

SIMULATION OF QUAD BIKE (ATV) ROLLOVERS USING PC-CRASH TO EVALUATE ALTERNATIVE SAFETY SYSTEMS

Shane Richardson, Tia Orton, Andreas Sandvik, Chris Jones, Nikola Josevski and Wei Pei (Tandy) Pok
Delta-V Experts
Australia
Paper Number 13-0286

ABSTRACT

From 2001 to 2012, over 160 Australians have died in quad bike (ATV) incidents. Annually in the USA there will be at least 700 fatalities from quad bike related incidents. The options which have been considered to protect riders in the event of a quad bike rollover are: 1) Personal protective equipment; 2) Active riding; 3) Crush Protection Devices (CPD); 4) Roll Over Protective Structure (ROPS) without restraint; and 5) ROPS with restraint. The Institute for Safety Compensation and Recovery Research identified: "...*serious issues with the simulation methods used and the nature of incidents tested to predict the effect of crush protection devices on Quad bike roll over injuries and fatalities*".

PC-Crash is a commercially available collision simulation tool, which can output simulated forces of a simulated riders body parts. A PC-Crash model of a motorcycle and rider was adapted to create an exemplar Original Equipment Manufacturer (OEM) quad bike and quad bike with CPD. 18 riderless quad bike rollover tests (7 OEM quad bikes and 11 quad bikes with CPD) were used to validate the PC-Crash models of OEM quad bike and quad bike with CPD. In a serious or fatal quad bike rollover, injuries could result from impact or crush to either the torso, neck, head or combination. Entrapment, specifically of the torso, can result in traumatic or mechanical asphyxia. 400 simulations (4 x 100) were used to comparatively evaluate impact and crush injuries of quad bike riders. The rollover simulations identified that the rider of: OEM quad bike and unrestrained rider, quad bike with CPD and unrestrained rider, quad bike with ROPS and unrestrained rider and quad bike with ROPS and restrained rider could be traumatically or mechanically asphyxiated 32, 17, 0 and 0 times respectively. Four real world fatal rollover crashes were simulated which further illustrated the positive effect of CPD and ROPS.

Where there is an identifiable risk of serious or fatal injury from quad bike rollover, consideration should be given to fitting either: CPD, ROPS or ROPS with rider restraint; to mitigate the potential for serious and/or fatal injury due to torso impact, crush or entrapment during a quad bike rollover.

BACKGROUND

A Safe Work Australia discussion paper [1] detailed research of Lower et al. [2]:

1. Since 2001, over 160 Australians have died in quad bike incidents.
2. 45% of fatalities are work related and 55% are from recreational use. In 2011 there were 23 quad bike related fatalities and 18 of these occurred on a farm.
3. Deaths due to roll over account for about half of the quad bike fatalities and 90% of rollover deaths occur on farms.
4. Quad bikes are the leading cause of injury and death on Australian farms.
5. Children under 15 years account for almost 20% of all quad bike deaths.
6. In 2011 the youngest and oldest quad bike riders killed were 4 years old and 94 years old respectively.
7. 45% of deaths are those aged 45 years and over.

US Consumer Product Safety Commission, Commissioner Mr Robert Adler [3] stated: "*Each year there will be at least 700 funerals because of a (quad bike) ATV-related incident. Since 1982, the US CPSC has received more than 11,000 reports of ATV-related fatalities. Almost 3,000 have been children...*"

The options which have been considered to mitigate and/or protect quad bike riders in the event of a rollover are:

1. The Original Equipment Manufacturer (OEM) quad bike, i.e. without any structural modification;
2. Active riding;
3. Personal protective equipment (specifically helmets);
4. Crush Protection Device (CPD), refer to Figure 1;
5. Roll Over Protective Structure (ROPS) without occupant restraint;
6. ROPS with occupant restraint [5] and [13], refer to Figure 2.



Figure 1: A Quadbar [4] CPD.

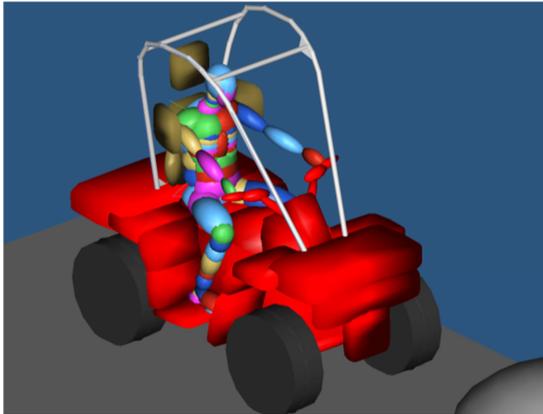


Figure 2: ROPS with occupant restraint [5] and [13] (seatback and seatbelt).

Lower et al. [2] identified that $\frac{1}{3}$ of Australian quad bike fatalities involve head injury as the primary cause. The quad bike industry does actively promote the wearing of helmets, which will most likely mitigate the number of head injuries.

The quad bike industry appears to have adopted ROPS with occupant restraints for side by side's (Figure 3) [6]. However the quad bike industry appears opposed to and advertises against CPD's or ROPS for quad bikes [7] (refer to Figure 4).



Figure 3: Side by side with ROPS and occupant restraints (3 point seatbelt).

We won't have a bar of it...

ROLL BARS, CRUSH PROTECTION DEVICES AND ROLL OVER PROTECTION SYSTEMS CAN CAUSE INJURY AND DEATH.

ATV manufacturers do not recommend that Roll Over Protection Structures (ROPS) or Crush Protection Devices (CPDs) be fitted to All Terrain Vehicles.

WE ISSUE THIS MESSAGE IN THE INTEREST OF ATV RIDER SAFETY.

We ask you to wear a helmet, read your owners manual, watch the safety video provided with your ATV, choose the correct ATV for application and undertake rider training.

Find out all of the facts at www.atvsafety.com.au



... and neither should you.



Figure 4: The Australian Federal Chamber of Automotive Industries advertisement for BRP (Can-am), Honda, Kawasaki, Kymco, Polaris, Suzuki, and Yamaha [7].

Wordley and Field [8] reviewed 20 references ([9] to [28]) and found that:

1. "Quad bikes were the leading cause of death on Australian farms in 2011, accounting for around one-third of fatalities. These deaths commonly resulted from chest, head or spinal injuries. Children under 14 years and older people over 45 years were the most common victims;
2. Various simulation programs (including MADYMO, ATB and MATD) were adapted and used by researchers to model Quad bike accident scenarios. A large number of shortcomings were identified with these models. Most importantly, none of the models were able to predict asphyxiation fatalities...";
3. "The computer simulations were loosely based on Quad bike incident descriptions provided by the UK Health and Safety Executive and the US Consumer Product Safety Committee. In general, these incident descriptions were extremely brief and contained insufficient information to accurately define the accident scenarios;
4. Many assumptions and interpretations were made by the researchers attempting to simulate these scenarios, most of which had the potential to significantly alter the simulation results. A

clear and agreed interpretation of data by researchers and a defined test methodology is required in order to minimise variations in findings by researchers.

5. Several issues were identified with the methods used to model the different terrains, particularly the ground stiffness and friction coefficients chosen, and the extreme length of the slopes commonly modelled. These factors appear to have generated roll dynamics and injury outcomes which are potentially inaccurate;
6. The Dynamic Research Inc. (DRI) research in particular caused a substantial and unexplained shift in the nature of the injuries predicted, dramatically over-predicting head injuries and virtually eliminating chest injuries. This shift in the nature of injuries predicted by the simulations removed much of the potential for crush protection devices tested to reduce the simulated rider injuries;
7. The method described by ISO 13232 for calculating risk benefit ratios was found to be extremely susceptible to influences from a range of factors including: the test scenarios chosen, the inherent variability in each case, and the methods used to compare minor, non-permanent injuries with fatalities;
8. Experimental tests conducted by the University of Southern Queensland indicate that the Quad Bar CPD is successful in arresting and preventing the roll of a driverless Quad bike for both side roll and back flip scenarios. These results indicate the potential effectiveness of the Quad Bar and other similar CPDs in preventing rider injuries and fatalities due to low speed roll over incidents;
9. The Federal Chamber of Automotive Industries (FCAI) is an industry body which represents the major importers and distributors of Quad bikes within Australia, including Suzuki, Honda, Yamaha, Kawasaki, Polaris and Bombardier. The FCAI's strong opposition to the fitment of CPDs in general and the Quad Bar in particular was found to be based on the research produced by Failure Analysis Associates and DRI. Their reasons for rejecting such devices cannot be supported given the major problems with the research methodologies identified by this review.

