Rollover Crashworthiness of Quad Bikes and Side by Side Vehicles: A Comparative Laboratory Testing Study

Raphael Grzebieta, George Rechnitzer, Keith Simmons, David Hicks

Abstract An in-depth case series study of 106 Australian quad bike (otherwise known as ATVs) for the period 2000-2012 showed rollover incidents constituted around 70% of all cases. The percentage of deaths attributed to ATV rollovers in the US is similar at around 72%. These 106 cases were extracted from a total number of 141 deaths collected from the Australian National Corners Information System (NCIS) that involved either a quad bike which the rider straddles and steers via handle bars or a side-by-side (SSV) or other terrain vehicle in which the rider sits in it similar to a car and steers via a steering wheel. The remaining 35 cases were identified as 32 cases involving public road crashes that included three SSV fatalities, two off road SSV fatalities and one off road six wheel vehicle with a straddle seat. Around half of the 106 quad bike fatalities studied in detail were farm work related with the other 50% recreational. Around 68% (n=36) of the farmers killed were pinned under the quad bike, with 42% (n=22) dying by mechanical asphyxia. The two SSV fatalities were farm related where the occupants were not wearing the installed seat belts and were ejected and injured by the four post Rollover Protective Structure (ROPS) surrounding the occupants similar to a vehicle roof structure. Operator Protection Devices (OPDs) (essentially a rollbar behind the rider), have been proposed for aftermarket fitment to quad bikes to reduce such injuries. This study presents the results of a rollover crashworthiness test program consisting of: quad bike (with and without an OPD) and SSV laboratory rollover crash tests using a tilt table with a release mechanism and an instrumented Motorcycle Anthropomorphic Test Device (MATD); ROPS load and retention tests for five SSVs; and quad bike ground contact load tests. SSVs with a well-designed rollover protection system (ROPS and 3 point or harness restraints) provide much greater rollover crashworthiness compared to quad bikes fitted with an OPD. This benefit may not apply if the rider and/or passenger do not use a helmet or the installed seat belt.

Keywords All-Terrain Vehicles, Mechanical Asphyxia, Quad bikes, Rollbar, Rollover,

I. INTRODUCTION

Quad bike rollover-involved crashes in Australia represent the major mechanism in fatal and serious injuries for quad bike users. The regulatory Heads of Workplace Safety Authorities (HWSA) in Australia and New Zealand identified in 2011 quad bike safety to be a major issue on farms in Australia and New Zealand [1]. Quad bikes are the highest killer of workers on farms in Australia [2-4].

A quad bike (Fig. 1) is a motor-powered four wheel vehicle operated on low pressure tyres where the rider straddles the seat and steers the vehicle using handle bars. The vehicle is usually accelerated using a small thumb throttle and decelerated using hand brakes.

A Side by Side Vehicle (SSV) is also a motorised vehicle but larger than a quad bike (Fig. 2), with a wider track width and longer wheel base. It is operated the same way as a car with a steering wheel and foot pedals. It has seats allowing more than one person to be seated 'side-by-side' inside the vehicle and usually includes seat belts and a four post rollover protective structure (ROPS) surrounding the occupants as is evident in Fig. 2, in order to provide protection for the occupants in the event of a roll over. This is in contrast to a quad bike that can have an Operator Protection Devices (OPDs) fitted, which is essentially a rollbar connected at two points behind the rider as shown in Fig. 3 and Fig. 4.

In the United States of America (USA), the quad bike is referred to as an All-Terrain Vehicle or ATV and SSVs are commonly referred to as 'Recreational Off Highway Vehicles' or ROVs. This terminology has been defined in

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US industry voluntary standards [5-6]. However, in regards to ATVs it is worth noting that a New Zealand Coroner, two Australian Coroners and the USA Federal Government's Consumer Product Safety Commission (CPSC) [7-8] have indicated that the term 'All-Terrain Vehicles' is misleading and may result in false assumptions as to the terrain that such vehicles can safely traverse. Hence, there is considerable resistance by Australian and New Zealand safety stakeholders in regards to the use of the term All-Terrain Vehicles or ATV. In this paper the term quad bike will be used throughout to describe this vehicle type shown in Fig. 1.

Fig. 1. Quad bike (ATV).

Fig. 2. Side by Side Vehicle (SSV) is driven like a car.

Fig. 3. Quadbar OPD.

Fig. 4. Lifeguard OPD.

An in-depth case series study of 106 Australian quad bike fatalities for the period 2000-2012 showed rollover incidents (in any direction) constituted around 70% of all cases [2,3]. Whilst the raw numbers of fatalities for quad bikes (ATVs only) are much higher in the USA at around 2718 from 2000 to 2010, the percentage attributed to rollovers is around 72%. Reference [2] provides details of how these values were determined. These 106 (quad-bike only) Australian cases were extracted from a total number of 141 deaths collected from the Australian National Corners Information System (NCIS) that involved either a quad bike or a side-by-side (SSV) or other similar terrain vehicle [2,3]. The remaining 35 cases were identified as 32 cases involving public road crashes that included three SSV fatalities, two off road SSV fatalities and one off road six wheel vehicle with a straddle seat [2,3].

Around half of the Australian fatalities are work related occurring on farms (n=53) and the other 50% are recreational (n=53). Of the fatalities occurring on farms around 85% involved a rollover (n=45) of which 68% (n=36) of the farm workers fatally injured were pinned under the quad bike, and almost 42% of deaths (n=22) were caused by mechanical asphyxia, with approximately three quarters (¾) of these asphyxiations (n=16) estimated to have been survivable incidents if the rider had not remained pinned [2,3].

As a means of reducing such crush related rollover injuries OPDs have been proposed for aftermarket fitment to quad bikes for use when travelling over rough and sloping off-road terrains. Fig. 3 and Fig. 4 show two different types of OPDs currently sold in Australia. The Quadbar manufactured by QB Industries has a mass of 8.5 kg. The Lifeguard OPD made by Ag TECH Industries in New Zealand has a mass of 14.8 kg. It has been hypothesised by some researchers, engineers and OPD manufacturers that OPDs will reduce deaths and serious injuries [9-11]. Some quad bike manufacturers, however, claim that OPDs have the potential to increase the incidence of injuries and deaths during a rollover event and instead recommend the use of SSVs which are designed with a rollover protection system [9][12-14]. For example, the Federal Chamber of Automotive Industries (FCAI) [13] indicate that the device itself, because it does not incorporate a properly designed seat belt restraint system, may impact and/or crush various body regions during a rollover event, and/or change the nature of the overturning motions of the ATV preventing the vehicle from rolling off the rider. Van Ee et al [14] demonstrate in their paper how such an OPD could restrict proper separation from the quad bike at a critical moment in the rollover event where separation is a common strategy implemented by riders to avoid injury. They show a forward rollover pitch situation where the OPD can potentially stab the rider in the back or neck causing severe paralysis or result in death.

The objective of this study was to assess and compare the rollover crashworthiness of both quad bikes (with and without an OPD) and SSVs through a rollover crash testing program using Motorcycle Anthropomorphic Test Device (MATD).

II. METHODS

The rollover crashworthiness test program consisted of 65 quad bike and SSV tests and SSV inspections focussing on four different areas all relating to vehicle rollover crashworthiness characteristics, namely, measurement of quad bike ground contact loads; measurements of the SSV's occupant retention system; quad bike and SSV dynamic rollover tests; and SSV ROPS structure load tests. The two OPDs shown in Fig. 3 and Fig. 4 were assessed in this test series to determine their effect on rollover crashworthiness. Each of the OPDs was fitted to a Honda TRX500 quad bike which was then subjected to rollover crash tests. The Honda TRX500 quad bike was selected to represent a typical quad bike with respect to rollover crashworthiness factors. The mass of the quad bike was 293 kg. The five SSVs assessed in regards to the occupant retention system were: a Honda Big Red MUV 700; a Kuboto RTV500; a John Deer Gatro XUV825i; a Yamaha Rhino 700; and a Tomcar TM2.

All tests were carried out at the New South Wales state government Roads and Maritime Services Crashlab laboratory facility in Huntingwood (an outer suburb of Sydney), NSW, Australia.

