Quad bike Crush Protection Devices (CPDs): Updates to ISCRR Snapshot Review - C-I-12-022-10

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Executive Summary

In 2011, ISCRR commissioned a literature review on behalf of WorkSafe Victoria, to assess the efficacy of crush protection devices (CPDs) for use on Quad bikes, in response to growing concerns about the number of injuries and deaths attributed to these vehicles. This initial review examined eighteen primary references containing statistics on Quad bike injuries and deaths, and a range of experimental and simulated predictions relating to the Quad bike CPDs. Various critiques from local and international experts in the field were considered, as well as position statements published by relevant industry, government and community stake holders.

The initial review found that Quad bikes had become the leading cause of death on Australian farms, and in 2011 accounted for around one-third of fatalities. These deaths commonly resulted from chest, head or spinal injuries. Children under 14 years and older people (>45 years) were found to be the most common victims. A number of serious limitations were identified with respect to the scenarios chosen and simulation methods utilised by the existing research. The limited number of experimental and simulation results considered valid indicated that CPDs demonstrated the potential to reduce rider harm in low speed roll-over events. This finding was contrary to the advice and position held by the Federal Chamber of Automotive Industries (FCAI) which represents the vast majority of manufacturers who sell Quad bikes within Australia. The initial review suggested that a range of further (predominantly experimental) research be conducted to confirm and quantify these predicted benefits. In the meantime, the use of appropriately tested CPDs was recommended for riders who use Quad bikes at low speeds on farms and in other work places.

It was considered necessary to reassess these findings and recommendations in light of an updated work[2] recently self-published by the company Dynamic Research, Inc. (DRI) relating to the effectiveness of an Australian designed and manufactured CPD, named the QuadBar.

The present review examines the updated DRI research in detail, and in summary, it finds:

- A number of detail changes have been made to the simulation model to address some of the limitations identified in the initial work;
- New injury criteria for rider asphyxiation and face and skull fracture have been developed and added to the simulation;
- A significant difference between the style/standard of helmet being simulated (full-face) and that which is currently recommended by the industry and government bodies for Quad bike use (i.e. compliant with AS/NZS:1698);
- Major changes were made to the recorded injury data set which was used to compare with the simulated injuries; and
- Predicted Injury/Benefit ratios from this updated work have been presented using a "single baseline" method rather than the commonly accepted and more valid "multiple baseline" method.

The updated results presented by DRI show a dramatic and implied statistically significant increase in the risks associated with the use of a CPD for un-helmeted riders. A risk/benefit

ratio of 492% is quoted (much less safe), in comparison to the 71% (slightly safer) returned by their previous study of the same device. Detail analysis found that this increase could be attributed to their adoption of a “single baseline” method. This reported increase was implied by calculating the injury/benefit ratios for an *unhelmeted* rider with a CPD, via comparison with a *helmeted* rider, without the CPD. Such comparisons were found by this review to be invalid, and a potential misrepresentation of the true results.

Recalculation of the injury risk/benefit ratios using the more valid multiple (or matched) baseline method showed that, according to DRI’s updated research, the use of a CPD actually returns a risk/benefit ratio of 68% [42%, 114%] (slightly safer) for the unhelmeted condition, and 108% [69%, 169%] (slightly less safe) for the helmeted condition. Moreover, due to the fact that the 95% confidence intervals (shown previously in the square brackets) for both these results were observed to straddle the neutral risk/benefit value (100%), these findings should be, and were, considered statistically insignificant.

Despite the many changes made to the simulation methods used in the updated work, the (valid) results of the updated study were observed to be very similar to the initial study, which predicted a risk/benefit ratio of 71% [41%, 137%] (slightly safer) for the unhelmeted condition, and 99% [53%, 192%] (slightly safer) for the helmeted condition.

Given no significant change in the updated DRI research and in consideration of other publications (initially reviewed) supporting the benefits of CPDs, the findings and recommendations of the original review have been reaffirmed.

Further testing and the development of standards for Quad bike CPDs is clearly required. In the mean time, regulatory bodies should consider recommending the use of appropriately tested crush protection devices (CPDs) for riders who use Quad bikes at low speeds in the workplace and on farms. Such devices have been shown to reduce the severity of Quad bike roll-overs, and have the potential to reduce the injuries and fatalities associated with these loss-of-control events.

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1 Introduction

Quad bikes accidents have become the leading cause of death and serious injury on Australian farms. Quad bike accidents are commonly associated with roll-over of the vehicle, which can result in crushing injuries, potential entrapment and even asphyxiation of the rider beneath the vehicle. Children and workers over the age of 45 are the most common victims of on-farm roll-over deaths.

In 2011 the Institute for Safety, Compensation and Recovery Research (ISCRR) commissioned a snapshot review of Quad bike safety devices[1], which focused on published literature relating to the potential safety benefits of Crush Protection Devices (CPDs). Such devices are generally designed to prevent the full weight of the Quad bike from being applied to, or coming to rest on, the rider in the event of a roll-over. CPDs do not incorporate any rider restraints (unlike earlier proposed Roll Over Protection Systems or ROPSs) and have minimal if any impact on the utility of the vehicle or the use of active riding techniques.

The 2011 review[1] found that:

- The vast majority of prior research into Quad bike CPDs made use of computer simulations which were adapted from those used to model two-wheeled motorbike accidents. Several critical limitations were identified with these numerical models;
- These computer simulations generally modelled roll-over incidents based on 110 brief and largely incomplete accident descriptions drawn from the US and the UK. A large number of assumptions and interpretations were required, many of which had the potential to greatly affect the predicted injury outcomes;
- A range of simulation findings were returned with respect to a selection of proposed crush protection devices. Several inconsistencies and inaccuracies were identified in these works and the interpretation and representation of the stated results. A systematic review of these results indicated that the most promising CPDs had the potential to slightly increase the safety of Quad bike riders when subjected to roll-over for both the helmeted (recommended use) and non-helmeted (foreseeable use) conditions. Opinions were mixed as to whether the magnitude of this benefit could be deemed to be statistically significant;
- Experimental tests of a Quad bike fitted with a CPD (but without a crash dummy) and subjected to a range of different roll-over modes, velocities and terrain types found that CPDs could be effective in reducing the likelihood of complete roll-over of the bike. With a CPD fitted, there were no scenarios tested where the Quad bike came to rest in a position which was considered to be more detrimental to rider safety than the bike without such protection. Based on this research, it appears likely that appropriately designed CPDs could lead to reduced injuries and fatalities for the common roll scenarios tested; and
- The Federal Chamber of Automotive Industries (FCAI) which represents Quad bike manufacturers including Honda, Yamaha, Kawasaki, Polaris and Bombardier voiced strong opposition to the fitment of appropriately tested CPDs. It was found that such opposition cannot be supported, given the limitations of the simulation research identified, and in light of the favourable experimental results discussed previously.