This review identifies serious issues with the simulation methods used and the nature of incidents tested to predict the effect of crush protection devices on Quad bike roll over injuries and fatalities. Limited experimental and simulation results indicate that the Quad Bar crush protection device demonstrates potential to reduce rider harm in such events. Further research conducted by

researchers with experience in the field is needed to fully examine these potential benefits.”

INTRODUCTION

PC-Crash is a computer based crash reconstruction software program which combines the simulation of pre-collision, collision and post-collision dynamics for multiple vehicles in a graphical environment. Twenty four papers published by the Society of Automotive Engineers ([29] to [53]) and a book by Wach [54] detail examples and validations of the use of PC-Crash in vehicle collision reconstruction. The multi-body function within PC-Crash can output body part displacement, velocity, accelerations and forces verse's time.

SNOOK DATA

Snook [20] detailed 42 tests of two riderless quad bikes.

The mass of the quad bikes used by Snook were approximately 250kg, with and without CPD (Quadbar [4]), which can be condensed into 29 tests (with 13 repeated tests). A summary of the data presented by Snook is detailed in Table 1 to Table 6.

Serial	Ramp angle	Speed	¼ turns	Snook video
1	21.5 ⁰	4.7km/h	2	1745
2	23.0 ⁰	5.2km/h	2	1665
3	23.0 ⁰	6.6km/h	2	1666, 1667 and 1668
4	23.0 ⁰	7.7km/h	3	1669 and 1670
5	23.0 ⁰	8.6km/h	3	1671 and 1672

Table 1: Side roll, no CPD on a horizontal surface.

Serial	Ramp angle	Speed	¼ turns	Snook video
6	12.0 ⁰	3.5km/h	4 [#]	1743
7	23.0 ⁰	4.1km/h*	8	1689
8	23.0 ⁰	5.4km/h	8	1688

Table 2: Side roll, no CPD on a sloping 20⁰ surface (*estimated and # on wheels and rolled).

Serial	Ramp angle	Speed	¼ turns	Snook video
9	24.0 ⁰	4.1km/h	8	1734
10	24.0 ⁰	4.3km/h	2	1728 and 1730
11	24.0 ⁰	4.4km/h	2	1729

Table 3: Backflip, no CPD on a sloping 20⁰ surface.

Serial	Ramp angle	Speed	¼ turns	Snook video
12	21.5°	4.6km/h	1	1746
13	23.0°	5.2km/h	1	1679
14	23.0°	6.5km/h	1	1678
15	23.0°	7.6km/h	1	1676 and 1677
16	23.0°	8.6km/h	1	1673
17	23.0°	8.6km/h	3	1675
18	23.0°	9.3km/h	3	1680 and 1681

Table 4: Side roll, CPD on a horizontal surface.

Serial	Ramp angle	Speed	¼ turns	Snook video
19	12.0°	3.5km/h	4 [#]	1742
20	12.0°	3.8km/h	4 [#]	1741
21	24.0°	4.6km/h	4 [#]	1735, 1737 and 1738
22	24.0°	5.2km/h	4 [#]	1736
23	23.0°	5.4km/h	1	1686 and 1687
24	26.0°	5.6km/h	1	1685
25	26.0°	7.1km/h	4	1683 and 1684
26	26.0°	10.1km/h	8	1682

Table 5: Side roll, CPD on a sloping 20° surface ([#] on wheels and rolled).

Serial	Ramp angle	Speed	¼ turns	Snook video
27	24.0°	4.2km/h	1	1731 and 1733
28	24.0°	4.3km/h	1	1726 and 1727
29	24.0°	4.4km/h	1	1725

Table 6: Backflip, CPD on a sloping 20° surface.

QUAD BIKE OVERTURN ANGLE

The centre of gravity for a 241kg OEM quad bike (less fuel) was detailed at 0.591m behind the front axle (based on wheel masses and wheelbase) [13]. The riderless OEM quad bike left and right overturn angles were 39.2° and 38.8° respectively. An overturn angle of 39° has been used for the OEM quad bike.

Assuming 9kg of fuel 0.450m behind the front axle; a 250kg quad bike would have a centre of gravity 0.586m behind the front axle and an overturn angle of 39°.

PC-CRASH MODEL

A quad bike and rider model was created by adapting the existing PC-Crash motorcycle and rider multi-body model. Six variations of the PC-Crash multi-body model were created. Models 1 and 2 were riderless and are used to validate the models. Models 3 to 6 had riders and are used to comparatively evaluate rider injury potential: 1) Riderless OEM quad bike [Figure 5]; 2) Riderless quad bike with CPD [Figure 6]; 3) OEM quad bike

and unrestrained rider; 4) Quad bike with CPD and unrestrained rider; 5) Quad bike with ROPS and unrestrained rider; and 6) Quad bike with ROPS and restrained rider. The quad bike only, quad bike with CPD and quad bike with ROPS were all rigid body models, i.e. no suspension motion was simulated. Active riding was not simulated.

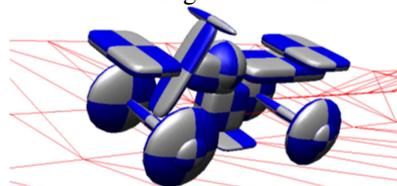


Figure 5: The OEM quad bike.

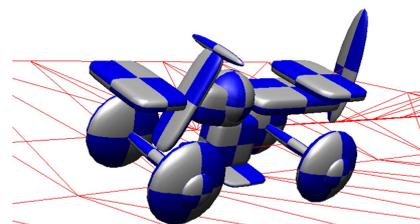


Figure 6: Quad bike with CPD.

VALIDATION

The simulation of the OEM quad bike does not roll at a side inclination of 38°, whereas it does roll onto its side at a side inclination of 39°, corresponding to the side tilt table test data (from the Monash University Accident Research Centre [13] tests).

Serials 1 to 5; 7 and 8; 12 to 18; and 23 to 26 from Table 1 to Table 6 are used to validate the PC-Crash simulation of the OEM quad bike (refer to Table 7) and quad bike with CPD (refer to Table 8) based on the number of ¼ turns. In serials:

1. 6 and 19 to 22 the quad rollover was onto its wheels and then rolled away, the PC-Crash multi-body simulation cannot replicate this event and therefore was excluded from the validation pool.
2. 9 to 11 and 27 to 29 the quad rollover was a backflip, which has not been evaluated in this paper and therefore was excluded from the validation pool.

Serial	Ramp angle	Speed	Slope	Snook ¼ turns	Modelled ¼ turns
1	21.5°	4.7km/h	0°	2	2
2	23.0°	5.2km/h	0°	2	2
3	23.0°	6.6km/h	0°	2	2
4	23.0°	7.7km/h	0°	3	3
5	23.0°	8.6km/h	0°	3	3
7	23.0°	4.1km/h	20°	8	+8
8	23.0°	5.4km/h	20°	8	+8

Table 7: Comparison of Snook ¼ turns to PC-Crash multi-body OEM quad bike ¼ turns.

Serial	Ramp angle	Speed	Slope	Snook ¼ turns	Modelled ¼ turns
12	21.5°	4.6km/h	0°	1	1
13	23.0°	5.2km/h	0°	1	1
14	23.0°	6.5km/h	0°	1	1
15	23.0°	7.6km/h	0°	1	1
16	23.0°	8.6km/h	0°	1	1
17	23.0°	8.6km/h	0°	3	2
18	23.0°	9.3km/h	0°	3	3
23	23.0°	5.4km/h	20°	1	1
24	26.0°	5.6km/h	20°	1	1
25	26.0°	7.1km/h	20°	4	5
26	26.0°	10.1km/h	20°	8	5

Table 8: Comparison of Snook ¼ turns to PC-Crash multi-body quad bike with CPD ¼ turns.

Note that in Table 7 and Table 8 in:

1. All serials, the overall width of the cargo frames on the front and rear of the rear of the quad were reduced to 720mm. This was undertaken to compensate for the lack of suspension movement and to correlate with the Snook ¼ turn data.
2. Serials 12 to 18, the overall height of the CPD was lowered by approximately 300mm to compensate for the lack of suspension movement and to correlate with the Snook ¼ turn data.
3. Serials 23 to 26, the multi-body quad bike with CPD on the 20° slope the height of the CPD was raised by 305mm to correlate with the Snook ¼ turn data.

The modelled OEM quad bike and quad bike with CPD ¼ turn data correlates well with the Snook ¼ turn data.

TEG

The Heads of Workplace Health and Safety (HWSA) Trans-Tasman Working-Party on 'Quad Bike Safety' tasked a Technical Engineering Group (TEG) [24] to identify if it was: "...reasonably practicable for a device to be developed that when fitted to Quad Bike reduces the potential for death and/or serious injury caused by entrapment beneath an overturned vehicle?".