Measurement of Quad bike Ground Contact Load Tests

Measurements were carried out of static ground contact force for the quad bike with and without an OPD on its left and right side and when inverted (Fig.5).

Fig. 5. Contact force tests measured using load scales.

Fig. 6. Occupant retention tests using tilt table

McIntosh and Patton [2-3] identified from scientific literature that a load of around 50 kg applied for 10 minutes to the chest to be an applicable test criterion for mechanical asphyxia of a person in the context of a quad bike rollover. It was identified from the 36 pinned fatality cases analysed [2-3] that riders were predominantly pinned on the left (13) or right (7) side; with a further ten (10) pinned with the vehicle upside down; two (2) with the vehicle upright; and four (4) unknown. The contact load tests were carried out to assess if either OPD could assist with reducing the contact loads, and hence the risk of crush or asphyxia in such situations.

The quad bike was tested at a mass equal to the vehicle's unlade mass (unoccupied with all fluid reservoirs filled to nominal capacity including fuel, and with all standard equipment), plus the mass of the OPD if fitted. The tyres were inflated to the manufacturer's minimum tyre pressure recommended. The test was conducted by measuring the gravitational load of each ground contact point of the vehicle. The quad bike was positioned on a smooth flat ground plane and permitted to stabilise in a natural position without external support. All contact points with the ground were marked. The quad bike was then raised, load cells of equal height placed under each marked contact point and the vehicle lowered onto the load cells.

The test method not only included measuring the weight at contact points when the vehicle was: upright, all four wheels in contact with the ground; rolled onto its left side (around 90°); when inverted (around 180°); and when the vehicle was rolled partially to the left side (rolled between 100° and 170°) and only measured if the vehicle would stabilise in this position without external support. The vehicle was tested unladed without a rider or OPD, and then with a Quadbar OPD and Lifeguard OPD fitted respectively.

Measurements of the SSV's Occupant Retention System

The Side by Side Vehicle (SSV) occupant retention device tilt tests (Fig. 6) were based on those specified in the American National Standard for Recreational Off-Highway Vehicles ANSI/ROHVA 1-2011, Section 11 Occupant Retention Systems [5]. The characteristic assessed was the Occupant Retention System Performance (ORSP).

The ORSP performance tests consisted of placing a Motorcycle Anthropometric Test Device (MATD) in the front outboard seating position of an SSV and restraining the MATD by fastening the vehicle's seatbelts. The Tomcar uses a four point harness for restraint, the Honda, John Deer and Yamaha Rhino all each use 3 point seat belts whereas the Kuboto only provides 2 point lap belts for occupants.

The MATD dummy, specified in part 3 of the ISO 13232 standard [15], is based on the Hybrid-III frontal impact dummy. The most important features of the dummy are that: it has a modified head that is compatible with motorcycle helmets; a neck that allows the dummy to be put in a number of different motorcycle positions, while keeping the head in an up-right position; a Hybrid-III sit-stand pelvis, which allows positioning of the dummy on the quad bike; dummy hands that allow wrapping of the fingers around the handlebars with a tear away force of up to 356 Newtons (approximately 36 kg); frangible upper legs, lower legs, and knees; a frangible abdomen; and an on-board dummy data acquisition system located in a modified spine box.

The MATD was positioned in the seat with the pelvis centred on the seat centreline and the back upright and in contact with the seat back. The ANSI/ROHVA 1-2011 standard permits the MATD's gripping hands to be adjusted to either grip the steering wheel when in the driver's seat or any hand outboard grips provided when in the passenger seat. Hence, when positioned in the passenger seat the hands gripped the provided hand grips. Hand grip force was set at the maximum available. If no hand grips were present the hand was rested on the dummy's thigh without gripping any part of the vehicle. A number of vehicles were tested with the MATD positioned in the passenger seat with both hands resting on the MATD's thighs because no grips were available in this seat position.

In accordance with the ANSI/ROHVA 1-2011 standard, the vehicle was placed on the single axis tilt table (Fig. 6) and tilted about its longitudinal axis to an angle of 45°. Each vehicle was rolled towards both the driver side and passenger side with the MATD always located in the low side of the vehicle. In regards to the hand grip, the hand released from the steering wheel in two of the six driver side tests (Fig. 6), where details are presented in [16]. Two vertical-longitudinal planes were projected alongside the vehicle located 127mm and 178mm outside the widest part of the vehicle. When the SSV was tilted, measurements of the displacement of the torso of the MATD relative to the 127mm plane and the displacement of the MATD's hands and arm relative to the 178mm plane were carried out, again in accordance with the ANSI/ROHVA 1-2011 standard.

Quad Bike and SSV Dynamic Rollover Tests

Vehicle and rider/driver dynamic rollover tests consisted of positioning MATD in the operator's position of a quad bike or SSV, tilting the vehicle to an angle at which rollover would occur, and releasing the vehicle from an initial static position to rollover to observe survival space and functionality of the OPD, and in the case of the two SSVs the ROPS and restraints.

Table 1 shows the test matrix for the quad bike and the SSV dynamic rollover tests. The Honda TRX500 quad bike with a MATD rider was subjected to rollover tests in nine (3 x 3 matrix) configurations, i.e. roll direction (lateral roll, rearward pitch and forward pitch) and without/with an OPD (none, Lifeguard OPD and Quadbar OPD). Two SSVs were also tested for comparative purposes, i.e. a Tomcar and the Yamaha Rhino SSVs.

Table 1
QUAD BIKE AND SSV DYNAMIC ROLLOVER TEST MATRIX [16]

Test number	G140075	G140076	G140077	G140078	G140079	G140080	G140082	G140085	G140087	G140088	G140107	G140108
Vehicle make	Honda	Honda	Honda	Honda	Honda	Honda	Honda	Honda	Honda	Honda	Tomcar	Yamaha
Vehicle model	TRX500	TRX500	TRX500	TRX500	TRX500	TRX500	TRX500	TRX500	TRX500	TRX500	TM-2	Rhino
Tilt direction	Lateral roll (right)	Lateral roll (right)	Lateral roll (right)	Rear pitch	Rear pitch	Rear pitch	Forward pitch	Forward pitch	Forward pitch	Forward pitch	Lateral roll (right)	Lateral roll (left)
Protection device fitted	No bar	Lifeguard	Quadbar	Quadbar	Lifeguard	No bar	Lifeguard	Quadbar	Lifeguard	No bar	Vehicle ROPS	Vehicle ROPS
ATD	MATD	MATD	MATD	MATD	MATD	MATD	MATD	MATD (HIII neck)	MATD (HIII neck)	MATD (HIII neck)	MATD (HIII neck)	MATD (HIII neck)
Roll distance from tilt table edge (mm)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Tilt table angle at release (degrees)	40	40	40	51	51	51	50	50	50	50	45	40

Each vehicle was positioned on a single axis tilt table (Fig. 7 and Fig. 8) with the tyres located 1,000mm from the lowered edge of the tilt table. Prior to carrying out the rollover tests detailed in Table 1, a series of exploratory rollover tests were carried out for the quad bike where the Honda TRX500 was raised to 1,500 mm from the lower edge of the tilt table. It was found that tests from a height of 1,500 mm was damaging to the MATD [16]. It was felt that 1,000 mm from the lower edge of the tilt table was sufficient to demonstrate the difference between a quad bike with the two different types of OPDs and tests where no OPD was attached to the quad bike.

The vehicle brakes were applied and the tyres located on expanded mesh anti-slip plates so the vehicle would tip over rather than slide down the tilt table surface. The quad bike and MATD were tethered to the table to prevent premature vehicle tip over. The tilt table was slowly raised from horizontal to the angle at which the vehicle alone would rollover, plus 5 degrees to ensure vehicle overturn (Table 1). When the desired angle was reached, tethers securing the vehicle and ATD were simultaneously released, allowing the vehicle to

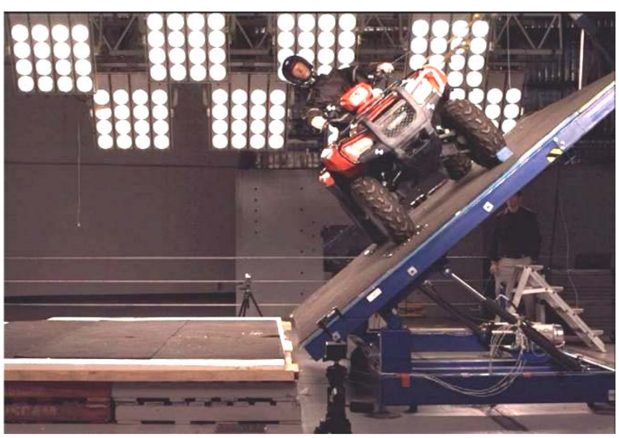

Fig. 7 Dynamic rollover test, lateral roll just prior to release, quad bike with no OPD (G140075).