The review concluded that more experimental research (in particular) is clearly required, but that in the meantime, regulatory bodies should consider recommending the use of appropriately tested crush protection devices for riders who use Quad bikes at low speeds, particularly on farms and in other work places.

Since the publication of the 2011 review, two new technical reports have been released by Dynamic Research Inc (DRI) relating to Quad bike crush protection devices.

This document provides a review of these reports, and guidance on how these new works might affect the findings and recommendations put forward by the 2011 ISCRR Snapshot Review of Quad Bike Safety Devices[1].

The first of these reports, DRI-TR-12-05 which is entitled ***Replies to Lower (2011) Comments***[2] provides replies made to a summary of comments presented by Lower[3], which in turn are a summary of research conducted and comments made by Lambert[4,5,6], McDonald and Richardson[7] with regard to previous research conducted by DRI into Rollover Protection Systems (ROPSs) and Crush Protective Devices (CPDs) for use on Quad bikes. This document will not be reviewed in detail as many of the issues discussed within it are more substantially addressed by the second publication.

The second report, DRI-TR-12-06 which is entitled ***Updated Injury Risk/Benefit Analysis of Quadbar Crush Protection Device (CPD) for All-Terrain Vehicle (ATVS)***[8] is a complete reworking and update of DRI's previous 2007 research into the same device[9]. Two of the three listed authors are common to both these works, and the same general simulation procedures are utilised, with a number of detail modifications made to the capabilities of the model and the methods used to generate initial parameters for the roll-over scenarios. Quite significantly, this report returns vastly different predictions for the potential safety benefits due to the addition of the CPD compared to the earlier work. DRI's implied risk/benefit ratio for the use of a CPD by an unhelmeted Quad bike rider increased from 71% in 2007, to 492% in the recent work (implying that the rider is now statistically significantly much more likely to be injured due to the fitment of the CPD). The magnitude of this change and the shift to claimed statistical significance necessitates a careful and thorough review of the new research before any of its findings or associated recommendations can be supported. Such analysis is particularly important given that both reports are categorised as "grey literature", in that they have been self-published by the authors' own company, Dynamic Research, Inc. of Torrance, California. Neither the initial report, nor the updated report, has been subjected to a scientific peer review process.

This document will critically review the new research presented by Zellner, Kebschull and Van Auken on behalf of DRI, and their findings, with respect to the safety performance of a crush protection device (CPD) for Quad bikes. The conclusions and recommendations made by the 2011 ISCRR Snapshot Review into Quad bike Safety Devices[1] will be reconsidered in light of any significant new findings made by this research. The conclusions and recommendations made by the 2011 review will be either reaffirmed, or updated accordingly.

2 Table of Abbreviations

Abbreviation	Stands for
AIS	Abbreviated Injury Scale
ATB	Articulated Total Body
ATV	All Terrain Vehicle
CPD	Crush Protection Device
CPSC	Consumer Product Safety Commission
DRI	Dynamic Research Inc.
FCAI	Federal Chamber of Automotive Industries
ISCRR	Institute for Safety, Compensation and Recovery Research
ISO	International Organisation for Standardisation
MATD	Motorcyclist Anthropometric Test Device
NZ	New Zealand
ROPS	Roll Over Protective Structure or System
TR	Technical Report
TM	Technical Memorandum
UK HSE	United Kingdom Health and Safety Executive
UTV	Utility Task Vehicle

3 Definitions and Nomenclature

Clear definition and differentiation is required with respect to several important terms used in this review, as explained below. These definitions are consistent with the prior ISCRR review[1].

'Quad bike' or 'All-Terrain Vehicle' (ATV)?

This review will examine the use of four-wheeled, motorised bikes, having a straddle seat and handlebars. Such bikes are commonly referred to as either Quad bikes, or All-Terrain Vehicles (ATVs). For clarity and simplicity, this review will henceforth refer to these vehicles exclusively as Quad bikes. In instances where a vehicle has been described as an ATV by the original authors, the term Quad bike will be used in its place. Three-wheeled motorbikes (which were phased out of the market in the late 1980s) and larger 'side-by-side' vehicles (also known as UTVs or Utility Task Vehicles) are not considered Quad bikes, and as such do not fall within the scope of this work.

ROPS or CPD?

This review will largely focus on crush protection devices (CPDs). Some mention of Roll Over Protective Structures or Systems (ROPS) will also be provided. For the purposes of this review, CPDs will be distinguished from ROPSs on the following basis:

ROPS: A Roll Over Protective Structure or System (ROPS), is an external frame or structure which forms a compartment to protect the rider from injuries caused by vehicle overturns and to a lesser extent, collisions. Such structures may also incorporate crushable components designed to absorb energy during a crash and reduce the magnitude of vehicle and rider accelerations during these events. A ROPS 'system' generally incorporates additional rider restraints, such as seatbelts, to ensure that the rider remains within the protective structure during the roll or crash event. ROPSs are commonly used on heavy vehicles such as earth-moving equipment and tractors, high performance on-road vehicles such as race cars, and high speed off-road vehicle such as buggies.

CPD: A Crush Protection Device (CPD) is a structure designed to form a protective space between the bike and the ground in the event of roll-over. Such devices aim to prevent or reduce rider injuries incurred due to crushing and/or asphyxiation. In general, CPDs are not designed to be used with occupant restraints, thereby allowing the use of active riding techniques and enabling rider separation from the vehicle during loss of control events. Existing CPD designs include the UK HSE U-Bar, the NZ T-Bar and the QuadBar.

4 Review of DRI-TR-12-06

Updated Injury Risk/Benefit Analysis of Quadbar Crush Protection Device (CPD) for All-Terrain Vehicle (ATVS)

Zellner, J.W., Kebschull, S.A. and Van Auken, R.M.

Technical Report DRI-TR-12-06
Dynamic Research, Inc.
6th of August, 2012.
Self published and available from: http://www.dri-atv-rops-research.com/

This work provides an update to prior simulations[9] of the predicted injury risk/benefits related to the addition of the QuadBar CPD to a Quad bike. A brief overview of the techniques and methods used in the initial work will first be provided, to serve as a basis for comparison with the updated research. The new research will then be examined in detail, including the reported changes made to: the rider model; rider, bike and ground interactions; the AIS coding of reported injuries; and the calculation methods used to determine the headline injury risk/benefit ratios.

