TARS Research Report

REDUCING MOTORCYCLE TRAUMA IN THE A.C.T.

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Executive Summary

Serious injury rates and fatality rates per vehicle number for motorcyclists in the ACT are 10 times and 20 times those for cars, respectively. Serious injury rates and fatality rates for motorcyclists have also increased over the past decade. This project furthers our understanding of causal factors in motorcycle crashes in the ACT, and proposes strategies to reduce road trauma amongst motorcyclists. The project is aligned with the Safe Systems strategy, ensuring that our roads are safe for all road users, including motorcyclists.

Key findings related to the analysis of ACT motorcyclists injured or killed during the ten year period between 2001 and 2010 (inclusive), include:

- A total of 1,199 ACT residents presented to Canberra hospital with injuries sustained in a motorcycle crash
- The 16-25 year old age group had the highest number of individuals
- The number of injured motorcyclists per year has increased around two times in this period, roughly in-line with the increase in motorcycle registrations, however this increase is nearly six times for motorcyclists aged 46 years and over
- Older riders also experienced more severe injury outcomes and longer stays in hospital
- Nearly one third of motorcyclists were injured in non-traffic areas (non-public roads)
- The highest frequency of crash modes was non-collisions, which accounted for more than half of hospitalisations, and had less severe injury outcomes than other crash modes
- Motorcycle into passenger vehicle collisions, followed by motorcycle into fixed object collisions, resulted in the most severe injury outcomes
- Motorcycle into passenger vehicle collisions and motorcycle into fixed object collisions were more likely to result in head and spine injuries, than non-collision crashes
- The most frequently injured body region was the extremities, followed by the torso, head and spine
- The most frequently sustained individual injury was extremity fracture, followed by traumatic brain injury, vertebral column fracture and rib fracture
- The most frequently sustained *serious* injury was thoracic organ injury, followed by traumatic brain injury, vertebral column fracture and rib fracture
- A number of significant contributors to motorcycle trauma in the ACT have been identified, including; risky riding behaviour, fixed roadside objects, intersections, vehicles turning in front of motorcyclists, thoracic and head impacts
- Collisions with fixed objects in the roadside occurred in 52% of fatal crashes
- Risky riding behaviour was a contributing causal factor in 51% of fatal crashes
- In 43% of fatal crashes the motorcyclist was under the influence of alcohol and/or drugs
- In 20% of fatal crashes the motorcyclist was considered to be riding with excessive speed

- Around half of crashes and fatalities occurred at intersections
- Vehicles turning in front of motorcyclists occurred in 58% of fatal multi-vehicle crashes
- Amongst fatal and non-fatal cases, the most frequently occurring *serious* injury was thoracic injury, and the most frequently *seriously* injured body region was the thorax, followed by the head
- Around one quarter of injured motorcyclists and three quarters of killed motorcyclists sustained *serious* thoracic injuries
- A numerical simulation methodology to assess thoracic injury has been established and validated against real-world cases, and provides a useful tool for researchers to investigate the injury potential of fixed hazards and infrastructure to motorcyclists

Key recommendations for policy actions and/or further research derived from the analysis of motorcyclist casualties include;

- **Education campaigns to reduce risky riding amongst motorcyclists**. This recommendation is derived from the finding that risky riding behaviour was a contributing causal factor in 51% of fatal crashes, and could include campaigns to highlight the risk of speeding, alcohol and drugs to motorcyclists.
- **Enforcement campaigns**. This recommendation is derived from the extensive presence of alcohol, drugs and speeding amongst fatal motorcycle crashes. Additionally, 14% of motorcycles in fatal crashes were unregistered.
- **Education campaigns for returning riders**. This recommendation is derived from the finding that the rate of hospitalisations for over 45 year olds increased by six times over the study period, and could include campaigns aimed at older riders highlighting the risks of returning to riding after an extended period without riding.
- **Education campaigns for young riders**. This recommendation is derived from the finding that the rate of hospitalisations of young riders (16-25) remains the highest of any age group, and could include campaigns aimed at highlighting the risks of inexperience, speed, alcohol and drugs for young motorcyclists.
- **Promote motorcycle awareness amongst motorcyclists and other road users**. This recommendation is derived from the finding that vehicles turning in front of motorcyclists occurred in 58% of multi-vehicle fatal crashes (typically the vehicle driver did not see the motorcyclist or misjudged the distance).
- **Further research into the nature of non-traffic crashes and education campaigns aimed at motorcyclists who ride in such areas**. This recommendation is derived from the finding that 31% of hospitalised motorcyclists crashed in non-traffic areas, including non-traffic roadways, forests, racetracks and private land. These crashes are not well understood since they are not reported to police, therefore the details of such crashes are not recorded.
- **Improve the safety of intersections for motorcyclists**. This recommendation is derived from the finding that around half of motorcyclist crashes and fatalities occur at

intersections, and could include campaigns to promote motorcycle awareness amongst motorcyclists and other road users.

- **Improve the safety of roadside infrastructure for motorcyclists, and include motorcyclist crash tests in the Australian barrier standard.** This recommendation is derived from the finding that collisions with fixed objects in the roadside occurred in 52% of fatal crashes, and roadside barriers were the fixed object most frequently struck.
- **Investigate and develop crash test procedures to assess thoracic injury potential in barrier crash tests.** This recommendation is derived from the finding that while serious thoracic injury was the predominant injury mechanism, currently there are no thoracic injury assessment methods in motorcycle crash tests.
- **Investigate hazard treatments and safety devices to reduce thoracic injury potential.** As above, serious thoracic injury was the predominant injury mechanism amongst both fatal and non-fatal crashes. The numerical simulation methodology for thoracic injury developed in the present study would be a useful tool by which researchers could assess and develop infrastructure and safety solutions that reduce the thoracic injury potential to motorcyclists (for example barrier design, ‘motorcycle-friendly’ barrier modifications, hazard treatments, padding devices, shielding devices, chest protection devices, etc).
- **Investigate the potential for thoracic impact protection devices to reduce injury, develop product standards and promote/educate motorcyclists.** This recommendation is derived from the finding that while serious thoracic injury was the predominant injury mechanism, currently no thoracic impact protection devices are worn by motorcyclists on the roadways.
- **Improve helmet designs and standards.** This recommendation is derived from the finding that helmets were worn in 89% of fatal crashes yet 60% sustained a serious head injury, which indicates that the functional limit of helmets is regularly being exceeded. The occurrence of intracranial injuries amongst helmeted motorcyclists was particularly noted.

Funding partners and researchers

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Researchers that have worked on the project are:

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1. Project background and introduction

Motorcyclist injuries and fatalities contribute significantly to road trauma in the ACT. Fatality rates per 10,000 vehicles in the ACT in 2011 were 2.47 for motorcycles and 0.12 for cars, resulting in a fatality rate for motorcycles 20.6 times that for cars [1]. Motorcyclists are also overly represented amongst serious injuries. In the 2006-2007 financial year the serious injury rate per 100,000 registered vehicles in the ACT was 1474 for motorcycles and 141 for cars, resulting in a serious injury rate for motorcycles 10.5 times that for cars [2]. In the same period in the ACT the serious injury rate per 100 million vehicle kilometres was 413 for motorcycles and 11 for cars, resulting in a serious injury rate for motorcycles 37.5 times that for cars [2].

This project aims to investigate the incidence of and causal factors in fatal and non-fatal motorcycle crashes in the ACT during the period 2001 – 2010, and propose strategies to reduce road trauma amongst this group. The project involved two stages of data collection and analysis, in which detailed fatality and injury data was analysed respectively. Forensic reconstruction analysis of fatal crashes was performed. Injury data was collected and used to identify crash characteristics and injury profiles. The results were used to propose road safety strategies to reduce motorcycle trauma on ACT roads.

Stage 1 - Fatal crashes and forensic reconstruction

Motorcyclist fatality cases that occurred in the period 2001 - 2010 were collected from the ACT Coroners’ court. Crash reconstructions and computer simulations developed a detailed picture of the causal factors that led to the crash, and the biomechanical causal factors that led to the fatal injuries.

Stage 2 - Injury statistical analysis

Police-reported crash data and hospital separations data from Canberra Hospital in the period 2001 - 2010 were collected for motorcycle crashes in the ACT leading to injuries. Statistical analyses of these data provided general information pertaining to injury profiles, and crash and rider characteristics.

Stage 3 - Policy outcomes to reduce motorcycle trauma

The results of the first two stages were used to propose road safety strategies and/or identify areas of further research to reduce motorcycle trauma on ACT roads. These include rider behaviour campaigns, education/enforcement tactics and engineering design solutions.

2. Ethics approvals

1. Ethics approval to use the National Coroners Information System (NCIS) and view Coronial case files was received from the Justice Human Research Ethics Committee, Department of Justice (CF/09/4288).
2. Ethics approval to use de-identified unit record files of hospital separations line data was received from the ACT Government Health Directorate Human Research Ethics Committee, ACT Government Health Department (ETHLR.11.151).
3. Ethics approval to perform the research was received from the University of New South Wales Human Research Ethics Committee (HREC 08180).

3. Methods

3.1 Analysis of police-reported motorcycle crashes, ACT 2001-2010

This study is a retrospective descriptive analysis of police-reported road traffic crashes involving motorcyclists in the ACT, during the ten year period between 2001 and 2010. The crashes resulted in property damage only, injury or death. The de-identified unit record files of all motorcyclists were requested from the Department of Traffic Management and Safety, Roads ACT. In this study an 'ACT crash' was identified as a motorcycle crash that occurred in the ACT and was reported to police. Descriptive analyses were performed on motorcyclist demographics (age, gender, licence), crash mode (number of vehicles, collision type, collision location) and crash environment (day of the week, light condition, road condition, weather). These analyses provide general information relating to when, where and how motorcycle crashes occur in the ACT.

3.2 Analysis of injuries sustained in motorcycle crashes from hospital records, ACT 2001-2010

This study is a retrospective descriptive analysis of hospital separations data. In the Canberra region, all trauma cases requiring public hospital admission are treated at Canberra Hospital [3]. Private hospital treatment of road trauma in the ACT is negligible, however Canberra Hospital also treats serious trauma occurring in surrounding areas of NSW, and a smaller number of ACT residents who were injured elsewhere. In an attempt to restrict the analysis to ACT hospitalisations, de-identified unit record files of hospital separations were collected from Canberra Hospital, limited to residents of the ACT. Thus in this study an 'ACT hospitalisation' was identified as a motorcyclist who was an ACT resident and crashed either in the ACT or the surrounding area, and was admitted to Canberra Hospital. All non-fatal separations resulting from injury to a motorcyclist that occurred in the ten year period between 2001 and 2010 were collected, by limiting to the following ICD-10-AM [4] codes:

1. Injury as the Principal Diagnosis (ICD-10-AM range S00–T98)
2. Motorcycle riders in Land Transport Accidents (external causes of injury ICD-10-AM range V20 to V29)

Data for motorcycle registrations in the ACT were collected from the Australian Bureau of Statistics [5].

In the hospital separations unit record files, an episode of care ends with a discharge, transfer or the death of the patient. Some types of transfers (statistical transfers) involve the patient becoming a different type of patient within the same stay in hospital, for example a patient moving from acute care to rehabilitative care. In some cases the patient was discharged, then returned some days later to receive further treatment for the injuries sustained in the motorcycle crash. Such cases were identified using the patient ID number, and multiple episodes were merged by summing the lengths of multiple admissions. This resulted in one record per individual presenting at the hospital with injuries received from a single motorcycle crash, with the length of stay being the cumulative length of stay for all episodes related to that crash.

The unit record files contained up to 20 injury diagnoses per person, an external cause of injury and a place of occurrence, all coded according to ICD-10-AM [4]. Injury diagnoses were grouped according to particular types of injuries and injuries occurring to specific body regions. Logistic regression was used to provide odds ratios and 95% confidence intervals, and statistical significance was measured at the level $p < 0.05$.

Injury severity is not straightforward to calculate from ICD-10 coding, however two methods have been developed in the literature. The first involves the proprietary software ICDMAP-90 [6], where ICD-9-CM diagnosis codes are translated to the Abbreviated Injury Scale (AIS) [7], which score injuries from one (minor) to six (major). However, this technique involves first mapping the ICD-10-AM codes to ICD-9-CM-A codes, then mapping those to ICD-9-CM codes, then translating those to AIS scores. This is a complex process and predictive power would be lost at each translation step. An alternative technique that has been developed is the ICD-based Injury Severity Score (ICISS) [8,9], which involves estimating the probability of death directly from the ICD diagnoses codes. The ICISS method involves calculating a Survival Risk Ratio (SRR), that is the probability of survival for each individual injury diagnosis code, as the ratio of the number of individuals with that injury code who have not died to the total number of individuals diagnosed with that code. Thus, a given SRR represents the likelihood that a patient will survive a particular injury. Each patient's ICISS score (survival probability) is then the product of the probabilities of surviving each of their injuries individually. This may be a single SRR, as in the case of a patient with a single injury, or it may be multiple SRRs, as in the case of a patient with multiple injuries [9]. The SRRs require a large database of cases for which survival is known in order to be calculated, however may nominally be applied to cases in other similar data collections. The present data did not provide sufficient cases for the calculation of SRRs, however SRRs developed with Australian data of 523,633 hospital separations were obtained [9], where the resulting ICISS scores were shown to perform well [9]. These SRRs are used with the present data to calculate ICISS scores for each patient. The SRR is also used to define serious injuries, where a threshold value of 0.965 was used. This value represents a 96.5% chance of survival, and corresponds to the survival rate for a serious injury (AIS3) according to the AIS [7]. All analyses were performed in SAS v9.2 [10].

3.3 Analysis of injuries sustained in fatal motorcycle crashes, ACT 2001-2010

This study is a retrospective descriptive analysis of motorcyclist fatalities that occurred during the ten year period between 2001 and 2010 in the ACT. The fatalities were identified using 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 includes 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 police, autopsy and toxicology reports. 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.

To identify the motorcycle crashes in the NCIS database, the initial query was designed as follows:

1) The ACT jurisdiction was selected;
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. A request was then made to the ACT Coroner for permission to view the Coronial case reports, and the full reports were accessed and copied at the ACT Coroners Court. The Coronial cases typically contained the Coroners finding, police report, autopsy and toxicology report.

Injuries were coded according to the Abbreviated Injury Scale (AIS) [7] from the autopsy reports, and only serious (AIS3+) injuries were coded. The serious injuries sustained in the fatal crashes were then compared with the serious injuries sustained in non-fatal crashes from hospital records (Section 3.2).

3.4 Reconstructions of fatal motorcycle crashes, ACT 2001-2010

The police reports were reviewed in order to establish the characteristics and contributing causal factors associated with the fatal crashes. The characteristics of the crash included the motorcyclist demographics (age, gender, licence), crash mode (number of vehicles, collision type, collision location) and crash environment (day of the week, light condition, road condition, weather). The reports from the crash investigation team, on-scene police officers and witnesses, combined with the maps and photos of the crash scenes, were used to reconstruct the crashes and identify the contributing causal factors that led to the crash.