Lower et al. [9] from the Australian Centre for Agricultural Health and Safety presented to the TEG, data on quad bike rollovers in Australia that:

1. "Of the 127 quad bike fatalities, eight cases could not be classified as either a rollover or non-rollover incident. Of the remaining 119 cases, 56 (47%) were rollovers."
2. "Rollovers accounted for 59% of on-farm and 18% of non-farm deaths."

3. "Rollover deaths were primarily associated with asphyxiation or respiratory difficulty (n=14), head injury (n=11), chest (n=6) and spine injuries (n=4). This compares with injuries from non-rollovers where multiple injuries (n=13), head (n=10) and brain injuries (n=4) predominate".
4. "The data clearly indicate that the major risk for use of quad bikes on Australian farms in undertaking the current range of tasks, is death due to rollover and being trapped and crushed under the machine."

The fundamental criterion posed by the HWSA to the TEG was to prevent entrapment. Entrapment could result in crush injury to the either the torso, neck, head or combination. Entrapment of the torso could result in traumatic or mechanical asphyxia.

QUAD BIKES AND RIDER

The mass of the multi-body rider is 77kg.

The rider multi-body was initially held in position by 50N or 100N tension only tethers between the: head and seat; torso and seat; feet and footplate; and hands and handlebar. The tension only tethers prevented the multi-body rider from initially flopping forward.

Figure 7 illustrates the multi-body quad bike and unrestrained rider.

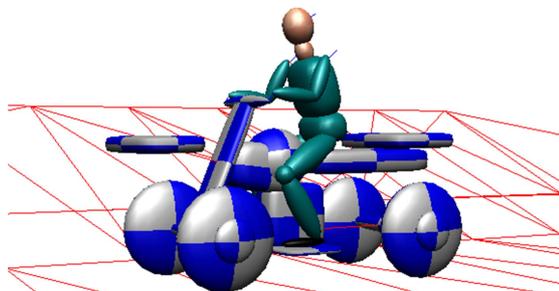


Figure 7: Quad bike and unrestrained rider.

Figure 8 illustrates the multi-body quad bike with CPD and unrestrained rider.

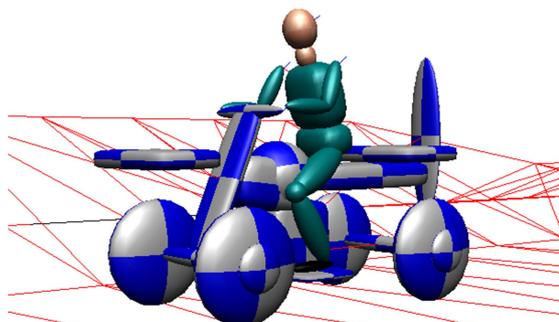


Figure 8: Quad bike with CPD and unrestrained rider.

Figure 9 illustrates the multi-body quad bike with ROPS and unrestrained rider. The width of the frames at the front and rear of the quad has been increased by 200mm to have the frames engaged with ground in a rollover.

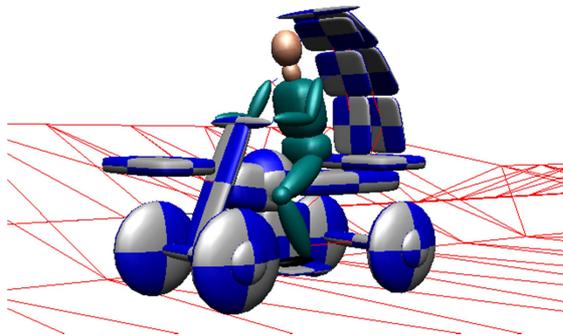


Figure 9: Quad bike with ROPS and unrestrained rider.

Figure 10 illustrates the multi-body quad bike with ROPS and restrained rider. The restraints are provided via a seat back and two over shoulder seat belt loops.

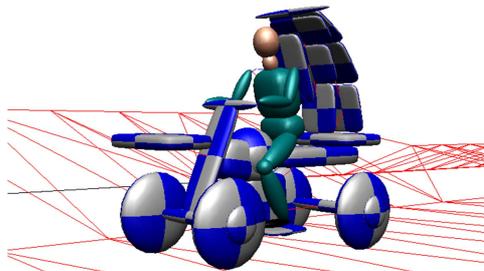


Figure 10: Quad bike with ROPS and restrained rider.

SIMULATION SENARIOS

Given the critical observation made by Wordley and Field [8] with respect to slope length in previous simulations, the initially simulated rollovers (with riders) in this paper were on a horizontal surface.

A comparative evaluation matrix of 100 simulations for the quad bike combinations (i.e. 400 simulations) were conducted at ramp angles of 20° to 29° (in 1° intervals) and at speeds of 6km/h to 15km/h (in 1km/h intervals). The forces on the torso, neck and head were evaluated. The raw data from PC-Crash was filtered (refer to Figure 11).

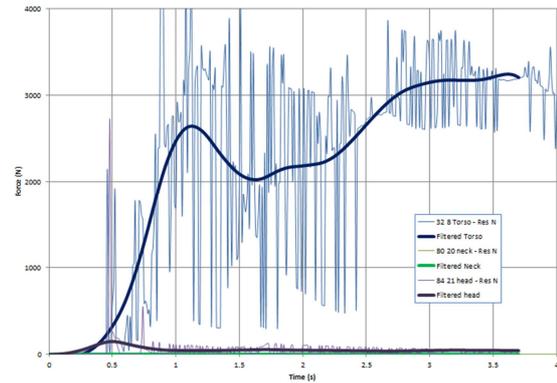


Figure 11: Example of the raw and filtered data (quad bike and unrestrained rider rollover at a ramp angle of 26° and lateral speed of 13km/h).

The torso impact force injury tolerance for a PC-Crash multi-body is not known. The 77kg rider has a torso mass of 22kg, hence a torso force of 1,500N and 3,000N could equate to a torso acceleration of 6.9g and 13.9g. The peak torso impact force in the first 1.5s was plotted for all the 400 PC-Crash simulations. (Note that torso impacts of 1,500N or 3,000N are unlikely to be fatally injurious. The peak torso impact force in the first 1.5s is used to compare the different configurations.)

Zellner et al. [55] using a different simulation tool (Articulated Total Body) utilises a compressive force of 490N as potential for “...significant breathing difficulty beyond 1 hour”. Zellner et al. present that 490N: “...might be relevant to assessing potential for hypothetical mechanical/traumatic (compressive) asphyxia phenomena.” From the 400 simulations conducted using PC-Crash it was possible for the ejected rider to have a resting torso force greater than 490N without being beneath a rolled quad (i.e. the body orientation on the ground can result in a resting torso force of greater than 490N). Zellner et al. cites Hopkins et al [56] and presents Figure 12.

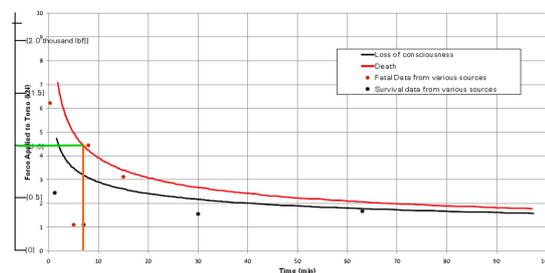


Figure 12: Extracted from Zellner et al. p52, Figure 8: “Estimate of Human Tolerance to Mechanical Asphyxia With Fatal and Survival Data”. This is identified as being sourced from Hopkins et al. The green line is at 1000N and the orange line is at approximately 7 minutes.

Based on Figure 12 a quad bike rider could be traumatically or mechanically asphyxiated if the

average resting force on the rider torso was greater than 1,000N for greater than 7 minutes. The resting average torso force, from 1.5s to 4.0s after the simulation started, was plotted for all the 400 PC-Crash simulations.

The ramp angle, speed, forces [peak (torso, neck and head) and resting torso] are plotted for all the 400 simulated configurations, refer to Figure 13 to Figure 28.

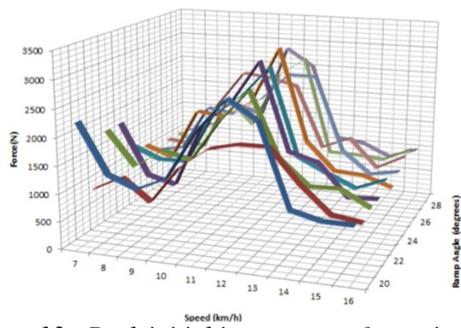


Figure 13: Peak initial impact torso forces in the first 1.5s for a range of simulated quad bike and unrestrained rider rollovers. 41 of the 100 simulations exceed 1,500N impact torso force and 11 of the 41 simulations exceeded 3,000N.