4.1 Overview of the initial research

The initial 2007 work is titled **"*An Assessment of The Effects of The Robertson V-Bar ROPS on The Risk of Rider Injury Due To Overturns Resulting From ATV Misuse*"**. The "Robertson V-bar" device name refers to the inventor and manufacturer of this particular device, Mr David Robertson. In the interval between the publication of the initial report and the updated work, the design of this vertical hoop shaped device was modified slightly (narrowed at its base so that the bars became parallel) and renamed and marketed as the QuadBar. On the basis of the currently accepted terminology previously defined, this bar is more appropriately designated as a crush protection device (CPD), rather than a Roll Over Protection Structure or System (ROPS) as stated by the title of the initial report.

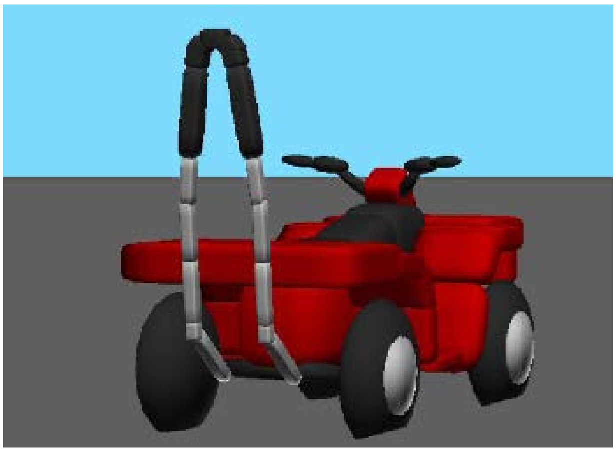


Figure 1: Computer generated representation of the simulated Quad bike, (left) fitted with the initial "Robertson V-Bar" design tested in 2007[9]; (right) fitted with the slightly revised and renamed QuadBar (with rider model), which was retested in 2012[8].

In the initial study, rider injury and risk benefits were calculated based on the outcomes of computer simulations which utilised DRI's own proprietary version of the Articulated Total Body (ATB) simulation model. This model was adapted by DRI to represent a physical Motorcyclist Anthropometric Test Device (MATD), or motorcycle specific crash testing dummy. This initial simulation model had no in-built capability for prediction of asphyxiation fatalities. A full face "Bieffe" style helmet was modelled and used for all helmeted scenarios tested, based on the pre-existing ISO 13232-7[10] standard, previous used for the simulation of on-road, two wheeled motorcycle crashes. Examples of typical, commercially available, full face motorcycle helmets are shown below.

Figure 2: Typical full face, motorcycle helmets for on-road use.

A sample of 113 overturn events were initially simulated, these being loosely based upon brief and incomplete Quad bike overturn incident reports drawn from the UK's Health and Safety Executive (HSE) and the USA's Consumer Product Safety Commission (CPSC). The authors acknowledged that, on average, only 8 out of 17 initial conditions were reported for these 113 overturn events, and no estimate or confirmation of the accuracy of these reports was provided. The researchers devised their own estimates for all unreported initial conditions, with the only criterion being that an overturn event resulted. The size of this scenario data set was then also artificially increased via the generation of an additional six cases for each reported case, via unspecified perturbations made to the initial conditions of each case.

The recorded injury outcomes from this sample of 113 crashes, which were also observed to be ambiguous and lacking in adequate detail, were initially translated into approximate Abbreviated Injury Scale (AIS) codings in a separate publication, mostly by the same authors[11]. This approximation of the recorded injuries was intended to provide comparison with the computer simulated injury results. Such comparisons were only performed in an aggregate manner by contrasting the relative probabilities and distribution of the Abbreviated Injury Scales for the actual and simulated datasets. Case-by-case comparison of predicted injuries with recorded injuries for the matching scenario was not attempted. The authors considered such comparisons inappropriate due to the likelihood of significant and unaccountable differences between the simulated and actual initial conditions (i.e. velocity, steering, accelerator and brake application), bike size and type, rider size and terrain modelling (slope angle, slope length, obstacle size, friction factors etc.).

These initial simulations predicted a 99% risk/benefit ratio (i.e. a 1% improvement in safety) for helmeted riders due to the addition of the QuadBar, and a 71% risk benefit ratio (i.e. a 29% improvement in safety) for unhelmeted riders. These findings were dismissed by the authors as statistically insignificant, on the basis that the calculated 95% confidence intervals for both results straddled the neutral risk/benefit baseline.

In conclusion, the initial report recommends that the QuadBar (and other CPDs previously researched) should not be fitted to Quad bikes on the basis that, for this category of small straddle seat vehicles, the injury risks from a CPD are similar in magnitude to the injury benefits.

4.2 Modifications and additions made in the updated work

The updated work[8] introduces a large number of changes across many different facets of the research. The most significant changes include:

- the manner in which the rider interacts with the bike controls and maintains contact with the handlebars;
- an asphyxiation model and associated fatality criteria;
- new skull fracture and facial fracture injury criteria which have been enabled for non-helmeted cases;
- a tightening of the requirements for the AIS coding of reported injuries, resulting in a filtering of certain key injury regions from the re-coded injury data set;
- a change to the baseline(s) used to normalise and present the revised injury risk/benefit results; and
- the provision of a fatality risk/benefit analysis.

Clarifications are provided with respect to:

- the methods used to generate guesses for incident initial conditions which were not provided by the incident descriptions; and

- the methods used to generate the additional six perturbations for each recorded incident.

These changes, updates and new additions are discussed in detail below.

4.2.1 Changes to the dummy, bike and ground interactions and simulation domain

The mechanics and interactions of the proprietary ATB dummy simulation were modified in the updated work, apparently in an attempt to address some of the limitations identified by critics of the original research[1,3,4,5,6,7].

Hand grip release forces were reportedly increased in order to minimize the occurrence of pre-overturn hand release. In the initial study, the passive rider was frequently observed to begin falling off the bike prior to the overturn event due to the lack of any, or adequate, hand grip force.

Modifications to the simulation logic were also reported, designed to ensure that control inputs to the bike (i.e. steering, throttle and brake) were terminated upon release of the dummy hands from the bike hand grips. This change appears intended to the prevent “phantom” control inputs observed in the initial study, such as the bike braking or being steered, after the rider has lost contact with the handle bars.

Updated frictional coefficients for the dummy/soil interactions were also measured and incorporated into the new research, with the aim of addressing prior criticisms relating to the potentially unrealistic way in which the bike and rider bounced in previous simulations. New force-deflection characteristics for the helmet, head, upper and lower legs were also introduced, potentially to address the same issue.

Further changes to the simulation methodology include the addition of a terminal horizontal plane, which was imposed three metres vertically below the starting point of the Quad bike for all simulations conducted on sloping ground. This change was reported to limit the extent and number of rolls that both the bike and dummy would be subjected to, as previous research frequently utilised potentially unrealistically long slopes (perhaps 50m).