3.5 Development of a numerical modelling protocol to assess thoracic injury potential

The non-fatal and fatal injury analyses indicated that thoracic injury was the predominant serious injury mechanism sustained by motorcyclists in the ACT (see results sections 4.3 and 4.4). While spine and head injury are relatively well understood injury mechanisms, thoracic injury and the potential for motorcyclists to sustain thoracic injury, is relatively poorly understood. Therefore the numerical simulation task focussed on thoracic injury, and the development of a simulation protocol to assess thoracic injury potential to motorcyclists. A validated simulation protocol will allow researchers to assess and develop infrastructure and safety solutions that reduce the thoracic injury potential to motorcyclists (for example barrier design, ‘motorcycle-friendly’ barrier modifications, hazard treatments, padding devices, shielding devices, chest protection devices, etc).

From the results of the injury analyses, it was determined that fixed object collisions were the leading cause of fatality, and guardrail roadside barriers were the most frequently occurring type of fixed object. Therefore the numerical simulation task focussed on thoracic injury resulting from guardrail barriers.

Cases were identified that involved a motorcyclist colliding with a steel W-beam barrier (guardrail) in the sliding posture, and for which a full reconstruction of the crash scene was available, including the approach angle, sliding distance, pre-crash speed and final resting position of the motorcyclist. The sliding posture involves the motorcyclist impacting the roadway prior to contact with the barrier, then sliding along the road surface into the barrier. Cases were identified where the motorcyclist was likely to have collided with the post of the guardrail. These were identified as when either: a witness saw the motorcyclist impact a post; the motorcyclist was found lying in contact with a post; the motorcyclist was found immediately adjacent to a post. Since only two ACT cases satisfied these conditions, seven further cases identified from a broader Australian study were included in the crash cases from [11].

The post-collision cases with serious thoracic injury were assumed to have impacted the post in the thorax-leading orientation. Two thorax-leading impact scenarios were considered, where the motorcyclist was assumed to impact the guardrail post with the thorax laterally or frontally, as shown in Figure 1a and 1b, respectively. Cases where the thoracic injuries occurred predominantly unilaterally were assumed to have resulted from impact with a post in the lateral orientation, and those occurring bilaterally were assumed in the frontal orientation.

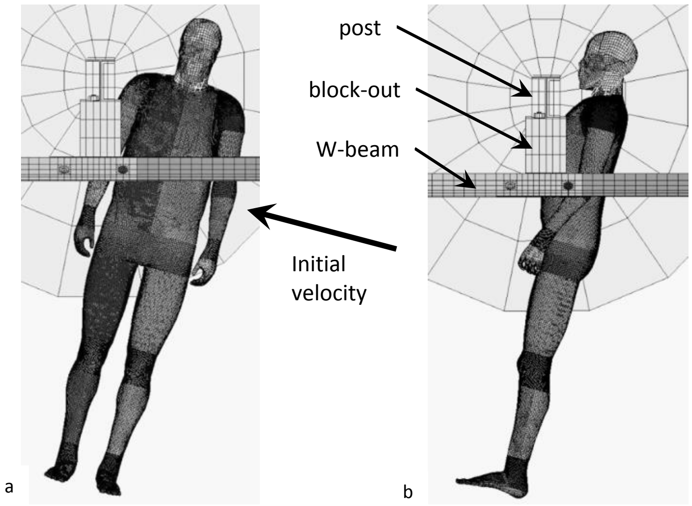


Figure 1. FEM model of THUMS impacting a guardrail post in the thorax-leading orientation; a) lateral impact, b) frontal impact

The post impact speed was determined from the pre-crash speed and the measured distance the motorcyclist slid on the roadway. Several authors have determined drag coefficients for humans sliding on roadways, with values ranging from 0.37 to 0.75 [12-15]. A mean value of 0.6 was used in the present analysis, and standard equations for velocity changes occurring from sliding distances were employed.

The Total Human Model for Safety (THUMS) average size male (50th percentile - AM50) FEM model was used to simulate the human body (Figure 1), developed by Toyota Motor Corporation [16]. The THUMS model simulates human body kinematics and injury responses in crashes. High-resolution CT scans were used to digitise the interior of the body and to generate precise geometrical data for the bones, organs, tissues, ligaments, muscles, skin etc. The FE mesh consists of around 2,000,000 elements representing the components of the human body.

The steel W-beam barrier FEM model developed by the National Crash Analysis Centre (NCAC) at George Washington University in the United States was used to simulate the barrier. The barrier model consists of steel posts set into the ground, wooden blockouts and steel W-beams (Figure 1). The FEM mesh consists of around 125,000 elements and is used extensively for vehicle-barrier collision modelling. In Australia, guardrail posts are typically 150mm deep steel C-sections. The steel post in the FEM model is a 150mm deep I-section, thus the use of this model assumes the motorcyclist impacted the open face side of a C-section post. The impact position of the thorax on the post was assumed to be the same in all cases, and was determined by sliding the THUMS model into the barrier at an angle of 15 degrees (the average angle of all cases), such that the head did not contact the preceding post.

The biofidelity of the THUMS model was validated against experiments on cadavers subjected to blunt anterior-posterior and lateral impacts to the chest. The anterior-posterior thoracic impacts [17,18] were generated with a 6 inch diameter unpadded impactor of varying mass (3.6 to 52 pounds) propelled at varying velocities (11 to 32 mph). The lateral thoracic impacts [19] were generated with a 150mm diameter unpadded impactor with a mass of 23.4kg propelled at varying velocities (4.5 to 9.4 m/s). The experimental setup and impact conditions were modelled with THUMS. The force-deflection response corridors of the impactors in the cadaver experiments were compared with those obtained with the THUMS model.

The numerical model of the motorcyclist-guardrail collision was validated against the field-observed motorcyclist-barrier collisions. For each crash case, the initial crash conditions were input into the model (impact speed, angle and frontal/lateral orientation). In the cadaver studies [17-19], the incidence and severity of thoracic injuries were found to be closely associated with the normalised thoracic compression, being the thoracic deflection divided by the thoracic diameter. The thoracic diameter is the width of the thorax measured along the direction of the applied impact load. The normalised thoracic compression was used to compare the motorcyclist-guardrail collision model results with the field-observed crashes.

4. Results

4.1 Descriptive results of police-reported motorcycle crashes, ACT 2001-2010

A total of 1,918 motorcycle crashes were identified in the police-reported database of road crashes that occurred during the ten year period between 2001 and 2010 in the ACT. Of these 1,918 crashes, 1,216 (63.4%) did not result in injury to the motorcyclist (property damage only), while the remaining 702 (36.6%) resulted in injury. The motorcyclists were predominantly males (92%), 35% of crashes were single-vehicle crashes and 47% occurred at an intersection.

It is important to note that there are large differences between the police-reported injured motorcyclists and those identified from the Canberra hospital separations data. This results from the fact that not all crashes are reported to the police. A data linkage study between police reported crashes in the ACT and hospital separations at Canberra hospital during the period 2001 to 2003 [4], indicated that 33.5% of individuals presenting to hospital following a motorcycle crash reported the crash to police. For single vehicle motorcycle crashes the police-reporting rate was only 21.4%. While the police-reported crash data do not include a large number of motorcycle crashes, they contain more detailed information about the crashes than are available in the hospital separations data. These data are a useful source of information pertaining to the characteristics of motorcycle crashes in the ACT, and are summarised in Figures 2 to 9.

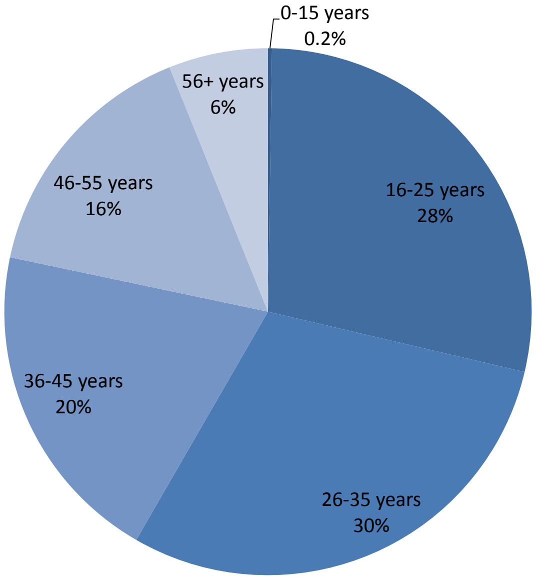


Figure 2: Age distribution of police-reported motorcycle crashes, ACT 2001-2010 (n=1,231 known cases)

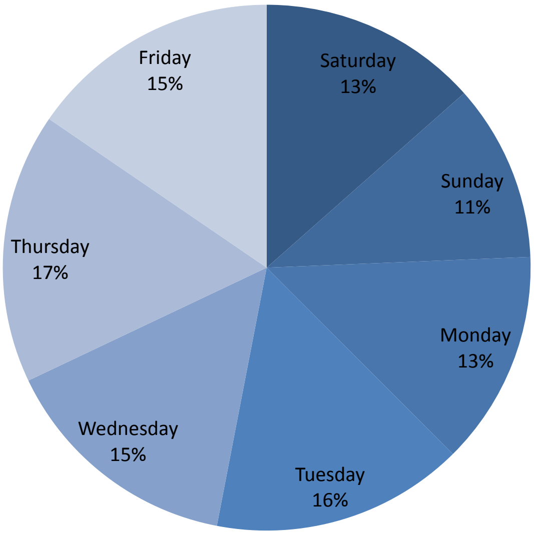


Figure 3: Day of the week of police-reported motorcycle crashes, ACT 2001-2010 (n=1,918)

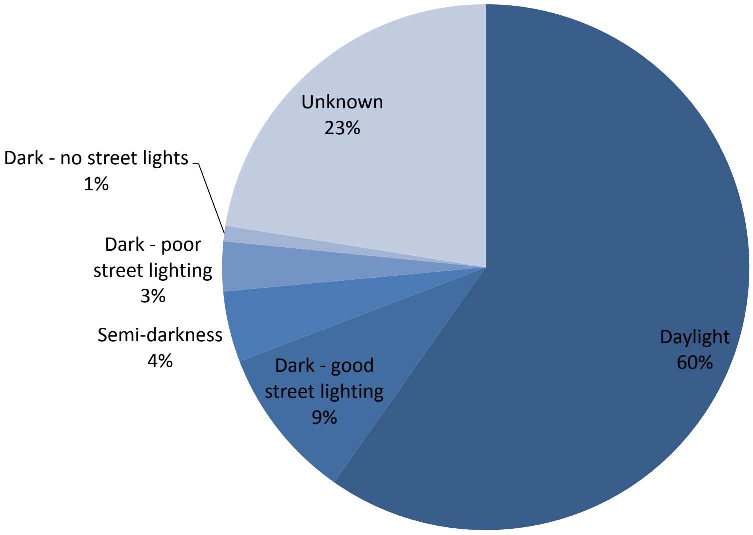


Figure 4: Lighting condition of police-reported motorcycle crashes, ACT 2001-2010 (n=1,918)

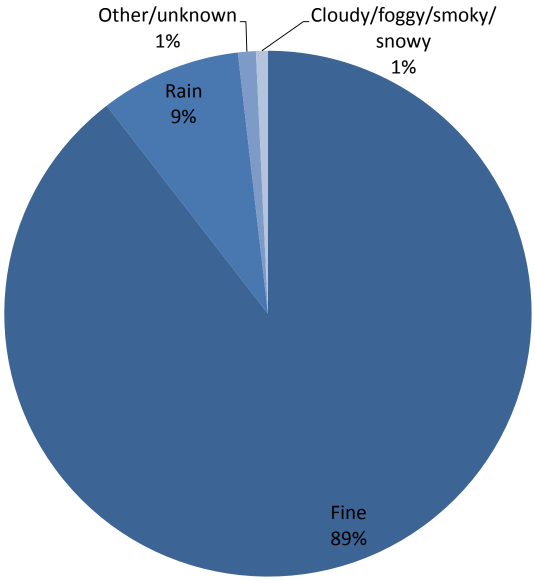


Figure 5: Weather condition of police-reported motorcycle crashes, ACT 2001-2010 (n=1,918)

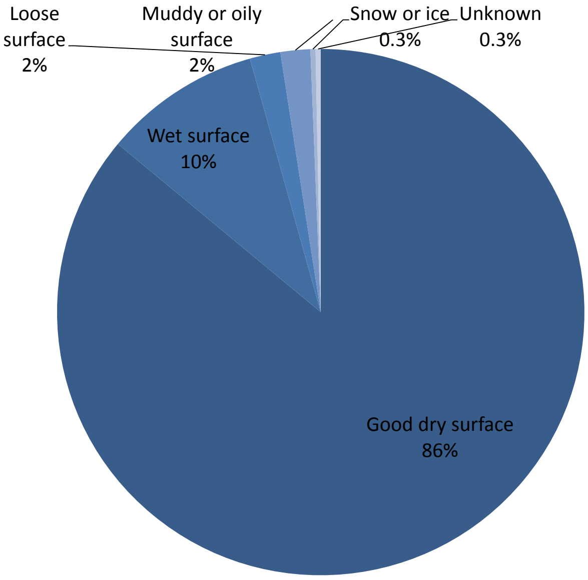


Figure 6: Roadway condition of police-reported motorcycle crashes, ACT 2001-2010 (n=1,918)

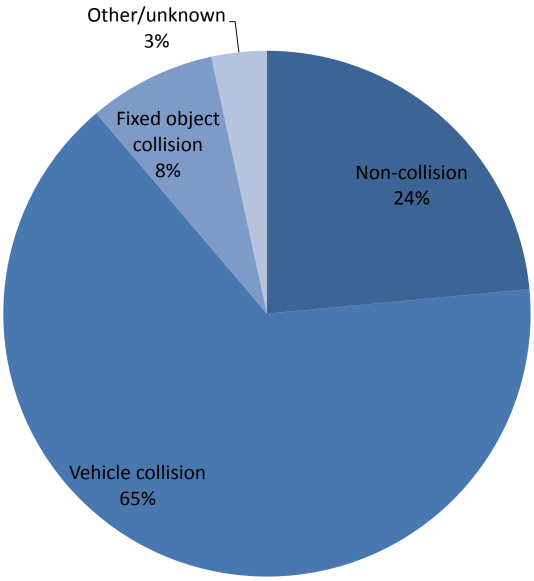


Figure 7: Collision mode of police-reported motorcycle crashes, ACT 2001-2010 (n=1,918)