Fig. 8 Dynamic rollover test, forward pitch roll just prior to release, quad bike with lifeguard OPD (G140085).

rollover under the force of gravity and impact with the ground plane which was horizontal (i.e., at an angle of approximately 130 to 150 degrees to the tilt table). The ground surface that the vehicle was rolled onto consisted of a raised floor constructed from two layers of timber pallets with a sheet of 100mm thick polystyrene (Clark Rubber part number: 75717) placed on top. The polystyrene was then covered with 10mm thick industrial rubber floor matting. The polystyrene layer was not replaced after each test. The height of the raised floor coincided approximately with the height of the lower edge of the tilt table when the table was raised to the test angles. It was felt that this surface represented a compliant ground surface similar to hardened clay though no tests were carried out to confirm this.

In all tests the MATD was instrumented. The MATD was supplied and calibrated prior to testing by Dynamic Research, Inc. (DRI) [17]. The dummy was instrumented to the requirements of ISO 13232 with the following parameters recorded: Head acceleration (9 channels); Chest displacement (4 channels); Upper neck force (3 channels); Upper neck moment (3 channels); Chest acceleration (3 channels); Pelvis acceleration (3 channels); Lumbar force (3 channels); Lumbar moment (3 channels); Upper femur force (1 channel) left; Upper femur moment (3 channels) left; Upper femur force (1 channel) right; and Upper femur moment (3 channels) right. In addition to instruments, the MATD was fitted with the following frangible components: Femur (left and right); Tibia (left and right); Knee varus valgus (left and right shear pin); and Knee torsion (left and right shear pin). Damage to any frangible components was recorded after the test and the damaged component replaced.

The recorded MATD instrument data from each test were processed in accordance with ISO 13232 using post-processing software for standardised injury probability analysis software provide by DRI with the following data reported: Maximum Abbreviated Injury Scale (AIS) injury; Probability of fatality; Probability of AIS I+ head injury; Probability of AIS I+ neck injury; Probability of AIS I+ chest injury; Probability of AIS I+ leg injury; Head Injury Criterion (HIC). Determination of the probabilities of different AIS levels for different body regions being calculated are detailed in ISO 13232-5 [18].

The MATD was clothed in firm fitting cotton stretch shorts and a waterproof single piece motorcycle rain suit. The MATD was also fitted with leather shoes equivalent to those specified in MIL-S13192 revP [16]. A Bell Custom 500 open face helmet was fitted to the MATD head and positioned using the alignment tool specified in ISO 13232 [15-17]. The same helmet was used in each test, i.e. it was not replaced after each test.

SSV ROPS Structure Load Tests

SSV ROPS structure load tests consisting of applying a lateral load (Fig. 9 and Fig. 10) followed by a vertical load, then a longitudinal load to the vehicle ROPS whilst recording the deflection and noting the structural integrity, in accordance with the ISO 3471:2008(E) test option for the US ANSI/ROHVA 1-2011 requirements [5]. Each vehicle's ROPS was tested by applying a uni-axial load to the top of the structure sequentially in three different directions. The load directions in order were: Lateral (from driver side towards passenger side of vehicle); Vertical (from top of vehicle towards bottom); and Longitudinal (from front of vehicle towards rear).

The lateral and longitudinal loads were applied through a load distribution device by a single hydraulic cylinder attached to a rigid test fixture. The vertical load was applied through two hydraulic cylinders, one

Fig. 9. Honda Big Red SSV subjected to lateral loading. Fig. 10. Honda Big Red SSV subjected to vertical loading.

located on each side of the vehicle. The two cylinders pulled down on a flat rigid steel load plate that was positioned to cover the top surface of the ROPS.

The vehicle chassis was rigidly mounted to the test fixture structure close to the vehicle suspension pickup points. The magnitude of the applied forces were calculated using formulas supplied in ANSI/ROHVA 1-2011 and were as follows: Lateral force (N or Newtons) = 6m; Lateral energy (Joules) = $13000(m/10^4)^{1.25}$; Vertical force (N) = 19.61m; and Longitudinal force (N) = 4.8m. The variable m = maximum vehicle laden mass (kg).

When applying the lateral force, the load was applied to meet both the lateral force requirement and the theoretical required lateral energy. The actual energy applied was calculated post test. During the tests the applied load in kiloNewtons (kN) was recorded for each hydraulic ram and structure deflection was measured in millimeters (mm) co-liner with direction of applied load. The data reported were the total applied load (kN), the structure deflection (mm), the applied energy (J) for lateral load application and permanent deflection/ damage to ROPS structure.

III. RESULTS

The results are presented for the four different series of tests detailed in the Methods section all relating to vehicle rollover crashworthiness characteristics, namely quad bike ground contact loads; SSV occupant retention occupant; quad bike (with and without an OPD) and SSV dynamic rollover crash behavior; and SSV ROPS structure load strength and deformation.

Quad bike Ground Contact Loads

A summary of the contact loads measured for the different orientations of the quad bike are shown in Table 2. When rolled 90° the quad bike rested on the same four contact points irrespective of whether an OPD was fitted or not. The ground contact points were the left front wheel, left rear wheel, left front plastic wheel guard, left rear plastic wheel guard. The front left wheel applied the greatest load, typically accounting for one third of the vehicle mass of 293kg. The load split front to rear however was almost equal. Only in one of the four contact points (left front plastic wheel guard) was the load less than 50 kg. The contact loads ranged from 42kg to 114kg.

Table 2

MEASURED QUAD BIKE CONTACT LOADS

	Ground Contact Load Range (kg) & Contact Points < 50 kg					
Load & Orientation of the Honda TRX500 quad	**Quad only (kg)**	**Contact points < 50 kg quad only**	**With Quadbar OPD (kg)**	**Contact points < 50 kg with Quadbar**	**With LifeGuard OPD (kg)**	**Contact points < 50 kg with Lifeguard**
Total Load	293		303		309	
On wheels	68 to 77	none	71 to 77	none	71 to 84	none
On side	42 to 114	left front wheel guard (42.5 kg)	31 to 118	left front wheel guard (31.5 kg)	36 to 113	left front wheel guard (36 kg)
Inverted	74 to 131	none	27 to 274	Quadbar (27 kg)	31 to 133	front load rack (31.5 kg) Lifeguard (47.5 kg)
Inverted and partially rolled on side	NA	NA	66 to 146	none	54 to 140	none

When inverted the vehicle had ground contact points at the front of the vehicle, typically the handlebars or headlight shroud, and a single point at the rear of the vehicle, either the OPD if fitted or the rear load rack when the OPD was not fitted. Typically a large portion of the vehicle mass was applied through the ground contact points at the front of the vehicle. Without an OPD fitted 75% of the vehicle mass was applied to the ground through the two handlebars with only 25% applied through the rear load rack. However, none of the loads were less than 50 kg, and ranged from 74kg to 131kg.

With an OPD fitted and the vehicle inverted, the proportion of load applied through the rear vehicle contact point reduced further. The Lifeguard applied 16% of the load (48 kg) with the handlebars and front load rack applying the remaining load with a range of 31kg to 133kg.

The Quadbar applied less than 10% of the load (27 kg) with the headlight shroud at the front of the quad bike applying more than 90% of the load at a single contact point (i.e. 274kg).