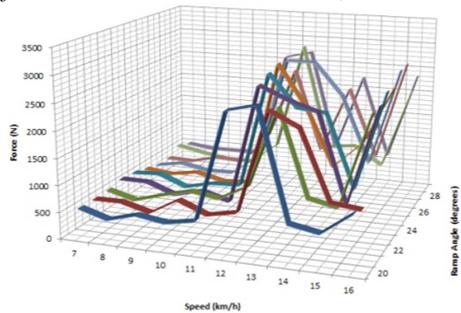


Figure 14: Resting torso forces for a range of simulated quad bike and unrestrained rider rollovers. 32 of the 100 simulations exceed 1,000N resting torso force.

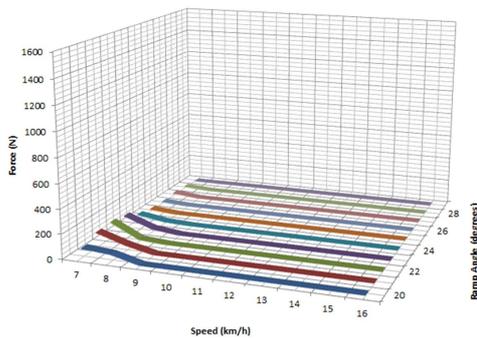


Figure 15: Peak neck forces for a range of simulated quad bike and unrestrained rider rollovers.

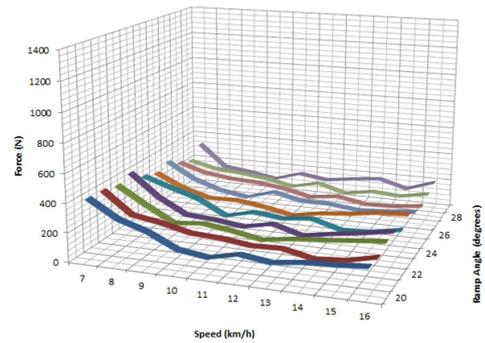


Figure 16: Peak head forces for a range of simulated quad bike and unrestrained rider rollovers.

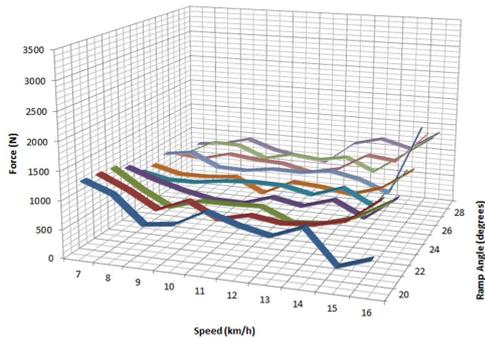


Figure 17: Peak initial impact torso forces in the first 1.5s for a range of simulated quad bike with CPD and unrestrained rider rollovers. 2 of the 100 simulations exceed 1,500N impact torso force. Neither of the 2 simulations exceeded 3,000N.

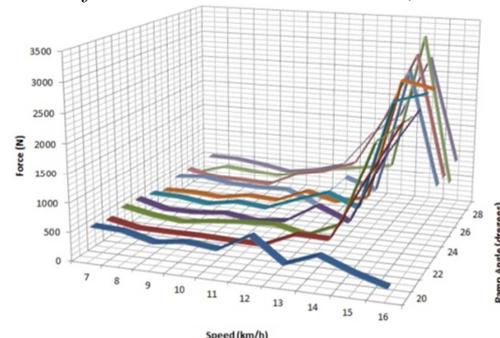


Figure 18: Resting torso forces for a range of simulated quad bike with CPD and unrestrained rider rollovers. 17 of the 100 simulations exceed 1,000N resting torso force.

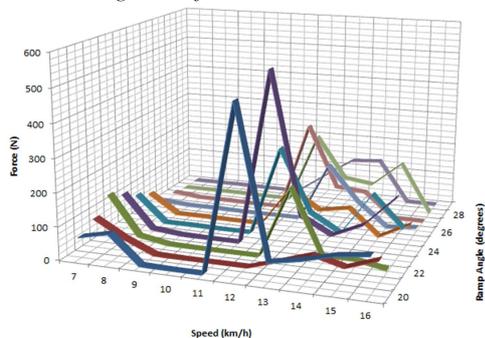


Figure 19: Peak neck forces for a range of simulated quad bike with CPD and unrestrained rider rollovers.

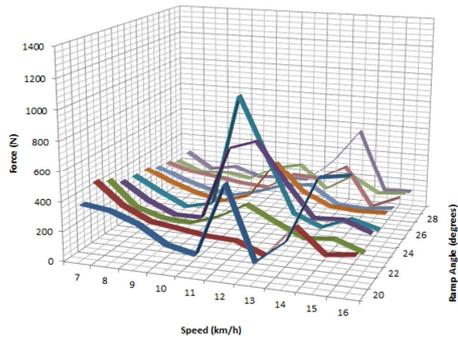


Figure 20: Peak head forces for a range of simulated quad bike with CPD and unrestrained rider rollovers.

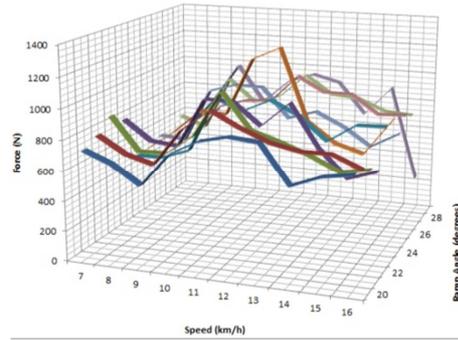


Figure 24: Peak head forces for a range of simulated quad bike with ROPS and unrestrained rider rollovers.

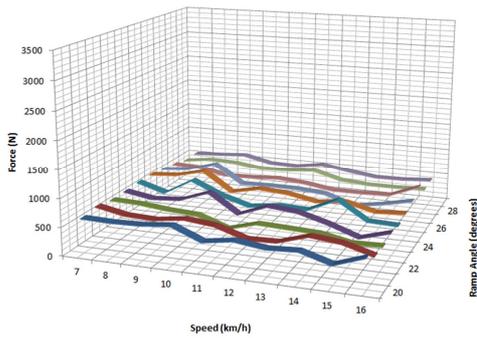


Figure 21: Peak initial torso forces for a range of simulated quad bike with ROPS and unrestrained rider rollovers. None of the 100 simulations exceed 1,500N impact torso force. (Hence none of the 100 simulations exceeded 3,000N impact torso force.)

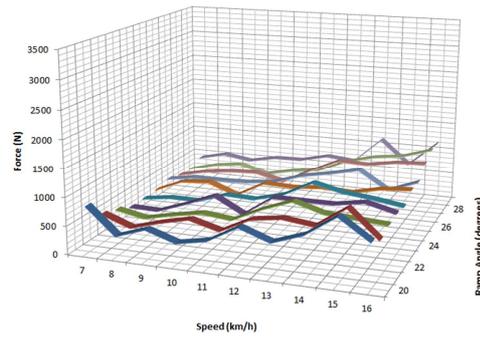


Figure 25: Peak initial torso forces for a range of simulated quad bike with ROPS and restrained rider rollovers. None of the 100 simulations exceed 1,500N impact torso force. (Hence none of the 100 simulations exceeded 3,000N impact torso force.)

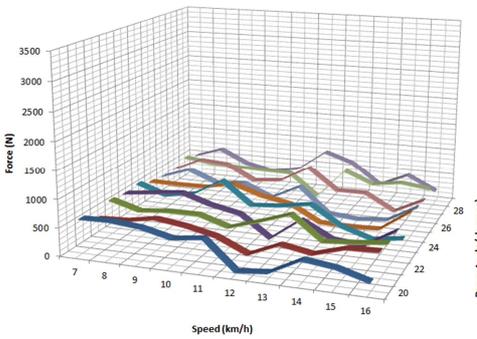


Figure 22: Resting torso forces for a range of simulated quad bike with ROPS and unrestrained rider rollovers. None of the 100 simulations exceed 1,000N impact torso force

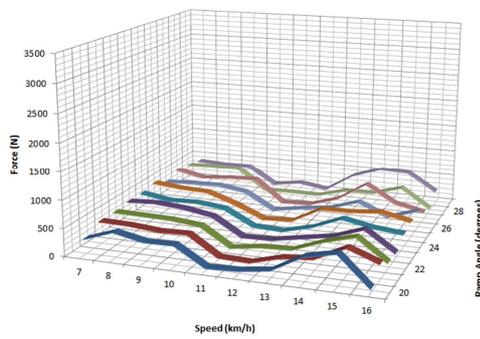


Figure 26: Resting torso forces for a range of simulated quad bike with ROPS and restrained rider rollovers. None of the 100 simulations exceed 1,000N resting torso force.