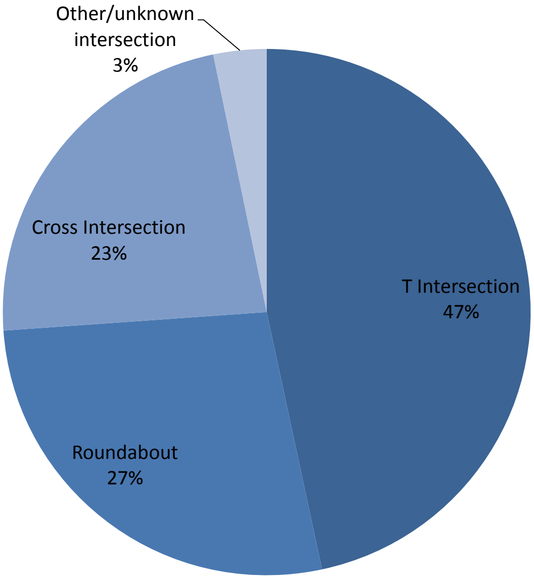


Figure 8: Intersection type of police-reported motorcycle crashes, ACT 2001-2010 (n=892 intersection crashes)

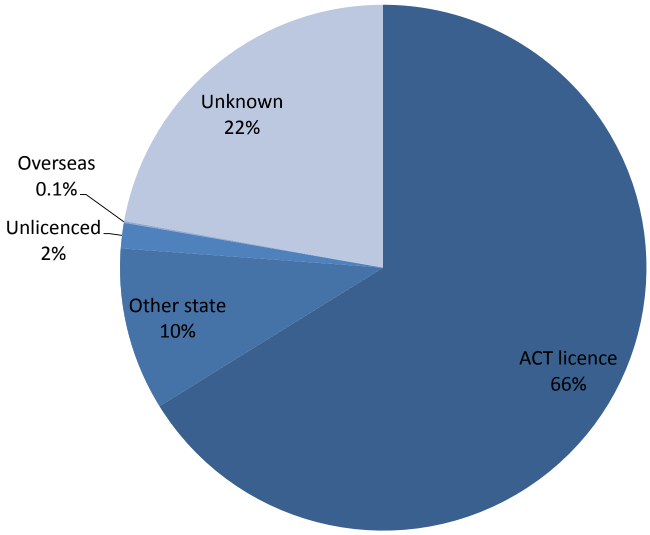


Figure 9: Licence type of police-reported motorcycle crashes, ACT 2001-2010 (n=1,918)

Results for police-reported motorcycle crashes in Figures 2 to 9 indicate that: the majority involve 16-35 year olds (58%); they occur reasonably evenly amongst all days of the week; they occur predominantly in daylight during fine weather conditions on a dry roadway; they occur predominantly as a result of a collision with a vehicle; around half of crashes occur at intersections, with T-intersections being the most common; and the motorcyclists are predominantly licenced in the ACT.

4.2 Descriptive results of motorcycle crashes from hospital records, ACT 2001-2010

Following the merging of multiple episodes for individuals undergoing a single crash incident, a total of 1,199 separations were recorded at Canberra Hospital for ACT residents that received injury resulting from a motorcycle crash during the period 2001-2010. Of these 1,199 individuals, 92% were male. The mean number of separations per year, separations per year for older age groups, and motorcycle registrations per year are compared in Figure 10.

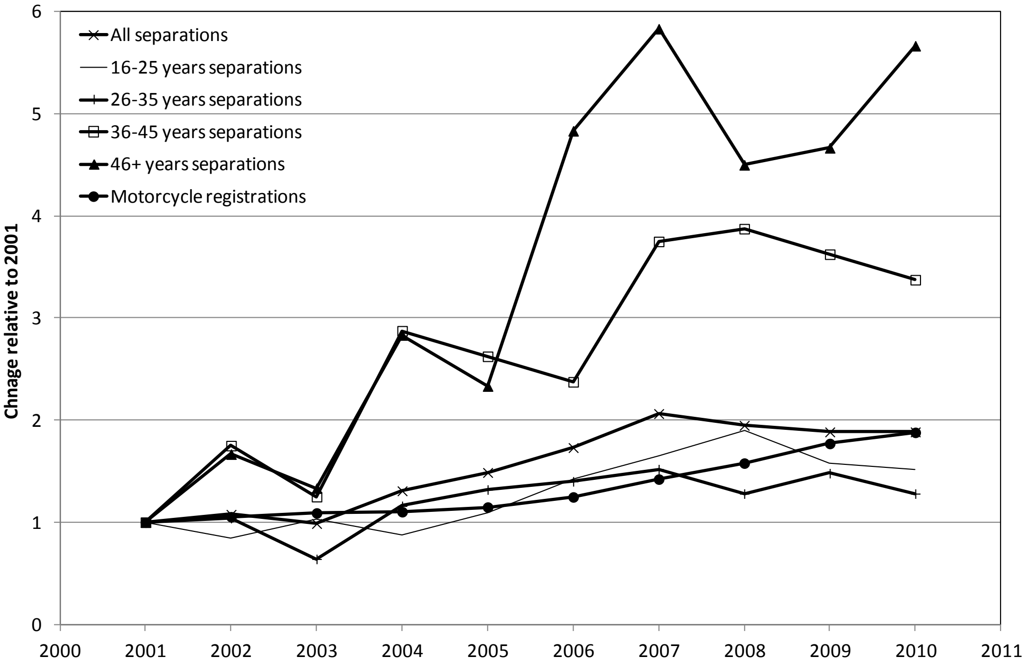


Figure 10: Temporal change in motorcyclist separations and motorcycle registrations

The number of separations per age group over the study period is shown in Figure 11. The age group of 16 to 25 years had the greatest number of separations, and as the age increased the frequency of separations decreased. The proportions of total separations in the older age groups were; 36% for the 36+ age group, and 18% for the 46+ age group.

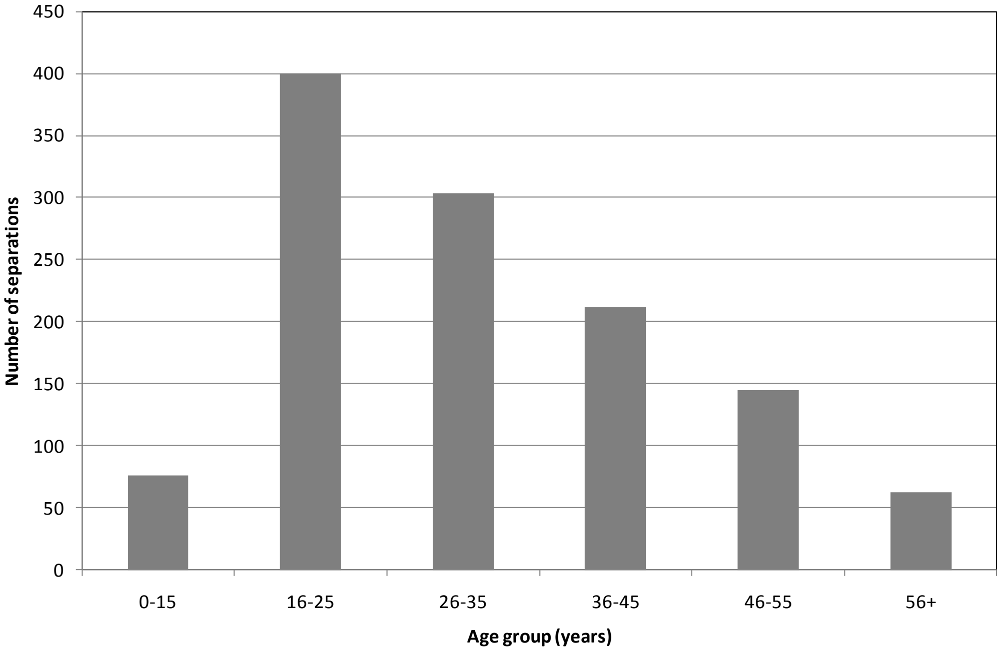


Figure 11: Separations by age group

Analysis of the external cause codes indicated that 31% of the separations resulted from crashes occurring in non-traffic areas. The areas where these occurred are shown in Figure 12. In all age groups except those less than 15 years, the majority of crashes occurred in traffic areas. The majority of separations in the less than 15 years group occurred in non-traffic areas, likely due to the fact that these persons would not be licensed and would therefore be unable to lawfully ride in traffic areas.

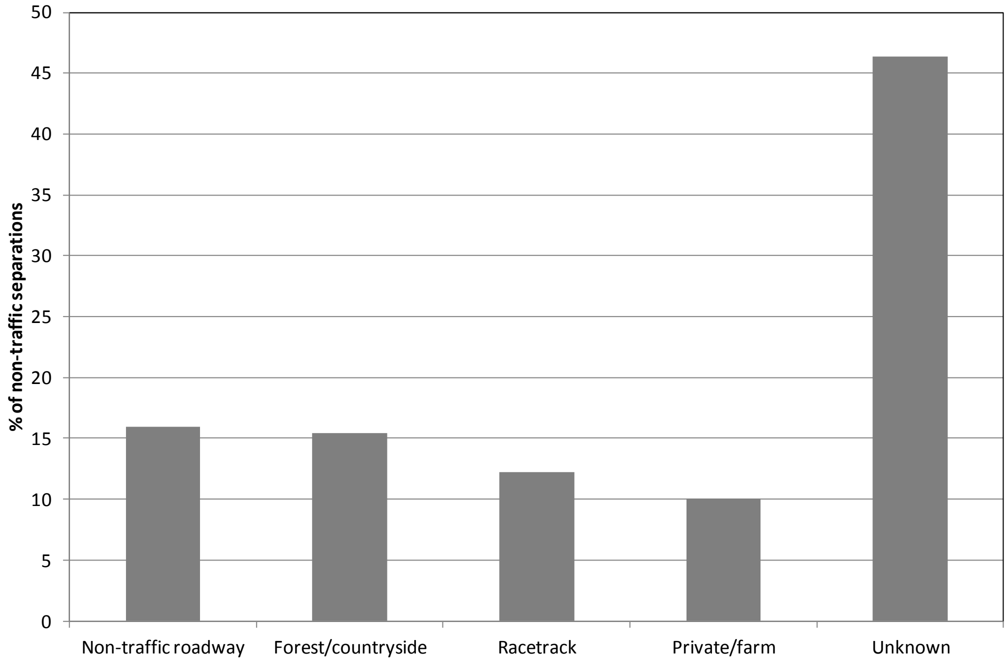


Figure 12: Place of occurrence for non-traffic separations (n = 370)

Analysis of the external cause codes indicated the counterpart in the crash with the motorcyclist. As shown in Figure 13, the majority of crashes (51%) occurred without a collision with a counterpart. That is, the motorcyclist crashed onto the ground without striking another vehicle or fixed object. This crash mode does not preclude the involvement of other road users, for example a car may have pulled out in front of the motorcyclist causing the motorcyclist to swerve, lose control and fall to the ground without striking any object. Collisions with passenger vehicles were the next most frequent crash mode (18%), followed by collisions with fixed objects (9%). A small number of collisions occurred with pedestrians (2%), other 2/3 wheeled motorcycles (2%) and heavy vehicles/buses (1%).

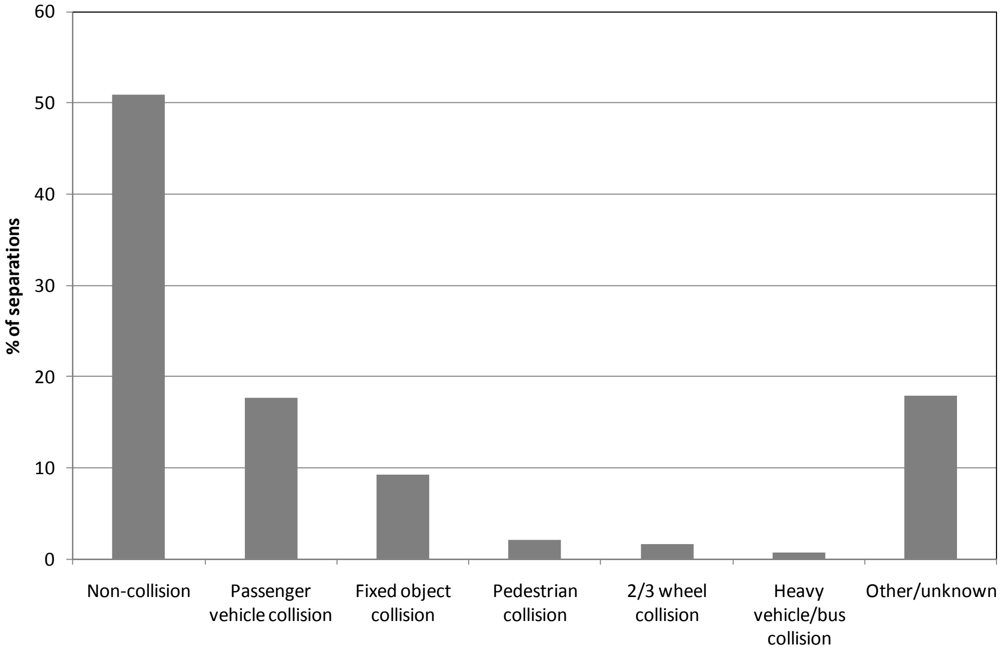
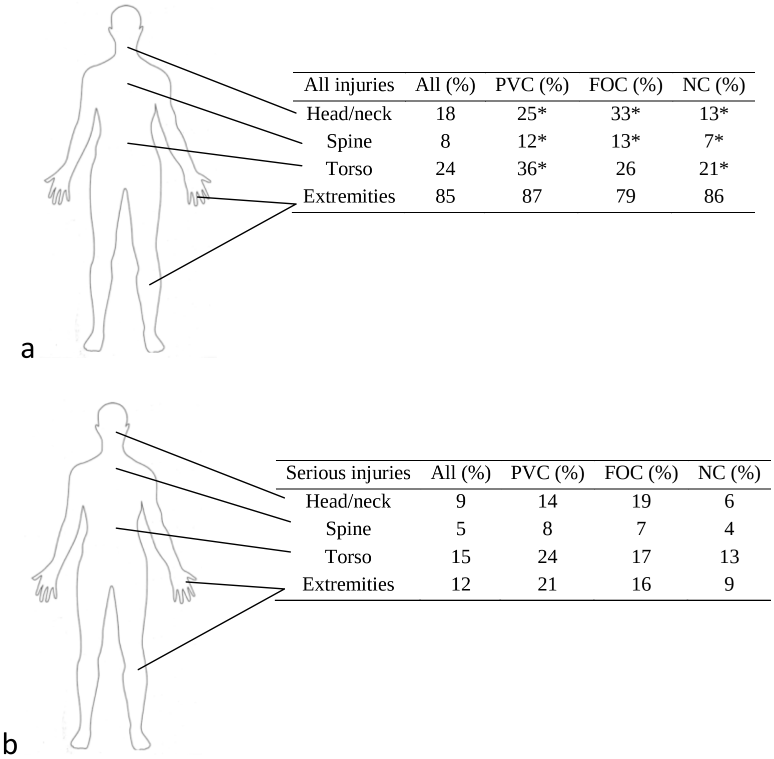


Figure 13: Counterpart in the collision with the motorcyclist (n = 1,199)

4.3 Injury results sustained in motorcycle crashes from hospital records, ACT 2001-2010

The injury results are presented as injury totals, and as individuals that received at least one injury to each body region. In the former case the total is the total number of injuries, in the latter the total is the total number of individuals. Results are also presented for all injuries, and serious injuries only. Figure 14 presents the number of individuals that received at least one injury to the principle body regions. Statistically significant results for comparisons between different crash modes are indicated in Figure 14, and the corresponding statistical results are shown in Table 1. More detailed results for these injuries are presented in Table 2. Traumatic brain injury (Table 2) is defined in Appendix A.



