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

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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.*

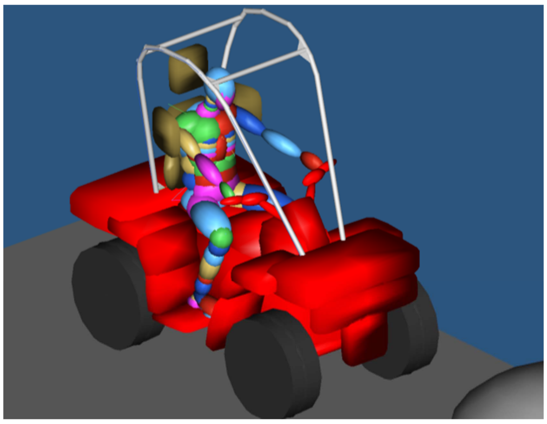

Figure 2: ROPS with occupant restraint [5] *and* [13] *(seatback and seatbelt).*

Lower et al. [2] identified that $^1/_3$ 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).

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 20 ^{0} 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 20 ^{0} surface.

Serial	Ramp angle	Speed	¼ turns	Snook video
12	21.5^0	4.6km/h	1	1746
13	23.0^0	5.2km/h	1	1679
14	23.0^0	6.5km/h	1	1678
15	23.0^0	7.6km/h	1	1676 and 1677
16	23.0^0	8.6km/h	1	1673
17	23.0^0	8.6km/h	3	1675
18	23.0^0	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	12.0^0	3.5km/h	$4^{\#}$	1742
20	12.0^0	3.8km/h	$4^{\#}$	1741
21	24.0^0	4.6km/h	$4^{\#}$	1735, 1737 and 1738
22	24.0^0	5.2km/h	$4^{\#}$	1736
23	23.0^0	5.4km/h	1	1686 and 1687
24	26.0^0	5.6km/h	1	1685
25	26.0^0	7.1km/h	4	1683 and 1684
26	26.0^0	10.1km/h	8	1682

Table 5: Side roll, CPD on a sloping 20^0 surface ($^{\#}$ on wheels and rolled).

Serial	Ramp angle	Speed	¼ turns	Snook video
27	24.0^0	4.2km/h	1	1731 and 1733
28	24.0^0	4.3km/h	1	1726 and 1727
29	24.0^0	4.4km/h	1	1725

Table 6: Backflip, CPD on a sloping 20^0 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 39.2^0 and 38.8^0 respectively. An overturn angle of 39^0 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 39^0.

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.

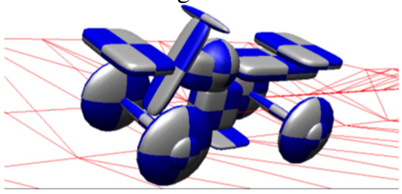

Figure 5: The OEM quad bike.

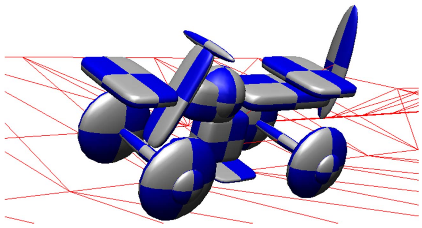

Figure 6: Quad bike with CPD.

VALIDATION

The simulation of the OEM quad bike does not roll at a side inclination of 38^0, whereas it does roll onto its side at a side inclination of 39^0, 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	21.5^0	4.7km/h	0^0	2	2
2	23.0^0	5.2km/h	0^0	2	2
3	23.0^0	6.6km/h	0^0	2	2
4	23.0^0	7.7km/h	0^0	3	3
5	23.0^0	8.6km/h	0^0	3	3
7	23.0^0	4.1km/h	20^0	8	+8
8	23.0^0	5.4km/h	20^0	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	21.5^0	4.6km/h	0^0	1	1
13	23.0^0	5.2km/h	0^0	1	1
14	23.0^0	6.5km/h	0^0	1	1
15	23.0^0	7.6km/h	0^0	1	1
16	23.0^0	8.6km/h	0^0	1	1
17	23.0^0	8.6km/h	0^0	3	2
18	23.0^0	9.3km/h	0^0	3	3
23	23.0^0	5.4km/h	20^0	1	1
24	26.0^0	5.6km/h	20^0	1	1
25	26.0^0	7.1km/h	20^0	4	5
26	26.0^0	10.1km/h	20^0	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 20^0 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.

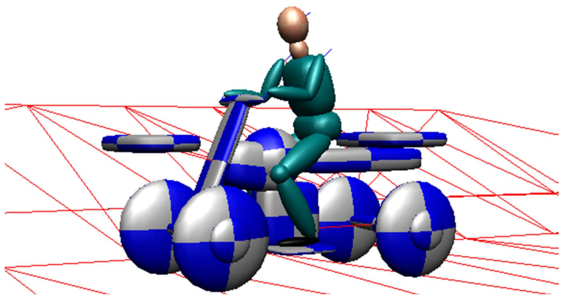

Figure 7: Quad bike and unrestrained rider.

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

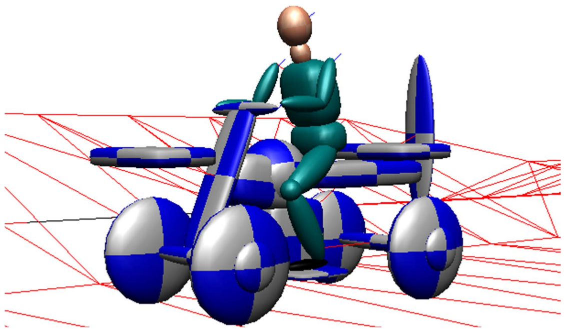

Figure 8: Quad bike with CPD and unrestrained rider.