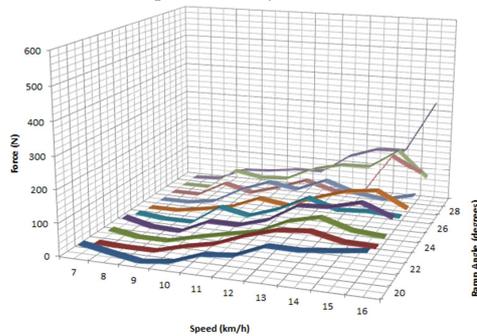


Figure 23: Peak neck forces for a range of simulated quad bike with ROPS and unrestrained rider rollovers.

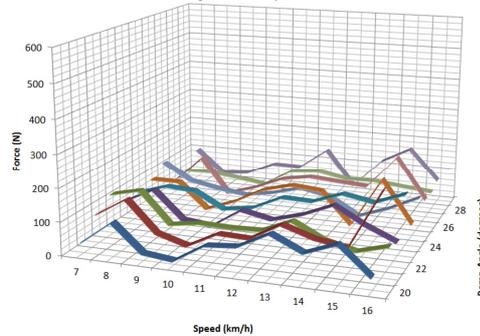


Figure 27: Peak neck forces for a range of simulated quad bike with ROPS and restrained rider rollovers.

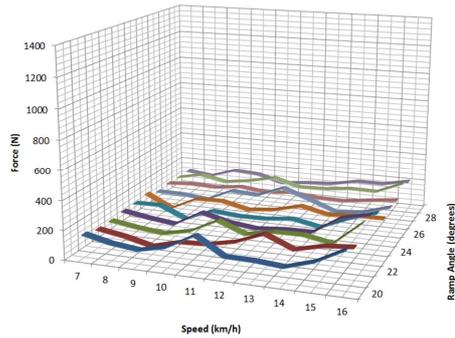


Figure 28: Peak head forces for a range of simulated quad bike with ROPS and restrained rider rollovers.

Simulation Scenarios Analysis

From the 100 simulations for each of the four quad bike configurations:

1. The number of $\frac{1}{4}$ turns:
 - a. The OEM quad bike did $24 \frac{1}{4}$ turns, $26 \frac{2}{4}$ turns and $50 \frac{3}{4}$ turns.
 - b. The quad with CPD did $34 \frac{1}{4}$ turns, $9 \frac{2}{4}$ turns and $57 \frac{3}{4}$ turns.
 - c. The quad with ROPS did $100 \frac{1}{4}$ turns.
 - d. The quad with ROPS and restrained rider did $100 \frac{1}{4}$ turns.
2. The rider's torso was impacted with force greater than 1,500N:
 - a. 41 times for the quad bike and unrestrained rider.
 - b. 2 times for the quad bike with CPD and unrestrained rider.
 - c. Zero times for the quad bike with ROPS and unrestrained rider.
 - d. Zero times for the quad bike with ROPS and restrained rider.
3. The rider's torso was impacted with force greater than 3,000N:
 - a. 11 times for the quad bike and unrestrained rider.
 - b. Zero times for the quad bike with CPD and unrestrained rider.
 - c. Zero times for the quad bike with ROPS and unrestrained rider.
 - d. Zero times for the quad bike with ROPS and restrained rider.
4. The rider could have been traumatically or mechanically asphyxiated with a resting torso force of greater than 1,000N if trapped beneath the quad for more than 7 minutes:
 - a. 32 times for the quad bike and unrestrained rider.
 - b. 17 times for the quad bike with CPD and unrestrained rider.

- c. Zero times for the quad bike with ROPS and unrestrained rider.
- d. Zero times for the quad bike with ROPS and restrained rider.

Based on the 400 simulations (4 x 100 comparative simulations) where there is an identifiable risk of serious or fatal injury from quad rollover, consideration should be given to fitting either: CPD, ROPS or ROPS with rider restraint to mitigate the potential for serious or fatal injury due to torso impact or entrapment during a quad bike rollover.

The peak head force was 1,272N for the quad bike with ROPS and unrestrained rider. Wearing a helmet could mitigate the potential for serious or fatal injury consequences of head impact or crush injuries for all quad bike configurations. The effect of wearing a helmet was not evaluated as part of this paper.

REAL WORLD CRASHES

The authors have access to 15 documented serious injury real world quad bike rollover crashes. Four serious injury cases involving riders who were involved in rollover incidents have been simulated and presented.

The initial conditions for the OEM quad bike and rider for the four cases have been adopted for the other three configurations simulated; hence the initial conditions in each case are the same for the four simulated configurations in each case.

Case 1

Riding parallel to a creek bank the rider has ridden up an embankment (refer to Figure 29). The OEM quad bike rolled trapping the rider's torso (refer to Figure 30). The rider sustained fatal injuries as a result of the rollover.

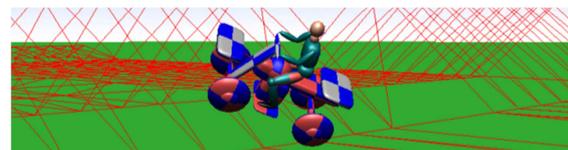


Figure 29: The initial position for Case 1.

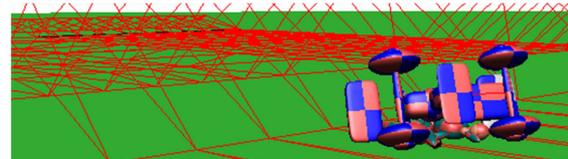


Figure 30: The rest position of the OEM quad bike and rider for the simulation of Case 1. The rider has been ejected from the quad bike and the rider is under the quad bike.

From the simulations for Case 1 in each quad bike configuration:

1. The number of ¼ turns:
 - a. The OEM quad bike did 3 ¼ turns.
 - b. The quad with CPD did 3 ¼ turns.
 - c. The quad with ROPS did 1 ¼ turn.
 - d. The quad with ROPS and restrained rider did 1 ¼ turn.
2. The rider's torso was impacted with force of:
 - a. 3,529N for the quad bike and unrestrained rider.
 - b. 600N for the quad bike with CPD and unrestrained rider.
 - c. 353N for the quad bike with ROPS and unrestrained rider.
 - d. 645N for the quad bike with ROPS and restrained rider.

Given the torso impact forces it is more likely that the OEM quad bike and unrestrained rider would have injured that the other configurations.

3. In the OEM quad bike and unrestrained rider simulation the ejected rider was trapped beneath the OEM quad bike and could have been traumatically or mechanically asphyxiated (resting torso force of 2,975N).
4. The rider was not trapped under the quad bike with:
 - a. CPD and unrestrained rider. The resting torso force was 317N, refer to Figure 31.
 - b. ROPS and unrestrained rider. The resting torso force was 154N, refer to Figure 32.
 - c. ROPS and restrained rider. The resting torso force was 141N, refer to Figure 33.

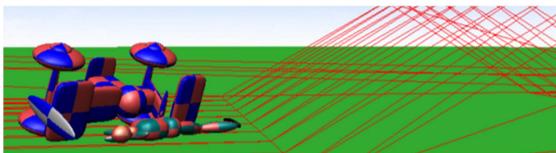


Figure 31: The rest position of the quad bike with CPD and unrestrained rider for Case 1.

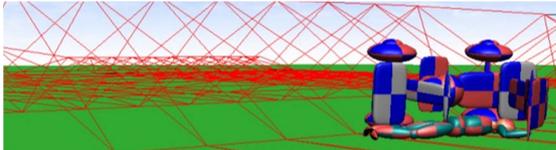


Figure 32: The rest position of the quad bike with ROPS and unrestrained rider for Case 1.

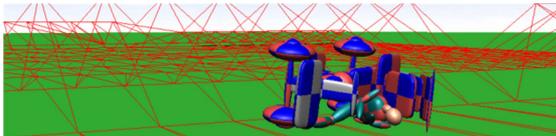


Figure 33: The rest position of the quad bike with ROPS and restrained rider for Case 1.

If the quad bike in Case 1 had been fitted with a CPD or ROPS (whether unrestrained or restrained rider) the rider could have survived the rollover.

Case 2

The OEM quad bike was ridden over flat ground to a steep creek bank. The OEM quad bike was braked and then topped over the edge (refer to Figure 34) and rolled down the creek bank (refer to Figure 35). The bank was approximately 60° with a drop of approximately 5m. The rider sustained fatal trauma to the torso (chest and back).