All injuries	All (%)	PVC (%)	FOC (%)	NC (%)
Head/neck	18	25*	33*	13*
Spine	8	12*	13*	7*
Torso	24	36*	26	21*
Extremities	85	87	79	86

Serious injuries	All (%)	PVC (%)	FOC (%)	NC (%)
Head/neck	9	14	19	6
Spine	5	8	7	4
Torso	15	24	17	13
Extremities	12	21	16	9

Figure 14: Proportion of motorcyclists that received at least one injury to a body region disaggregated by crash mode; a) all injuries, and b) serious injuries (PVC = passenger vehicle collision, FOC = fixed object collision, NC = no collision). * indicates results that are statistically significant between different crash modes (Table 1).

	Comparison	Odds ratio	95% CI	95% CI	*p*
Head/neck	PVC vs NC	2.13	1.44	3.15	0.0001
Head/neck	FOC vs NC	3.17	1.99	5.03	<.0001
Spine	PVC vs NC	1.81	1.08	3.06	0.024
Spine	FOC vs NC	1.97	1.04	3.74	0.036
Torso	PVC vs NC	2.09	1.49	2.95	<.0001
Traumatic brain injury	PVC vs NC	2.34	1.56	3.53	<.0001
Traumatic brain injury	FOC vs NC	2.85	1.74	4.67	<.0001

Table 1: Odds ratios for differences in injuries amongst different crash modes. (PVC = passenger vehicle collision, FOC = fixed object collision, NC = no collision).

All injuries	*n*	%
traumatic brain injury	179	14.93
other head	67	5.59
neck	16	1.33
spinal cord	11	0.92
vertebral column	96	8.01
thorax	179	14.93
abdomen	69	5.75
pelvis & lower back	83	6.92
other abd, lb, & pelvis	37	3.09
trunk, other	13	1.08
upper extremity	645	53.79
hip	29	2.42
other lower extremity	576	48.04
multiple body regions	2	0.17
system wide	29	2.42
unspecified region	16	1.33

a

Serious injuries	*n*	%
traumatic brain injury	103	8.59
other head	2	0.17
neck	4	0.33
spinal cord	10	0.83
vertebral column	53	4.42
thorax	116	9.67
abdomen	50	4.17
pelvis & lower back	56	4.67
other abd, lb, & pelvis	1	0.08
trunk, other	1	0.08
upper extremity	51	4.25
hip	25	2.09
other lower extremity	82	6.84
system wide	19	1.58
unspecified region	2	0.17

b

Table 2: Number of individuals that received at least one injury to specific body regions; a) all injuries, and b) serious injuries

A total of 3,338 injuries were received by the 1,199 individuals, and of these 1,425 were serious injuries. The injuries are summarised in Table 3, and further detailed in Table 4. Individual injury counts are provided in Appendix B.

All injuries	*n*	%
head & neck	417	12.49
spine & back	217	6.50
torso	541	16.21
extremities	2112	63.27
not classifiable by site	33	0.99
unspecified	18	0.54
TOTALS:	3338	100

a

Serious injuries	*n*	%
head & neck	298	20.91
spine & back	185	12.98
torso	528	37.05
extremities	386	27.09
not classifiable by site	25	1.75
unspecified	3	0.21
TOTALS:	1425	100

b

Table 3: Injury counts by general body region; a) all injuries, and b) serious injuries

All injuries	*n*	%
traumatic brain injury	313	9.38
other head	87	2.61
neck	17	0.51
spinal cord	26	0.78
vertebral column	191	5.72
thorax	300	8.99
abdomen	86	2.58
pelvis & lower back	101	3.03
other abd, lb, & pelvis	39	1.17
trunk, other	15	0.45
upper extremity	1048	31.40
hip	33	0.99
other lower extremity	1031	30.89
multiple body regions	3	0.09
system wide	30	0.90
unspecified region	18	0.54
TOTALS:	3338	100

a

Serious injuries	*n*	%
traumatic brain injury	279	19.58
other head	6	0.42
neck	13	0.91
spinal cord	33	2.32
vertebral column	152	10.67
thorax	322	22.60
abdomen	102	7.16
pelvis & lower back	102	7.16
other abd, lb, & pelvis	1	0.07
trunk, other	1	0.07
upper extremity	117	8.21
hip	58	4.07
other lower extremity	211	14.81
system wide	25	1.75
unspecified region	3	0.21
TOTALS:	1425	100

b

Table 4: Injury counts by specific body region; a) all injuries, and b) serious injuries

The ICISS scores are summarised in Figure 15, where 41% of the injury outcomes were serious (or worse). Means for different crash modes, crash locations and age groups are shown in Table 5, and length of hospital stays (LOS) are included for comparison purposes.

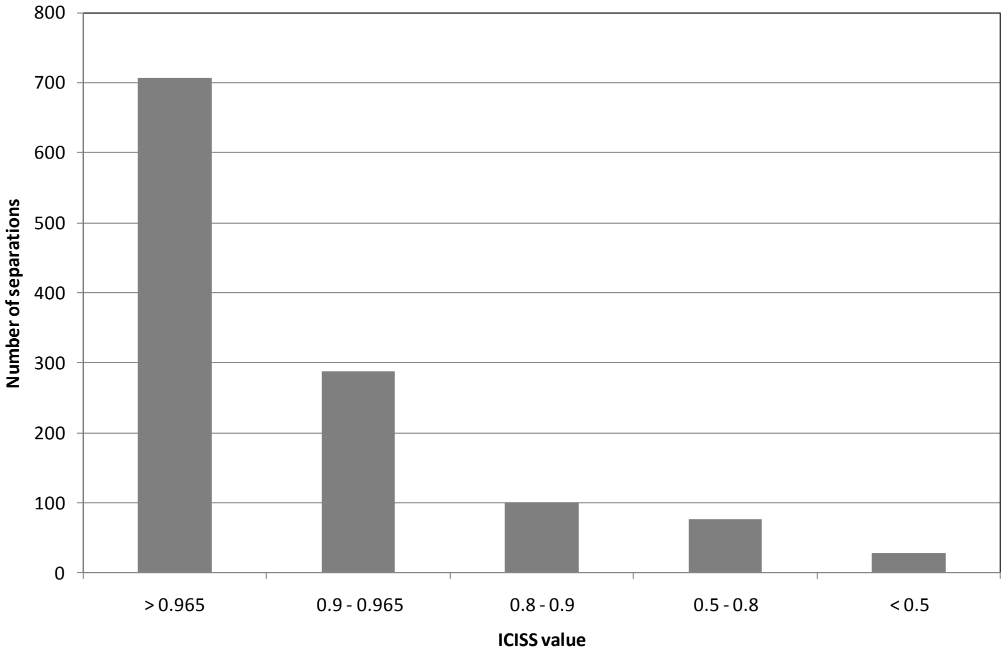


Figure 15: Mean injury outcome severities (ICISS) value ranges for all separations

	n	Mean ICISS	Mean LOS
Passenger vehicle collisions	211	0.884	7.60
Fixed object collisions	110	0.901	6.02
Non-collisions	609	0.949	4.28
Traffic crashes	828	0.922	5.35
Non-traffic crashes	370	0.949	4.19
0-15 years	76	0.960	5.17
16-25 years	400	0.941	3.84
26-35 years	303	0.926	6.35
36-45 years	212	0.921	5.70
46-55 years	145	0.921	5.95
56+ years	63	0.906	8.67

Table 5: Mean injury outcome severities (ICISS) and length of hospital stays (LOS)

A summary of the injury analyses is presented in Figure 16, where the predominance of thoracic injury is highlighted in terms of the most frequently occurring particular serious injury, the highest proportion of serious injuries to any body region, and the highest proportion of motorcyclists with at least one serious injury in the region.

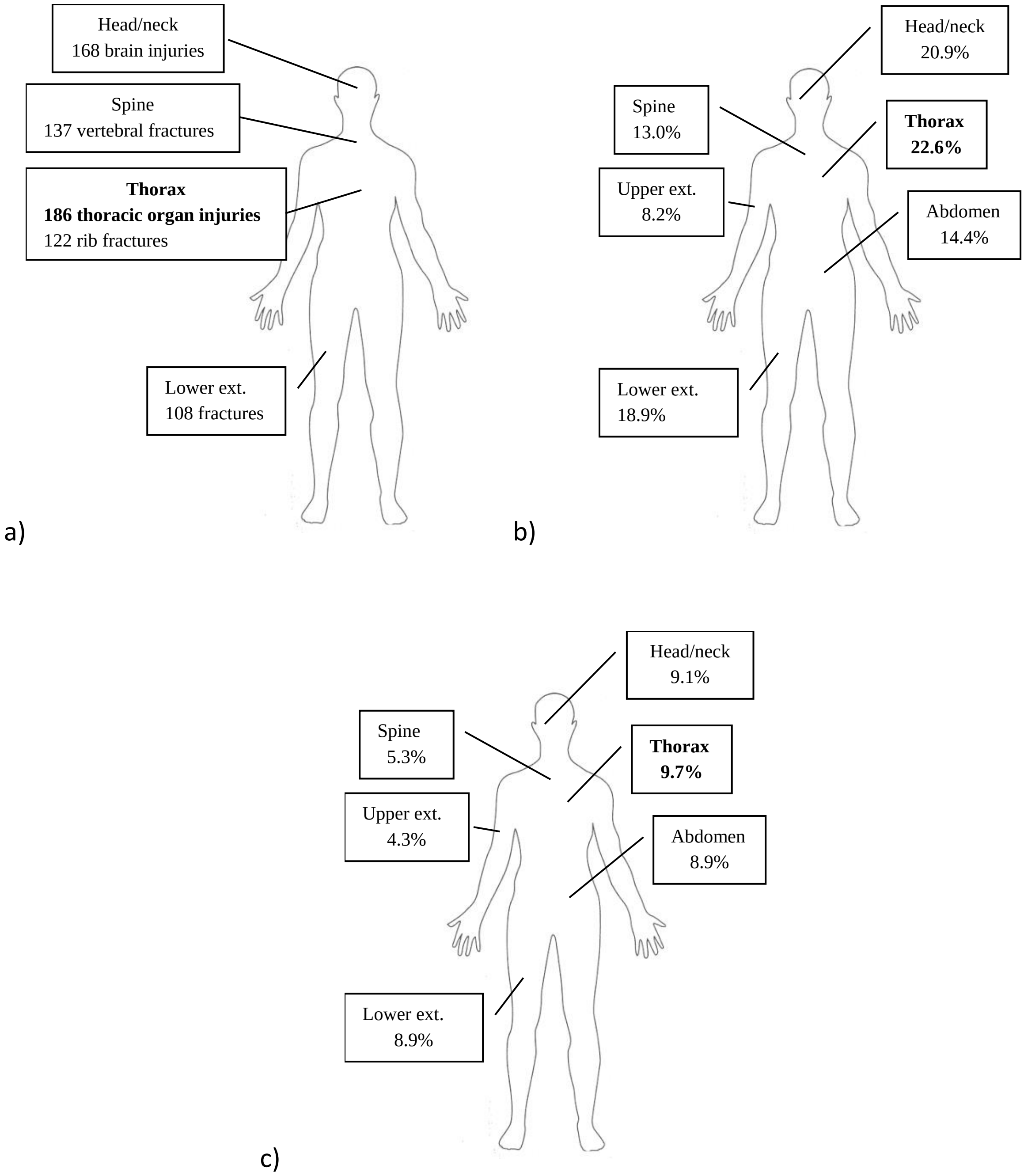


Figure 16: Summary of serious injuries sustained by 1,199 motorcyclist casualties admitted to Canberra Hospital, 2001-2010; a) five most frequent serious injuries, b) proportion of all serious injuries in each body region (n=1,425 serious injuries), c) proportion of motorcyclists with at least one serious injury in each body region (n=1,199 motorcyclists)

4.4 Injury results sustained in fatal motorcycle crashes, ACT 2001-2010

A total of 35 motorcycle fatalities occurred during the ten year period between 2001 and 2010 in the ACT, and the full Coronial case reports for all fatalities were collected from the ACT Coroner. All case reports contained a police report, Coronial finding and autopsy, while 77% of cases contained a toxicology report. The analysis of serious injuries sustained by the 35 motorcyclist fatalities is presented in Figure 17, based on the autopsy reports. The results in Figures 16 and 17 indicate that thoracic injuries account for the greatest number of serious injuries and the greatest proportion of serious injuries, and the thorax is the most frequently seriously injured body region amongst hospitalised casualties and fatal casualties.

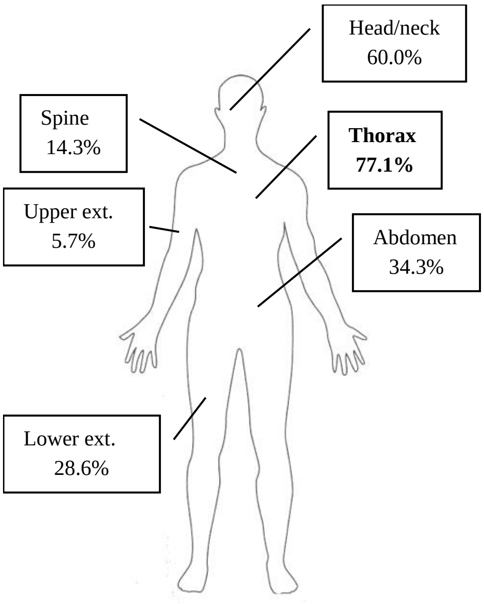


Figure 17: Proportion of motorcyclist fatalities with at least one serious injury in each body region, ACT 2001-2010 (n=35 motorcyclists)

4.5 Head injuries sustained by helmeted fatally injured motorcyclists, ACT 2001-2010

The analysis of serious injuries sustained by motorcyclists that were fatally injured also identified that serious head injury occurred frequently (Figure 17). Twelve of these head-injured motorcyclists were wearing a helmet at the time of the crash. These results indicate that the functional limits of current helmets are being exceeded in some cases. It is possible that improvements in helmet design might assist in reducing the incidence and/or severity of serious head injuries amongst motorcyclists in severe crashes. In order to assist this process, a detailed analysis was performed of the nature of the head injuries sustained by these 12 helmeted motorcyclists with head injury.