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.

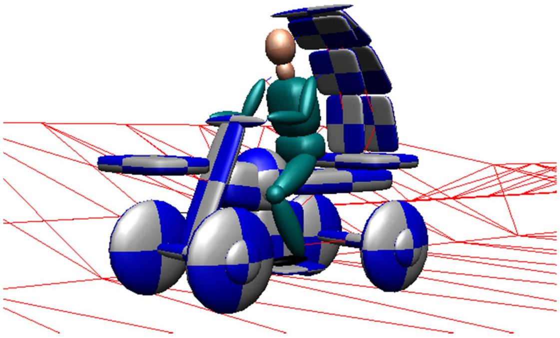

Figure 9: Quad bike with ROPS and unrestrained rider.

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.

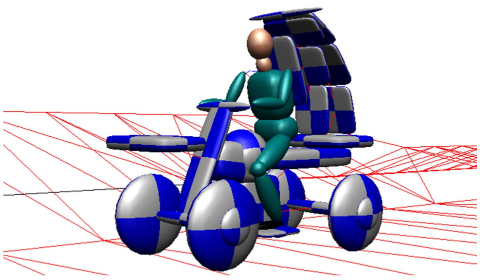

Figure 10: Quad bike with ROPS and restrained rider.

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 20^0 to 29^0 (in 1^0 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).

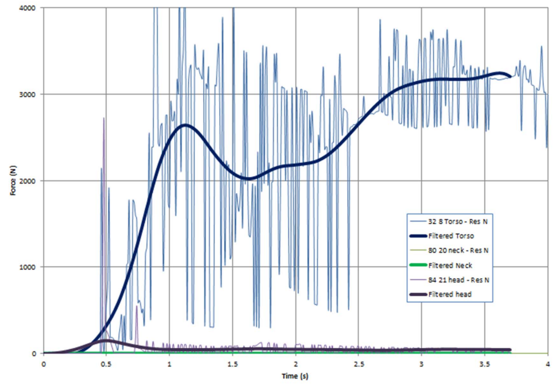

Figure 11: Example of the raw and filtered data (quad bike and unrestrained rider rollover at a ramp angle of 26 ^{0} and lateral speed of 13km/h).

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 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*". Zelllner 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.

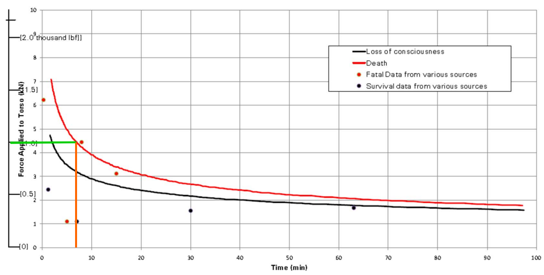

Figure 12: Extracted from Zellner et al. p52, Figure 8: "Estimate of Human Tolerance to Mechanical Asphyxia With Fatal and Survival Data". This is identified as being sourced from Hopkins et al. The green line is at 1000N and the orange line is at approximately 7 minutes.

Based on Figure 12 a quad bike rider could be traumatically or mechanical 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.

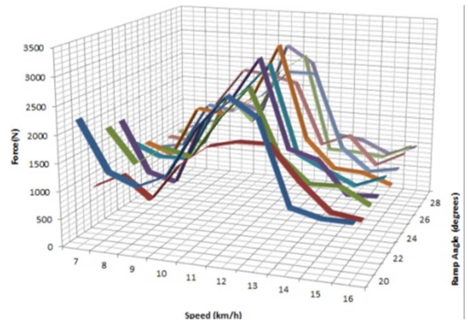

Figure 13: Peak initial impact torso forces in the first 1.5s for a range of simulated quad bike and unrestrained rider rollovers. 41 of the 100 simulations exceed 1,500N impact torso force and 11 of the 41 simulations exceeded 3,000N.

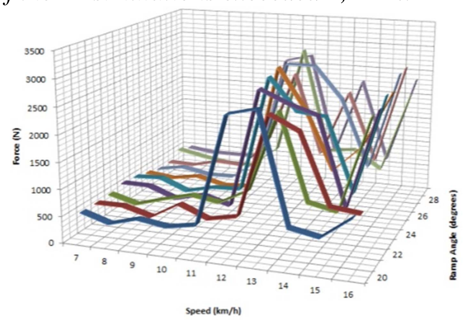

Figure 14: Resting torso forces for a range of simulated quad bike and unrestrained rider rollovers. 32 of the 100 simulations exceed 1,000N resting torso force.

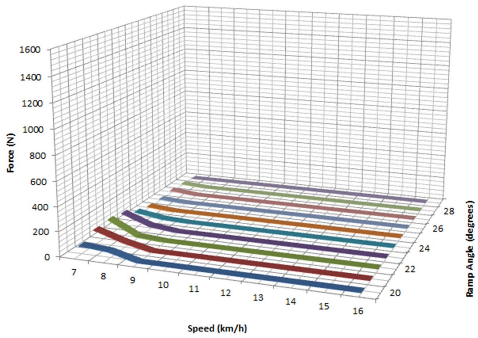

Figure 15: Peak neck forces for a range of simulated quad bike and unrestrained rider rollovers.