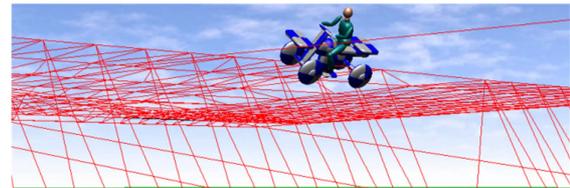


Figure 34: The initial position for Case 2.

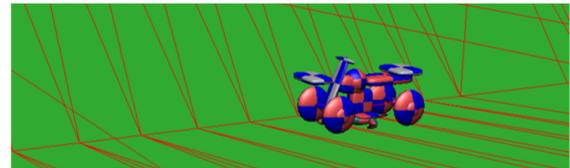


Figure 35: The rest position of the OEM quad bike and rider for the simulation of Case 2. The rider has been ejected from the quad bike and the rider is beneath the quad bike.

From the simulations for Case 2 in each quad bike configuration:

1. The number of ¼ turns:
 - a. The OEM quad bike did 8 ¼ turns.
 - b. The quad with CPD did 7 ¼ turns.
 - c. The quad with ROPS did 5 ¼ turns.
 - d. The quad with ROPS and restrained rider did 6 ¼ turns.
2. The rider's torso was impacted with force of:
 - a. 3,964N for the OEM quad bike and unrestrained rider.
 - b. 1,211N for the quad bike with CPD and unrestrained rider.
 - c. 2,088N for the quad bike with ROPS and unrestrained rider.
 - d. 1,384N for the quad bike with ROPS and restrained rider.

Given the torso impact forces it is more likely that the OEM quad bike and unrestrained rider would have injured and likely that the quad bike with ROPS and unrestrained rider would have been injured. The other configurations were less likely to have injured the rider.

3. In the OEM quad bike and unrestrained rider simulation the ejected rider was trapped beneath

the OEM quad bike and could have been traumatically or mechanically asphyxiated (resting torso force of 1,529N).

4. The rider was not trapped under the quad bike with:
 - a. CPD and unrestrained rider. The resting torso force was 540N, refer to Figure 36.
 - b. ROPS and unrestrained rider. The resting torso force was 550N, refer to Figure 37.
 - c. ROPS and restrained rider. The resting torso force was 6N, refer to Figure 38.

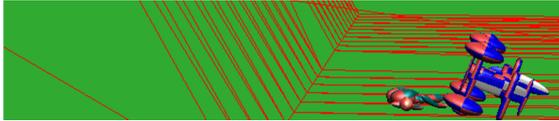


Figure 36: The rest position of the quad bike with CPD and unrestrained rider for Case 2.



Figure 37: The rest position of the quad bike with ROPS and unrestrained rider for Case 2.

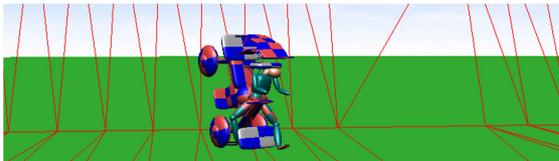


Figure 38: The rest position of the quad bike with ROPS and restrained rider for Case 2.

If the quad bike in Case 2 had been fitted with either a CPD or ROPS (whether unrestrained or restrained rider) the rider could have survived the rollover.

Case 3

The OEM quad bike impacted an ant-hill (1.1m long, 0.5m high and 0.4m wide) at approximately 19km/h and was ejected with OEM quad bike landing on top of rider (refer to Figure 39 and Figure 40). The OEM quad bike rolled 3 ¼ turns.

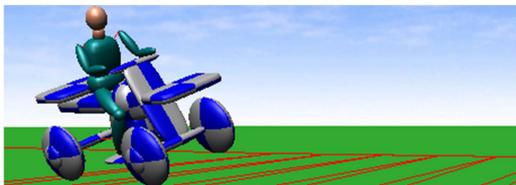


Figure 39: The initial position for Case 3.

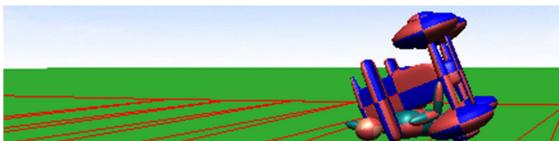


Figure 40: The rest position of the OEM quad bike and rider for the simulation of Case 3. The rider

has been ejected from the quad bike and the rider is beneath the quad bike.

From the simulations for Case 3 in each quad bike configuration:

1. The number of ¼ turns:
 - a. The OEM quad bike did 3 ¼ turns.
 - b. The quad with CPD did 3 ¼ turns.
 - c. The quad with ROPS did 2 ¼ turns.
 - d. The quad with ROPS and restrained rider did 3 ¼ turns.
2. The rider's torso was impacted with force of:
 - a. 1,736N for the OEM quad bike and unrestrained rider.
 - b. 278N for the quad bike with CPD and unrestrained rider.
 - c. 2088N for the quad bike with ROPS and unrestrained rider.
 - d. 980N for the quad bike with ROPS and restrained rider.

Given the torso impact forces it is more likely that the quad bike with ROPS and unrestrained rider would have injured and likely that the OEM quad bike and unrestrained rider would have been injured. The other configurations were less likely to have injured the rider.

3. In the OEM quad bike and unrestrained rider simulation the ejected rider was trapped beneath the OEM quad bike and could have been traumatically or mechanically asphyxiated (resting torso force of 1,657N).
4. The rider was not trapped under the quad bike with:
 - a. CPD and unrestrained rider. The resting torso force was 138N, refer to Figure 41.
 - b. ROPS and unrestrained rider. The resting torso force was 550N, refer to Figure 42.
 - c. ROPS and restrained rider. The resting torso force was 221N, refer to Figure 43.

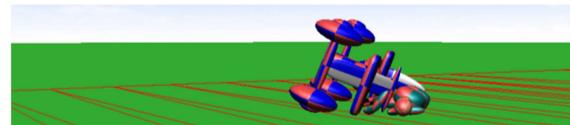


Figure 41: The rest position of the quad bike with CPD and unrestrained rider for Case 3.

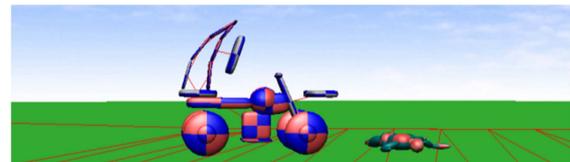


Figure 42: The rest position of the quad bike with ROPS and unrestrained rider for Case 3.

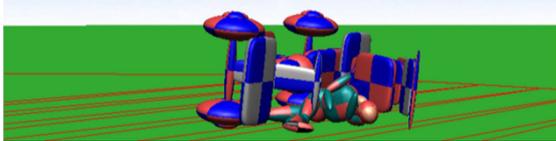


Figure 43: The rest position of the quad bike with ROPS and restrained rider for Case 3.

If the quad bike in Case 3 had been fitted with either a CPD or ROPS (whether unrestrained or restrained rider) the rider could have survived the rollover.

Case 4

A 105kg adult male riding across a side slope on a quad bike with a spray tank fitted to the rear frame (refer to Figure 44) rolled laterally and ejected the rider. The rider was found beneath the OEM quad bike (refer to Figure 45). The Coroner identified that the cause of death was traumatic asphyxiation.

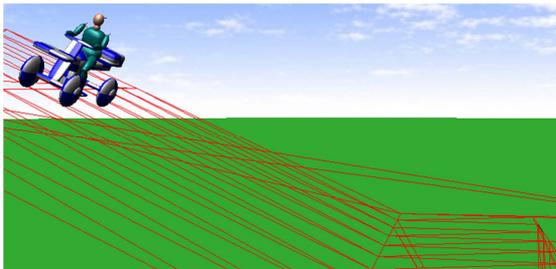


Figure 44: The initial position for Case 4.

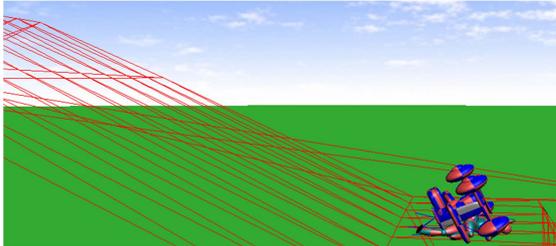


Figure 45: The rest position of the OEM quad bike and rider for the simulation of Case 4. The rider has been ejected from the quad bike and the rider is beneath the quad bike.

From the simulations for Case 4 in each quad bike configuration:

1. The number of ¼ turns:
 - a. The OEM quad bike did 7 ¼ turns.
 - b. The quad with CPD did 5 ¼ turns.
 - c. The quad with ROPS did 1 ¼ turn.
 - d. The quad with ROPS and restrained rider did 1 ¼ turn.
2. The rider's torso was impacted with force of:
 - a. 1,197N for the OEM quad bike and unrestrained rider.
 - b. 781N for the quad bike with CPD and unrestrained rider.

