8km/h (SD = 31.1km/hr). Further analysis of speeds and their comparison with injury outcomes are presented in the following section.

5.6 Motorcyclist kinetic energy

It is of general interest to know how much of the motorcyclists' kinetic energy is dissipated as a result of a collision with a roadside barrier. While it is unknown how much energy is dissipated as a motorcyclist slides along a barrier in the upright posture, there have been a number of studies that have determined drag coefficients for humans sliding on roadways. Searle (1983) recommended a coefficient of friction of 0.66 for a person sliding on normal dry asphalt, Fricke (1990) recommended the use of a range from 0.45 to 0.6, Obenski et al (2007) recommended a value of 0.5 and Wood (1991) cited values of between 0.37 and 0.75. A range of 0.4 to 0.6 was used in the present analysis, and standard equations for velocity changes occurring from sliding distances were employed. A subset of 19 crashes were selected where the motorcyclist slid in and the pre-crash speed, pre-impact (entry) slide distance and post-impact (exit) slide distance of the motorcyclist were known. Pre-crash speed estimates were taken as the lower bound value in those cases where a range was provided, and the typical range was 10km/h. Thus an upper bound pre-crash speed may be determined by adding 10km/h to the lower bound value. Lower bound impact speeds were determined using the lower bound pre-crash speed and upper bound drag factor, and upper bound speeds vice versa. The energy dissipated during the barrier contact was calculated as the pre-crash kinetic energy less the kinetic energy dissipated during entry and exit sliding. This energy may be expressed as a percentage of the pre-crash kinetic energy, such that it is independent of the motorcyclist mass. The resulting mean kinetic energy loss as a result of the barrier contact was 52% for the lower bound values and 58% for the upper bound values. While there was significant scatter, three quarters of results were between 30% and 80% of the motorcyclists' energy being dissipated during the barrier contact.

6. Injury causation results

The injuries received by 70 of the fatally injured motorcyclists are detailed in this section. The seven motorcyclists that conclusively received injuries only from secondary non-barrier contacts were excluded from the injury analysis, and one case file did not contain an autopsy report.

The total number of AIS3+ injuries received by the fatally injured group of 70 motorcyclists was 341. This is on average nearly five AIS3+ injuries per motorcyclist. This included 190 AIS3 injuries (56%), 82 AIS4 injuries (24%), 35 AIS5 injuries (10%) and 34 AIS6 injuries (10%). The number of AIS3+ injuries received by individual motorcyclists is plotted against the pre-crash speed (for the 54 cases where the speed was estimated) in Figure 5. The minimum and maximum numbers of AIS3+ injuries received were one and 11 respectively, and there is a general trend towards motorcyclists with greater pre-crash speeds receiving more injuries, however the coefficient of determination is low (0.23).

6.1 Body regions injured

The body regions injured amongst the 70 motorcyclists are summarised in Table 3 and Figure 6. In Table 3, column b) indicates the total number of AIS3+ injuries in each body region and the percentage of the total 341 AIS3+ injuries recorded. Column d) indicates the number of motorcyclists that received at least one AIS3+ injury in each body region and the number as a

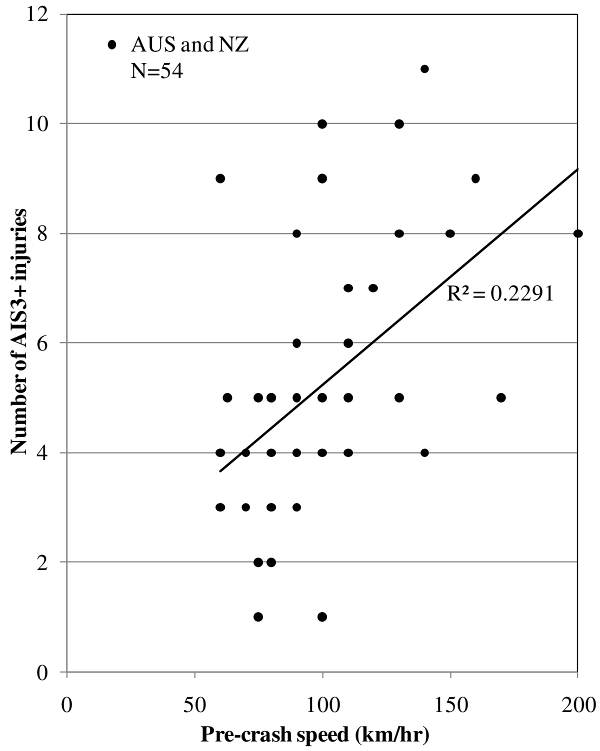


Figure 5: Pre-crash speed and number of AIS3+ injuries received by motorcyclists (for which the pre-crash speed was estimated)