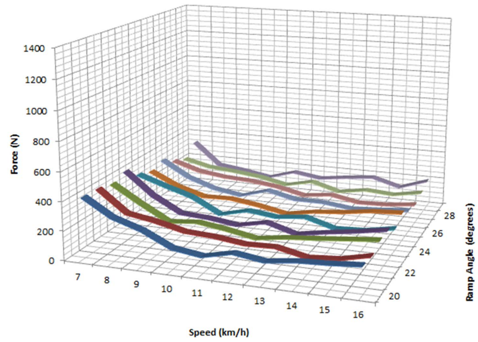

Figure 16: Peak head forces for a range of simulated quad bike and unrestrained rider rollovers.

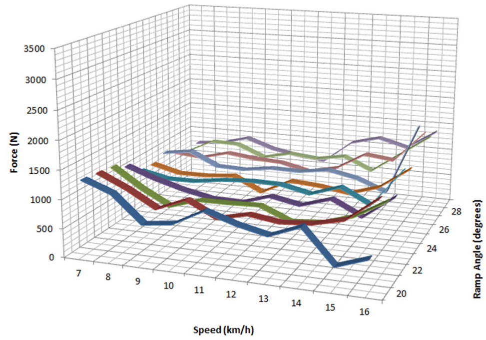

Figure 17: Peak initial impact torso forces in the first 1.5s for a range of simulated quad bike with CPD and unrestrained rider rollovers. 2 of the 100 simulations exceed 1,500N impact torso force. Neither of the 2 simulations exceeded 3,000N.

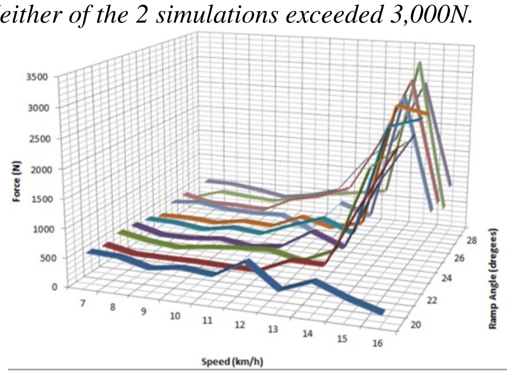

Figure 18: Resting torso forces for a range of simulated quad bike with CPD and unrestrained rider rollovers. 17 of the 100 simulations exceed 1,000N resting torso force.

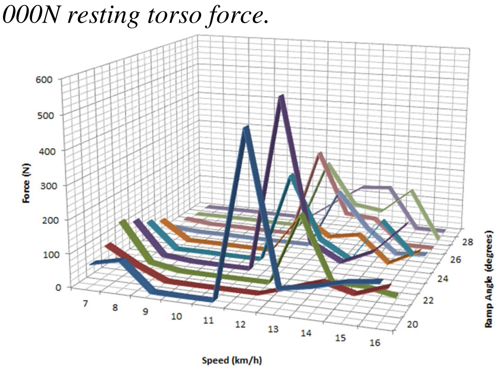

Figure 19: Peak neck forces for a range of simulated quad bike with CPD and unrestrained rider rollovers.

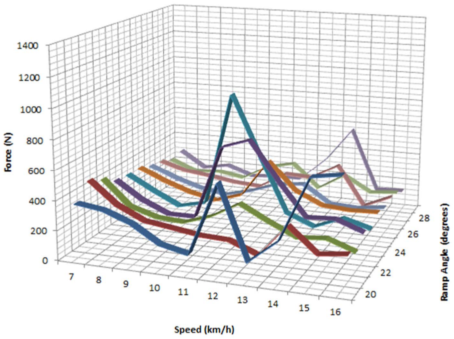

Figure 20: Peak head forces for a range of simulated quad bike with CPD and unrestrained rider rollovers.

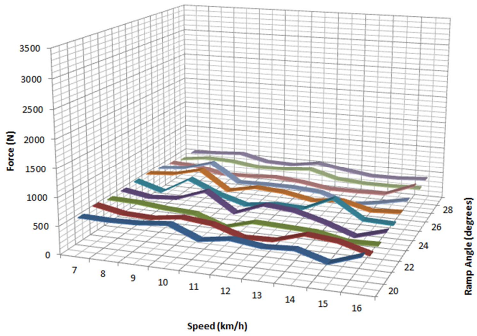

Figure 21: Peak initial torso forces for a range of simulated quad bike with ROPS and unrestrained rider rollovers. None of the 100 simulations exceed 1,500N impact torso force. (Hence none of the 100 simulations exceeded 3,000N impact torso force.)

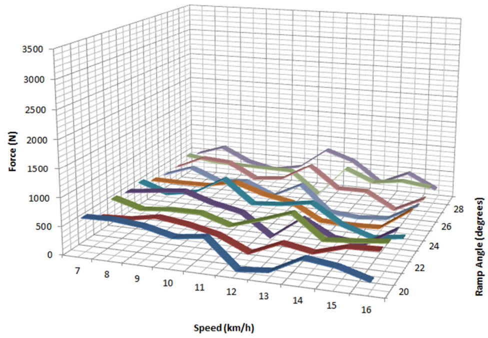

Figure 22: Resting torso forces for a range of simulated quad bike with ROPS and unrestrained rider rollovers. None of the 100 simulations exceed 1,000N impact torso force

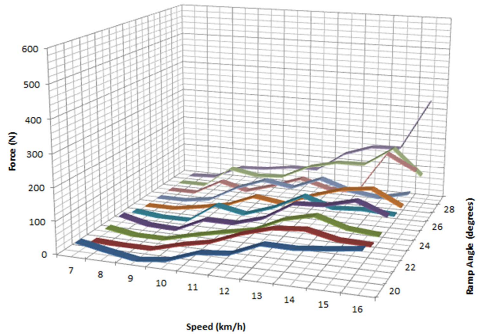

Figure 23: Peak neck forces for a range of simulated quad bike with ROPS and unrestrained rider rollovers.