Unfortunately, this review is unable to comment in more detail on how these reported changes have affected the quality and realism of the simulated overturn events. This would require viewing and analysis of the video outputs produced by DRI for this updated work. These videos were not made available for this review.

4.2.2 The addition of a new asphyxiation injury criterion

In the updated work, DRI has introduced what they term a *“preliminary, potential mechanical/traumatic (compressive) asphyxia criterion”* which was applied to the rider model. This new injury mechanism is intended to identify instances in which the Quad bike over turns and comes to rest on the rider in such a manner that it could *“potentially restrict respiratory movements over some extended period of time*”.

DRI selected *"significant breathing difficultly beyond an hour"* as the time scale for this new fatality criterion and assumed that a chest compressive force of 490 Newtons (110 lbs) or greater would generate said difficulty, based on a review of the existing literature and a pilot study conducted by two of the present authors and published via an internal DRI Technical Memorandum[12]. It was reported that published tolerance levels for chest compressive force varied widely and were found to be highly duration dependant. Their chosen fatality limit was noted to be conservative, and substantially lower than both the predicted compressive forces which would result in a loss of consciousness and death (following an hour of exposure) proposed by other external sources.

Using this new criterion, DRI's updated overall simulation results reported no change in the number (11) of predicted potential breathing difficulties arising due to the fitment of the CPD. The total number of these predictions (both with and without CPDs) was observed to make up only a very small proportion of the total number of overturns simulated (3080). Without reviewing the relevant simulation videos it is difficult to generalise further about the reasons for this result. DRI suggest that the addition of the CPD resulted in a higher likelihood that the bike would come to rest on its side, rather than upside down, and that this caused as many new potential asphyxiation cases as it prevented. Their report of entrapments occurring underneath the side of the bike is a relatively new phenomena compared to the initial study, and may be an artefact of the newly increased hand grip forces and the new "low energy" scenarios tested (discussed in more detail in Section 4.2.5). If the new series of simulated over-turn events were sufficiently slow and the dummy more likely to retain its grip of the handlebars, then the probability of (perhaps very unrealistic) rider entrapment under the side of the vehicle might be expected. Video review is certainly required to determine if such entrapments appear realistic, or if a real rider might have easily and instinctively avoided injury in such cases, simply by releasing their grip on the bars.

4.2.3 New face and skull fracture mechanisms for unhelmeted riders

The updated research utilises extensions to the face and skull fracture modelling, via the derivation of probability curves for vault and face fracture as functions of peak skull contact force and resulting energy. These new injury criteria were based on recent research published in 2011 by Van Auken and Zellner, two of the same authors of the current work[13].

It is important to note that the newly introduced face and skull fracture mechanisms were deemed by DRI to only be applicable to the non-helmeted scenarios, and hence were only enabled/allowed for non-helmeted cases. Hence their results automatically presume that a "helmeted" Quad bike rider is always wearing a full face type helmet.

The assumption of the use of a full face, on-road style motorbike helmet represents a serious disconnect with contemporary Australian Quad bike helmet wearing practices, and more significantly, the recommendations being made by Australian regulatory bodies and even Quad bike manufacturers. The helmet standard which currently applies to Australian Quad bike users is AS/NZS 1698:2006[14], and an example of the style of helmet which passes this standard is shown in the figure below. DRI, Quad bike manufacturers and associated industry groups like the FCAI should be extremely careful in publicising the stated benefits of helmet use given the significant differences noted in the types of helmets being simulated versus those actually recommended for use. It is possible that DRI's quoted risk/benefit ratios for helmet use potentially over state the benefits provided by the use of AS/NZS:1698 certified helmet designs.

Figure 3: The THH T-70 Helmet, which complies with AS/NZS:1698[14].

4.2.4 Revised AIS Injury Codings

In 2004, DRI initially AIS-coded (i.e. translated into the standardised Abbreviated Injury Scale[15]) the injury outcomes described in the 113 incidents[11] to provide comparison with the output of their simulations of the time[9]. In 2011, shortly before the release of the current paper, they reworked and updated these AIS-codings via an internal technical memorandum[16], which is referenced by the current work but is not available in the public domain. A copy of this memorandum was not available for review. A table of final results from this re-coding is however presented in the current work and is utilised by DRI as a key comparative resource for their updated simulations.

It is important to note the significant changes that have been made to the baseline injury data-set as part of this re-coding process. DRI have chosen to filter the reported injury data, so that any injury which cannot be predicted by a physical crash dummy is excluded. As a result, the number of injuries translated into AIS codes has been greatly reduced in the updated version, and some inconsistencies are evident. Table 1 below summarises the total 128 injuries which were originally coded[11], i.e. 137 minus eight which were unknown or unspecified, and one which had no injury or was not applicable.

	Frequency	Percent	Cumulative Percent
Head	16	11.7%	11.7%
Face	12	8.8%	20.4%
Thorax	27	19.7%	40.1%
Abdomen	5	3.6%	43.8%
Spine	8	5.8%	49.6%
Upper extremity	36	26.3%	75.9%
Lower extremity	24	17.5%	93.4%
Not applicable, no injury	1	0.7%	94.2%
Unknown or unspecified	8	5.8%	100.0%
Total	137	100.0%	

Table 1: DRI's initial distribution of AIS coded injuries by body region, for the 113 accident scenarios[11].

DRI concede that, *"in general, current technology (physical) crash dummies cannot monitor for external contusions, abrasions, lacerations, the full range of thoracic and lumbar spinal injury severities, and many other locations, types and severities of human body injury"*. DRI further state that "o*nly those actual human injury locations, types and severities that can be monitored by the crash dummy using existing technology can be validly compared."* This comment is not strictly correct, as it could be argued that no such comparison between physical crash dummy injuries and reported injuries is being made by this work. Rather, the reported injuries are being compared with the injury predictions generated by the ATB simulation package, which conceivably could be modified to include more of these injury modes. DRI themselves have demonstrated that such modifications are possible with the addition of new face fracture, skull fracture and asphyxiation criteria.

The revised coding procedure only accepts injuries which fall within the following narrow definitions based on physical crash dummy capabilities:

- Head concussive injuries;
- DRI's own extensions to the model to incorporate face and skull fractures for unhelmeted riders only;
- Upper neck fracture/dislocation;
- Chest compression (associated with internal organ crush, rupture and now asphyxia as added by DRI);
- Abdominal penetration (associated with internal organ rupture);
- Upper leg fracture;
- Knee dislocation; and
- Lower leg fracture.