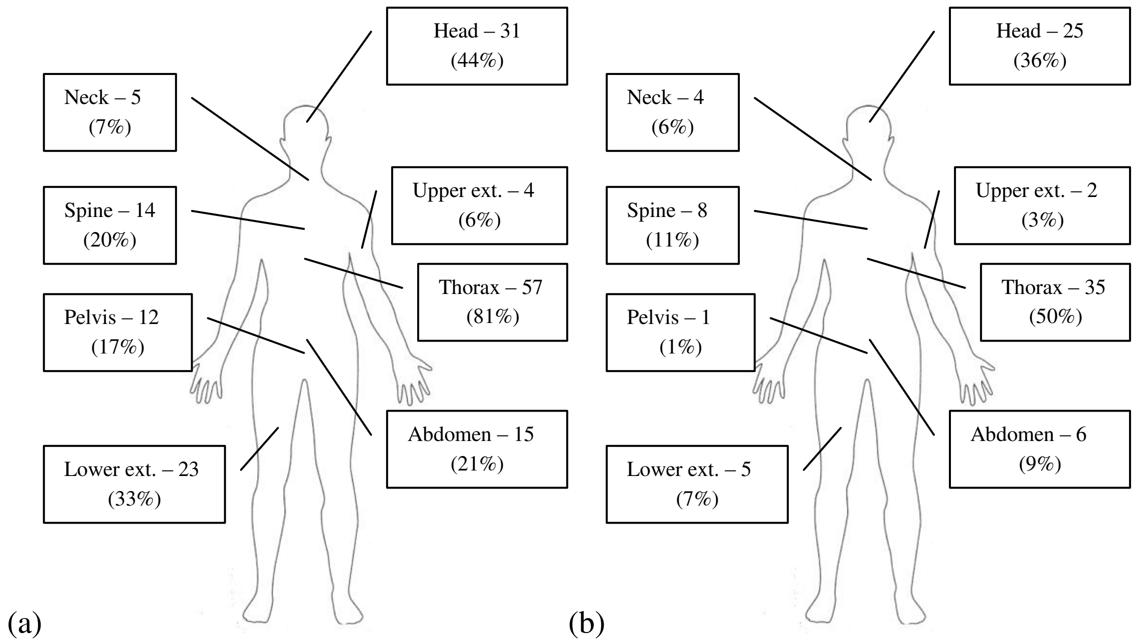


Figure 6: a) Number of motorcyclists who received 1 or more AIS 3+ injuries in each body region; b) Number of motorcyclists who received the most severe injury (MAIS) in each body region (and % of total of 70)

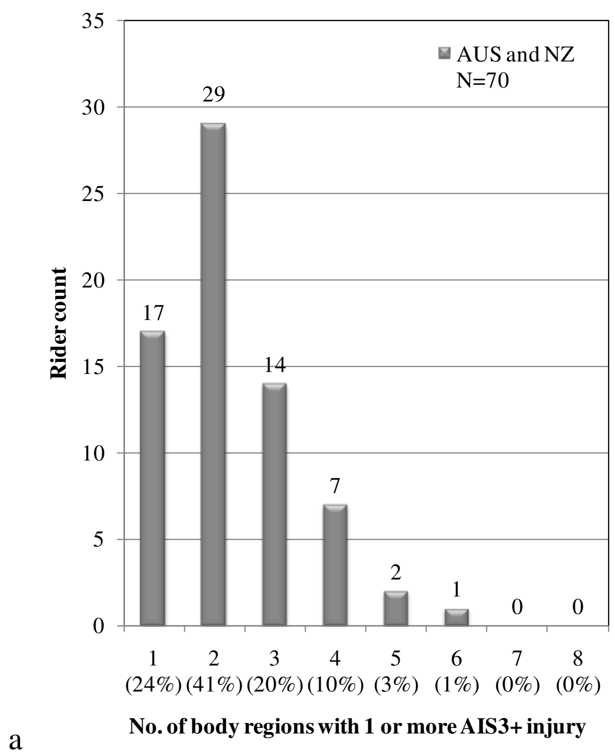
(a) **Body region injured** and organ/bone injury/injured		(b) No. of AIS3+ injuries (% of total)	(c) No. of MAIS injuries (% of total)	(d) No. of riders that received ≥1 AIS 3+ injury to a body region (% of riders)	(e) No. of riders that received ≥1 MAIS injury to a body region (% of riders)
Head		**76 (22%)**	**29 (27%)**	**31 (44%)**	**25 (36%)**
	Head crush	2 (3%)	2 (7%)		
	Brain stem	16 (21%)	16 (55%)		
	Cerebellum	8 (11%)	0 (0%)		
	Cerebrum	27 (36%)	4 (14%)		
	Skull base	18 (24%)	5 (17%)		
	Skull vault	4 (5%)	2 (7%)		
Neck		**7 (2%)**	**4 (4%)**	**5 (7%)**	**4 (6%)**
	Decapitation	4 (57%)	4 (100%)		
	Carotid/larynx/trachea	3 (43%)	0 (0%)		
Thorax		**166 (49%)**	**49 (46%)**	**57 (81%)**	**35 (50%)**
	Aorta	13 (8%)	8 (16%)		
	Other vein/artery	3 (2%)	2 (4%)		
	Bronchus/diaphragm	9 (5%)	2 (4%)		
	Heart	13 (8%)	9 (18%)		
	Hemopericardium	3 (2%)	0 (0%)		
	Lung	40 (24%)	9 (18%)		
	Hemo/pneumo/hemopneumo/ thorax (and tension)	45 (27%)	11 (22%)		
	Ribs	40 (24%)	8 (16%)		
Abdomen		**25 (7%)**	**7 (7%)**	**15 (21%)**	**6 (9%)**
	Vein/artery	6 (24%)	0 (0%)		
	Bladder	1 (4%)	1 (14%)		
	Kidney	3 (12%)	1 (14%)		
	Liver	5 (20%)	1 (14%)		
	Mesentery	1 (4%)	1 (14%)		
	Spleen	6 (24%)	1 (14%)		
	Stomach/uterus	3 (12%)	2 (28%)		
Spine		**16 (5%)**	**9 (8%)**	**14 (20%)**	**8 (11%)**
	Atlanto-axial/atlanto-occipital	4 (25%)	2 (22%)		
	Cervical cord	6 (38%)	5 (56%)		
	Thoracic cord	5 (31%)	1 (11%)		
	Lumbar cord	1 (6%)	1 (11%)		
Upper Ext.		**7 (2%)**	**2 (2%)**	**4 (6%)**	**2 (3%)**
	Amputation	4 (57%)	2 (100%)		
	Complex open long bone	3 (43%)	0 (0%)		
Lower Ext.		**44 (13%)**	**7 (7%)**	**27 (39%)**	**6 (9%)**
	Amputation	6 (14%)	0 (0%)		
	Femoral artery	2 (5%)	0 (0%)		
	Femur	19 (43%)	4 (57%)		
	Tibia open	5 (11%)	2 (29%)		
	Pelvis	12 (27%)	1 (14%)		
All regions		**341 (100%)**	**107 (100%)**	**153 (219%)**+	**86 (123%)**+

+ some motorcyclists received injuries to multiple body regions, thus the total number of body regions with injury exceeds the total number of motorcyclists (70)

Table 3: AIS3+ injuries and maximum AIS injuries (MAIS) received by the 70 motorcyclists – injury totals and injuries per motorcyclist

percentage of the total 70 motorcyclists. The total in column d) is 153, since amongst the 70 motorcyclists many motorcyclists received at least one AIS3+ in more than one body region (on average 2.2). Thorax, head and lower extremity regions were the most frequently seriously injured body regions amongst the fatally injured group. Thorax injuries accounted for 49% of the total 341 AIS3+ injuries, and 57 motorcyclists (81%) received at least one AIS3+ thorax injury. Head injuries accounted for 22% of the total 341 AIS3+ injuries, and 31 motorcyclists (44%) received at least one AIS3+ head injury. Lower extremity injuries accounted for 13% of the total 341 AIS3+ injuries, and 27 motorcyclists (39%) received at least one AIS3+ lower extremity injury.