When the vehicle (with an OPD fitted) was tilted to one side and it settled in a stable position, the load applied by the OPD contact point at the rear of the vehicle accounted for approximately one third of the vehicle's total mass for both OPDs (i.e., 114kg for the Lifeguard and 90kg for the Quadbar). In this configuration all of the contact loads were over the 50 kg limit criterion for mechanical asphyxia if the McIntosh and Patton [2-3] criterion is used.

SSV's Occupant Retention System

The performance requirements of ANSI/ROHVA 1-2011 [5] state that the torso of the ATD must not extend beyond the plane 127mm outside the vehicle width and that the hands and arm of the ATD must not extend beyond the plane 178mm outside the vehicle width. The MATD torso did not extend more than 127mm outside vehicle width for all vehicles. Similarly for all vehicles the MATD hands and arms did not extend more than 178mm outside the vehicle width.

Table 3 indicates that the best performers in terms of restraining the driver and the passenger were the John Deer Gator XUV825i and the Tomcar TM2. Both the Yamaha Rhino 700 and the Kuboto RTV500 allowed the head to extend outside the vehicle's width. The Yamaha Rhino 700 allowed the Torso/shoulder and elbow to also extend outside the vehicle width.

Table 3

OCCUPANT RETENTION TEST RESULTS

SSV make and model	Tilt direction	Setup	Does ATD extend beyond vehicle width (Comment)
Honda Big Red MUV700 (3 pt. lap/sash belt)	Right (passenger side)	Right hand on A-pillar hand hold, left hand gripping seat centre. Net in place	No (ATD restrained. Wrist lightly touched net but did not deflect it)
	Left (driver side)	Hands on steering wheel. Net in place	No (ATD restrained. ATD elbow, shoulder and head touched net)
	Left (driver side)	Hands on steering wheel. Net removed	No (ATD restrained)
Kubota RTV500 (2 pt. lap belt)	Right (passenger side)	Right hand on A-pillar hand hold, left hand gripping seat centre. ATD yawed and leant forward to reach hand hold	No (ATD restrained, pelvis slid on seat)
	Right (passenger side)	Right hand on waist height hand grip/bar, left hand holding seat	Yes. (ATD head approx. 137mm outside vehicle width. Pelvis slid on seat)
	Right (passenger side)	Hands on lap	Yes. (ATD head approx.50mm outside vehicle width Pelvis slid on seat, right elbow braced against waist bar)
	Left (driver side)	Hands on steering wheel	Yes. ATD head approx. 50mm outside vehicle width Both hands came off steering wheel
John Deer Gator XUV825i (3 pt. lap/sash belt)	Right (passenger side)	Right hand on A-pillar hand hold, left hand gripping centre console	No (ATD restrained)
	Right (passenger side)	Hands on lap	No (ATD restrained)
	Left (driver side)	Hands on steering wheel	No (ATD restrained)
Yamaha Rhino 700 (3 pt. lap/sash belt)	Right (passenger side)	Right hand on A-pillar hand hold, left hand gripping centre hand hold	Yes. (ATD elbow approx. 92mm outside vehicle width)
	Right (passenger side)	Hands on lap	Yes. (ATD head approx. 127mm outside vehicle width. ATD torso/shoulder approx. 82mm outside vehicle width
	Left (driver side)	Hands on steering wheel	Yes. ATD torso/shoulder. Approx. 25mm outside vehicle width
Tomcar TM2 (4 pt. harness & right hand drive SSV)	Left (passenger side)	Left hand on A-pillar hand hold, right hand on lap	No (ATD restrained)
	Left (passenger side)	Hands on lap	No (ATD restrained)
	Right (driver side)	Hands on steering wheel	No (ATD restrained)

Quad Bike and SSV Dynamic Rollover Tests

Table 4 shows the dynamic rollover test results in regards to the damage to the MATD, the vehicle damage and the final rest position of the vehicle.

Table 4
QUAD BIKE AND SSV DYNAMIC ROLLOVER TEST RESULTS (see also Table 1)

Test number	G140075	G140076	G140077	G140078	G140079	G140080	G140082	G140085	G140087	G140088	G140107	G140108
MATD damage	1 finger, 1 thumb broken right hand	Nil	Nil	Nil	Nil	2 fingers broken right hand	MATD neck broken, 3 fingers broken left hand	Nil	Nil	Nil	Nil	Nil
Vehicle damage	Handlebar bent	Handlebar bent	Handlebar bent	Quadbar bent	Front rack bent, dents in lifeguard plastic ribs	Minor front & rear rack deformation	Dents in lifeguard plastic ribs	Nil	Lifeguard crack at base	Nil	ROPS laterally deformed approx 35mm	Nil
Vehicle rest position	Inverted	Inverted, rear supported by Lifeguard	On right side	On rear/Quadbar, tyres in contact with tilt table	On wheels	Inverted	On wheels	Inverted, rear supported by Quadbar	On right side	Inverted	On ROPS/RHS, tyres in contact with tilt table	On ROPS/LHS, tyres in contact with tilt table

In all forward pitch tests (G140082, G140085, G140087, G140088) for the quad bike the first point of contact with the ground was the MATD's head. This was the worst case in terms of injury potential as is clearly evident in Fig. 11 for test G140082. In test G140082 the MATD neck broke in half and was replaced with a Hybrid III neck. All subsequent forward pitch tests carried out (G140085, G140087, G140088) the Hybrid III neck was used for the MATD with the forward pitch test (G140087) being a repeated test.

Fig. 11 Forward pitch test (G140088) demonstrating how rider can receive serious cervical spine injury. MATD neck was fractured twice during testing.

In all three tests without an OPD fitted (G140075, G140080, G140088) the quad bike rolled onto the MATD and came to rest on the MATD with the MATD located between the quad bike and the ground (Fig. 12 and Fig. 13). The vehicle came to rest on top of the MATD in the lateral roll (G140075) and forward pitch (G140088) scenarios and rolled off the MATD in the rearward pitch (G140080) scenario.

With a Lifeguard OPD fitted (G140076, G140079, G140082, G140087) the quad bike rolled over and on top of the MATD such that the rear of the quad bike was being supported by the Lifeguard during this rollover/pitch process. The quad bike did not load the MATD as can be ascertained in the 2nd row frames in Fig. 12 and Fig. 13. The quad bike came to rest over the MATD in the lateral roll (G140076) and forward pitch (G140082 & G140087) scenarios. In the rearward pitch (G140079) scenario, the vehicle rolled off to one side after having been over the MATD. The Lifeguard OPD increased the clearance (survival space) under the quad bike relative to no OPD.

With a Quadbar OPD fitted (G140077 and Fig. 12) the quad bike did not fully roll onto the MATD. In the rearward pitch (G140078) the vehicle remained vertical resting on the Quadbar. In the forward pitch scenario (G140085 and Fig. 13) the Quadbar OPD increased the clearance (survival space) under the quad bike relative to no OPD in the inverted position (G140088).

Two SSVs were also tested in lateral roll (G140107, G140108 and Fig. 14) with the MATD located in the driver seat on the low-side of the tilt table. Each vehicle had previously been subjected to ROPS loading (Fig. 9 and Fig. 10), and as such each vehicle ROPS had minor permanent deformation prior to rollover testing. The Tomcar and Yamaha Rhino had 4 mm and 30 mm lateral permanent deformation respectively.

When tested in roll the Tomcar TM2 ROPS made initial contact with the ground and resisted the vehicle from rolling over. The ROPS did not fail or collapse and exhibited approximately 35mm of permanent lateral deformation after the test. The MATD torso was well contained, however the head impacted the ground surface after the ROPS made contact and arrested the vehicle roll.

Fig. 12. Lateral rollover: top - no OPD; middle - with Lifeguard OPD; bottom – with Quadbar OPD.