It is unclear how the arm fractures that DRI identifies are treated, and if these results are included in some form in the results. For example, for Case IDs 11, 96, 100 and 890501BEP0011, DRI report the assumption of radius or ulna fractures (elbow bones) at AIS = 2, but no values are recorded in their results table[8].

Table 2 presents a summary of the DRI updated AIS codings, based upon a best estimate collation of the results presented in the current review document[8]. A total of only 49 injuries are now coded, down from 128 originally. It should also be noted that this update draws upon a reduced total number of incidents (110 rather than 113) following DRI's recent observation that three of the initial cases did not actually involve Quad bikes.

AIS Coded Injury Regions (Type)	Number of Injures AIS Coded	% of Total Coded
Head / Brain (Closed Head injuries)	10	20%
Head (Vault Fracture)	5	10%
Head (Face Fracture)	1	2%
Neck (Vertabrae Fracture)	3	6%
Chest (Rib Fracture only)	13	27%
Asphyxia (Fatalities only)	3	6%
Abdomen (Penetration)	1	2%
Femurs (Upper Leg Fracture only)	0	0%
Knees (Dislocation only)	2	4%
Tibias (Lower Leg Fracture only)	7	14%
Various other non categorised, but coded	4	8%
Total	**49**	100%

Table 2: DRI's updated distribution of AIS coded injuries by injury region, for the 110 accident scenarios (adapted from data provided by [8]).

Thus, it is apparent that the following injury regions and types have been excluded from the updated data set:

- Shoulder injuries (including fractures, dislocations and lacerations);
- Back injuries;
- Many types of trunk injury (including fractures, contusions, abrasions);
- Collar bone injuries (including breakages and dislocations);
- Arm injuries (upper, lower, elbow, wrist, hand and fingers, including fractures); and
- Other site specific or full body contusions, abrasions, lacerations, bruising and sprains.

Table 3 presents a summary of the recorded injuries which were excluded by DRI from the revised AIS injury coded dataset.

Injury Regions Excluded from Dataset	Number of Injuries Excluded	% of Total Excluded	Combined Regions (Trunk and Arms)	% of Total Excluded
Shoulder	9	13%	25	37%
Back	4	6%		
Trunk	8	12%		
Collar bone	4	6%		
Upper Arm (inc elbow)	3	4%	15	22%
Lower Arm (inc wrist)	9	13%		
Hands	3	4%		
Other non-coded specific or full body contusions, abrasions, lacerations, bruising and sprains. (Excludes non-categorised but coded*)	27	40%		
TOTAL	**67**	100%		

Table 3: Number and proportion of injuries excluded by DRI from the updated AIS coded dataset, based on injury region, for the 110 accident scenarios (adapted from [8]).
**Note: The four elbow injuries from Case ID's 11, 96, 100 and 890501BEP0011 which were coded as AIS=2 by DRI but not included in their summary table have not been included in these totals.*

It can be seen that a total of at least 67 injuries have been excluded, with 25 of these excluded injuries (37%) observed to occur in the general "trunk" region of the body, and a further 15 injuries (22%) occurring in the "arm" regions. The large proportion of recorded injuries being excluded from these body regions raises the obvious question as to why DRI did not consider improving and extending their injury simulation of these commonly affected and currently neglected body regions rather than focusing on the addition of yet more head injury mechanisms which were only applied to the non-helmeted condition.

The lack of any formally acknowledged arm injury cases and or predictions, and the elimination of approximately reported 25 trunk region injuries (leaving only 14) calls into question the overall validity and generalisability of the simulation results and the claimed success of what is at best, a heavily filtered correlation with the reported accident injuries. Given the significant margin for interpretation available in this approach, there existed an obvious potential for the injury codings to be tuned to closely match the forth coming results, particularly given the majority of authors are common to both works. Such a bias is not automatically implied, but the opportunity should be acknowledged.

4.2.5 Methods used to generate unknown scenario variables

In earlier works, DRI has stated that it based its simulation of Quad bike roll-over events on information provided by the short description capture by the UK HSE and the US CPSC, and where necessary, *"assumed plausible values which appeared consistent with the information in the case file, and which resulted in a simulated overturn".* In the updated work DRI has introduced a different method for generating these unknown or unreported values (e.g. speed, slope, obstacle height). The final unknown values used by the simulation were found through *"systematic variation"* which has been illustrated with system diagrams[8]. These explain how the scenario parameters were escalated until a roll-over was achieved for each case. In general, it was reported that low values were initially guessed for the unknown or unreported metrics and these were incrementally increased until such a point that a simulated overturn barely occurred. These new incident interpretations have been called *"low energy"* overturns, in comparison to the previous overturns which were classified as *"high energy"*, based on the assumption that they used comparatively more extreme values to guarantee an overturn. DRI states that these changes resulted in generally reduced slope angles, slope lengths, speeds, and obstacle sizes used compared to their previous research. These new low energy overturns reportedly resulted in the need for much longer simulation times, and consequently each simulated run was solved for a total of 10 seconds rather than the 6 seconds used previously. This increased length of simulation time highlights an important difference between the Quad bike incidents being modelled, compared to traditional on-road motorcycle accidents, which one might assume, occur at generally higher speeds and have a much shorter required simulation period. A short total simulation time and high speeds/energies would contribute to minimising the influence that dynamic movement by the rider could have on the results. Hence a static dummy could reasonably be assumed to be a good approximation of a live human, over a very short time period when subjected to accelerations and inertial effects an order of magnitude greater than the rider's capability to react or resist such effects. The same assumption does not necessarily hold when we consider Quad bike accidents, particularly those occurring at low speeds, with less energy and a much greater incident time period. It may be that inaction on the part of the static rider could render such simulated accidents highly unrealistic and unrepresentative of "what a real person would do". A review of the simulation video outputs is required to comment in more detail on this potential issue. Given that DRI have claimed that passive riders are still the "state of the art", and that it is not currently possible to simulate more realistic human behaviour, serious consideration should be given to the question of whether any of these low energy, low speed, long duration simulation results can be trusted at a very fundamental level. In this specific instance, the best computer science can currently do may not be good enough, which invites us to investigate and develop more appropriate techniques for quantifying the performance of potential safety devices.

4.2.6 Process used to generate additional scenario perturbations

A revised and more consistent methodology is also presented to explain the process by which DRI generates six additional perturbations of each these initial 110 low energy overturns to increase the incident sample size by a factor of 7, up to a total of 770. This process involves the systematic increase and decrease of input variables by around 5%, in most cases. These variations are made in a set order: steering, followed by braking, speed, obstacle height, initial heading and slope, up until the point that an additional six cases, all resulting in roll-over, have been generated. It is unclear whether this process was used (but not reported) in the initial work, or if this methodology is a new feature of the updated research.