Figure 7a plots the number of motorcyclists that received at least one AIS3+ injury in multiple body regions. The most common number of body regions to be seriously injured was two (41%), and the maximum was six. Figure 7b plots the level of severity of the injuries received in each body region. Of the 57 motorcyclists that received AIS3+ thorax injuries, 20 of these motorcyclists received serious injury, 19 received severe injury, nine critical and nine untreatable. Of the 31 motorcyclists that received AIS3+ head injuries, six of these motorcyclists received serious injury, eight severe injury, two critical and 15 untreatable. In comparison with thoracic injuries, head injuries were less numerous in total however tended to be more severe. While the total count of lower extremity AIS3+ injuries was relatively high, none were above AIS4 in severity.



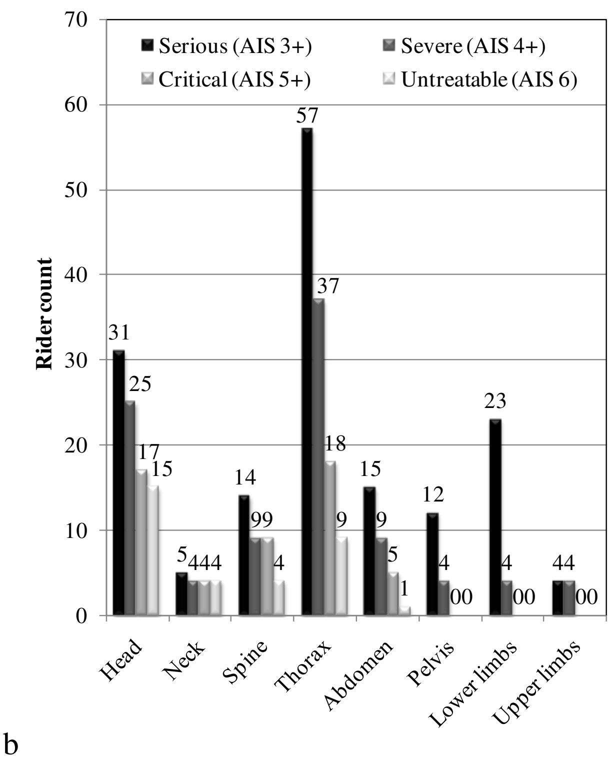
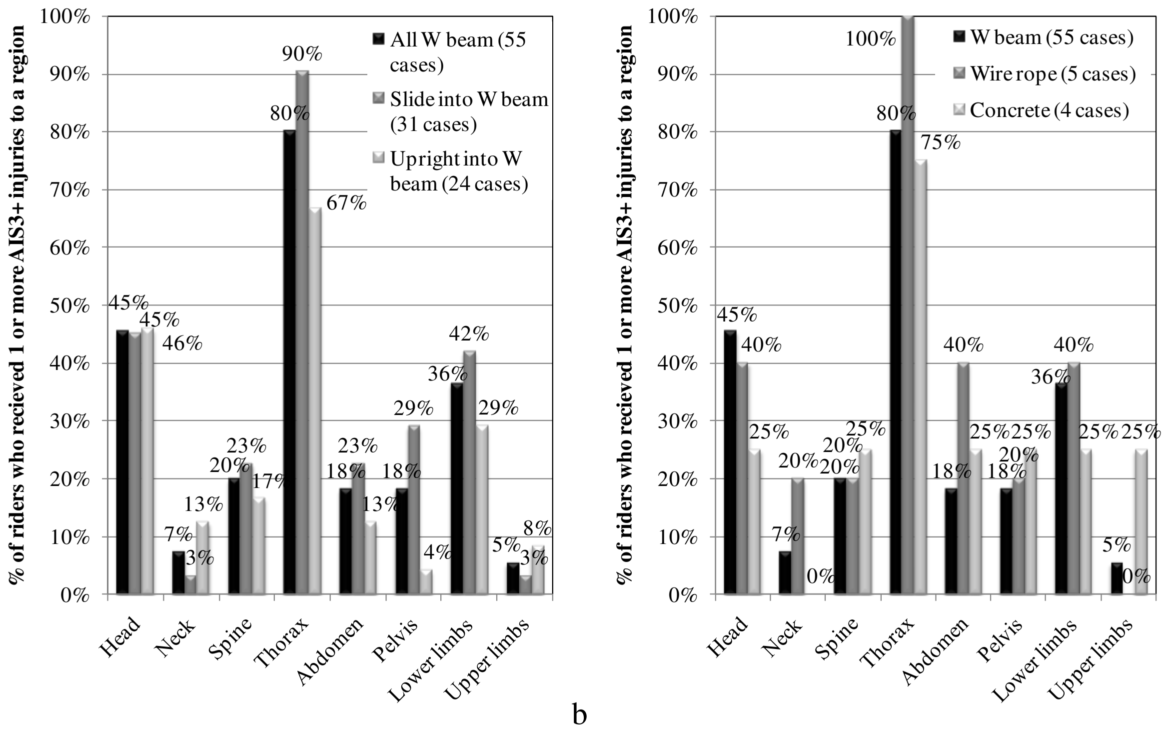


Figure 7: a) Number of motorcyclists that received AIS3+ injuries to multiple body regions, b) Severity distribution of injuries to motorcyclist body regions

Figure 8a plots the percentage of motorcyclists that received at least one AIS3+ injury in each body region amongst the group of motorcyclists that collided with W beam barriers, and the motorcyclists that collided with W beams in the sliding posture or the upright posture. While the injury profiles of the two crash postures were similar, notably thorax and pelvis injuries occurred more frequently amongst motorcyclists that slid into W beam barriers. In Figure 8b the injury profiles are compared for the three different barrier types of W beam, wire rope and concrete. The distribution of injuries are quite similar. However, the results must be treated cautiously due to the small datasets for the wire rope and concrete barriers (five cases and four cases respectively).