- c. 706N for the quad bike with ROPS and unrestrained rider.
- d. 982N for the quad bike with ROPS and restrained rider.

3. In the OEM quad bike and unrestrained rider simulation the ejected rider was trapped beneath the OEM quad bike and could have been traumatically or mechanically asphyxiated (resting torso force of 1,300N). This is consistent with the outcome of Case 4.
4. The rider was not trapped under the quad bike with:
 - a. CPD and unrestrained rider. The resting torso force was 241N, refer to Figure 46.
 - b. ROPS and unrestrained rider. The resting torso force was 325N, refer to Figure 47.
 - c. ROPS and restrained rider. The resting torso force was 390N, refer to Figure 48.

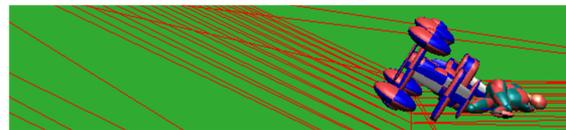


Figure 46: The rest position of the quad bike with CPD and unrestrained rider for Case 4.

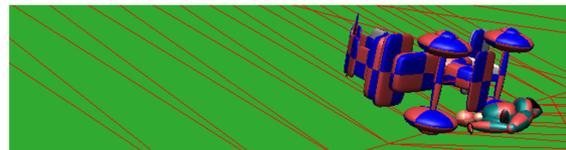


Figure 47: The rest position of the quad bike with ROPS and unrestrained rider for Case 4.

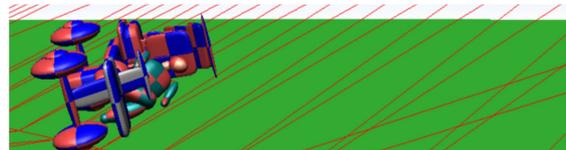


Figure 48: The rest position of the quad bike with ROPS and restrained rider for Case 4.

If the quad bike in Case 4 had been fitted with either a CPD or ROPS (and unrestrained or restrained rider) the rider could most likely have survived the rollover.

Real World Crashes Analysis

Simulation animations of Cases 1 to 4 (for OEM quad bike and unrestrained rider; quad bike with CPD and unrestrained rider; quad bike with ROPS unrestrained rider; and quad bike with ROPS and restrained rider) can be viewed online at: http://www.youtube.com/playlist?list=PLjYkHo7lOqxU5jYA2A1dqKE2F3oMGZAvI&feature=mh_1olz

Based on the simulations of real world crashes where there is an identifiable risk of fatal injury from quad rollover, consideration should be given

to fitting either: CPD, ROPS or ROPS with rider restraint; to mitigate the potential for serious and/or fatal injury due to torso impact or entrapment during a quad bike rollover.

LIMITATIONS

The use of PC-Crash as a quad bike rollover analysis tool needs to be further validated with respect to:

1. Different sized quad bikes i.e. 150kg to 200kg and 300kg to 450kg;
2. Quad bikes with ROPS and unrestrained and restrained rider.

Future simulations should include:

1. A combination of forward and lateral motion;
2. Backflips;
3. The effect of helmet use;
4. Torso impact injury consideration;
5. A range of rider sizes and masses;
6. Improved shape of the quad bike multi-body.

The database of well documented serious injury rollovers is limited. Provision of additional data files will be gratefully accepted by the authors to create additional simulations of real world crashes to further quantify the potential injury mitigation from CPD, ROPS or ROPS with rider restraint.

CONCLUSIONS

Using the multi-body feature within PC-Crash can be used to:

1. Simulate 250kg quad bike rollover crashes.
2. Comparatively evaluate the effectiveness of alternative safety systems for quad bikes.

Based on the presented research where there is an identifiable risk of serious or fatal injury from quad rollover, consideration should be given to fitting either: CPD, ROPS or ROPS with rider restraint; to mitigate the potential for serious and/or fatal injury due to torso impact or entrapment during a quad bike rollover.

ACKNOWLEDGMENTS

The authors would acknowledge the assistance of Mr Thomas Emmett and Mr Dale Aston in sequentially running multiple PC-Crash simulations to support the development of this paper.

REFERENCES

[1] Safe Work Australia, Public Discussion Paper, 'Review of Design and Engineering Controls for Improving Quad Bike Safety'.
<http://www.safeworkaustralia.gov.au/sites/SWA/w>

[hs-information/agriculture/quad-watch/Documents/Discussion-paper-PC/Discussion-Paper/Discussion_paper_quad_bike_safety.pdf](http://www.safeworkaustralia.gov.au/sites/SWA/w/hs-information/agriculture/quad-watch/Documents/Discussion-paper-PC/Discussion-Paper/Discussion_paper_quad_bike_safety.pdf)

[2] Lower T., Herde E., and Fragar L., 'Quad bike deaths in Australia 2001 to 2010', Journal of Health Safety and Environment 28(1) 2012.

[3] <http://ministers.deewr.gov.au/shorten/quad-bike-crush-protection-devices-be-mandatory-federal-employers>

[4] <http://www.quadbar.com.au/> Quadbar is a commercially available retrofit product which is sold as a Crush Protection Device. "The Quadbar is a small unobtrusive, hairpin shaped hoop mounted on the quadbike behind the rider designed to counter some of the risks associated with rollovers. The Quadbar acts as a Crush Protection Device (CPD) as opposed to the more commonly known roll over protective structures (ROPS). A typical ROPS would require a full cage and driver restraint, which are not feasible on a rider active vehicle such as a quadbike.

The Quadbar (aluminium tube) is mounted on the tow bar and is telescopically adjustable at the base. A support mount is attached to the rear rack, where the bar passes through sliding collars (bushes), which subsequently allow the suspension to move freely. The use of the tow bar is not affected by attachment of the Quadbar. The Quadbar is a device designed to reduce the risk of injury caused by quadbike rollovers. Research has identified injury caused by the pinning of the rider to be of particular concern."

[5] Richardson S., 'Performance Criteria for Effective Structural Rollover Protective Systems for Light Passenger Vehicles Performance Criteria for Effective Structural Rollover Protective Systems for Light Passenger Vehicles', PhD Thesis, Department of Civil Engineering, Monash University, 2009.

[6] Draft Standard in the United States of America Recreational Off-Highway Vehicle Association, ANSI/ROHVA 1 – 201X
http://www.atvea.org/CobraManagedFiles/110628-US_ANSI_ROHVA_1-201X_UTILITY_draft_standard_Recirculation_Ballot_Draft_4_29_11_1.pdf

[7] Australian Federal Chamber of Automotive Industries <http://www.atvsafety.com.au/>

[8] Wordley S. and Field B., 'Quad Bike Safety Devices: A Snapshot Review', Institute for Safety Compensation and Recovery Research, Monash University, Research Report #C-1-11-022-010, dated 3 February 2012.

[9] Lower T., Fragar L. and Herde E., 'Quad bike rollover deaths in Australia (2001-09)', Report

prepared for the Trans-Tasman Quad Bike (Engineering) Group, October 5-6, 2010.

[10] Anon., 'Proportion of Victorian Hospital Admissions for Quad bike injuries by age group, Jan 2005- Dec 2009'. Victorian Injury Surveillance Unit, Australia, 2011.

[11] Piziali R. L., Ayres T. J., Paver J. G., Fowler G. and McCarthy R. L., 'Investigation of the Net Safety Impact of an Occupant Protection System From All-Terrain Vehicles', SAE Technical Paper 930208.

[12] Van Auken R. M. and Zellner J. W., 'Preliminary analysis of the effects of ATV ROPS on rider injury potential'. DRI Technical Report DRI-TR-96-4B, Torrance, California, USA.

[13] Rechnitzer G., Day L., Grzebieta R., Zou R. and Richardson S. 'All Terrain Vehicle Injuries and Deaths' Monash University Accident Research Centre, 19 March 2003.

[14] Zellner J. W., Keschull S. A., Van Auken R. M., Lenkeit J. F. and Broen P. C., 'Review and Analysis of MUARC Report "ATV Injuries and Deaths," and Additional Simulations and Initial Testing of MUARC ATV Rollover Protection System (ROPS)'. DRI Technical Report DRI-TR-04-01, Torrance, California, USA.

[15] Muñoz S., Van Auken R. M., Zellner J. W., 'An assessment of the effects of the Robertson V-Bar ROPS on the risk of rider injury due to overturns resulting from ATV misuse'. DRI Technical Report DRI-TR-07-14, Torrance, California, USA.