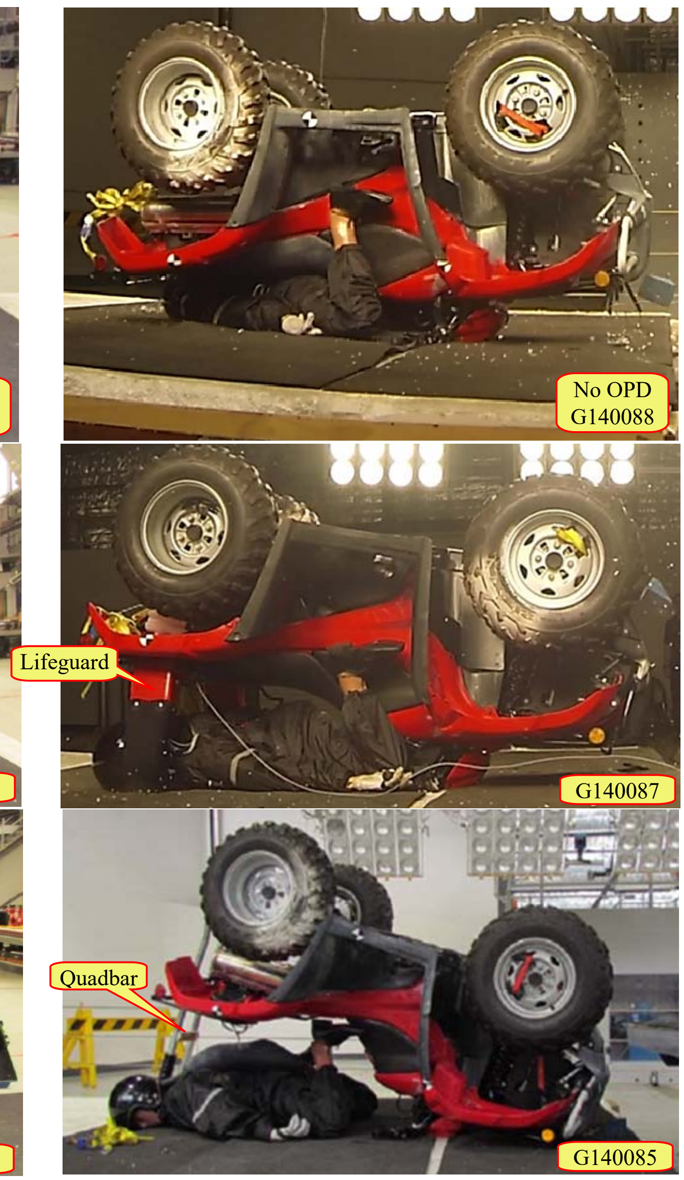

Fig. 13. Forward pitch: top - no OPD; middle - with Lifeguard OPD; bottom – with Quadbar OPD.

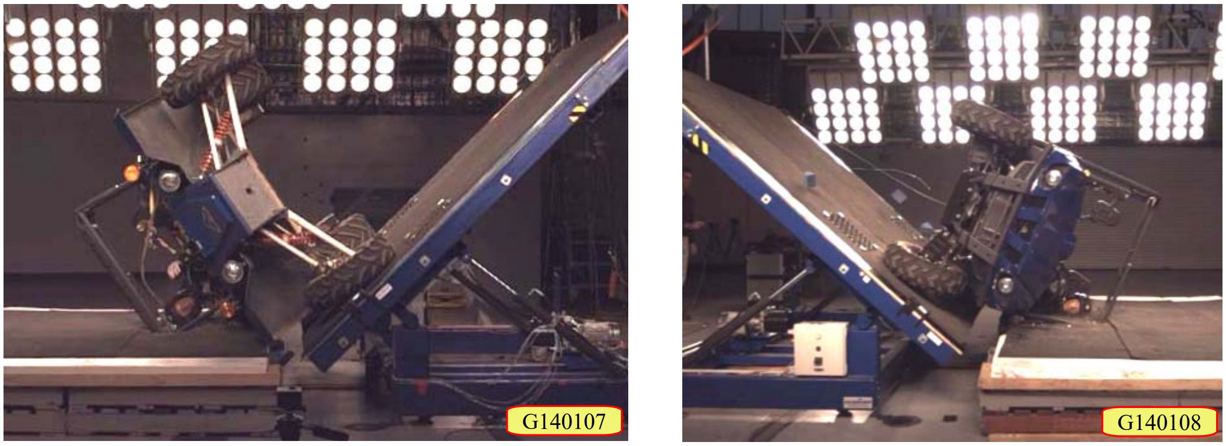

Fig. 14. Rollover testing of Tomcar (left) and Yamaha Rhino (right) SSVs.

The Yamaha Rhino vehicle ROPS (G140108) (Fig. 14) made initial contact with the ground and resisted the vehicle from rolling over. The ROPS did not fail or collapse and showed any deformation after the test. The MATD head and shoulder contacted the ground surface. These two lateral rollover tests (G140107, G140108) support the need for SSV operators to wear a helmet.

Table 4 presents the results of all the injury measures recorded by the MATD for the quad bike and SSV dynamic rollover tests.

Table 5

MATD INJURY MEASURES FOR QUAD BIKE AND SSV DYNAMIC ROLLOVER TEST RESULTS (see also Table 1 and 4)

Test number	G140075	G140076	G140077	G140078	G140079	G140080	G140082	G140085	G140087	G140088	G140107	G140108
Maximum AIS injury	0	0	0	0	0	0	0	0	0	0	0	0
Probability of fatality	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Probability of AIS Head injury	0.027	0.030	0.033	0.038	0.079	0.008	0.005	0.004	0.003	0.004	0.031	0.011
Probability of AIS Neck injury	0.002	0.002	0.002	0.000	0.000	0.000	0.005	0.170	0.098	0.067	0.000	0.000
Probability of AIS Chest injury	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.000	0.003	0.000	0.000
Probability of AIS Leg injury	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Head Injury Criterion, HIC	167	173	179	188	180	99	78	84	83	87	125	71
Gambit	0.25	0.24	0.25	0.29	0.37	0.19	0.17	0.14	0.15	0.15	0.28	0.21
Neck Injury Index, NII	1.81	1.82	1.8	0.49	0.75	0.91	2.05	3.77	3.35	3.1	0.63	0.94
Neck Fz compression (kN)	-3.53	-3.26	-3.6	-0.68	-0.38	-0.78	-4.32	-7.94	-7.05	-6.54	-0.78	-1.91
Neck Mx (Nm)	89.2	82.6	85.6	9.5	6.4	7.8	41.0	24.2	33.7	44.3	34.8	55.8
Neck My, extension (Nm)	-35.0	-47.0	-36.5	-10.5	-35.6	-45.7	-4.9	-32.7	-35.8	-15.8	-5.7	-3.7
Neck My, flexion (Nm)	15.4	13.8	16.0	20.5	44.2	39.8	66.4	193.2	168.7	167.5	7.8	12.9
Upper sternum deflection x (mm)	-8.2	-11.9	-8.5	-2.7	-2.8	-3.8	-3.4	-21.5	-8.6	-19.9	-3.0	-0.4
Upper sternum deflection y (mm)	20.2	20.3	18.4	2.0	5.4	2.0	12.8	18.4	8.6	20.6	4.3	13.2
Upper sternum VC (m/s)	0.02	0.03	0.01	0	0	0.01	0	0.08	0.02	0.06	0	0
Lower sternum deflection x (mm)	-4.4	-7.5	-6.9	-2.2	-1.6	-2.1	-0.1	-24.2	-11.9	-20.2	-2.3	-0.1
Lower sternum deflection y (mm)	19.3	19.5	18.1	1.9	5.2	2.0	11.2	19.5	8.6	21.6	4.4	13.2
Lower sternum VC (m/s)	0.01	0.01	0.01	0	0	0	0	0.1	0.03	0.06	0	0
Lumbar Fz compression (kN)	-1.69	-1.71	-1.51	-0.53	-0.56	-1.73	-1.71	-2.66	-2.24	-2.25	-0.16	-0.6
Lumbar Mx (Nm)	80.6	85.4	83.6	21.3	11.9	12.8	24.3	30.9	45.2	40.1	16.1	34.5
Lumbar My, extension (Nm)	-218.4	-217.1	-232.8	-202.9	-42.1	-44.8	-135.9	*-758.46	-435.8	-624.6	-67.0	-105.6
Lumbar My, flexion (Nm)	550.5	503.8	575.6	560.5	592.4	*780.1	658.6	166.3	325.0	144.1	96.5	255.7
Frangible femur fracture	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Frangible tibia fracture	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Frangible knee pin fracture (varus valgus)	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Frangible knee pin fracture (torsion)	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

*Lumbar signal clipped

In regards to the impact response data from the MATD, the measured results indicated no risk of serious injury (i.e., Abbreviated Injury Score (AIS) greater than or equal to 3), when processed in accordance with ISO 13232 using software provided by DRI. It was later found for the forward pitch over of the quad bike without an OPD (G140088) a fatal injury was recorded although not evident in the MATD injury measures presented in Table 5 which was a direct output from the DRI software. It was found that there was an extended chest loading exceeding 551 N. The maximum AIS was 6 and the probability of fatality was 1.0. This exceeds the asphyxiation criterion proposed by McIntosh and Patton [2-3]. Chest loading is not included in the tabularised output recommended in accordance with ISO 13232 for motorcycle crash testing and hence was not included in the standard test results. However, the values are recorded. As a result of this test program DRI have now included this measure into the standard output. All test results from the MATD are presented in [12].