a b

Figure 8: Injury profiles for; a) different crash postures in collisions with W beams, b) different barrier types in all crash postures

6.2 Organ and skeletal injuries

The individual organs and bones that received AIS3+ injury amongst the fatally injured group of 70 motorcyclists are shown in Table 3. In column b) the total number of injuries to each organ/bone and the percentage of the total number of organs/bones that received injury in that body region are tabulated. There were in total 166 AIS3+ thorax injuries, and the mean number of concurrent AIS3+ thorax injuries was 2.9 per motorcyclist (for those motorcyclists that received at least one thorax injury). Of the 70 motorcyclists, 40 received rib injury, 45 received hemo/pneumo/hemopneumo/ thorax, 36 received at least one lung injury, 20 had concurring rib and lung injuries with intrathoracic bleeding, and 10 of those 20 also had injury to other thoracic organs or vessels (all

AIS3+ injuries). There were 13 aorta injuries (tears, lacerations, transections and ruptures), which are typically critical injuries and are discussed further in this report.

There were in total 76 AIS3+ head injuries, and the mean number of concurrent AIS3+ head injuries was 2.5 per motorcyclist (for those motorcyclists that received at least one head injury). The most frequently injured organ/bone in the head region was the cerebrum (36%). While only four motorcyclists received skull vault fractures, 27 received cerebrum injuries and eight received cerebellum injuries (all AIS3+ injuries). This may be related to the fact that 97% of motorcyclists were wearing a helmet prior to the crash, where the helmet protects the skull from serious fracture. However, the deceleration forces of the impact damage the brain. It is noted that many closed, simple vault fractures were recorded in the autopsy reports, however such fractures are AIS2 and were thus not coded for the present analysis of AIS3+ injuries.

Other injuries and frequencies are presented in Table 3. Lower extremity injuries featured highly, where 27 motorcyclists received at least one AIS3+ injury, predominantly femur and pelvis injuries. There were 14 motorcyclists that received at least one AIS3+ spine injury, with more injuries occurring in the upper spine. While there were only seven AIS3+ neck injuries, four of them were untreatable (decapitation). There were 15 motorcyclists that received at least one AIS3+ abdominal injury, with spleen, liver and vein/artery injuries predominating.

6.3 Injury severity

The maximum AIS injury (MAIS) and the injury severity score (ISS) received by each of the fatally injured group of 70 motorcyclists was determined, where 10 motorcyclists received an MAIS of 3, 17 received an MAIS of 4, 12 received an MAIS of 5 and 31 received an MAIS of 6. The number of MAIS injuries occurring in each of the body regions and the percentage of the total number of 107 is tabulated in Table 3. The total number exceeds 70 due to a number of motorcyclists receiving more than one injury with the same MAIS. The body region that recorded the maximum number of MAIS injuries was the thorax (46%), followed by the head (27%). In the thorax body region hemo/pneumo/hemopneumo/thorax was the most common MAIS (22%), and in the head region brain stem injury was the most common (55%). The number of motorcyclists that received one or more MAIS injuries to a body region are also tabulated in Table 3, where again the thorax and head regions predominate (50% of motorcyclists received a thorax MAIS and 36% of motorcyclists received a head MAIS). Of the 35 motorcyclists that recorded an MAIS in the thorax, 29 (83%) received an AIS3+ rib injury. The mean MAIS value for the 70 motorcyclists was 4.9, where the mean MAIS for those motorcyclists that received the MAIS in the thorax and in the head were 4.7 and 5.3 respectively. This indicates that while the thorax was the body region most seriously injured in more cases than the head, the severity of the head injuries was slightly greater. The mean MAIS values for the spine and neck for those motorcyclists that received the MAIS in the spine and the neck were also of note, being 5.8 and 6.0 respectively, indicating very severe injuries (although occurring less frequently).

The ISS values varied between 9 and 75, where 32 motorcyclists received the maximum value of 75. The mean ISS for the fatally injured group of 70 motorcyclists was 48.0. Robertson et al (2002) found the mean ISS of their fatally injured group of 66 motorcyclists was 36. Kraus et al (2002) reported the mean ISS of their fatally injured group of 548 motorcyclists was 39.3. Since in these two studies the ISS was calculated for all single- and multi- vehicle motorcycle crash modes, this suggests that motorcyclist fatalities involving barriers may be generally more severe than those in all crash modes.

6.4 AIS6 untreatable injuries

A large number of injuries occurred amongst the group that are currently considered untreatable, where 34 AIS6 injuries were received by 31 motorcyclists (three motorcyclists each received two AIS6 injuries). These injuries are tabulated in Table 4. Of the 34 injuries, 24 occurred to the head and upper cervical spine, nine to the thorax and one to the abdomen. Heart injury predominated the thorax injuries, brain stem injury predominated the head injuries, and there were four upper cervical cord injuries. There were additionally 11 motorcyclists that received amputation injury, including six leg and four arm amputations and four decapitations (one motorcyclist received decapitation with both arms amputated, and another received decapitation with a leg amputated). Wyatt et al (1999) noted that of 30 AIS6 injuries amongst fatally injured motorcyclists in all crash modes; 14 occurred to the head and upper cervical spine (including nine brain stem injuries and one decapitation), 14 to the thorax (including 11 aortic ruptures), and two to the abdomen (liver avulsions).

AIS6 injury	Count
Head crush	2
Brain stem laceration/transection	14
Decapitation	4
Upper cervical cord laceration	4
Aorta transection with bleeding not confined to the mediastinum	2
Pulmonary artery transection	1
Heart lacerations/ventricular rupture	6
Liver avulsion	1

Table 4: AIS6 injuries received amongst 31 motorcyclists

Traumatic brain injury followed by traumatic rupture of the aorta are the two leading causes of death associated with motor vehicle crashes (Cavanaugh et al, 2005). Amputation injury is less common generally, however it can occur amongst less protected road users such as pedestrians and motorcyclists, and are also severe and generally untreatable. The occurrence of amputations, aorta and brain stem injuries are tabulated in Table 5, for those cases in which the pre-crash speed was estimated. The minimum and mean pre-crash speeds at which these injuries occurred were respectively: 90km/h and 132km/h; 60 km/h and 104km/h; and 80 km/h and 105km/h.