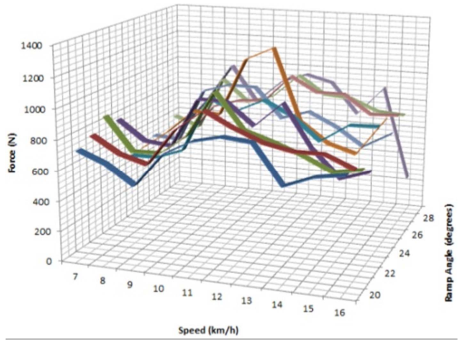

Figure 24: Peak head forces for a range of simulated quad bike with ROPS and unrestrained rider rollovers.

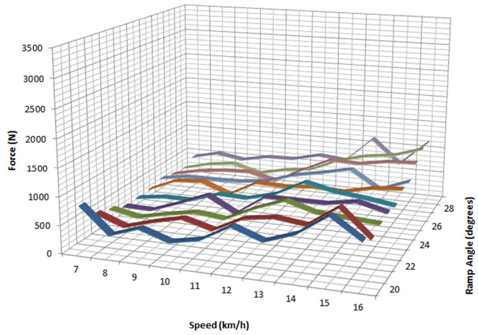

Figure 25: Peak initial torso forces for a range of simulated quad bike with ROPS and restrained rider rollovers. None of the 100 simulations exceed 1,500N impact torso force. (Hence none of the 100 simulations exceeded 3,000N impact torso force.)

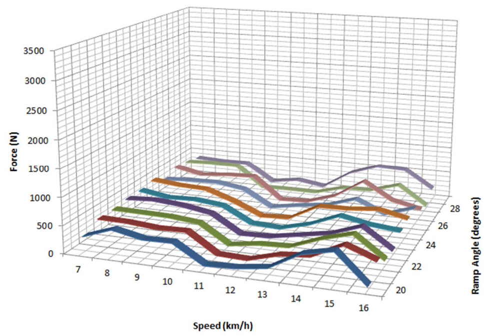

Figure 26: Resting torso forces for a range of simulated quad bike with ROPS and restrained rider rollovers. None of the 100 simulations exceed 1,000N resting torso force.

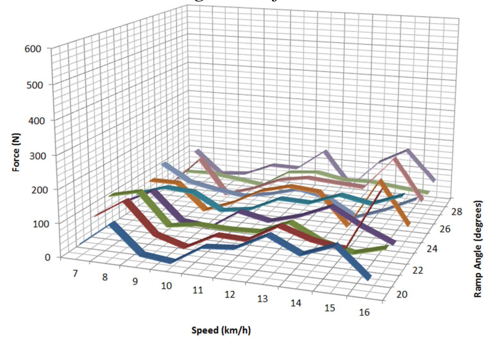

Figure 27: Peak neck forces for a range of simulated quad bike with ROPS and restrained rider rollovers.

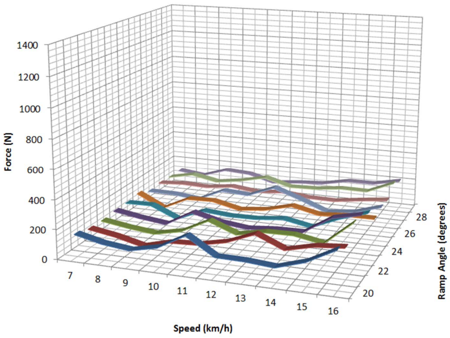

Figure 28: Peak head forces for a range of simulated quad bike with ROPS and restrained rider rollovers.

Simulation Scenarios Analysis

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

1. The number of ¼ turns:
   a. The OEM quad bike did 24 ¼ turns, 26 $^2/_4$ turns and 50 ¾ turns.
   b. The quad with CPD did 34 ¼ turns, 9 $^2/_4$ turns and 57 ¾ turns.
   c. The quad with ROPS did 100 ¼ turns.
   d. The quad with ROPS and restrained rider did 100 ¼ 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.

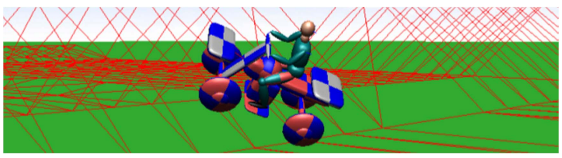
Figure 29: The initial position for Case 1.

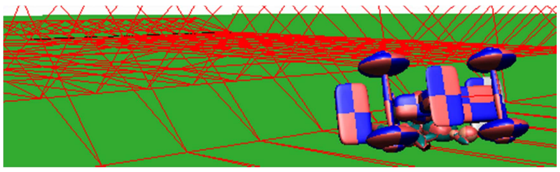
Figure 30: The rest position of the OEM quad bike and rider for the simulation of Case 1. The rider has been ejected from the quad bike and the rider is under the quad bike.

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.

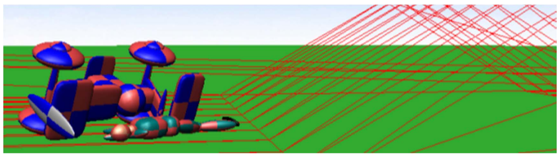

Figure 31: The rest position of the quad bike with CPD and unrestrained rider for Case 1.