It should be noted that on the first forward pitch test (G140079) the MATD neck was mechanically fractured without a corresponding large value of NII or neck compression load (Fz) recorded (Table 5) indicating potentially a severe or fatal injury. This mechanical fracture can occur because the MATD does not have a lateral shoulder stop for the neck. This component was replaced with a standard Hybrid III 50th percentile male ATD neck to conduct the remaining tests. Obviously in all subsequent three forward pitch tests (no OPD: G140088, Quadbar OPD: G140085 and Lifeguard OPD: G140087) the risk of a fatality or serious spinal injury appeared high (Fig. 11) even though the instrumentation in the Hybrid III neck resulted in NII values where the risk of an AIS3+ injury was assess as very low [18]. Also it should be further noted that the Hybrid III neck on the MATD was not calibrated against a MATD neck to measure the neck loads and hence the values of NII for these tests need to be treated with caution.

SSV ROPS Structure Load Tests

Table 6 shows the results of the SSV ROPS structural load tests. Only one vehicle did not meet the ISO 3471:2008(E) Option of the ANSI/ROHVA requirements specification, namely the Honda Big Red MUV700. The Honda Big red ROPS yielded appreciably when vertically loaded as shown in Fig. 9 and Fig. 10.

Table 6
SSV ROPS STRUCTURE TEST LOAD RESULTS

Vehicle make	Vehicle model	Maximum vehicle mass (kg)	Test number	ROPS test direction	Calculated required pull force (N)	Maximum achieved pull force (N)	Calculated required pull energy (J)	Maximum achieved pull energy (J)	Maximum deflection (mm)	Permanent deflection after test (mm)
John Deere	Gator XUV825i	1411	G140093	Lateral pull	8466	11142	1124	1883	242	108
John Deere	Gator XUV825i	1411	G140104	Vertical pull	27670	28135	-	-	32	4
John Deere	Gator XUV825i	1411	G140106	Longitudinal pull	6773	6879	-	-	39	3
Yamaha	Rhino 700	920	G140092	Lateral pull	5520	11971	659	684	109	30
Yamaha	Rhino 700	920	G140099	Vertical pull	18041	18626	-	-	8	1
Yamaha	Rhino 700	920	G140102	Longitudinal pull	4416	4463	-	-	23	4
Kubota	RTV500	1051	G140094	Lateral pull	6306	12442	778	994	130	43
Kubota	RTV500	1051	G140100	Vertical pull	20610	20928	-	-	17	2
Kubota	RTV500	1051	G140101	Longitudinal pull	5045	5222	-	-	25	0
Honda	Big red MUV700	1414	G140096	Lateral pull	8484	9854	1127	1573	242	117
Honda	Big red MUV700	1414	G140097	Vertical pull	27729	24326	-	-	121	82
Tomcar	TM2	1166	G140095	Lateral pull	6996	14592	886	198	23	4
Tomcar	TM2	1166	G140098	Vertical pull	22865	23433	-	-	11	4
Tomcar	TM2	1166	G140103	Longitudinal pull	5597	5630	-	-	8	1

The Tomcar TM2 ROPS was the stiffest, whereas the Honda Big Red ROPS offered the least resistance to load. In lateral pull loading, the Yamaha Rhino (G140092) and Tomcar TM2 (G140095) exhibited the least permanent deformation whereas the Honda Big Red (G140096) and John Deere Gator (G140093) showed the greatest permanent deformation.

Although the Honda Big Red ROPS met and exceeded the initial lateral force requirements (by 16%) and energy requirements (by 40%), the maximum ROPS deflection during the lateral pull test was 242mm with a permanent deflection of 117mm. The ROPS also did not meet the vertical load requirement. The applied force reached 88% of the required load at which point the ROPS structure began to yield and deform. Once the structure had begun to yield, the ROPS continued to deform with a reduction in applied force. The test was stopped with substantial permanent deflection and buckling to the ROPS.

IV. DISCUSSION

The characteristics determined from the four series of tests, namely contact loads when a quad bike pins a rider as a result of a rollover incident, occupant containment provided by vehicle restraints, occupant survival space provided by an OPD and ROPS, has provided some useful information that can potentially help with the design of quad bikes and SSVs to reduce a driver's/rider's risk of harm in a rollover crash within the workplace.

In regards to the contact ground load tests for the quad bike on its side or up-side-down, results in Table 2 showed that point loads on a person under the quad bike irrespective of its orientation (on wheels, on side, inverted or inverted and partially rolled on side) at certain locations still exceed the mechanical asphyxia load criterion of 50kg proposed by McIntosh and Patton [2-3] with and without OPDs. It appears that the minimum vehicle contact load reduces when using a Lifeguard OPD and measured under the OPD and front load rack (47.5 kg and 31.5 kg). Similarly the minimum contact load reduces for a Quadbar to 27 kg but in this case the maximum contact load doubles from 131 kg to 274 kg. Regardless, OPDs would likely reduce the risk due to increasing survival space underneath the quad bike for the inverted position, but not for a quad bike on its side.

The limited (low speed) dynamic rollover tests carried out on the quad bikes without an OPD fitted (G140075, G140080, G140088) (Fig. 12 and Fig. 13) indicate, typically, the vehicle came to rest on the MATD imparting a load. It was also evident when reviewing the video recording of these three tests that the vehicle's weight was being transferred to the MATD in such a way that the quad bike was supported, at a particular stage in the rollover event, only by the MATD that was trapped between the quad bike and the ground. This indicates that the rider can potentially be subjected to either the full weight of the quad bike or at least a significant portion of the vehicle's mass in a rollover if trapped by the quad bike. This is consistent with the fatality data investigated by the Authors [2-3] where crush and asphyxia related injuries were common.

Typically, with an OPD fitted, the vehicle came to rest separated from the MATD, or supported the mass of the vehicle above the MATD.

In one of the rearward pitch tests with the Lifeguard OPD a concern regarding the rearward pitch test was noted. The MATD was found to fall into the hollow part of the Lifeguard as shown in Fig. 15. The flexible (black) part of the Lifeguard device distorted such that the MATD's rear buttocks protruded through the gap surrounded by the Lifeguard's distorted flexible (black) part and the lumbar spine contacted the upper edge of this distorted part of the device. The flexible (black) part then straightened out to the position shown in Fig. 15 and the quad bike subsequently rolled away off the MATD.