Amputation				**Aorta injury**			**Brain stem laceration/transection**		
Barrier (crash posture)	Pre-crash speed (km/hr)	Member	Amputation on post?	Barrier (crash posture)	Pre-crash speed (km/hr)	Aorta injury	Barrier (crash posture)	Pre-crash speed (km/hr)	Head impact with post?
W beam (U)	90	Decapitated	Yes	Concrete (U)	60	Transection	W beam (U)	80	Yes
W beam (S)	90	Arm		W beam (U)	60	Transection	W beam (U)	90	Yes
Wire rope (S)	100	Leg	Yes	W beam (S)	80	Laceration	W beam (U)	90	
W beam (U)	110	Both arms, decapitated	Yes	W beam (S)	90	Laceration	Concrete (U)	90	Yes*
Concrete (U)	110	Arm	Yes*	W beam (S)	100	Transection+	W beam (S)	100	
W beam (S)	140	Leg	Yes	Wire rope (E)	110	Transection	W beam (S)	100	
W beam (S)	150	Leg	Yes	W beam (S)	160	Intimal tear	Wire rope (S)	100	
W beam (S)	160	Leg	Yes	W beam (S)	170	Transection	W beam (S)	110	Yes
W beam (S)	170	Leg					W beam (S)	140	
Wire rope (E)	200	Leg, decapitated					W beam (S)	150	Yes

*signpost on top +with haemorrhage not confined to the mediastinum U = upright posture S = sliding posture E = ejected

Table 5: Details of crashes that resulted in severe aorta injuries, brain stem injuries and amputations (for which the pre-crash speed was estimated)

Depending on the study, traumatic rupture of the intrathoracic aorta accounts for 10 – 25% of all deaths from motor vehicle accidents (Cavanaugh et al, 2005). Traumatic aortic rupture is associated with a mortality rate of 86 – 98%, and 47 – 91% of crash victims die at the crash scene or within one hour after the crash (Forman et al, 2005). In the present study, all except one of the motorcyclists with aorta injury died at the crash scene. Karger et al (2000) studied 47 cases of pedestrian fatalities resulting from vehicle collisions, finding that 21 cases involved aortic rupture. The minimum impact velocity for aortic rupture was found to be 63km/h, which is similar to that in the present study of 60km/h (Table 5).

Traumatic injuries to the brain stem are nearly always fatal. In a study of 149 traffic fatalities including brain stem and/or upper cervical spinal cord by Ohshima and Kondo (1998), 138 died immediately at the crash scene. In the present study all of the 14 motorcyclists that received AIS6 brain stem injury died at the crash scene. Four brain stem injuries occurred following a head impact with a W beam post (Table 5). Brain stem injury often occurred with severe skull base fractures, where 11 of the 16 motorcyclists (69%) that received a complex AIS4 skull base fracture (including ring and hinge type fractures), also received a brain stem injury. Amongst four motorcyclists that received dislocations of the atlanto-occipital joint, two also received a brain-stem injury. Ohshima and Kondo (1998) found that of the 130 cases of brain stem injury, 82 involved skull base fractures (of which 25 were complex ring fractures), and 45 involved atlanto-occipital, atlanto-axial or upper cervical dislocations.

While not necessarily fatal (except for decapitations), dismemberment injuries are generally severe and if not treated immediately can lead to fatal blood loss. In the present study, all except one of the motorcyclists with dismemberment died at the crash scene. In five cases dismemberments occurred on a W beam post, and in one case a wire rope post (Table 5). Karger et al (2000) reported five cases involving dismemberment, where the minimum impact velocity was found to be 99km/h, which is similar to that in the present study of 90km/h (Table 5).

6.5 Injuries associated with barrier post impacts

In the present study there were 34 confirmed post impacts, predominantly on W beam barriers. However, two were wire rope posts and three resulted from sign posts located on top of concrete barriers. Of the 34 impacts, 19 were in the upright posture, 13 were sliding and two were ejected. Of the motorcyclists that impacted a W beam or wire rope barrier post, 92% recorded AIS3+ injury to the body region that contacted the post, and 76% recorded an MAIS for the body region that contacted the post.

6.6 Comparison of injuries with fatal motorcycle crashes in all crash modes

The results of the analysis of body region injured are summarised in Table 1, and compared with the results from various literature studies of fatal motorcycle crashes in all single- and multi- vehicle modes. This comparison suggests that fatal crashes with barriers produce a higher incidence of thorax injury and lower incidence of head/neck injury than fatal crashes in general.

7. Statistical associations between crash mechanics and injuries

In this section associations are determined between crash severity and injury severity (Table 6), and logistic regression is used to provide odds ratios and 95% confidence intervals between different injuries, and between injuries and crash postures (Tables 7 to 9). Relationships that are not statistically significant in Tables 7 to 9 are shown in italics (odds ratios with lower bound 95%

confidence intervals of less than one and/or chi-squared *p* values greater than 0.05). The confidence intervals are quite wide due to the small dataset. The full dataset of 70 fatally injured motorcyclists was used to determine associations between specific injuries. To relate injuries to crash postures only the motorcyclists that collided with W beam barriers are used, since this excludes the effect of the barrier type on the results, and the W beam barrier dataset is the most comprehensive. The W beam crash dataset includes 55 motorcyclists, which excludes three motorcyclists injured by secondary non-barrier objects only, one motorcyclist whose crash posture resulted in ejection and one motorcyclist whose crash posture was unknown (leaving 31 motorcyclists that slid into W beams and 24 that collided upright).

7.1 Associations between crash severity and injury severity

Table 6 tabulates the mean pre-crash speeds, ISS and MAIS values for various subsets of the data relating to barrier type and crash posture. There is a clear correlation between crash severity (as indicated by the mean pre-crash speed) and injury severity (as indicated by the mean ISS and MAIS), when the effect of the type of barrier and crash posture is excluded. When plotted in Figure 9, there is a strongly linear relationship amongst this fatally injured group (coefficients of determination of 0.986 and 0.990 for the mean ISS and MAIS respectively).