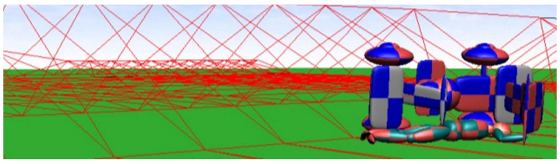

Figure 32: The rest position of the quad bike with ROPS and unrestrained rider for Case 1.

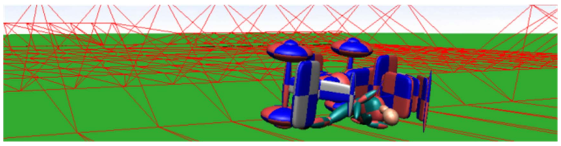

Figure 33: The rest position of the quad bike with ROPS and restrained rider for Case 1.

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 60^0 with a drop of approximately 5m. The rider sustained fatal trauma to the torso (chest and back).

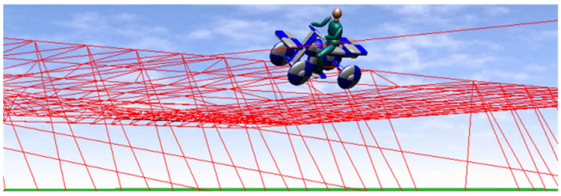

Figure 34: The initial position for Case 2.

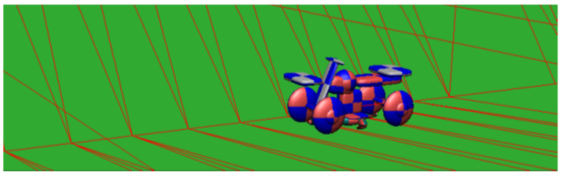

Figure 35: The rest position of the OEM quad bike and rider for the simulation of Case 2. The rider has been ejected from the quad bike and the rider is beneath the quad bike.

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.

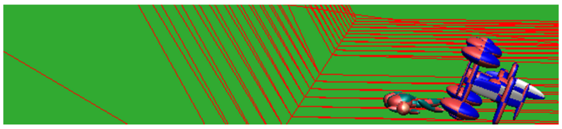

Figure 36: The rest position of the quad bike with CPD and unrestrained rider for Case 2.

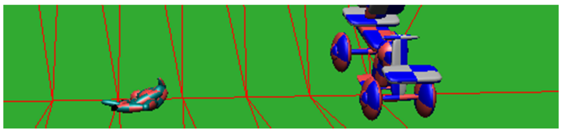

Figure 37: The rest position of the quad bike with ROPS and unrestrained rider for Case 2.

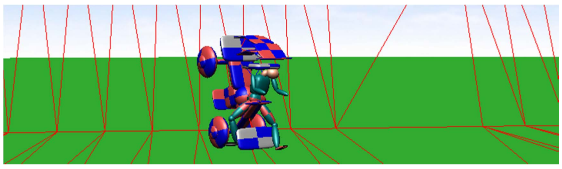

Figure 38: The rest position of the quad bike with ROPS and restrained rider for Case 2.

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.

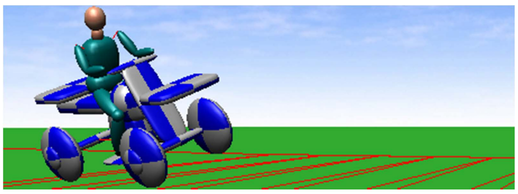

Figure 39: The initial position for Case 3.

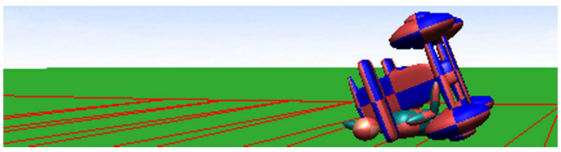

Figure 40: The rest position of the OEM quad bike and rider for the simulation of Case 3. The rider has been ejected from the quad bike and the rider is beneath the quad bike.

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 antd 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.

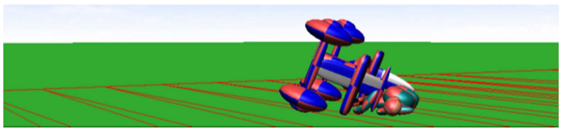

Figure 41: The rest position of the quad bike with CPD and unrestrained rider for Case 3.

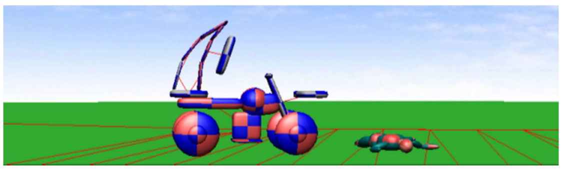

Figure 42: The rest position of the quad bike with ROPS and unrestrained rider for Case 3.

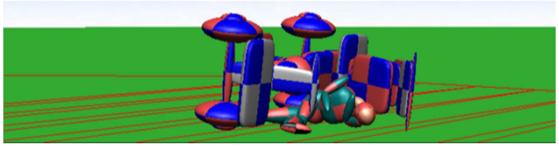

Figure 43: The rest position of the quad bike with ROPS and restrained rider for Case 3.

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.