To properly assess the changes made to the generation of unknown scenario variables and the scenario perturbations it is necessary to carefully review the video outputs, at least for a representative range of the 3080 individual simulations conducted.

4.2.7 Changes to the baseline(s) used to normalise reported results

The many modifications that DRI have made to their modelling and simulation techniques are over shadowed and potentially misrepresented by a critical change they have simultaneously made to the way in which they present their comparative results.

In all of their past Quad bike related research, DRI have presented the results of various different ROPSs and CPDs by drawing comparison between the injury outcomes predicted, with and without these devices fitted, with everything else being equal. Due to the significant proportion of recorded injuries and fatalities where the victims were not wearing safety helmets, it is common practice, and indeed common sense, to state the injury risks or benefits in terms of a fair comparison between riders either with helmets, or without them. This is technique that DRI have themselves developed and popularised, and is demonstrated via the equations A1 and A2 below:

$$\text{A1: } \frac{\text{Standard bike with HELMET with ROPS/CPD}}{\text{Standard bike with HELMET}} = \text{Injury Risk / Benefits [95\% conf. int.] of the addition of ROPS/CPD when a Helmet is used}$$

$$\text{A2: } \frac{\text{Standard bike with ROPS/CPD}}{\text{Standard bike}} = \text{Injury Risk / Benefits [95\% conf. int.] of the addition of ROPS/CPD when NO Helmet is used}$$

Assuming we accept the accuracy of the simulation techniques, scenarios and methodologies used (for which serious issues and limitation still remain), Equation A1 would provide a valid comparison of the changes due to the addition of a given ROPS or CPD in the case where the rider was wearing a helmet. Likewise, Equation A2 would provide a valid comparison of changes due to the addition of ROPS/CPD in the case where the rider was not wearing a helmet. Anecdotally speaking, apples are being compared with apples. Naturally, the baseline case, or denominator in this instance, must be appropriate for the comparison to remain a valid one.

Despite this observation, in the presentation of their new and updated results pertaining to the effectiveness of the QuadBar CPD, DRI have elected to use *"a single baseline condition* *(i.e., the baseline ATV with helmet, which represents the intended use of the vehicle) in describing the main results"*. The use of this new single baseline condition is demonstrated via equations B1 and B2 below:

Standard bike with HELMET with ROPS/CPD — Injury Risk / Benefits [95% conf. int.]
B1: ———————————— = of the addition of ROPS/CPD
Standard bike with HELMET — Helmeted Condition

Standard bike with ROPS/CPD — Injury Risk / Benefits [95% conf. int.]
B2: ———————————— = of the addition of ROPS/CPD
Standard bike **with HELMET** — **IMPLIED Unhelmeted Condition**

It can be seen that the first calculation B1 is no different to A1, however the change between A2 and B2 results in an invalid and potentially misleading comparison being drawn, where the effectiveness of the standard bike with ROPS/CPD but ***without a helmet*** is measured against the new *"singular"* baseline of the standard bike with no ROPS/CPD but ***with a helmet***.

DRI attempts to justify this otherwise inexplicable change within the body of the report by stating that (among other comments):

"In summary, reasons for using the "baseline ATV with helmet" as the single baseline for the main presentation of results include the facts that: a) the "baseline ATV with helmet" is the "intended use" of an ATV, and is the most appropriate baseline configuration for calculating injury risks and benefits; b) ISO 13232 does not define which baseline to use for misuse analysis; c) previously, multiple baselines were used, however they can create a potential for confusion and misinterpretation; and d) multiple baselines can also result in the possibility of inappropriately giving preference to misuse conditions."

The reference to a shift to a "single baseline" suggests an increasing "fairness", when in fact the exact opposite is true. With regard to comments c) and d), it seems more logical to assume that multiple and appropriate baselines would be more likely to create potential for correct understanding and interpretation of these results, and the generation of valid comparisons of the effects of the addition of ROPSS/CPDs for both recommended use (helmeted) and foreseeable use (unhelmeted) conditions. Further discussion regarding comment d) is provided later in this review.

Given their preference for the "single baseline" method (B Equations) DRI have chosen to present these headline results in both the main body and executive summaries of their report. To a casual reader of the executive summary in particular, the possibility of misinterpreting the invalid comparison made with respect to the unhelmeted condition is extremely high, given that the details of, and justification for the change in method are only described much later, on page 63 of the report. DRI have also gone to the considerable effort of providing updates of all of their previous published results (i.e. other ROPSs/CPDs and also the initial “high energy” QuadBar work) using this new “single baseline” method within the appendices of this report. A cynical read of these changes might observe that casual readers are being invited to attribute the drastic changes in the updated results to improvements in the capabilities and accuracy of the modelling, rather than the heavy handed changes which have been made to commonly accepted comparison practises.

Fortunately, and much more usefully, DRI did provided calculated results for the current “low energy” study using the established and more valid “multiple baseline” method. These supplementary results can be found in tables I-3 and I-4 in Appendix I, on page 163 of the report. It is informative to contrast these results with the “single baseline” results presented in the main body, as shown in the Table below.

		Helmet			No Helmet		
2012 QuadBar Study using "Low Energy" roll over events	Multiple Baselines	A1	108% [69%,168%]	Correct	A2	68% [42%,114%]	Correct
	Single Baseline	B1	108% [69%, 168%]	Correct	B2	492% [255%, 788%]	Invalid
						+ 428%	Delta (B2 - A2)
2007 QuadBar Study using "High Energy" roll over events	Multiple Baselines	A1	99% [53%,192%]	Correct	A2	71% [41%,137%]	Correct
	Single Baseline	B1	99% [53%,192%]	Correct	B2	275% [144%, 477%]	Invalid
						+ 274%	Delta (B2 - A2)

	Helmet		No Helmet	
Deltas between 2007 "High Energy" study and 2012 "Low Energy" study, wrt Multiple Baseline results	+ 7 %	Predicted to be slightly **LESS** safe	- 3 %	Predicted to be slightly **MORE** safe

Table 4: Comparison of the results from two different studies[8,9] conducted by DRI into the risk/benefits ratios resulting from the fitment of the QuadBar CPD to a Quad bike; with and without helmets; employing both single and multiple baseline calculations. Predicted 95% confidence intervals shown in [].

Table 4 demonstrates:

- The single baseline method results in dramatic and potentially misleading increases (428% and 274%) in the reported injury risks due to the implied use of the CPD. More accurately, this difference is predominantly due to the lack of a helmet in the CPD tests, but the inclusion of a helmet in the baseline case which it is compared against.