Barrier type/crash posture	Mean pre-crash speed (km/hr)	Mean ISS	Mean MAIS
All W beam	97	48	4.9
W beam - sliding posture	102	51	5.1
W beam - upright posture	92	44	4.7
W beam with post impact	102	49	5.0
Concrete	87	40	4.5
Wire rope	117	63	5.6

Table 6: Mean pre-crash speeds (crash severity) and mean ISS and MAIS values (injury severity) for barrier types, crash postures and post impacts (for which the pre-crash speed was estimated)

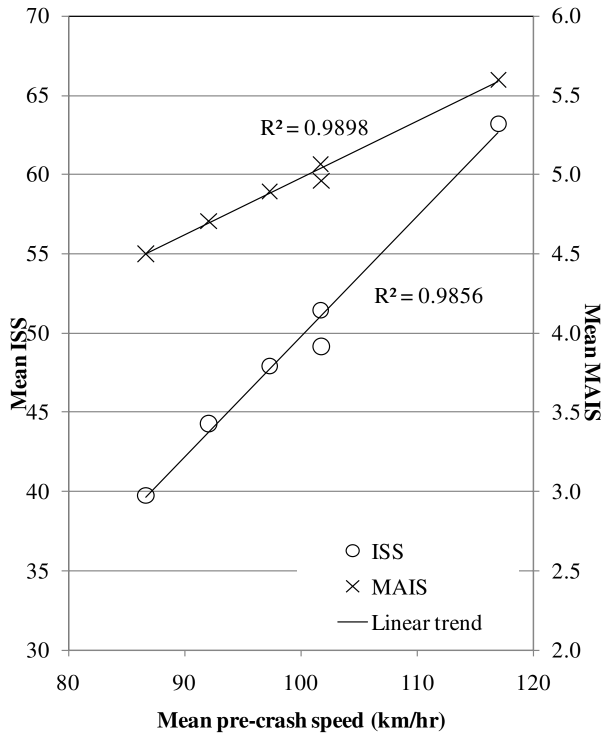


Figure 9: Mean pre-crash speeds and mean ISS and MAIS values determined independently for different barrier types and crash postures (Table 6)

7.2 Associations between types of injuries

The results of the statistical analyses of associations between specific injuries are tabulated in Table 7. Statistical significance was found in the occurrence of AIS3+ intrathoracic bleeding or injury to the heart or lung, concurrent with AIS3+ rib injury (three or more rib fractures or flail chest). Most significant was the occurrence of any intrathoracic organ/vessel injury concurrent with AIS3+ rib injury (p = 0.0006). Motorcyclists that received an AIS3+ rib injury were around six times more likely to receive an intrathoracic organ/vessel injury than those who did not receive rib injury. Also statistically significant was the occurrence of intrathoracic bleeding concurrent with an intrathoracic organ/vessel injury. Considering the anatomy of the thorax these associations are as expected, and have also been identified in other motorcycle studies (Kraus et al, 2002, Sarkar et al, 1995). It is noted that in the present study AIS3+ abdominal injury was not found to be significantly statistically associated with AIS3+ rib injury. However an odds ratio of 2.47 was determined and the lack of significance may be a result of the small sample size. Both Kraus et al (2002) and Sarkar et al (1995) found statistically significant associations between these variables. The association between brain stem injury and complex ring or hinge type skull base fracture was discussed previously and was also found to be statistically significant.

		Odds ratio	95% CI lower	95% CI upper	Chi-squared *p* value
Concurrent with rib injury					
	Aorta	*3.00*	*0.75*	*12.06*	*0.10*
	Bronchus/diaphragm	*2.97*	*0.57*	*15.47*	*0.17*
	Heart	5.31	1.08	26.14	0.02
	Lung	3.71	1.37	10.09	0.008
	Hemo/pneumo/hemopneumo/ thorax (and tension)	3.94	1.40	11.05	0.008
	Any thoracic organ/vessel	6.48	2.10	19.97	0.0006
	Abdomen	*2.47*	*0.70*	*8.70*	*0.14*
Concurrent with any thoracic organ/vessel injury					
	Hemo/pneumo/hemopneumo/ thorax (and tension)	5.89	1.96	17.66	0.001
Concurrent with complex skull base fracture					
	Brain stem	27.5	6.33	119.4	0.00004

Table 7: Odds ratios and 95% confidence intervals for concurrent injuries

7.3 Associations between injuries, barrier types and crash mechanics

Injury severity cannot be associated with the barrier type with the present dataset, since the crash severity is not uniform across the different barrier types (Table 6), non-fatal crashes were not considered, and the concrete and wire rope barrier datasets were not large enough to extract and compare crashes of equal severity with statistical significance. Similarly it is shown in Table 6 that relative to crash severity, it cannot be concluded that impacts with barrier posts result in a more severe injury outcome. That is, while particular and severe injuries may be attributed to these individual post impacts (Table 5), such impacts may not necessarily lead to more severe injury outcomes than if a post had not been impacted. Notwithstanding crash severity, it is noted that the particular injury of amputation appears to occur often as a result of a post impact (of the 10 amputation injuries that occurred on W beam or wire rope barriers, six resulted from contact with a post). This may result from the snagging hazard a post represents.

The results of the statistical analyses of associations between crash postures and injuries are presented in Table 8. The dataset of 55 crashes into W beams was used, and the results are thus independent of the effect of barrier type. For the analysis of the type of motorcycle ridden, three motorcyclists that were riding off-road motorcycles and four where the motorcycle was unknown were additionally excluded, resulting in 37 sports motorcycle riders and 11 touring motorcycle riders. In Figure 8a it is clear that while in both the sliding and upright crash postures the incidence of thorax injury was high, it was proportionally more so for motorcyclists that slid into W beams. This difference is statistically significant, and it is shown in Table 8 that motorcyclists that slid into W beams were more likely to receive thorax injury. Also statistically significant was the increased likelihood of pelvis injury for those motorcyclists that slid into W beams.