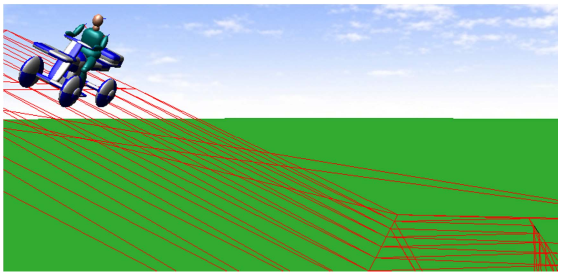

Figure 44: The initial position for Case 4.

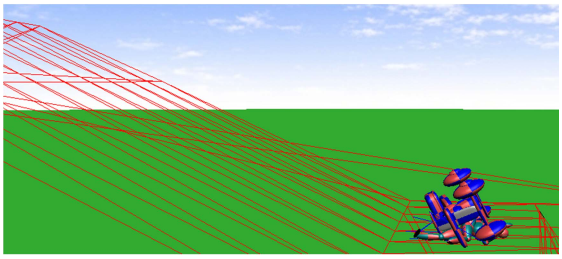

Figure 45: The rest position of the OEM quad bike and rider for the simulation of Case 4. The rider has been ejected from the quad bike and the rider is beneath the quad bike.

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.

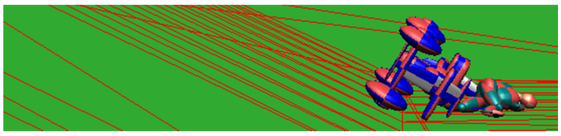

Figure 46: The rest position of the quad bike with CPD and unrestrained rider for Case 4.

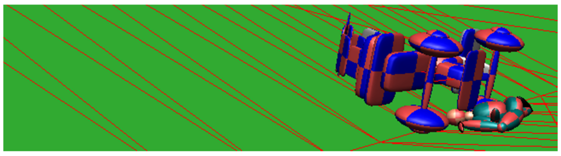

Figure 47: The rest position of the quad bike with ROPS and unrestrained rider for Case 4.

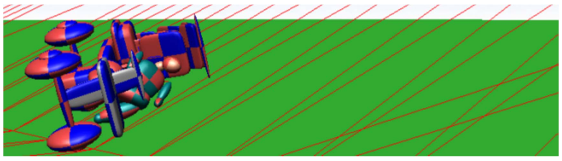

Figure 48: The rest position of the quad bike with ROPS and restrained rider for Case 4.

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 unrestraint 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=PLjYkHo7lOqxUsjYA2A1dqKE2F3oMGZAvI&feature=mh_lolz

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. Backfilps;
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

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[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."

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THE COMPARATIVE TESTING OF SINGLE AND DOUBLE RIDE HEIGHT CONTROL VALVE SUSPENSION CONTROL SYSTEMS

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ABSTRACT

The pneumatic control system on heavy vehicle air-bag suspension systems, typically designed in the United States of America (and other parts of the world), have one or two ride height control valves and a relatively complex pneumatic supply piping. BASE have developed a control system using two ride height control valves and simplified pneumatic piping. Handling and ride testing were conducted on: a petrol tanker (prime mover and trailer) fully loaded, half loaded and empty; and a concrete agitator fully loaded and empty with both the Original Equipment Manufacturer (OEM) and BASE suspension control systems. The suspension control systems, test method and results are detailed. On-road testing using two concrete agitators operating over the same route was also evaluated using Global Positioning System (GPS), accelerometer and video. The presented results show improvements in ride and handling with the BASE pneumatic air-bag suspension control system.

INTRODUCTION

BASE is a company that has developed and patented a heavy vehicle suspension air-bag control system. This report details and presents the comparative results of dynamic testing of the BASE system compared to the Original Equipment Manufacturer (OEM) suspension air-bag control systems.

A suspension control system needs to address both ride and handling. The ride is the vertical movement whereas handling is the response to manoeuvring. The suspension disconnects the vehicle from the wheels and tyres and attenuates the inputs from the road into the vehicle (ride) and also maintains the tyre contact with the road so that forces (acceleration, deceleration and cornering) can be extracted (handling). The suspension primarily affects the handling by the amount of pitch, roll and bounce and affects how the vehicle accelerates, decelerates, translates laterally and yaws.

Heavy vehicle (truck, trailer and bus) suspension evolved from horse drawn carriage suspension, which were equipped with leaf springs (wood and steel). Figure 1 illustrates a 1932 dump truck with leaf springs on both axles.

Figure 1: 1932 Oshkosh Model F all-wheel-drive dump truck with leaf springs on the front and rear axles.

Other types of suspensions which have been used on automobiles (and trucks) include: rubber block, coil spring, torsion bar, pneumatic (air) and hydropneumatic (hydraulic and air).

During the late 1990's and early 2000's most trucks moved from steel spring suspension to air-bags. The primary reasons were that the air-bag system was lighter, provided superior ride and reduced the damage to the road surface. The key benefits of an air-bag suspension for heavy vehicles is the ability to control ride height, relatively soft spring rate and load sharing. Air-bag suspensions with one ride height control valve have poor roll stiffness and require anti-roll devices to be included. Rolling of the vehicle on the suspension causes the centre-of-gravity to shift sideways relative to the wheels and this tends to destabilise a vehicle in a turn. The amount of roll depends principally on the suspension's roll stiffness and the suspension roll centre height.

The majority of air-bag suspension control systems used in heavy vehicles in Australia (and other countries around the world) is reliant on a single ride height control valve with air-lines connected in series or different length air-lines from the ride height control valve to the suspension air-bags. When one ride height control valve is used, it is typically offset from the vehicle centreline. Anti-roll-bars are also used to increase the roll stiffness.