Of these 12 cases, 8 sustained skull fractures and 10 sustained intracranial injuries. Of the 8 that sustained skull fractures, 6 sustained basal skull fractures that did not communicate with the cranial skull. Such fractures are typically associated with impacts that did not occur at the fracture site; that is the impact occurred to the cranial vault, however the fracture occurred in the base of the skull. Typically the presence of a helmet does little to ameliorate the occurrence of such fractures.

The intracranial injuries sustained by 10 motorcyclists are shown in Figure 18. Brain injuries were frequently sustained in the cerebrum, however the inferior aspects of the brain were also frequently injured, including the brain stem and the cerebellum.

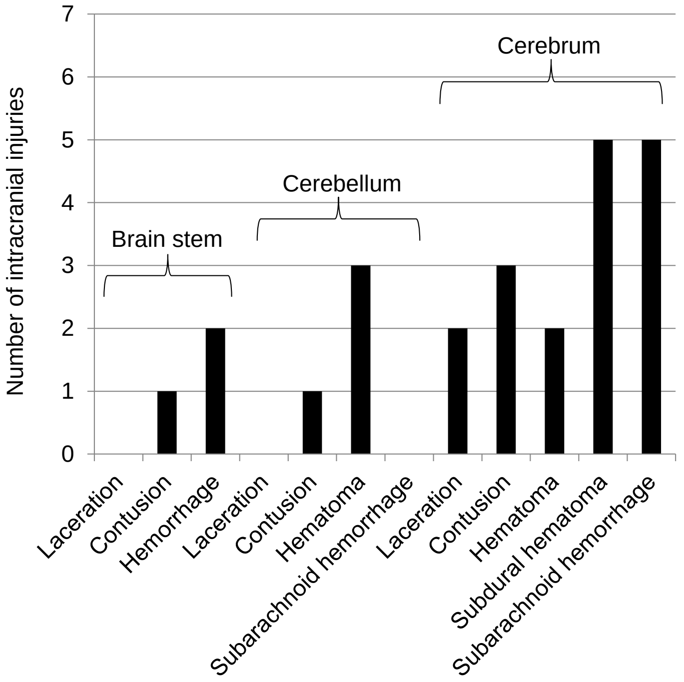


Figure 18: Intracranial injuries sustained by helmeted motorcyclists, ACT 2001-2010 (n=10 motorcyclists)

4.6 Characteristics of fatal motorcycle crashes from crash reconstructions, ACT 2001-2010

Analysis of the 35 fatalities indicate that the motorcyclists were predominantly males (94%), the average age was 34 years, 66% of fatal crashes were single-vehicle crashes, 91% occurred on public roadways, 11% of motorcyclists were not wearing a helmet, the weather was predominantly fine and dry, 14% of motorcycles involved were not registered, 9% of motorcyclists were not licenced and 9% had a learners licence. The crash characteristics are presented in Figures 19 to 24.

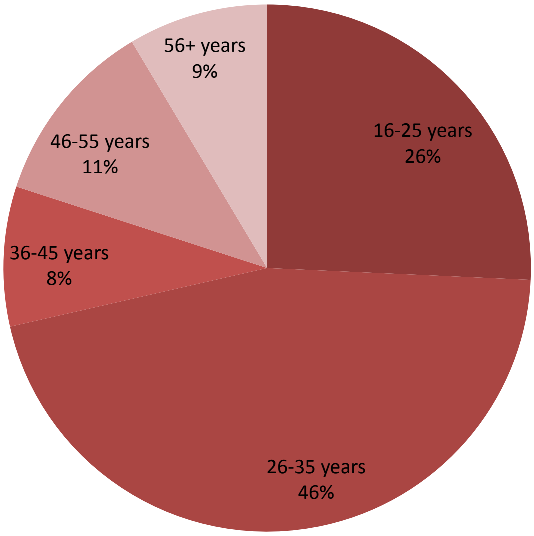


Figure 19: Age distribution of fatal motorcycle crashes, ACT 2001-2010 (n=35)

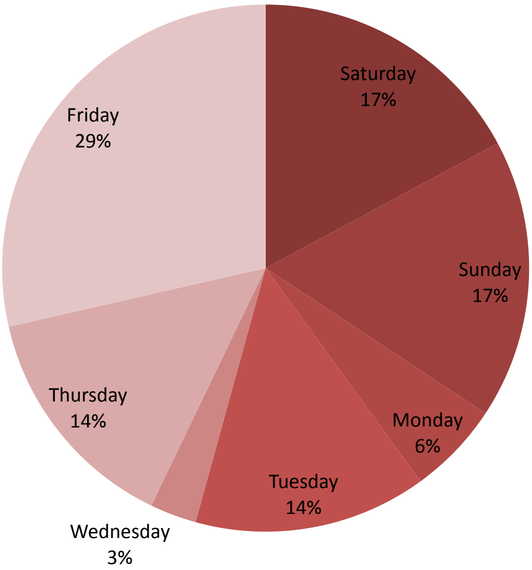


Figure 20: Day of the week of fatal motorcycle crashes, ACT 2001-2010 (n=35)

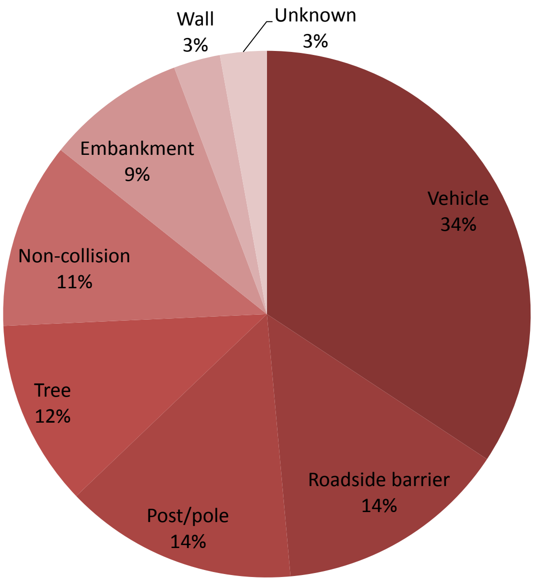


Figure 21: Collision object of fatal motorcycle crashes, ACT 2001-2010 (n=35)

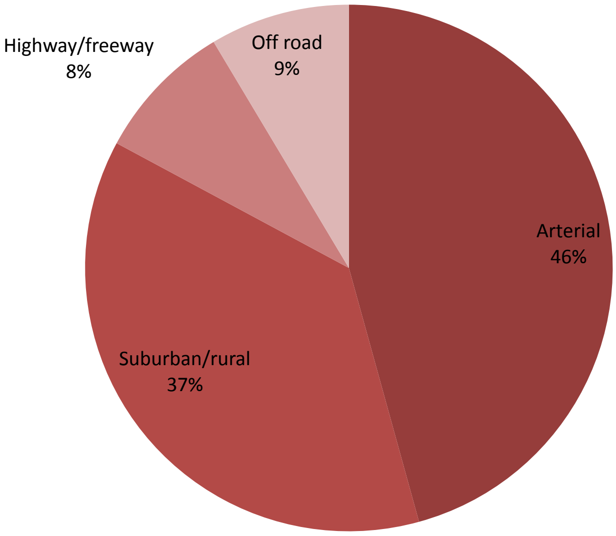


Figure 22: Location of fatal motorcycle crashes, ACT 2001-2010 (n=35)

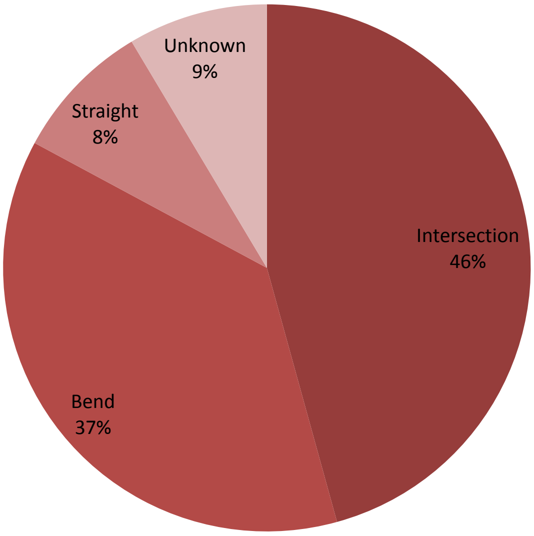


Figure 23: Roadway alignment of fatal motorcycle crashes, ACT 2001-2010 (n=35)

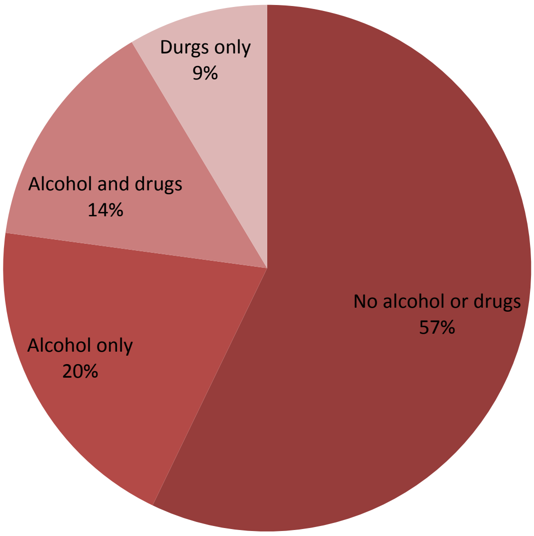


Figure 24: Toxicology of fatal motorcycle crashes, ACT 2001-2010 (n=35)

Results for the 35 fatalities in Figures 19 to 24 indicate that: the majority involved 16-35 year olds (72%); they occurred predominantly on Fridays, Saturdays and Sundays (63%); they occurred predominantly as a result of collisions with fixed objects (52%), with roadside barriers and posts/poles occurring most frequently (28%); they occurred predominantly on arterial (46%) and suburban/rural (37%) roadways; around half of crashes occurred at intersections (46%), with bend locations being the most common non-intersection locations (37%); and nearly half of the motorcyclists (43%) were under the influence of alcohol and/or drugs.

4.7 Contributing causal factors from reconstructions of fatal motorcycle crashes, ACT 2001-2010

The reports from the crash investigation team, on-scene police officers and witnesses, combined with the maps and photos of the crash scenes, were used to reconstruct the crashes and identify the contributing causal factors that led to the crash. The 35 fatalities were disaggregated into two groups, identifying when the motorcyclist was at fault (25 cases) or another road user was at fault (10 cases). The contributing casual factors of the crash are presented in Figure 25 for all fatalities. Of the total 35 fatalities, the predominant contributing causal factor was 'risky riding behaviour' by the motorcyclist (51%). 'Risky riding behaviour' includes one or more of; speed, alcohol use, drug use, non-helmet use or disobeying a traffic control. Speed includes speed considered excessive for the conditions and/or speed in excess of the speed limit.

Of the 25 fatalities where the motorcyclist was established to be at fault, in 7 cases the motorcyclist lost control of the motorcycle and no contributing factors could be established. In all of the other 18 cases, it was established that the motorcyclist was riding in a manner that was considered risky riding behaviour.

Of the 10 fatalities where the motorcyclist was established to not be at fault, in 9 cases another vehicle operator was at fault and in 1 case an animal on the roadway caused the crash. In the majority of cases when another vehicle was at fault, the vehicle turned in front of the motorcyclist while the motorcyclist was travelling along the roadway in a legal manner. It is noted that in Figure 24 there were 15 cases where the motorcyclist was under the influence of alcohol and/or drugs, however in Figure 25 for only 13 motorcyclists were alcohol and/or drugs considered contributing causal factors. This results from the fact that while 2 motorcyclists were under the influence, the other vehicle was considered to be at fault in those crashes (in one case a car ran through a red light in front of the motorcyclist and in the other a car veered across the median into the motorcyclist).

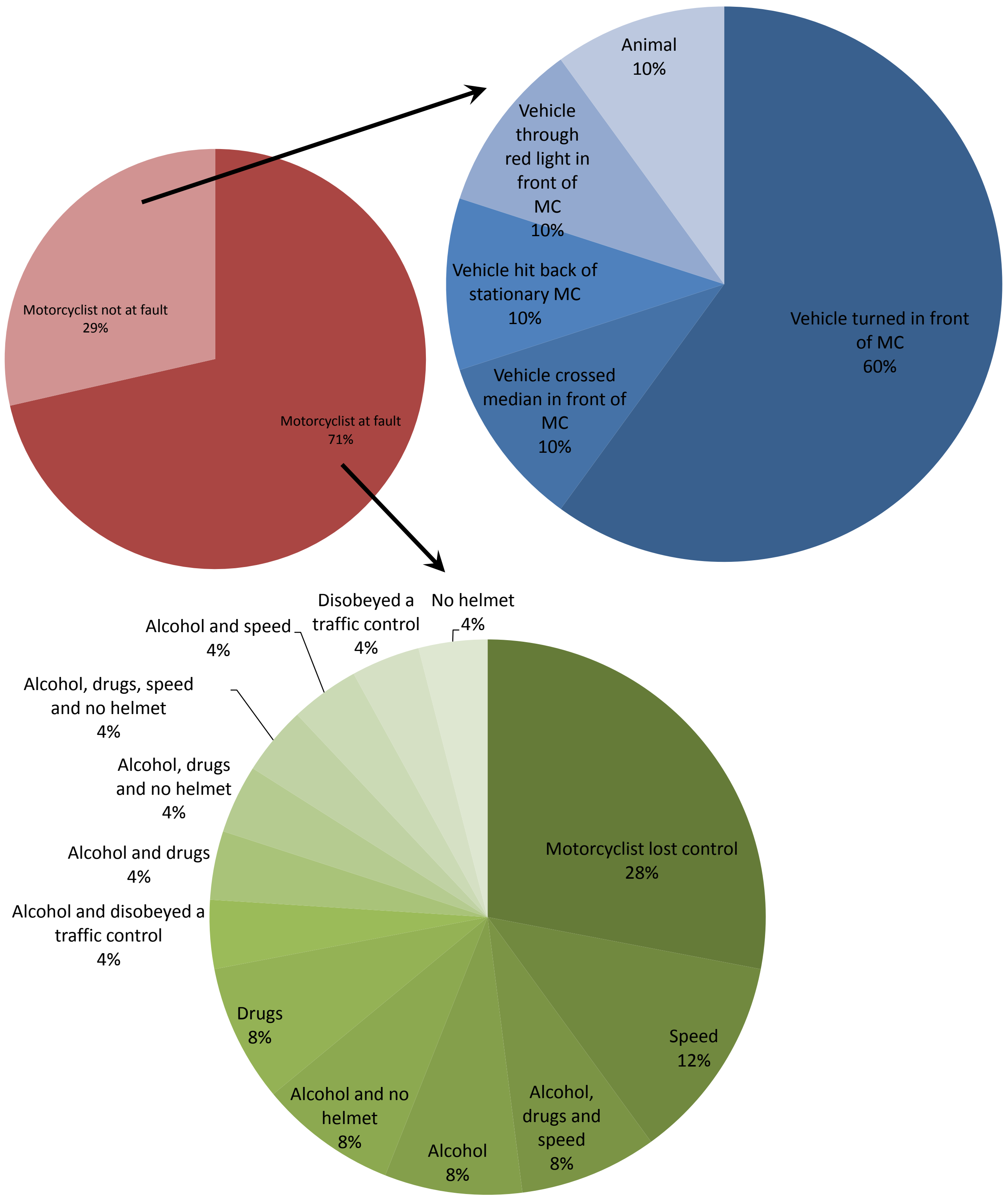


Figure 25: Contributing causal factors for the motorcyclist fatalities, ACT 2001-2010 (n=35)

4.8 Numerical modelling protocol to assess thoracic injury potential

Two ACT cases were identified of motorcyclist-barrier collision crash cases in the sliding posture, where the motorcyclist was likely to have collided with the post of the guardrail in the thorax-leading orientation, and a further seven were derived from other Australian states [11]. These cases are summarised in Table 6. The assumed impact orientation is tabulated in Table 6, where three cases were assumed to have occurred laterally with the remaining six frontally. The calculated post impact speeds varied between 25.9km/h and 76.2km/h, and the impact angles varied between 5 and 32 degrees. The maximum AIS severity levels of the thoracic injuries (MAIS) were generally quite severe, ranging from AIS3 to AIS6 with five cases of critical injury (AIS5+), which is to be expected considering the high impact speeds and the fact that the crashes were fatal.