Injured body region	Odds ratio	95% CI lower	95% CI upper	Chi-squared *p* value
Head	*0.97*	*0.33*	*2.84*	*0.960*
Neck	*0.23*	*0.02*	*2.40*	*0.186*
Thorax	4.67	1.08	20.14	0.029
Abdomen	*2.04*	*0.47*	*8.91*	*0.329*
Spine	*1.46*	*0.37*	*5.71*	*0.584*
Upper ext.	*0.37*	*0.03*	*4.30*	*0.409*
Lower ext.	*1.75*	*0.56*	*5.45*	*0.326*
Pelvis	9.41	1.10	80.54	0.011

Table 8: Odds ratios and 95% confidence intervals for injuries occurring to those that crashed sliding into a W beam, compared to those impacting a W beam in the upright posture

With regards to the type of motorcycle being ridden, it was determined that touring motorcycle riders tended to collide with the barriers upright, and sports motorcycle riders tended to slide into W beam barriers, and this result was statistically significant (Table 9). This results in part from the different riding positions whilst cornering, as discussed previously. As a result of sports motorcycle riders tending to slide into barriers, and the increased likelihood of thorax injury in the sliding posture, it is statistically significant that sports motorcycle riders are more likely to receive thorax injury (Table 9).

		Odds ratio	95% CI lower	95% CI upper	Chi-squared *p* value
Concurrent with riding a sports motorcycle (and crashing into a W beam)					
	Sliding	8.65	1.63	46.08	0.004
	Thorax	9.90	2.05	47.90	0.004

Table 9: Odds ratios and 95% confidence intervals for injuries concurrent with crash postures and motorcycle type

In a study by Ruiz et al (2010), simulations were performed of a Hybrid III ATD sliding such that the head impacted a rigid wall barrier at various angles. Head and upper neck accelerations, momentum and forces were determined, and neck load was used as a proxy for injury. The results predicted more severe head/neck injury (higher neck loads) as the angle of incidence increased from 10° to 90°. Analysis of motorcyclists in the present study that crashed in the sliding posture reveals that AIS3+ head, neck or cervical spine injury was associated with 4 of 5 motorcyclists that impacted at less than 10°, 7 of 13 motorcyclists that impacted between 10° and 20°, and 2 of 6 motorcyclists that impacted at greater than 20°. There does not appear to be an association between head/neck/cervical spine injury and impact angle in the present study. This may result from the greater uncertainty in the configuration of the motorcyclist upon impact with the barrier in real-world crashes.

8. Implications for motorcycle-barrier crash test protocols

European standards have recently been developed that define methods to evaluate the performance of barriers when impacted by a motorcyclist (prEN 1317-8, 2010, UNE 135900-1,2 2008). These standards prescribe crash tests in which an ATD is propelled into a barrier at an angle of 30° at an impact speed of 60km/h. While the standards recommend ATD head, neck and thorax instrumentation, only head and neck biomechanical indices are defined for determining the injury severity levels of the barrier crash.

For comparison of injury profiles resulting from conditions similar to those prescribed by these standards, those cases in which the impact speed of a sliding motorcyclist was likely to be around 60km/h were determined and are tabulated in Table 10. As before, lower bound impact speeds were determined using the lower bound pre-crash speed and upper bound drag factor, and upper bound speeds vice versa, to produce the impact speed ranges tabulated in Table 10. Amongst this group of 11 fatally injured motorcyclists there were a total of 31 thorax, six abdominal, six lower extremity, three spine, two head and one upper extremity AIS3+ injuries. The thorax received MAIS injury in 9 of the 11 cases. Since the number of motorcyclists and nature of injuries of motorcyclists that collide with a barrier at this speed and are not fatally injured is unknown, an injury or fatality risk cannot be determined. However from Table 10 it is clear that such collisions can certainly be fatal, and when motorcyclists were fatally injured in such collisions it was generally from thorax injury rather than head or neck injury.

This has significant implications for motorcyclist-barrier testing protocols. While some researchers have suggested thorax injury criteria, presently none have been adopted due to concerns regarding the biofidelity of current ATD thoraxes, and inconclusive relationships between measured loads and injury severity (Garcia et al, 2009, Ruiz et al, 2010). It may be appropriate to consider an additional test as part of a motorcycle-barrier crash test protocol, whereby an ATD slides into the barrier in the upright seated position. That is, the ATD slides on the ground seated upright and facing the W beam barrier, such that the collision involves the ATD's legs sliding underneath the W beam and the

ATD's thorax impacting the W beam. The test could be performed at the mean impact angle of 15° (Table 2). Alternatively, the test could be performed in a similar manner as the current sliding test (prEN 1317-8, 2010, UNE 135900-1,2 2008) whereby the ATD slides along the ground flat, however rather than positioned to impact the barrier post head-first, it could be positioned to impact the barrier post thorax-first. These two alternative test proposals would provide conditions whereby the ATD thorax takes the force of the impact (either from impact with the barrier beam or post), and would likely provide a worst-case scenario for thorax injury.

Barrier type	Angle (°)	Barrier impact speed range (km/hr)	ISS	MAIS	MAIS body region(s)	AIS3+ injuries
W beam	--	80*	25	4	Thorax	≥3 ribs fractured, lacerated aorta, ruptured diaphragm, haemopneumothorax, pelvic ring fracture
W beam	--	27-64	75	6	Thorax	≥3 ribs fractured, ventricular rupture of the heart, major haemothorax, major spleen laceration, cerebrum subdural hematoma
W beam	16	49-66	75	5	Thorax, Spine	Bilateral flail chest, perforated heart, haemothorax, cervical cord laceration, lumbar cord laceration
Wire rope	24	32-65	16	4	Thorax	≥3 ribs fractured, major haemothorax
W beam	19	26-63	43	5	Spine	thoracic cord laceration with fracture, haemothorax, intracerebral hematoma, femur fractures
W beam	18	29-66	18	3	Thorax, Lower ext.	≥3 ribs fractured, major unilateral lung contusion, unilateral lung laceration, haemothorax, open tibia shaft fracture
W beam	9	61-82	9	3	Thorax	≥3 ribs fractured, haemothorax
W beam	10	59-83	32	4	Thorax, Upper ext.	≥3 ribs fractured, lacerated aorta, unilateral lung laceration, haemothorax, arm amputation at shoulder
W beam	14	60*	16	4	Thorax	≥3 ribs fractured, bilateral lung contusion, major pneumothorax
W beam	28	46-62	41	5	Abdomen	unilateral flail chest with >5 ribs fractured, major unilateral lung laceration, ruptured diaphragm, stomach, uterus and spleen, renal artery and vein lacerations, major haemothorax
W beam	32	55-77	18	3	Thorax, Lower ext.	≥3 ribs fractured, both femurs fractured

* pre-crash speed shown since slide measurements were not available

Table 10: Summary of crashes in which the motorcyclist was likely to be travelling around 60km/h on impact with the barrier in the sliding posture

9. Wire rope barrier fatalities

There has been a significant concern raised by motorcycle organisations in Australia and overseas regarding the use of wire rope barriers. Amongst the motorcycling community, wire rope barriers have been given monikers such as “cheese cutters” and “egg slicers”, referring to the perception that if a motorcyclist was to contact the barrier at speed they would be sliced by the wires. In this section details of the fatalities that resulted from collisions with wire rope barriers in Australia and New Zealand between 2001 and 2006 are reported and discussed.