This method of control is biased to improve ride quality and has limited handling benefits.

Driscol [1] conducted a study into heavy vehicle (truck) crashes over the period 2003, 2005, 2007 and 2009. Driscol identified that over the period 2003, 2005, 2007 and 2009, inappropriate speed for the conditions and fatigue contributed to cause 51%, 54%, 47% and 42% of the crashes respectively.

VicRoads [2] in a study on 'Heavy Vehicle Rollover' have identified that rollover is a serious problem for the heavy vehicle industry. VicRoads identify that: "*…as little as 1km/h extra will make you roll over*."

The U.S. Department of Transportation has an ongoing major study on the causes of large truck crashes (Toth [3]). A database containing highly detailed data on serious large truck crashes is currently being created. To date, the NHTSA identified that driver error (including driver fatigue) was a factor in the vast majority of crashes. Additionally, the University of New Brunswick's Accident Research Team (Hildebrand [4]), under contract with Transport Canada, conducted over 50 in-depth investigations of heavy truck collisions over a 3-year period. Contributing factors were identified to include speed, driver inattention, visibility issues, road conditions/design/terrain, driver fatigue, load shift (directional stability), mechanical defects and driver inexperience. The majority of collisions were found to have excessive speed as a factor.

According to the Insurance Institute for Highway Safety (IIHS) [5], *"Truck driver fatigue is a known crash risk. Drivers of large trucks are allowed by federal hours-of-service regulations to drive up to 11 hours at a stretch and up to 77 hours over a 7-day period. Surveys indicate that many drivers violate the regulations and work longer than permitted."*

BACKGROUND

The fundamentals of the BASE system are that it dynamically controls the suspension:

1. Two (2) ride height control valves are used, one is fitted to either side of the vehicle;
2. Each ride height control valve is individually supplied;
3. The air-lines used to supply and distribute the pressurised air are Ø12mm (or Ø0.472");
4. All the air-lines are equal length (i.e. from the supply to the ride height control valve and from the ride height control valve to the suspension air-bags);
5. The separate control for either side means that there is variable roll stiffness.

Figure 2 illustrates the OEM twin axle suspension air-bag control system and Figure 3 illustrates the BASE twin axle suspension air-bag control system.

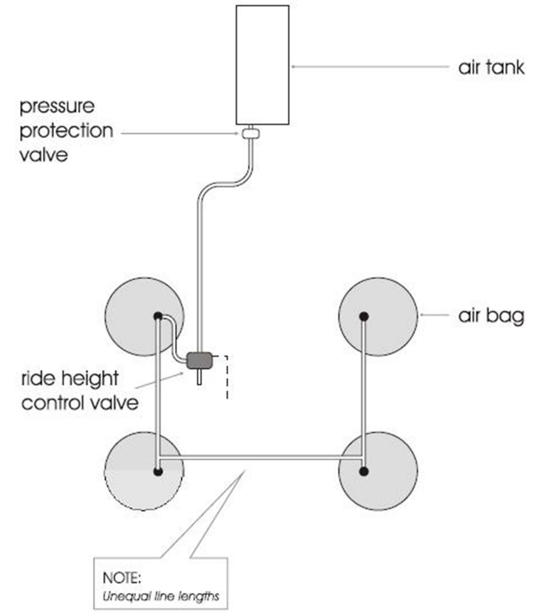

Figure 2: OEM suspension air-bag control system twin axle.

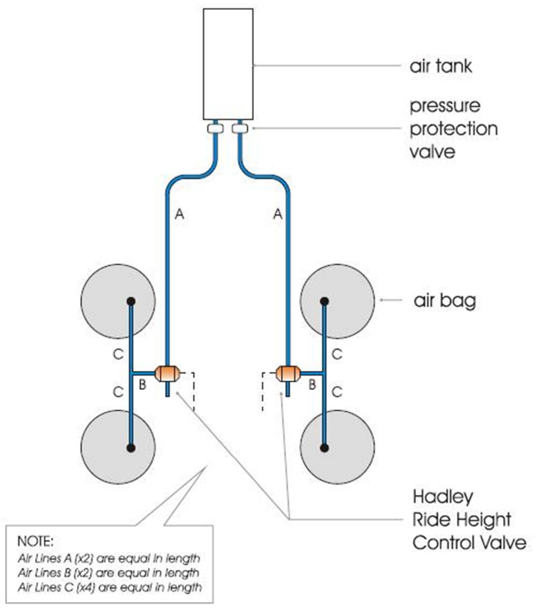

Figure 3: BASE suspension air-bag control system twin axle.

Figure 4 illustrates the OEM 8 air-bag twin axle suspension air-bag control system and Figure 5 illustrates the BASE 8 air-bag twin axle suspension air-bag control system.

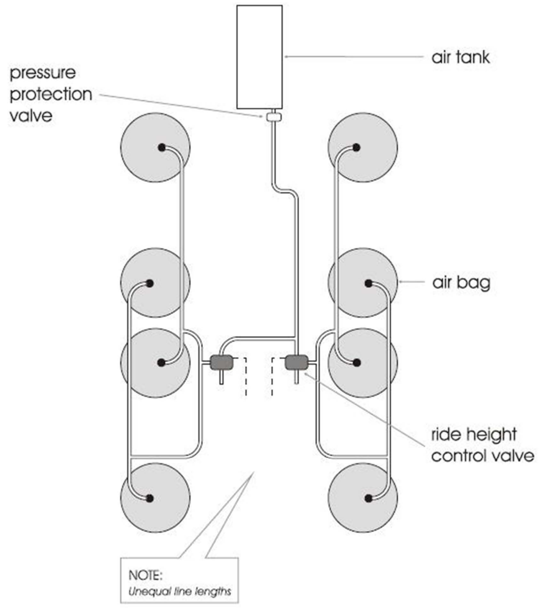

Figure 4: OEM suspension air-bag control system for 8 air-bags and twin axles.