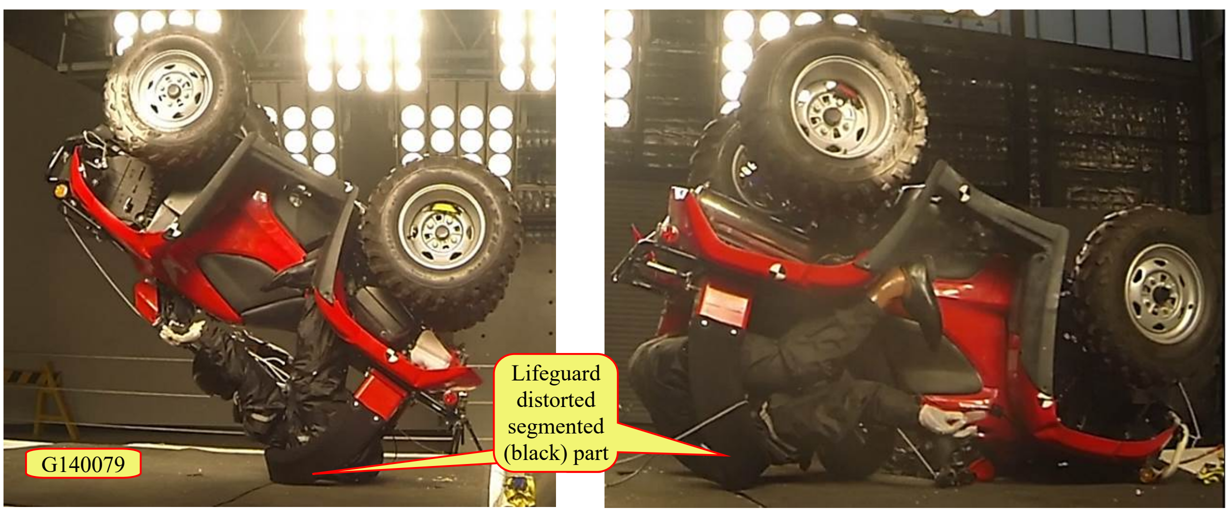

Fig. 15. Rearward pitch roll over test (G140079) with Lifeguard showing MATD posterior is not restrained from falling into gap. View from both sides of vehicle shown.

The concern is that this distortion in a rearward pitch rollover would present a serious hazard to a rider involved in such an incident particularly if the flexible (black) part impinged on the rider's spine (as it did in this test) and if the quad bike fell from a higher initial height. The device would need to be redesigned to ensure this would not occur.

Fig. 11 also shows how in a forward pitch the whole weight of the rider and quad bike can potentially spear a person into the ground where the rider would receive serious injuries much like as seen in typical shallow diving injuries [19]. There was one case in the fatalities files the Authors investigated [2] where such an injury mechanism occurred. The dead rider was found trapped supporting the quad bike in an upside down inclined position similar to the quad bike's orientation that is shown in Fig. 11.

Another potential hazard with the OPDs was noted in the quad bike forward pitch tests. If the rider were to use movement of their arms and body in a manner so as to avoid the diving mechanism shown in Fig. 11, they would still be thrust forward of the rotating vehicle. Fig. 16 shows how the rider's head can interact with the OPD when the quad bike rotates from the inclined tilt table such that the rear of the vehicle in the cargo rack region come down on top of the MATD's head. In regards to the Quadbar, the OPD almost speared the MATD in the back of the neck. In the case of the Lifeguard OPD the head was located in the gap surrounded by the Lifeguard and hence potentially trapped.

Fig. 16. Forward pitch roll over test showing how OPD interacts with MATD head and neck.

There is a concern from some quad bike manufacturers that the Quadbar may impart a load to the head, neck, or back as described above (or other body parts such as the chest), or prevent separation from the quad bike. Such concerns and scenarios have been hypothesised by Van Ee et al [14] and discussed by the Authors elsewhere [12]. Nevertheless, retrofitting an OPD has been encouraged by a number of quad bike safety stakeholders on the basis of the observations that OPDs inhibit continuous rollover and provide a survival space as demonstrated in Fig. 12 and Fig. 13. Indeed, one regulator in the State of Victoria in Australia has mandated that all quad bikes in the workplace be fitted with an OPD and other State regulators are currently considered following suit.

The rollover crash tests with the Honda TRX500 indicate that such devices do increase survivability and crawl out space (clearance) and change crush loads applied to the operator under certain rollover circumstances. The OPD may offer the conscious operator or rescuer an opportunity to self-extract (crawl out) or extract the pinned operator by increasing survival space when the vehicle is in an inverted position.

In contrast to quad bikes, the SSVs do adhere in general to rollover crashworthiness principles, in that they are fitted with ROPS, seatbelts and various degrees of containment measures. However, the effectiveness of such designs in terms of restraint can vary widely, as was observed with the tilt table test where the occupant retention systems were assessed. For example the Kubota only had 2 point lap belts and bench style seats with no side coaming to help restrain the occupants. Hence, this vehicle allowed the occupant to flail significantly outside the vehicle's width in the static tilt table test. In the Authors' opinion, this restraint system in a dynamic rollover crash has the potential of resulting in injuries from partial ejection. In contrast, the Tomcar had 4 point harness seat belts tightly restraining the occupant in a profiled seat with side coaming and a side bar to restrain lower torso movement. Flailing of the occupants inside the Tomcar in a rollover crash event would be constrained to a minimum providing the driver and passenger the best opportunity to survive a rollover crash as was demonstrated in the test depicted in Fig. 14.

The two SSV tests carried out (Fig. 14) also demonstrated that the roll-over protective structure stopped the vehicle from experiencing inverted rollover, and supported the partially rolled vehicle above the occupant without structural ROPS failure. For both the Tomcar and Yamaha vehicles, the MATD exhibited some head excursion from the vehicle resulting in ground surface impact, thus highlighting the importance of wearing a helmet.

The SSV ROPS for three vehicles met the US ANSI/ROHVA 1-2011 Industry voluntary standard. The Honda Big Red, while not meeting all the ROPS load requirements of the standard, did meet the lateral load requirement and 88% of the vertical load before the ROPS could no longer sustain any increase in load. The Honda Big Red met the US OSHA standard (Code of Federal Regulations) which requires a ROPS Strength to Weight Ratio (SWR) of only 1.5, which has been found by the Authors and others to be totally inadequate for occupant protection in rollover in regards to passenger vehicles [20-23].

The strength of the work is that it has demonstrated that SSVs with a well-designed ROPS can potentially provide greater rollover crashworthiness in comparison to quad bikes even when the quad bikes are fitted with an OPD. This benefit may not apply if the rider and/or passenger do not use a helmet or the installed seat belt. It is hypothesised that the demonstrated lateral strength of the ROPS would hold in the rearward and forward pitch-over conditions based on the quasi-static loading tests. However, since the dynamic forward and rearward pitch rollover tests were not conducted, and as the SSV retention tests did not include full inversion, a full comparison cannot been made and would need to be carried out in future research work.

One of the limitations of the study is the small number of rollover crash tests carried out on the SSVs. This was mainly because of budget limitations as well as limitations with the tilt table test rig. No forward pitch or rearward pitch tests were carried out. More extensive rollover testing of SSVs for lateral, forward and rearward pitch roll tests using the tilt table in the manner similar to that illustrated in Fig. 14 is planned for the future. Similarly, a moving sled or a rollover simulator to subject the SSVs to dynamic rollover tests to test occupant retention systems in the manner similar to what the CPSC have commissioned [24-26] and carried out is also planned for the future. The Authors will also be considering using the Jordan Rollover crash test device [26-28] to test not only occupant retention similar to what Gepner et al [29] have recently completed, but also ROPS strength in the one test.

Another limitation of the study was that the measured results from the MATD indicated no risk of serious injury. What this indicates is that the majority of the events that typify a Quad bike rollover are at a much lower energy level than what would more commonly occur in a typical road crash. Moreover, crash test dummies such as the MATD, are tuned to provide measures of acceleration and displacement that are associated with serious injuries that commonly occur in road crashes, and injury risk measures determined from laboratory tests with cadavers and other human surrogates. Measurements on Anthropomorphic Test Devices (ATDs), such as head accelerations, chest deformation or femur loads, are typically calibrated for specific load patterns and directions, e.g. forward impact for the head, axial load of the femur and anterior-posterior compression of the thorax. These loads are more predictable when measured by an occupant ATD contained within a vehicle in comparison to an ejected or separating occupant in a quad bike rollover test. Therefore, it is possible that an ATD, such as the MATD, may not register some loads during tests because of its design and intended purpose.

V. CONCLUSIONS

This study assessed and compared the rollover crashworthiness of both quad bikes (with and without an OPD) and SSVs through a testing program using a MATD crash test dummy. It found that, fundamentally, quad bikes where the rider straddles the vehicle, do not and cannot satisfy the well-known principles of occupant protection in a rollover crash offered by an SSV, i.e. good containment, restraint of the occupant, impact management and crush prevention.