There were six fatalities that resulted from collisions with wire rope barriers. However in one of these cases the motorcyclist was ejected clear over the barrier and was fatally injured by secondary, non-barrier impacts. The details of the remaining five fatalities are presented in Table 11.

Crash posture	Pre-crash speed (km/hr)	No. of AIS3+ injuries	Body regions injured	MAIS	MAIS injury	ISS	Amputation injury?
Low-sided, slid into barrier	75	2	Thorax	4	Major haemothorax	16	
Low-sided, slid into barrier	100	10	Head, spine, thorax, abdomen, pelvis, lower extremities	6	Brain stem laceration	75	Leg amputated
Hit gutter, ejected into barrier	100	5	Thorax	6	Ventricular rupture of the heart	75	
Hit object, ejected into barrier	110	7	Head, thorax, abdomen	6	Multiple heart lacerations	75	
Hit object, ejected into barrier	200	8	Neck, thorax, lower extremities	6	Decapitated	75	Decapitated, Leg amputated
Mean:	**117**	**6.4**		**5.6**		**63.2**	

Table 11: Details of fatal cases resulting from a collision with a wire rope barrier

The following conclusions may be drawn with regard to the fatal motorcyclist collisions with wire rope barriers:

- In Australia and New Zealand, there is on average around one motorcyclist fatality resulting from a collision with a wire rope barrier per year. This constitutes around 0.4% of the total motorcyclist road toll
- According to Table 6, impacting a W beam barrier at 100km/h on average results in an ISS of approximately 50. An ISS of 50 correlates with a mortality of approximately 75% for persons under the age of 50 years. Thus if the four motorcyclists with pre-crash speeds of

100km/h or more in Table 11 had impacted with a W beam barrier in place of a wire rope barrier, there is an approximate chance of at least 75% that the outcome would have proved fatal

- Thus of the five wire rope barrier fatalities in Table 11, it is unlikely that four would have survived if a W beam barrier had been deployed in place, as a result of the severity of these crashes

10. Conclusions

A retrospective study of motorcyclists that were fatally injured following a collision with a roadside barrier during the period 2001 to 2006 in Australia and New Zealand has been presented. The majority of crashes resulted from collisions with steel W beam barriers, which is representative of exposure. Both sliding and upright crash postures were approximately equally represented, and mean pre-crash speeds and impact angles were found to be 100.8 km/h and 15.4° respectively. The thorax region was found to have the highest incidence of injury and the highest incidence of maximum injury in fatal motorcycle-barrier crashes, followed by the head region. This is in contrast to motorcycle fatalities in all single- and multi-vehicle crash modes, where head injury occurs with greater frequency than thorax injury. As existing motorcycle-barrier crash testing protocols do not specify a thorax injury criterion, there appears to be a need to determine such criteria.

Nearly half of the fatally injured motorcyclists received untreatable injuries, including aorta, heart, brain stem, upper cervical cord and dismemberment injuries. 81% of motorcyclists died at the crash scene. These results suggest that the potential to reduce fatalities by improving hospital or pre-hospital treatment may be limited, and efforts should therefore be focussed on measures to prevent injuries.

An association between riding a sports motorcycle and receiving thorax injuries was determined, and in Stage 1 it was noted that a high proportion of the motorcyclists were on recreational rides in areas that provide challenging riding conditions when they collided with a barrier. It may therefore be beneficial to encourage sports motorcyclists planning a challenging recreational ride to wear (appropriate) chest protection, in addition to body abrasion and head protection.

Head injuries closely followed thorax injuries in the study, while 97% of motorcyclists were helmeted. This indicates that the crash severity exceeded the functional range of the helmets in many cases, thus efforts to improve helmet design should continue.

Analysis of motorcyclist pre-crash speeds in the sliding posture, and entry and exit sliding distances, determined that typically 30-80% of the motorcyclists' pre-crash kinetic energy is dissipated during the contact with the barrier. This suggests that there is significant scope for reducing motorcyclist injuries with barrier design. This could be achieved by either reducing the magnitude of kinetic energy dissipated on the barrier (redirecting the motorcyclist), or by ensuring that the kinetic energy is dissipated in a more controlled manner (barrier impact attenuators/protective devices), etc.

From the variables investigated of barrier type, crash posture and barrier post impacts, and within the limitations of the small dataset of fatal only motorcyclists, no statistically significant association between these variables and injury severity could be established. It appears that the strongest association with injury severity is pre-crash speed (crash severity), and a strongly linear relationship was determined between these two.

There are a number of limitations of the study that should be noted. Firstly, the sample size is small. However the dataset constitutes all known fatal motorcycle-barrier crashes that occurred in the period 2001 to 2006 in Australia and New Zealand, and is thus complete. The use of fatal- and barrier-only cases has obvious limitations. However the authors have attempted to cover relevant literature of non-barrier crashes in the introduction, and some comparisons were drawn with the results of the present analyses. Ideally, a supplementary study would include non-fatal injury cases and non-injury barrier crashes. Other limitations include those resulting from the lack of a control group (typical to case series analyses), and the incompleteness of the case files as a result of the files not having been designed specifically for such a study.

11. Further work

Stage 3 of the research focuses on the survivability envelopes for different barrier systems and engineering solutions to mitigate injuries, adressing parts ‘f’ and ‘g’ of the project outcomes listed in the Project introduction.

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