Assumed impact orientation	**Thoracic injuries determined from autopsy**	**MAIS thorax**	**Post impact speed [a] (km/h)**	**Impact angle (degrees)**	**Thoracic deflection/ thoracic diameter**
Frontal	L ribs #1-4 fx, R rib #2 fx, ruptured pericardial membrane, perforated R heart ventricle, L lung collapse, R lung oedema, R lung contusions, L haemothorax	6	75	21	0.562
Frontal	Multiple bilateral rib fx with flail chest, transected sternum, multiple heart lacerations with rupture, bilateral haemothorax	5	63	16	0.539
Frontal	Bilateral lung collapse, bilateral haemopneumothoraces, posterior subparietal pleural haemorrhages, transverse fx at T1-T2 with partial cord transection	4	26	19	0.423
Frontal	Tension pneumothorax, multiple bilateral rib fx	5	76	16	0.592
Lateral	L lung contusions and lacerations, L haemothorax, L ribs #3-8 fx (parasternal), R ribs #5-8 fx (lateral)	3	29	18	0.393
Frontal	Bilateral collapsed lungs, L ribs #1-12 fx (anterolateral), R ribs #1-6 fx (anterior), flail chest with sternum fx, bilateral haemothoraces, pericardium and heart lacerations, aorta transection	6	63	16	0.534
Lateral	L flail chest with ribs #5-11 fx (posterolateral), L lung contusions and lacerations, L lung collapsed, L haemopneumothorax, diaphragm lacerations	4	39	28	0.527
Lateral	L ribs #2-6 fx (parasternal)	3	30	32	0.417
Frontal	R ribs #3-5 fx, L ribs #3-5 fx, sternum fx, bilateral haemothoraces, R ventricle and L atrium ruptures, T3 fx with cord transection	6	72	5	0.566

L = left, R = right, fx = fracture

[a] calculated from the pre-crash speed estimate and measured sliding distance

Table 6. Motorcyclist-barrier collision crash cases with guardrail post impacts in the thorax-leading orientation

A variety of impactor mass and speed combinations were modelled for frontal and lateral thoracic impacts and the THUMS model generally performed well, with the force-deflection curves lying approximately within the response corridors. Some examples are presented in Figure 26.

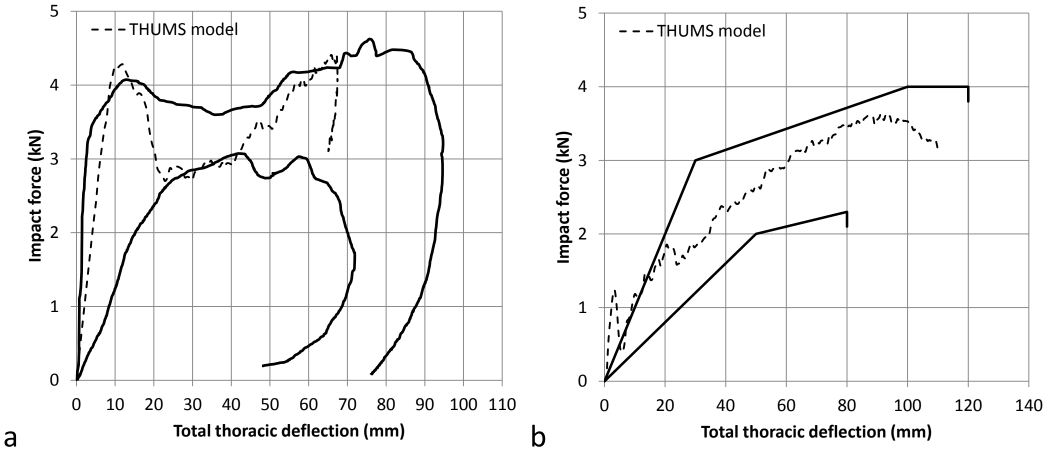


Figure 26. Force-deflection response of the THUMS model compared with the cadaver response corridors; a) frontal thoracic impact with a 23.1kg impactor at 7.2m/s [17,18], b) lateral thoracic impact with a 23.4kg impactor at 6.7m/s [19]

The crash mechanics of the motorcyclist-barrier post collision numerical model is presented in Figure 27 for the thorax-leading lateral orientation. The frontal orientation results were similar, where the majority of the motorcyclist kinetic energy is expended upon impact with the rigid post, and the motorcyclist body wraps around the post.

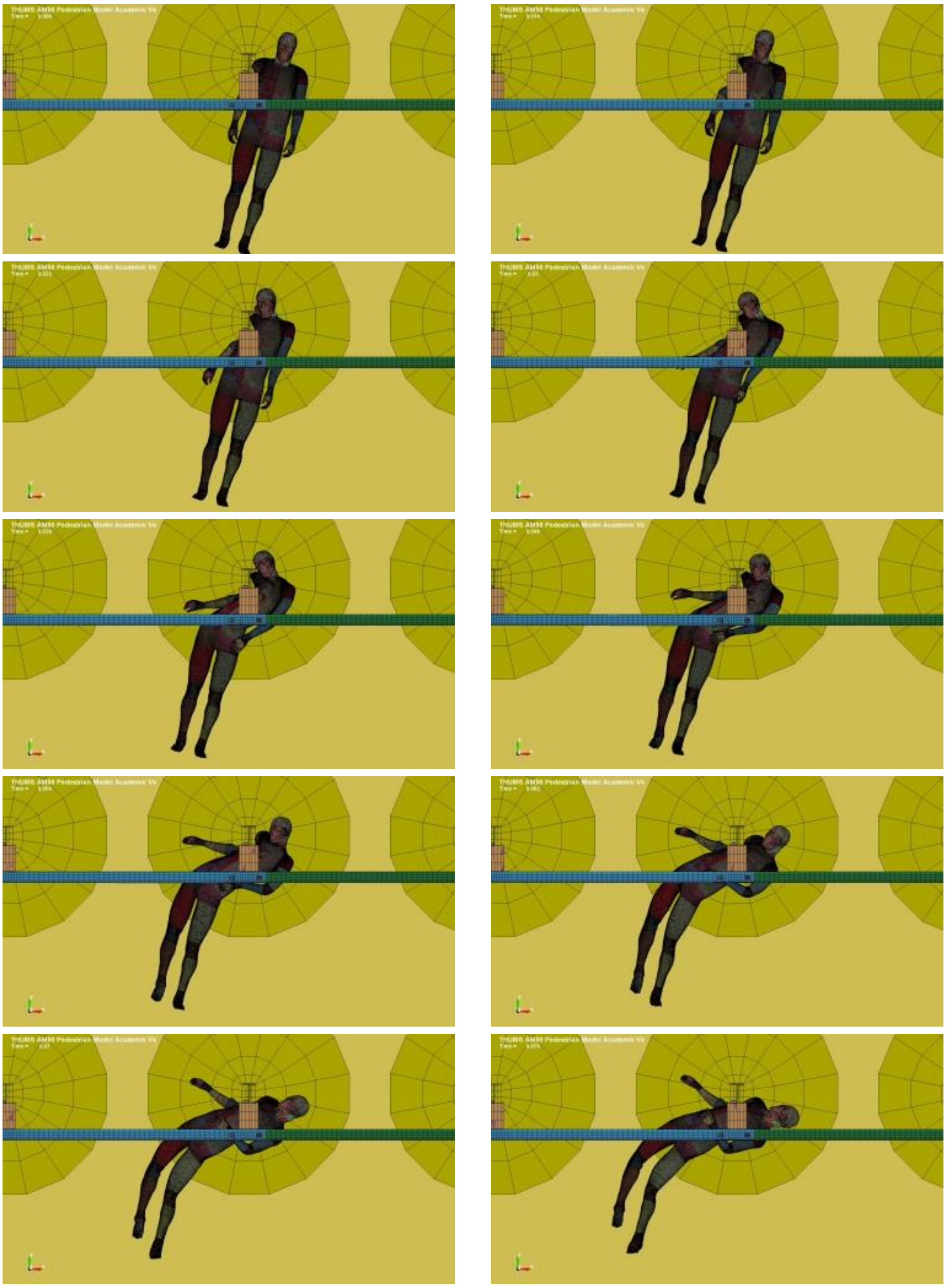


Figure 27. THUMS impact with a guardrail post in the thorax-leading lateral orientation at 40km/h. Each frame represents 0.008ms.

The response of the thoracic bony structures and internal organs to lateral impact is presented in Figure 28. The impact is somewhat dampened by the presence of the upper arm (not shown), however significant lateral compression of the thorax results as the leading side of the thorax stops against the post and the inertia of the torso compresses the ribs and internal organs.

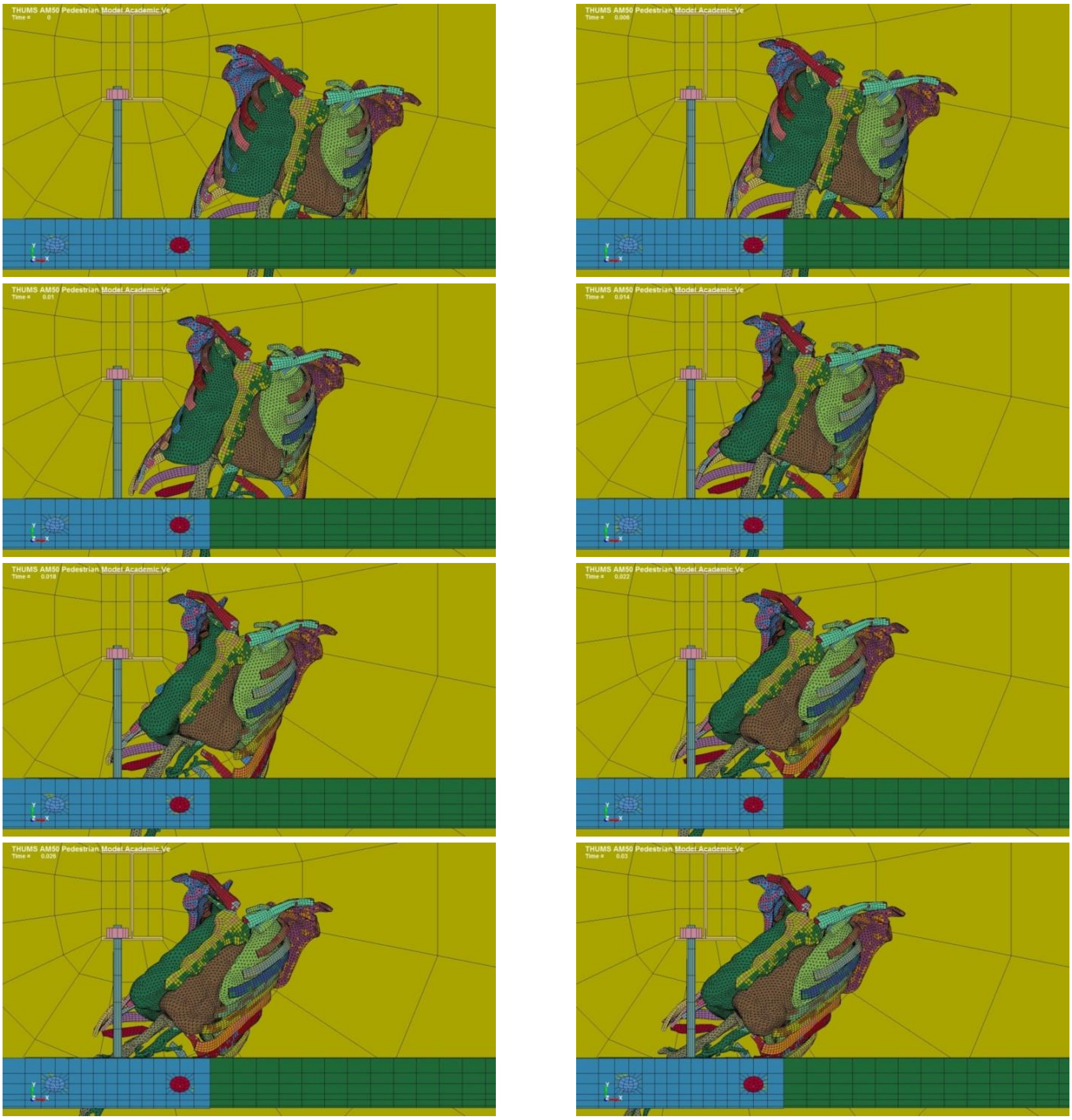


Figure 28: Deformation of the thoracic structures during the impact with the steel W-beam post. Each frame represents 0.004ms.