[16] Grzebieta R. and Achilles T., 'Report on the Quad-bar in Relation to ATV Rollover Crashworthiness'. Department of Civil Engineering, Monash University, Australia. April 2007.

[17] Zellner J. W., Van Auken R. M., Keschull S. A. and Muñoz S., 'Injury risk-benefit analysis of rollover protection systems (ROPS) for all terrain vehicles (ATVs) using computer simulation, full scale testing and ISO 13232', Poster Presentation F2008-08-009, Fisita World Automotive Congress, 14 – 19 September 2008, Munich, Germany.

[18] Sulman R., Kapke P. and Robertson D. 'Test Report – ATV Rollover Protection Structure', Sulman Forensics, Toowoomba, Queensland, Australia, 2007.

[19] Ridge C. J., 'QB Industries Quad Bar Tests Model 401', Ridge Solutions, Dry Creek, South Australia, 2009.

[20] Snook C., 'An assessment of passive roll over protection for Quad Bikes', University of Southern Queensland, Australia.

[21] Stevenson M. G., 'Feasibility of roll-over protective structures (ROPS) for all terrain

vehicles (ATVs): Assessment of an Analysis of Effects of ROPS on Rider Injury Potential by Dynamic Research Inc', Report for the Australasian Agricultural Health Unit, Moree, Australia, 1998.

[22] Lambert J., 'Version 4 of a paper reviewing: Quad bike design, Computer simulation of Quad bike incidents as reported in various papers and presentations by Dynamic Research Inc, Quad manufacturers cynicism in respect of safety; and Quad bike safety improvements', John Lambert and Associates, Wandana Heights, Victoria, Australia, 2011.

[23] McDonald G. and Richardson S. 'Framing Quad bikes: Rationale for Fitment', Geoff McDonald and Associates, Crestmead, Queensland, Australia, 2011.

[24] Anon. 'Report of the Technical Engineering Group (TEG) to the Heads of Workplace Health and Safety Authorities (HWSA)', Trans Tasman Working Party on "Quad Bike Safety" Meeting, October 5-6, 2010, Australia.

[25] Anon. 'Australian ATV Distributors Position Paper', January 2010, Federal Chamber of Automotive Industries, Australia.

[26] Lower T., Temperley J. and Fragar L., 'Preventing death and serious injury caused by rollover of quad bikes on Australian farms - Policy Paper', Australian Centre for Agricultural Health and Safety, Moree, NSW.

[27] Anon. 'Position Paper: Quadbikes, Royal Australasian College of Surgeons', Version 3, August, 2011.

[28] Anon. 'Union issues safety ban on quad-bike use', Australian Workers Union, 2011, http://www.awu.net.au/970655_5.html, published 26-5-2011.

[29] Cliff W. E. and Montgomery D. T., 'Validation of PC-Crash – A Momentum-Based Accident Reconstruction Program', Society of Automotive Engineers Paper #960885, 1996.

[30] Steffan H. & Moser, A., 'The Collision and Trajectory Models of PC-CRASH', Society of Automotive Engineers Paper #960886, 1996.

[31] Cliff W. E., MacInnis D. D. and Switzer D.A., 'An Evaluation of Rectified Bitmap 2D Photogrammetry with PC-Rect', Society of Automotive Engineers Paper #97095, 1997.

[32] Cliff W. E. and Bowler J. J., 'The Measured Rolling Resistance of Vehicles for Accident Reconstruction', Society of Automotive Engineers Paper #980368, 1998.

[33] Steffan H. and Moser A., 'The trailer simulation model of PC-Crash', Society of Automotive Engineers Paper #980372, 1998.

- [34] Steffan H. and Moser A., '*Automatic optimization of pre-impact parameters using post-impact trajectories and rest positions*', Society of Automotive Engineers Paper #980372, 1998.
- [35] Steffan H., Geigl B. C. and Moser A., '*A New Approach to Occupant Simulation Through the Coupling of PC-Crash and MADYMO*', Society of Automotive Engineers Paper #1999-01-0444, 1999.
- [36] Moser A., Steffan H. and Kasanický G., '*The Pedestrian Model in PC-Crash – The Introduction of a Multi Body System and its Validation*', Society of Automotive Engineers Paper #1999-01-0444, 1999.
- [37] Steffan H., Moser A., Geigl B. C. and Motomiya Y., '*Validation of the Coupled PC-CRASH – MADYMO Occupant Simulation Model*', Society of Automotive Engineers Paper #2000-01-0471, 2000.
- [38] Moser A., Hoschopf H., Steffan H. and Kasanický G., '*Validation of the PC-Crash Pedestrian Model*', Society of Automotive Engineers Paper #2000-01-0847, 2000.
- [39] Bailey M. N., Lawrence J. M., Fowler S. J., Williamson P. B., Cliff W. E. and Nickel J. S., '*Data from Five Staged Car to Car Collisions and Comparison with Simulations*', Society of Automotive Engineers Paper #2000-01-0849, 2000.
- [40] Fay R., Robinette R., Scott J. and Fay P., '*PC-Crash and HVE, an Overview of Similarities and Differences*', Society of Automotive Engineers Paper #2001-01-0505, 2001.
- [41] Cliff W. E. and Moser A., '*Reconstruction of Twenty Staged Collisions with PC-Crash's Optimizer*', Society of Automotive Engineers Paper #2001-01-0507, 2001.
- [42] Moser A., Steffan H., Spek A. and Makkinga W., '*Application of the Monte Carlo Methods for Stability Analysis within the Accident Reconstruction Software PC-CRASH*', Society of Automotive Engineers Paper #2003-01-0488, 2003.
- [43] Steffan H. and Moser A., '*How to Use PC-CRASH to Simulate Rollover Crashes*', Society of Automotive Engineers Paper #2004-01-0341, 2004.
- [44] Schubert P. J., '*Real-World Rollovers Reconstructed from Interviews and Measurements*', Society of Automotive Engineers Paper #2006-01-0060, 2006.
- [45] Maletz M., Steffan H. and Lankarani H. M., '*A Potential New Approach for the Evaluation of Occupant Response in Frontal Impact Scenarios*', Society of Automotive Engineers Paper #2006-01-0901, 2006.
- [46] Marine M. C., '*On the Concept of Inter-Vehicle Friction and Its Application in Automobile Accident Reconstruction*', Society of Automotive Engineers Paper #2007-01-0744, 2007.
- [47] Ootani R. and Pal C., '*Effective Numerical Simulation Tool for Real-World Rollover Accidents by Combining PC-Crash and FEA*', Society of Automotive Engineers Paper #2007-01-1773, 2007.
- [48] Ootani R. and Pal C., '*Soil Trip Rollover Simulation and Occupant Kinematics in Real World Accident*', Society of Automotive Engineers Paper #2007-01-3680, 2007.
- [49] Barrios J. M., Merino M. A., Aparicio A., De Miguel J. L., Olona A., Modrego S., Páez F. J., Furones A., Badea A. and Martín J. M., '*Evaluation of the Effectiveness of Pedestrian Protection Systems Through In-Depth Accident Investigation*', Reconstruction and Simulation, Society of Automotive Engineers Paper #2009-36-0398, 2009.
- [50] Rose N. A. and Beauchamp G., '*Analysis of a Dolly Rollover with PC-Crash*', Society of Automotive Engineers Paper #2009-01-0822, 2009.
- [51] Chen Y., Yang J. and Otte D., '*A Comparison Study on Head Injury Risk in Car-to-Pedestrian Collisions in Changsha and Hannover*', Society of Automotive Engineers Paper #2010-01-1167, 2010.
- [52] Zębala J., Wach W., Cięпка P., Janczur R. and Walczak S., '*Verification of ABS Models Applied in Programs for Road Accident Simulation*', Society of Automotive Engineers Paper #2010-01-0070, 2010.
- [53] Kiefer A., Bilek D., Moser A. and Webb A., '*A Comparison Study between PC-Crash Simulation and Instrumented Handling Maneuvers*', Society of Automotive Engineers Paper #2011-01-1121, 2011.
- [54] Wach W., '*Simulation of Vehicle Accidents using PC-Crash*', Institute of Forensic Research Publishers, ISBN 83-87425-68-0, 2011.
- [55] Zellner J. W., Kepschull S. A. and Van Auken R. M., '*Updated Injury Risk/Benefit Analysis of Quadbar Crush Protection Device (CPD) for All-Terrain Vehicle (ATVS)*', DRI-TR-12-06, updated 6 August 2012.
- [56] Hopkins I. H. G., Pountney S. J., Hayes P., and Sheppard M. A., '*Crowd Pressure Monitoring*', In: '*Engineering for Crowd Safety*', Smith R. A. and Dickie J. F. (editors), Elsevier Science Publishers B.V., 1993.