- The modified test methodologies and models used in the updated 2012 research have resulted in very little change to the overall risk/benefit results, based on the more appropriate multiple baseline comparison. For the helmeted condition the risk/benefit prediction has increased slightly by 7%, from 99% to 108% (predicted slightly less safe), while for the no helmet condition the risk/benefit prediction has decreased slightly by 3% (slightly more safe), from 71% to 68%.

4.2.8 Interpretation of the reported statistical analyses and confidence limits

Inspection of Table 4 also reveals important considerations with respect to statistical precision and confidence intervals relating to the risk estimates.

Given DRI's stated 95% confidence limits for the updated, multiple baseline results (i.e. helmet: [69%, 168%], and no helmet: [42%, 114%]) it is evident that both these results still straddle the neutral risk/benefit value (100%). Hence, according to both DRI and the recommendations made by ISO 13232[10], these results should be considered statistically insignificant. It should be noted though that for the no helmet condition, the addition of the QuadBar CPD is very close (within 14%) of providing what DRI would classify as a statically significant increase in safety (95% confidence, 5% likelihood of error). By comparison, the confidence limits for the helmeted case straddle the neutral value almost symmetrically.

4.2.9 Real world context in interpretation of the helmeted versus non-helmeted results

A key component of the interpretation of the results in the DRI report hinges on the weight assigned to 'intended use' of ATVs, as compared to 'foreseeable use' conditions. In a real world context, it could be argued that improved safety outcomes due to CPDs are most reasonably considered in light of common usage, as well as intended use.

In Appendix I, DRI state that:

> *"It is unreasonable for a device to increase injuries for the intended use of a vehicle (i.e., helmeted, on average, in the simulation sample), even if the same device decreases injuries for one type of misuse (i.e., unhelmeted, on average, in the simulation sample) for which the average injuries are several times greater than they are for the intended use. Multiple baselines can also result in the possibility of inappropriately giving preference to misuse conditions."*

Such a statement critically underplays the actual value in the previous observation that the QuadBar CPD is very close to providing a statistically significant injury benefit, even by DRI's own data. It also fails to account for the possibility that the predicted average injuries for the unhelmeted condition may be artificially high due to the additional skull and face fracture criteria that DRI have enabled for the unhelmeted scenario.

The DRI statement may hold some value in an ideal world where "misuse" cases form a very small proportion of the incident population, but elsewhere in the report DRI openly admit to the *"relatively high frequency of unhelmeted ATV (Quad bike) riders"*. It would be counter intuitive to dismiss the predicted safety improvements due to the use of CPDs for these scenarios on the basis that such scenarios do not conveniently represent the manufacturers' "*intended use*". Given the continued high proportional representation of unhelmeted riders in the injury and fatality data, giving at least equal standing to this foreseeable use condition is the most reasonable response, at least until such time as helmet use is more pervasive amongst Quad bike riders. As highlighted previously, researchers such as DRI, the FCAI and Quad bike manufacturers also need to clarify which style, or styles, of helmet they are simulating and which they are recommending. It is not possible to assume or claim that AS/NZS:1698 compliant helmets that are broadly recommended can provide the same injury protection as the more substantial, full face helmets that DRI are currently simulating.

To provide a local context to this point, a recent survey of health and safety on Australian farms[17] finds that 80% of farms report that they use at least one Quad bike. Of these, less than half (45%) reported that it was an accepted rule and practice for helmets to always be worn whilst riding these bikes. The detail survey results for this question are presented in Figure 4, and broken down by Australian states and also by commodity sectors. Further personal communication with the authors of this report[18] suggests that this number likely contains a significant positive response bias, with anecdotal estimates placing the real rate of use much lower, at approximately 20 - 25%.

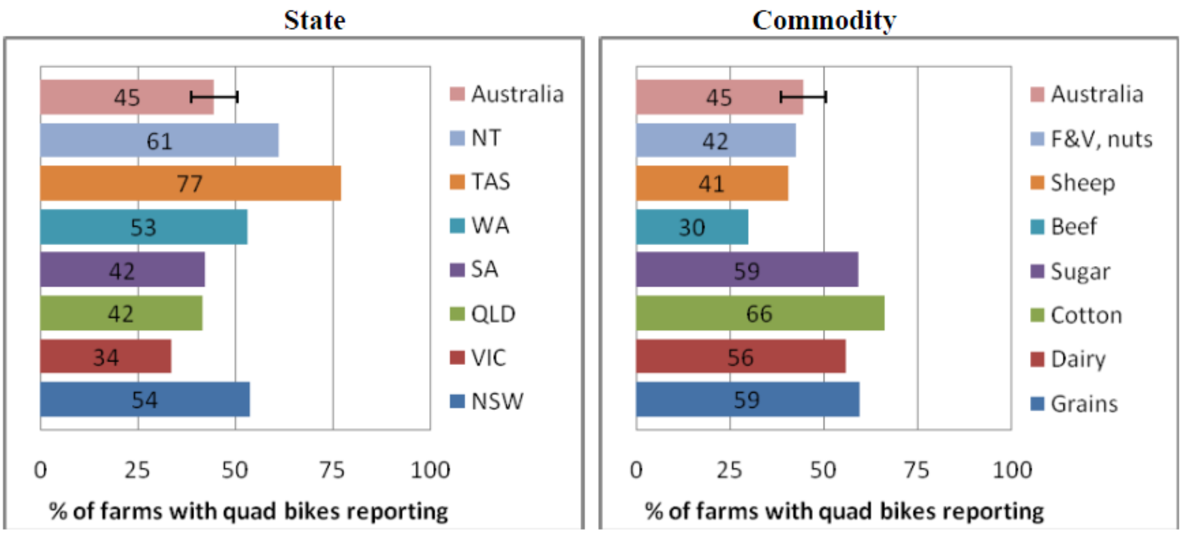

Figure 4: Proportion of respondents reporting that helmet use when riding quad bikes is an accepted rule and practice on the farm enterprise – National, State and Commodity sector[17].

4.2.10 Interpretation of fatality risk rates

In the updated work, DRI have provided, for the first time, fatality risk/benefit percentages for the use of the CPD. Based on their simulation results, they estimate the risk/benefit percentages at 134% [79%, 219%] for the helmeted condition and 1,088% [322%, 1,987%] for the unhelmeted condition. A single baseline condition is employed, which means that both results are being compared against the baseline where a helmet is used. If the underlying results are assumed to be correct, then the first estimate for the helmeted condition (134%) provides a valid comparison, but a statistically insignificant result, as also noted by DRI. The second risk/benefit estimate for the unhelmeted condition (1088%) is however invalid, due to the inappropriate baseline comparison used (i.e. no CPD, but with Helmet), and should be disregarded.