The biomechanical response of the THUMS model to thorax-leading impact with a guardrail post in the frontal and lateral orientations is expressed as the normalised thoracic deflection from the model. The FEM normalised thoracic deflection results are tabulated in Table 6, and plotted in Figure 29 against the MAIS of the field-observed injuries. The thoracic FEM normalised deflection and MAIS values are compared with those determined experimentally with cadavers [17-19] in Figure 29. The full results for the variety of initial impact conditions tested in the cadaver experiments are presented, and the results are generally in agreement. It may therefore be concluded that the simulation methodology is a generally valid representation of such impacts. The proposed methodology may be summarised as follows:

Proposed numerical protocol for assessing thoracic injury potential:

1. propel a suitable human body model into the barrier post at an impact angle of 15° to the longitudinal axis, such that the head does not impact the preceding post (Figure 1)
2. the human body model should impact the open face side of the post
3. a measured chest deflection of 0.347 times the chest depth frontally, or 0.383 times the chest depth laterally, indicates a serious (AIS3+) thoracic injury [17-19]

The biofidelity of the thorax of the human body model should be validated prior to use, for example against cadaver experiments [17-19]. The human body model could be replaced with a Hybrid III ATD model for the frontal-post orientation, if a human body model is not available or if sufficient computational resources are not available. Hybrid III ATD models are available from the distributers of the LSDYNA software.

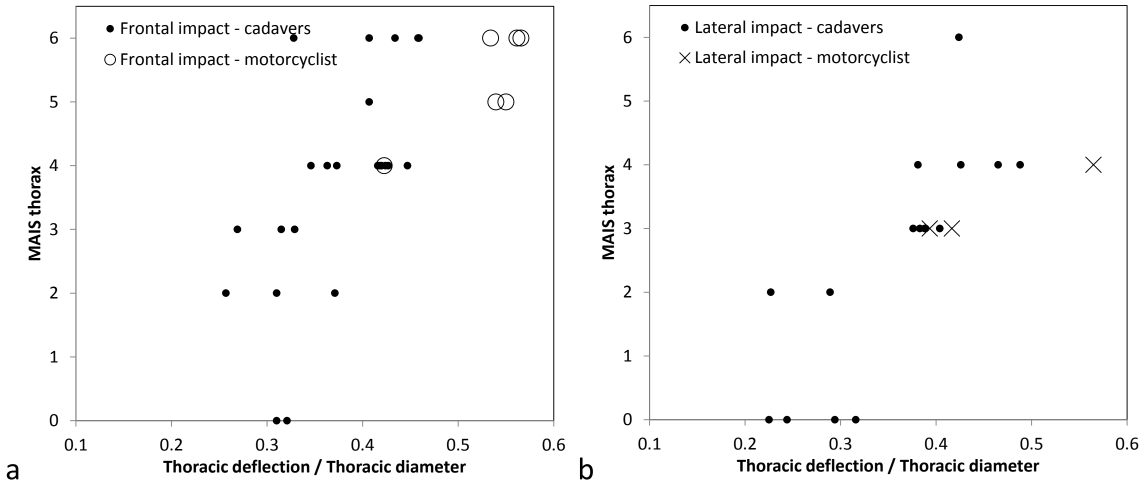


Figure 29. Comparison of the thoracic FEM normalised deflection and field-observed MAIS values from motorcyclist collisions with a guardrail post, with cadaver responses; a) frontal thoracic impact [17,18], b) lateral thoracic impact [19]

5. Discussion

5.1 Injuries sustained in motorcycle crashes in the ACT

The injury results in Figure 14 and Tables 1 – 4 indicate that extremity injuries featured highly amongst all injuries, however much less so amongst serious injuries. Serious thorax and traumatic brain injuries featured highly amongst specific injuries, where 10% and 9% of individuals received serious injuries to these regions, respectively. Around 5% of individuals received serious injury to the pelvis and lower back, and 4% seriously injured the vertebral column. The greatest proportions of total serious injuries were thoracic injuries, followed by traumatic brain injuries. The most common serious thoracic injury was an injury to the internal organs, followed closely by rib fractures (Figure 16). The most common serious traumatic brain injury was an injury to the internal organ (brain). Interestingly, there were three times as many serious brain injuries as skull fractures (Appendix B). Since on average 91% of motorcyclists wear helmets [20], this result indicates that while helmets protect the skull, they may be less effective in protecting the brain. It was statistically significant that the crash modes involving collisions with passenger vehicles or fixed objects, were more likely to result in head/neck, spine and traumatic brain injury than were non-collision crashes (Table 1).

The analyses of injury severities in Figure 15 and Table 5 indicate that the outcome of the motorcycle crash was serious injury in a large number of crashes (where the motorcyclist was injured and presented at hospital) – 41%. This confirms the well known fact that motorcycle crashes are generally injurious events, in part due to the fact that motorcyclists are largely unprotected from the environment around them. For the different crash modes (Table 5), as one would expect collisions with passenger vehicles were the most injurious, followed by fixed object collisions then non-collisions. Traffic crashes were more injurious than non-traffic crashes, likely due to exposure to passenger vehicle collisions. As the age of the individual increased, the injury outcome was more severe, which is a well known physiological result. The lengths of stays in hospital were generally in agreement with the ICISS scores of injury severity. That is, more severe injury outcomes required greater stays in hospital to receive medical procedures and rehabilitate.

Analyses of serious injuries in hospital admissions and fatal crash injuries data indicate that thoracic injury is the predominant serious injury sustained by motorcyclists, followed by head injury. Thoracic injury amongst motorcyclists is not well understood, and currently thorax protective devices are not used or encouraged for on-road motorcyclists, aside from the usual protective equipment recommended for general abrasion resistance. Thorax protective devices for impact do exist, however are typically marketed towards off-road and competition motorcyclists. In Europe there are currently two test Standards for impact protective devices for motorcyclists

[21,22], and a Standard for chest impact is currently under development [23]. Additionally, inflatable chest protection devices similar to air-bags in cars are under development, as is a test Standard [24]. Given the predominance of serious thoracic injury amongst motorcyclists, and the current lack of impact protective devices, there is a significant opportunity to reduce motorcyclist trauma through thoracic protection. The validated numerical simulation protocol could be used by researchers to determine the generic properties of thoracic impact protectors that are required to reduce the injury potential of collisions with fixed objects.

Similarly, while thoracic injury resulting from an impact with a barrier or fixed object has been identified as a serious injury mechanism for fatal and non-fatal motorcycle crashes, currently no crash test protocols and associated injury assessment reference values (IARVs) exist for assessing thoracic injury potential in such collisions. The European technical specification for assessing the injury potential of barriers and barrier modifications for motorcyclists [25] specifies crash test protocols for a Hybrid III anthropomorphic test device (ATD), to assess the injury potential for head, neck and spine injuries. The ATD is propelled head-leading into the barrier at an angle of 30° and speeds of 60km/h or 70km/h, sliding on the ground in the supine position, and maximum permissible values for neck loads and the head injury criterion (HIC) are provided. The current Australian roadside barrier standard AS/NZS 3845:1999 [26] does not consider motorcyclist collision test protocols. Since the European protocols do not address thoracic injury potential, this severely limits their applicability to Australian conditions. There is a significant opportunity to reduce motorcyclist trauma through developing crash test protocols for roadside barriers and ‘motorcycling-friendly’ barriers or barrier modifications, and incorporating these into the Australian barrier standard. The European specification needs to be assessed for its applicability to head and neck injury in Australian conditions, and a thoracic injury test and IARVs need to be developed to additionally assess the thoracic injury potential. Valid crash test protocols will lead to barrier improvements that will reduce the high trauma burden associated with motorcyclist collisions with roadside barriers and other fixed hazards.

Head injury was the second most frequent type of serious injury amongst hospitalised and killed motorcyclists, while the majority of motorcyclists wear helmets in accordance with road laws. These results indicate that in many cases the functional limits of current helmets are being exceeded in crashes, thus there is an opportunity to reduce motorcyclist trauma through improved helmet design. Head injuries sustained by helmeted motorcyclists were predominantly intracranial injuries without skull fractures at the location of the head impact. Thus the helmets worn may have protected the skull against fractures, however did not sufficiently ameliorate the impact forces to protect the brain from injury.

5.2 Crash characteristics and contributing causal factors of motorcycle crashes in the ACT

The temporal change in separations shown in Figure 10 indicates that separations increased on average by around two times over the study period. This was approximately in-line with the increase in motorcycle registrations in the ACT. However, the increase was significantly greater for those in older age groups. The number of separations involving persons aged 36-45 years increased nearly four times, and those aged 46 years and over increased nearly six times, over the ten year period. This is likely due to increases in the uptake of motorcycling in older age groups, as riders return to riding after a period without riding (typically referred as ‘returning riders’). While younger riders constitute the majority of separations, these older age groups represent 36% of total separations. Traditionally safety strategies have focused on younger riders, however these results indicate that older riders should also be targeted in safety strategies.

The analysis of the external cause codes indicated that 31% of the separations resulted from crashes occurring in non-traffic areas. This value is similar to the national average of 38% [27], and significantly greater than the national average for occupants of motor vehicles of 14% [27]. This indicates that motorcyclist safety strategies should not only focus on the public trafficable roadway environment, but should include those riding on private roadways, farms and off-road environments in the countryside.

The characteristics of the police-reported crashes and the fatal crashes are generally similar, and indicate that males aged 16 to 35 years account for the majority of motorcyclist crashes, and they typically occur in the daytime with fine, dry weather conditions, with around half occurring at intersections. Differences between the two data sources indicate that while motorcycle crashes generally occur evenly throughout the week, fatal crashes predominantly occurred between Friday and Sunday. Additionally, while motorcycle crashes generally occur as a result of a collision with another vehicle and rarely with a fixed object, fatal crashes predominantly occur as a result of a collision with a fixed object. However, this result also reflects the nature of police reporting of crashes, where multi-vehicle crashes are more likely to be reported to police than single vehicle crashes [3]. These results are in contrast to those found for all motorcycle hospital separations in Figure 13, where the most frequent crash mode was non-collisions followed by passenger vehicle collisions, again a result of the fact that non-collision crashes occur frequently but are rarely reported to police.

5.3 Numerical modelling protocol for assessing countermeasures to reduce thoracic injury potential

Notwithstanding the large variability in the cadaver experiments with respect to age, gender, physiological condition and experimental variability [17-19], the results in Figure 26 suggest that the THUMS thorax model is a biomechanically valid representation of the human thorax of an average size male. The THUMS thorax typically unloaded at a lower deflection than in the cadaver tests under frontal impact. However, in the majority of cases subjected to the impact conditions in Figure 26 (12 of 13 cadavers), the cadavers sustained multiple rib fractures. Rib fractures were not explicitly modelled with THUMS, thus the THUMS model could be expected to be stiffer than the cadavers subsequent to rib fracture.

The results of the THUMS impact with a guardrail post in the thorax-leading orientation, shown in Figures 27 and 28 for lateral impact, are generally in agreement with the field-observed collisions of direct impacts with a guardrail post, where the majority of the motorcyclist kinetic energy is dissipated during the impact and the motorcyclist resting position was against or adjacent to the post.

The biomechanical response of the THUMS thorax in response to the guardrail post impact is generally in agreement with that derived from cadaver experiments [17-19], where increasing kinetic energy results in increasing thoracic compression, which in turn results in increasing thoracic injury severity. However, the comparisons in Figure 29 indicate that the numerical predictions of thoracic compression for the motorcyclists tend to over-estimate those determined from the cadaver experiments. That is, for a motorcyclist that sustained a thoracic injury of a particular AIS severity, the numerical model of the motorcyclist impacting the guardrail post predicted thoracic compression greater than that observed in cadavers with the same AIS severity. Assuming that the THUMS model is a reasonable representation of an average size male thorax under impact (Figure 26), the over-estimation of the thoracic compression in the guardrail post impact numerical models may therefore be attributed to: the idealisation of the post impact orientation and impact surface; and/or uncertainties in establishing the initial post impact conditions; and/or physiological differences between the cadavers and the motorcyclists. These issues are discussed further below, and should be considered as limitations to the numerical modelling approach used in this study.

It is likely that in the motorcycle crashes the motorcyclist underwent substantial tumbling in addition to sliding along the surface of the roadway prior to impact with the barrier, thus the motorcyclist may not have impacted the barrier post in either the idealised orientation or position that was assumed in the numerical models (i.e. position of the thorax relative to the post). Indeed the fact that the motorcyclist directly impacted the post was inferred from the on-scene police investigation reports, and was not known for certain, except in one case where there was a witness to the crash. The direct thorax impact assumed in the numerical model may over-represent the severity of the impact, which may have led to an over-estimation of the thoracic compression.

Additionally, the impact surfaces were different between the motorcyclists and the cadavers, where the former consisted of the leading edge of an I-section post, while the latter was a comparatively large surface area of diameter 150mm. For the lateral-post orientation, the upper arm directly contacted the leading edge of the post which distributed the impact load to the thorax. The use of an I-section post FE model assumed that the motorcyclist impacted the open side of the C-section post. Different impact surfaces may lead to different load concentrations, which might result in different relationships between local maximum deflection and injury severity. Analysis of the crash scene photographs and reconstructions indicated that the motorcyclists were facing the open side of the C-section posts in one of the three lateral-post impacts and four of the six frontal-post impacts. The FE models were modified to close the face of the I-section post such that it presents the same shape as the closed face of a C-section post. This made negligible difference to the lateral-post impacts, due to the load spreading influence of the upper arm. An average decrease in thoracic compression of 3.7% resulted for the frontal-post impacts, which is nearly negligible due to the fact that the leading corner of the post contacts high on the rib cage at the 3rd rib (Figure 1), thus the presence of the closed face of the post above this point had little influence on the thoracic response. It is noted that the average impact speed for these two cases was 74km/h. It is possible that the shape of the post might have more of an influence at lower impact speeds.

Similarly, there is substantial uncertainty in the initial impact conditions, where the pre-crash speed is a police-reconstructed estimate and the coefficient of sliding friction is a mean value from a wide range of values reported in the literature. However, the impact angle and sliding distance were relatively well established from careful measurements of the markings on the roadway by on-scene police. The pre-crash speed may have been over-estimated by police and/or the sliding friction value may have under-estimated the real friction of the roadway, which may have led to an over-estimation of the severity of the impact and consequently the thoracic compression.

A further limitation of the study is that there were substantial physiological differences between the cadavers and the motorcyclists. The cadaver ages ranged from 19 to 81 years with a mean of 59 years, and 79% were male. The motorcyclist ages ranged from 21 to 70 years with a mean of 37 years, and all were male. It is possible that the THUMS average size male model predicted a relatively accurate magnitude of thoracic compression, and that the motorcyclists did indeed undergo such a compression, however for physiological reasons such compression magnitudes did not result in as severe injuries in the motorcyclists as those that occurred in the cadavers. It is well known that thoracic injury severity, particularly that resulting from rib fractures and concomitant organ injuries, is closely associated with age [28]. For example at a normalised frontal thoracic deflection of around 0.3, the probability of sustaining more than 6 rib fractures is around 10% for a 30 year old while around 40% for a 70 year old.