If ATDs are to be used to assess the crashworthiness of either Quad bikes or SSVs by measuring any potential injuries, such devices will need to be redesigned for the much lower energy levels that typify a quad bike or SSV rollover event than what would more commonly occur in a typical road crash.

SSVs with a well-designed ROPS provide greater potential rollover crashworthiness in comparison to quad bikes even when the quad bikes are fitted with an OPD. This benefit may not apply if the rider and/or passenger do not use a helmet or the installed seat belt.

A program of further tests for SSVs would be valuable to further improve the rollover crashworthiness of these vehicle types.

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VII. References

[1] Heads of Workplace Safety (HWSA). Working Together on Quad Bike Safety, WorkCover News: The Workplace Safety and Injury Management Magazine, Issue 85, Catalogue No: WC03487, WorkCover NSW, Sydney, Australia, ISSN 1033/5064.

[2] Grzebieta R.H., Rechnitzer G., et al. Investigation and Analysis of Quad Bike and Side By Side (SSV) Fatalities and Injuries. Quad Bike Performance Project (QBPP) Report 3-2014: Supplemental Report, Transport and Road Safety (TARS) Research Report, University of New South Wales, Sydney, Australia, 2014.

[3] McIntosh A.S., Patton D.A., Rechnitzer G. & Grzebieta R.H. (2016): Injury mechanisms in fatal Australian quad bike incidents, Traffic Injury Prevention, Vol. 17, Issue 4, DOI: 10.1080/15389588.2015.1091073.

[4] Lower T., Herde E. and Fragar L. Quad bike deaths in Australia 2001 to 2010; J Health Safety Environ, 2012, 28(1): 7-24.

[5] Recreational Off-Highway Vehicle Association, (2011). American National Standard for Recreational Off-Highway Vehicles, ANSI/ROHVA 1 - 2011, Recreational Off-Highway Vehicle Association, California, USA.

[6] American National Standard for Four Wheel All-Terrain Vehicles ANSI/SVIA 1 – 2010. Developed by Specialty Vehicles Institute of America (SVIA), Approved by American National Standards Institute (ANSI) 12/23/10, Published by Specialty Vehicle institute of America, 2 Jenner, Suite 150, Irvine California, USA, 92618-3806.

[7] Freund S., Inquest into the deaths of Donald Eveleigh, Angela Stackman, 'FW', 'ML', Anthony Waldron, Colin Reid, Bradley Jackson, Robert Beamish and 'LE' who died as a result of a Quad bike accident, New South Wales (NSW) Deputy State Coroner, 2015, Glebe, Sydney, Australia, http://www.coroners.justice.nsw.gov.au/Documents/Quad%20bike%20findings%20v2.pdf

[8] Elder J, Leland E. CPSC Staff Response Regarding Follow-Up Questions from Commissioner Moore after the June 15, 2006, ATV Safety Review Briefing, in editor: http://www.cpsc.gov/LIBRARY/FOIA/FOIA06/brief/atvmoore.pdf

[9] Lower T., Temperly J. Preventing Death And Serious Injury Caused By Quad Rollovers On Australian Farms - Policy Paper, Ausyralian Centre for Agricultural Health and Safety, University of Sydney, 2016, Sydney, Australia.http://www.aghealth.org.au/tinymce_fm/uploaded/Quad%20Bike/Position_Statement_Quads_Feb%202016.pdf

[10] Myers M.L. All-Terrain Vehicle Safety—Potential Effectiveness of the Quadbar as a Crush Prevention Device, Safety, 2016, 2(1), 3. doi: 10.3390/safety2010003

[11] Myers ML. Potential Benefit of the Quadbar™ on All-Terrain Vehicles, Safety, 2016, 2(1), 5. doi:10.3390/safety2010005

[12] Grzebieta R, Rechnitzer G, Simmons K and McIntosh AS, Final Summary Project Report: Test Results, Conclusions, and Recommendations, Quad Bike Performance Project TARS Research Report No 4, 2015, University of New South Wales, Sydney, Australia.

[13] Federal Chamber of Automotive Industries (2012) Australian ATV distributors' position paper - March 2012, Melbourne: FCAI. Available at: http://www.atvsafety.com.au/sites/default/files/Industry-Position-Paper-March-2012.pdf

[14] Van Ee C, Toomey D, Moroski-Browne B.A., Vander Roest M., Wilson A. ATV Rollover, Rider Response, and Determinants of Injury: In-depth Analysis of Video-documented ATV Rollover Events. Traffic Injury Prevention, 2014,15 Suppl 1:S190-6. doi: 10.1080/15389588.2014.935940.

[15] ISO 2005, Motorcycles – Test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles , ISO 13232:2005, ISO (International Organization for Standardization), Geneva Switzerland.

[16] Grzebieta R, Rechnitzer G, McIntosh A. Rollover Crashworthiness Test Results, Quad Bike Performance Project TARS Research Report No 3, University of New South Wales, 2015, Sydney, Australia.

[17] Dynamic Research Institute (DRI), http://www.dynres.com/.

[18] ISO 13232-5, Motorcycles — Test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles — Part 5: Injury indices and risk/benefit analysis, 2005, ISO (International Organization for Standardization), Geneva Switzerland.

[19] Cripps R., O'Connor P. Spinal Cord Injury, Australia 1996-97. Australian Injury Prevention Bulletin Series no. 18. Cat. no. INJ 13, 1998, Canberra: AIHW. Viewed 11 April 2016 <http://www.aihw.gov.au/publication-detail/?id=6442466955>.

[20] Rechnitzer G. and Lane J. 'Rollover Crash Study - Vehicle Design and Occupant Injuries', Monash University Accident Research Centre, Report No 65, 1994, Melbourne, Australia.

[21] Digges K. and Malliaris A.C., Crashworthiness Safety Features in Rollover Crashes, SAE Technical Paper Series No. 982296, from Proc. IBEC '98, Volume 6, Safety, Environmental, and Automotive Interior Systems, 1998, (P-335).

[22] Young D., Grzebieta R.H., Rechnitzer G., Bambach M. and Richardson S., Rollover crash safety: characteristics and issues, Proc. 5th Int. Crashworthiness Conf. ICRASH2006, Bolton Institute U.K., Athens, Greece, July 2006.

[23] Grzebieta R.H., Young D., et al. Rollover Crashworthiness: the final frontier for vehicle passive safety, Proceedings Road Safety Research, Policing and Education Conference, Melbourne, 2007, (also published in Journal of the Australasian College of Road Safety, 19(2), May 2008, pp. 29-38 and corrected reprint in 20(2) May 2009, pp. 46-55).

[24] Zagorski S.B., Guenther D., Heydinger G., Sidhu A. Validation of a Roll Simulator for Recreational Off-Highway Vehicles, Society of Automotive Engineers, 2012-01-0241.

[25] Active Safety Engineering. Pilot Study – Phase II of Recreational Off-Highway Vehicles (ROV), Test and Evaluation Report for the US Consumer Product Safety Commission, 2010, Bethesda, USA.

[26] US Consumer Product Safety Commission (CPSC). Safety Standard for Recreational Off-Highway Vehicles (ROVs), Notice of Proposed Rulemaking, 16 CFR Part 1422, RIN 3041-AC78, Docket No. CPSC-2009-0087, 2014.

[27] Gepner B.D., Cochran J., eta al. Recreational Off-Highway Vehicle Safety: Countermeasures for Ejection Mitigation in Rollover, SAE Technical Paper 2016-01-1513, 2016, doi:10.4271/2016-01-1513.

[28] Mongiardini M., Grzebieta R.H., Mattos G.A. & Bambach M.R. Computer modelling of vehicle rollover crash tests conducted with the UNSW Jordan Rollover System, International Journal of Crashworthiness, DOI: 10.1080/13588265.2015.1123342

[29] Gepner, B., Cochran, J., Foltz, P., Roberts, C., Toczyski J., Taracko M., Borth J., Wilson R., Upah A. and Kerrigan J., "Recreational Off-Highway Vehicle Safety: Countermeasures for Ejection Mitigation in Rollover," SAE Technical Paper 2016-01-1513, 2016, doi:10.4271/2016-01-1513.