Unlike the injury results, the DRI report provides no fatality risk/benefit estimates using the more valid multiple baseline method, where the CPD and no helmet cases would be compared to the baseline bike with no helmet cases. Without provision of this result or the underlying raw data, it is not possible to determine if the CPD would have provided a statistically significant fatality benefit for the true unhelmeted comparison.

As this review did not have access to the simulation videos, it is not possible to comment on the particular scenarios or initial conditions which led to these or any other simulated fatalities.

5 Conclusions

This review of the updated research conducted by DRI into the effectiveness of a Quad bike crush protection device found that:

- A number of detail changes have been made to the simulation model to address some of the limitations identified in the initial work. Unknown variables in the scenario descriptions were estimated using a new procedure which systematically escalated the magnitudes of these values until a roll-over was recorded. It was reported that this procedure resulted in "lower energy" incidents and lower injury rates, compared to the initial work. Unfortunately, the video outputs from the new simulations were not made available for review, hence it is not possible to comment on the effects that these changes may have had on the scenarios modelled, or the level of realism attained.

- A new rider asphyxiation criterion was developed and applied to all simulations. Only a small percentage of asphyxiation injuries were predicted, and the same likelihood of occurrence was observed both with and without the CPD added. In the CPD equipped cases, such incidents were almost exclusively due to the Quad bike coming to rest on its side, on top of the rider. It is hypothesised that this predicted mode of rider asphyxiation may have been caused by the combination of increased hand grip force and the new "low energy" overturn events simulated in the updated study. Further investigation of the video results outputs should be conducted to determine if this injury mode is in fact realistic.

- New face and skull fracture mechanisms were developed, and applied only to unhelmeted cases. DRI presumed that such injuries could not be inflicted on a rider wearing the full-face style helmet which was simulated. The increased sensitivity of the unhelmeted rider to head injuries, compared with other regions of the body, may have contributed to a relative over-prediction of the safety benefits due to the use of helmets, and the relative under-estimation of safety benefits due to other devices, including the CPD.

- A significant difference was noted between the style/standard of helmet being recommended by the industry and government bodies for Quad bike use (i.e. compliant with AS/NZS:1698) and that which was simulated by DRI. The current Australian standard allows a relatively light weight, half helmet style, whereas DRI simulates a full-face style helmet more commonly used by on-road motorcycle riders. Therefore, the estimates of increased safety due to the use of a helmet, as quoted by DRI, should be considered as a very best case scenario. It is recommended that the modelling and simulation of an AS/NZS:1698 compliant helmet be utilised for future Quad bike accident simulations.

- Major changes were made to the recorded injury data set used to compare with the simulated injuries. By revising their procedure for translating the recorded injuries into AIS codings, DRI reduced the overall reported injury total from 128 to only 49. These changes eliminated approximately 25 reported "trunk" injuries and 15 "arm" injuries. Approximately one third of the final 49 injuries retained were head injuries. The overall validity and usefulness of a correlation resulting from such a heavily filtered dataset was considered minor. The potential for researchers tune their AIS coding of injuries to match their simulated results was also noted.

- Predicted injury/benefit ratios from this updated work have been presented using a "single baseline" method rather than the commonly accepted and more valid "multiple baseline" method. Thus, the normalised injury/benefit ratios for an *unhelmeted* rider, with a CPD, are calculated via comparison against a *helmeted* rider, without the CPD. The result of this change is a dramatic implied increase in the risks associated with the use of a CPD for an unhelmeted rider. In actual fact, the reported increase is entirely due to the difference in helmet usage.

- Recalculation of the injury risk/benefit results using the more correct multiple (or matched) baseline method shows that, according to updated DRI's research, the use of a CPD provides a risk/benefit ratio of 108% [69%, 169%] (slightly less safe) for the helmeted condition, and 68% [42%, 114%] (slightly safer) for the unhelmeted condition. Due to the fact that the 95% confidence intervals (shown in the square brackets) for both these results were observed to straddle the neutral risk/benefit value (100%), both findings were considered statistically insignificant. It was noted though, that for the unhelmeted condition the CPD was very close (within 14%) to returning a statistically significant prediction of increased safety.

- Despite the many changes made to the simulation methods used in the updated work, the true updated results are in fact very similar to the initial study, which predicted a risk/benefit ratio of 99% [53%, 192%] (slightly safer) for the helmeted condition, and 71% [41%, 137%] (slightly safer) for the unhelmeted condition. Again, neither result was considered statistically significant.

6 Recommendations

Given that the current review has found no new evidence to contradict the previous conclusions arising from the ISCRR Quad Bike Safety Devices Snapshot Review[1], the prior recommendations can be ratified with only minor updates. It is therefore recommended that:

1. A working group containing representatives from the major stakeholders in this issue be formed and asked to plan out and agree on the nature and specification of future research activities before they are undertaken.
2. A new incident dataset be developed based on Australian and perhaps New Zealand Quad bike fatality reports, and a range of simple generic roll scenarios (as described below). This dataset should be used for future simulations into the effectiveness of crush protection devices.
3. A preliminary standard be proposed for the design and specification of Quad bike CPDs, perhaps based upon the existing New Zealand guidelines, those for Tractor ROPS, or the experiments proposed below.
4. Funding is sourced from government or OH&S regulatory bodies for additional research into Quad bike crush protection devices.
5. The proposed working group consider conducting the following new research:

   Experiments:

   > Basic Quad bike lateral roll, forward flip and back flip tests for a range of speeds and slope angles should be conducted using an instrumented dummy. The 'Vehicle Accelerator' developed by The University of Southern Queensland could be utilised for these tests. Such tests should confirm and quantify the level of injury protection provided by CPDs for these incident types.

   Simulations:

   > Computer simulations should be used to accurately correlate the experimental tests, on the basis of both dummy and bike motions, and recorded injuries. Providing adequate correlation can be achieved, these simulations can be extended to incorporate additional generic overturn events (which are more difficult to reproduce experimentally) and the proposed new injury dataset containing Australian fatality scenarios.

   In-the-field data gathering:

   > Fit a large sample (>100) of Quad bikes currently being used by farmers with light weight and inexpensive devices which are capable of recording video, accelerations, speed and map position of the bike whilst it is being used in the field. Data gathered from this study would provide insight into the operational characteristics of Quad bikes, and quite likely some examples of loss of control and roll events. It is acknowledged that some proportion of this sample

population will include bikes fitted with CPDs which would provide useful additional data as to the effectiveness of such devices.

In the mean time, regulatory bodies should consider recommending the use of appropriately tested crush protection devices (CPDs) for riders who use Quad bikes at low speeds in the workplace and on farms. Such devices have been shown to reduce the severity of Quad bike roll-over, and have the potential to reduce the injuries and fatalities associated with these loss-of-control events.

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