Considering the predominance of serious thoracic injury identified in the non-fatal and fatal injury studies, further research is required into understanding thoracic injury mechanisms and how the injury potential may be ameliorated. The validated simulation protocol will assist this process, by providing a simulation methodology by which researchers may assess and develop infrastructure and safety solutions that reduce the thoracic injury potential to motorcyclists (for example barrier design, 'motorcycle-friendly' barrier modifications, hazard treatments, padding devices, shielding devices, chest protection devices, etc).

Safe roads	**Safe road use and Safe speeds**	**Safe vehicles**
Collisions with fixed objects in the roadside occurred in 52% of fatal crashes *Improve the safety of roadside infrastructure for motorcyclists, particularly at black spots. Include motorcyclist crash tests in the Australian barrier standard*	Risky riding behaviour was a contributing causal factor in 51% of fatal crashes *Education and enforcement*	Protective clothing – helmets were worn in 89% of fatal crashes yet 60% sustained a serious head injury (functional limit is being exceeded) *Improve helmet designs and standards*
Serious thoracic injury was the predominant injury mechanism for both fatal and non-fatal crashes *Investigate hazard treatments and safety devices to reduce thoracic injury potential using the simulation protocol*	Vehicles turning in front of motorcyclists occurred in 58% of multi-vehicle fatal crashes (don't see the motorcyclist or misjudge the distance) *Promote motorcycle awareness amongst motorcyclists and other road users*	Protective clothing – Serious thoracic injury was predominant for both fatal and non-fatal crashes. Currently no thorax protection is worn *Investigate the potential for thorax protection to reduce injury. Develop standards and promote/educate motorcyclists*
Currently there are no thoracic injury assessment methods in motorcycle crash tests *Investigate and develop crash test procedures to assess thoracic injury potential in barrier tests*	The 16-25 year old group had the highest number of hospitalisations, while those for over 45 year olds increased six fold *Education for returning riders and campaigns for young riders*	14% of motorcycles in fatal crashes were unregistered *Education and enforcement*
Around half of crashes and fatalities occur at intersections *Improve the safety of intersections for motorcyclists*	In 43% of fatal crashes the motorcyclist was under the influence of alcohol and/or drugs *Education and enforcement*	
31% of hospitalised motorcyclists crashed in non-traffic areas *Further research into the nature of non-traffic crashes and education*	In 20% of fatal crashes the motorcyclist was considered to be riding with excessive speed *Education and enforcement*	

Table 7: Potential areas for reducing motorcyclist trauma in the ACT, within the framework of the Safe Systems approach

5.4 Policy recommendations to reduce motorcycle trauma in the ACT

Based on the police-reported motorcycle crashes, fatal crashes and injury analyses, a number of areas in which motorcyclist trauma may potentially be reduced have been identified, and are presented within the framework of the Safe Systems approach in Table 7.

6. Conclusions

This report has presented the results of an analysis of police reports, hospital separations and Coronial inquests of fatal and non-fatal motorcyclist crashes in the ACT during the ten year period between 2001 and 2010. The temporal analysis has indicated that over this period older motorcyclists have increasingly been injured, by up to six times for the 46+ age group, while younger motorcyclists continue to contribute to the majority of hospital separations and fatalities. Injury outcomes were generally quite severe, with serious injuries to the thorax, spine and traumatic brain injuries featuring highly. Serious thoracic injury was identified as the leading injury mechanism amongst both fatal and non-fatal cases. Risky riding behaviour, fixed objects in the roadside, intersections and vehicles turning in front of motorcyclists were identified as significant contributors to motorcycle crashes. In nearly three out of four motorcyclist fatalities the motorcyclist was considered to be at fault. Several policy and research areas where actions might assist in reducing motorcycle trauma in the ACT have been identified, including education/awareness/enforcement campaigns and engineering solutions to improve intersections/roadside infrastructure/protective devices for motorcyclists.

7. References

[1] Road Deaths Australia 2011 Statistical Summary. Department of Infrastructure, Transport, Regional Development and Local Government, 2012.

[2] Henley G. and Harrison J.E. (2009). Serious injury due to land transport accidents, Australia, 2006–07. AIHW Injury Research and Statistics Series No. 53. Australian Institute of Health and Welfare Canberra, 2009.

[3] Richardson D.B. (2008). Amalgamation of police and hospital trauma data in the ACT 2001-2003. Final Report to the NRMA-ACT Road Safety Trust, 2008. (www.roadsafetytrust.org.au).

[4] National Centre for Classification on Health (NCCH) (2006). The International Statistical Classification of Diseases and Related Helath Porblems, 10th Revision, Australian Modification (ICD-10_AM). Fifth Edition, July 2006, Sydney.

[5] ABS. Motor vehicle sensus, Australian Bureau of Statistics, Canberra.

[6] MacKenzie E. J. and Sacco W.J. (1997). ICDMAP-90 Software: User's Guide. T. J. H. University. USA, The Johns Hopkins University and Tri-Analytics: 1–25.

[7] AAAM, 2005. Abbreviated Injury Scale (AIS). Association for the Advancement of Automotive Medicine, 2005.

[8] Osler, T., R. Rutledge, et al. (1996). ICISS: An International Classification of Disease-9 Based Injury Severity Score. The Journal of Trauma: Injury, Infection and Critical Care 41(3): 380–388.

[9] Stephenson S., Henley G., Harrison J.E. and Langley J.D. (2004). Diagnosis based injury severity scaling: investigation of a method using Australian and New Zealand hospitalisations Injury Prevention 2004;10:379–383.

[10] SAS Institute, SAS: statistical software, version 9.2. (2010). SAS Institute: Cary, North Carolina.

[11] Bambach M.R, Grzebieta R. and McIntosh A.S. (2012). Injury typology in fatal motorcycle collisions with roadside barriers in Australia and New Zealand. Accident Analysis & Prevention, 49:253-260.

[12] Fricke, L.B. (1990). Traffic Accident Reconstruction, Northwestern University Traffic Institute, Traffic Accident Reconstruction, Volume 2.

[13] Obenski, K.S., Hill, P.F., Shapiro, E.S., Debes, J.C. (2007). Motorcycle accident reconstruction and litigation, Fourth Edition. Lawyers and Judges Publishing Co. USA.

[14] Searle, J.A., Searle, A. (1983). The Trajectories of Pedestrians, Motorcycles, Motorcyclists, etc., Following a Road Accident, SAE Paper No.831622.

[15] Wood, D.P., 1991 Application of Pedestrian Impact Model to Determination of Impact Speed, SAE Paper 910814.

[16] Iwamoto M, Kisanuki Y, Watanabe I, Furusu K, Miki K, Hasegawa J. (2002) Development of a Finite Element Model of the Total Human Model for Safety (THUMS) and Application to Injury Reconstruction. Proc. International Conference on the Biomechanics of Impacts, pp. 31–42.

[17] Kroell, C., Schneider, D. and Nahum, A. (1971). Impact Tolerance and Response of the Human Thorax. Proc. 15th Stapp Car Crash Conf., pp. 84-134, SAE Technical Paper 710851.

[18] Kroell, C., Schneider, D. and Nahum, A. (1974). Impact Tolerance and Response of the Human Thorax II. Proc. 18th Stapp Car Crash Conf., pp. 383-457, SAE Technical Paper 741187.

[19] Viano D.C., Lau I.V., Asbury C., King A.I. and Begman P. (1989). Biomechanics of the human chest, abdomen and pelvis in lateral impact. Accident Analysis and Prevention, 21(6):553-574.

[20] Johnston P., Brooks C. and Savage H. (2008). Fatal and serious road crashes involving motorcyclists. Road Safety Research ans Analysis Report Mongraph 20, Department of Infrastructure, Transport, Regional Development and Local Government, Australian Government.

[21] EN 1621-1, Motorcyclists' protective clothing against mechanical impact - Part 1: Requirements and test methods for impact protectors.

[22] EN 1621-2, Motorcyclists' protective clothing against mechanical impact - Part 2: Motorcyclists' back protectors; Requirements and test methods.

[23] prEN 1621-3:20XX, Motorcyclists' protective clothing against mechanical impact - Part 3: Motorcyclists' chest protectors; Requirements and test methods.

[24] prEN 1621-4:XX, Motorcyclists' protective clothing against mechanical impact - Part 4: Motorcyclists' inflatable protectors; Requirements and test methods

[25] TS 1317-8, 2012. Road restraint systems - Part 8 : Motorcycle road restraint systems which reduce the impact severity of motorcyclist collisions with safety barriers.

[26] AS/NZS 3845:1999. Road Safety Barrier Systems (1999). Sydney, Australia: Standards Australia.

[27] Henley G. and Harrison J.E. (2011). Trends in serious injury due to land transport accidents, Australia 2000–01 to 2007–08. AIHW Injury Research and Statistics Series No. 56. Australian Institute of Health and Welfare Canberra, Cat. no. INJCAT 132, 2011.

[28] Kent R., Patrie J., Poteau F., Matsuoka F. and Mullen C. (2003). Development of an age-dependent thoracic injury criterion for frontal impact restraint loading. 18th International Conference on Enhanced Safety of Vehicles, 2003.

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9. Appendix A – Traumatic brain injuries

S01: Open wound of head
S02.0: Fracture of vault of skull
S02.1: Fracture of base of skull
S02.3: Fracture of orbital floor
S02.7: Multiple fractures involving skull and facial bones
S02.8: Fractures of other skull and facial bones
S02.9: Fracture of skull and facial bones, part unspecified
S04.0: Injury of optic nerve and pathways
S06: Intracranial injury
S07: Crushing injury of head
S09.7: Multiple injuries of the head
S09.8: Other specified injuries of head
S09.9: Unspecified injury of head

Also included are associated sequelae (T90.1, T90.2, T90.4, T90.5, T90.8, T90.9)

10. Appendix B – Detailed injuries

All injuries		*n*	%
traumatic brain injury	fracture	42	1.26
traumatic brain injury	internal organ	182	5.45
traumatic brain injury	open wound	74	2.22
traumatic brain injury	other specified injuries	2	0.06
traumatic brain injury	unspecified nature	13	0.39
other head	fracture	39	1.17
other head	dislocation	1	0.03
other head	open wound	1	0.03
other head	amputation	1	0.03
other head	superficial/contusion	44	1.32
other head	unspecified nature	1	0.03
neck	dislocation	1	0.03
neck	open wound	4	0.12
neck	blood vessel	1	0.03
neck	superficial/contusion	3	0.09
neck	other specified injuries	5	0.15
neck	unspecified nature	3	0.09
spinal cord	internal organ	26	0.78
vertebral column	fracture	178	5.33
vertebral column	dislocation	8	0.24
vertebral column	other specified injuries	5	0.15
thorax	fracture	141	4.22
thorax	dislocation	2	0.06
thorax	internal organ	113	3.39
thorax	open wound	3	0.09
thorax	blood vessel	1	0.03
thorax	superficial/contusion	29	0.87
thorax	other specified injuries	6	0.18
thorax	unspecified nature	5	0.15
abdomen	internal organ	64	1.92
abdomen	open wound	9	0.27
abdomen	blood vessel	2	0.06
abdomen	superficial/contusion	11	0.33
pelvis & lower back	fracture	52	1.56
pelvis & lower back	dislocation	1	0.03
pelvis & lower back	internal organ	27	0.81
pelvis & lower back	open wound	5	0.15
pelvis & lower back	superficial/contusion	16	0.48
abd, lb, & pelvis	unspecified nature	39	1.17

All injuries		*n*	%
trunk, other	superficial/contusion	7	0.21
trunk, other	burn	4	0.12
trunk, other	multiple injuries	1	0.03
trunk, other	other specified injuries	1	0.03
trunk, other	unspecified nature	2	0.06
upper extremity	fracture	630	18.87
upper extremity	dislocation	93	2.79
upper extremity	open wound	117	3.51
upper extremity	amputation	6	0.18
upper extremity	blood vessel	3	0.09
upper extremity	superficial/contusion	123	3.68
upper extremity	burn	6	0.18
upper extremity	other specified injuries	45	1.35
upper extremity	unspecified nature	25	0.75
hip	fracture	27	0.81
hip	dislocation	3	0.09
hip	open wound	1	0.03
hip	superficial/contusion	2	0.06
other lower extremity	fracture	469	14.05
other lower extremity	dislocation	53	1.59
other lower extremity	open wound	241	7.22
other lower extremity	amputation	4	0.12
other lower extremity	blood vessel	5	0.15
other lower extremity	superficial/contusion	147	4.40
other lower extremity	burn	8	0.24
other lower extremity	other specified injuries	80	2.40
other lower extremity	unspecified nature	24	0.72
multiple body regions	superficial/contusion	3	0.09
system wide	other specified injuries	30	0.90
unspecified region	open wound	1	0.03
unspecified region	superficial/contusion	1	0.03
unspecified region	burn	14	0.42
unspecified region	other specified injuries	2	0.06
	TOTALS:	3338	100

Table B1: Injury counts by specific body region and type of injury for all injuries

Serious injuries		*n*	%
traumatic brain injury	fracture	56	3.93
traumatic brain injury	internal organ	168	11.79
traumatic brain injury	open wound	55	3.86
other head	superficial/contusion	6	0.42
neck	open wound	7	0.49
neck	blood vessel	5	0.35
neck	other specified injuries	1	0.07
spinal cord	internal organ	33	2.32
vertebral column	fracture	137	9.61
vertebral column	dislocation	15	1.05
thorax	fracture	122	8.56
thorax	dislocation	3	0.21
thorax	internal organ	186	13.05
thorax	open wound	3	0.21
thorax	blood vessel	1	0.07
thorax	other specified injuries	7	0.49
abdomen	internal organ	87	6.11
abdomen	open wound	10	0.70
abdomen	blood vessel	5	0.35
pelvis & lower back	fracture	72	5.05
pelvis & lower back	dislocation	1	0.07
pelvis & lower back	internal organ	29	2.04
abd, lb, & pelvis	internal organ	1	0.07
trunk, other	burn	1	0.07
upper extremity	fracture	55	3.86
upper extremity	dislocation	1	0.07
upper extremity	open wound	43	3.02
upper extremity	blood vessel	2	0.14
upper extremity	superficial/contusion	5	0.35
upper extremity	burn	10	0.70
upper extremity	unspecified nature	1	0.07
hip	fracture	58	4.07
other lower extremity	fracture	108	7.58
other lower extremity	open wound	82	5.75
other lower extremity	amputation	2	0.14
other lower extremity	superficial/contusion	5	0.35
other lower extremity	burn	14	0.98
system wide	other specified injuries	25	1.75
unspecified region	superficial/contusion	1	0.07
unspecified region	other specified injuries	2	0.14
	TOTALS:	1425	100

Table B2: Injury counts by specific body region and type of injury for serious injuries