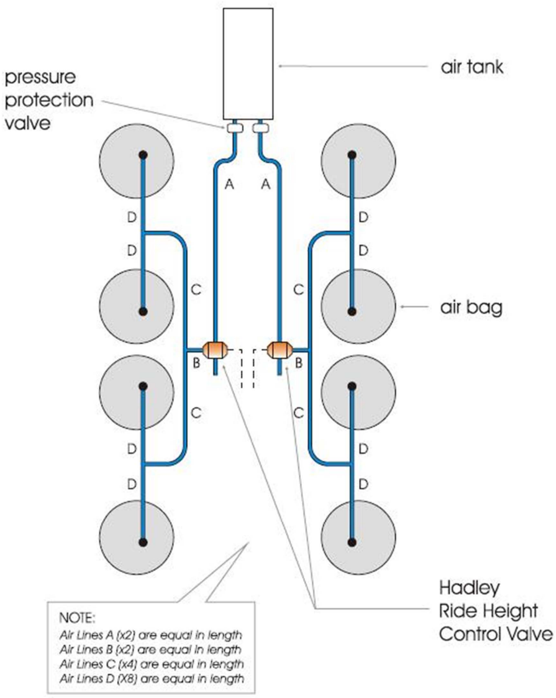

Figure 5: BASE suspension air-bag control system for 8 air-bags and twin axles.

Figure 6 illustrates the OEM 3 axle suspension air-bag control system and Figure 7 illustrates the BASE 3 axle suspension air-bag control system.

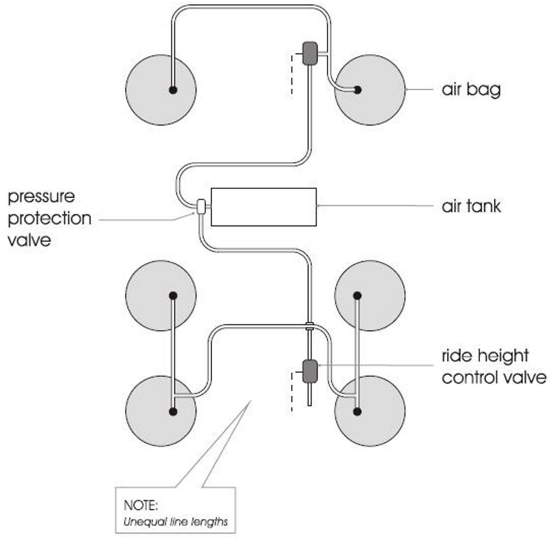

Figure 6: OEM suspension air-bag control system 3 axle.

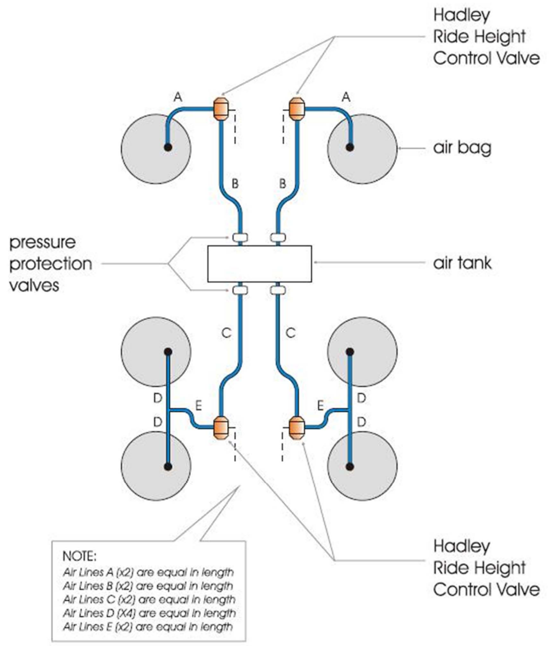

Figure 7: BASE suspension air-bag control system 3 axle.

Figure 8 illustrates the OEM 4 axle suspension air-bag control system and Figure 9 illustrates the BASE 4 axle suspension air-bag control system.

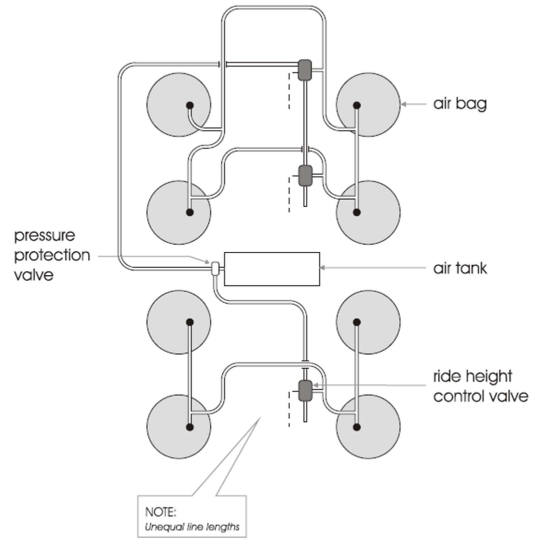

Figure 8: OEM suspension air-bag control system 4 axle.

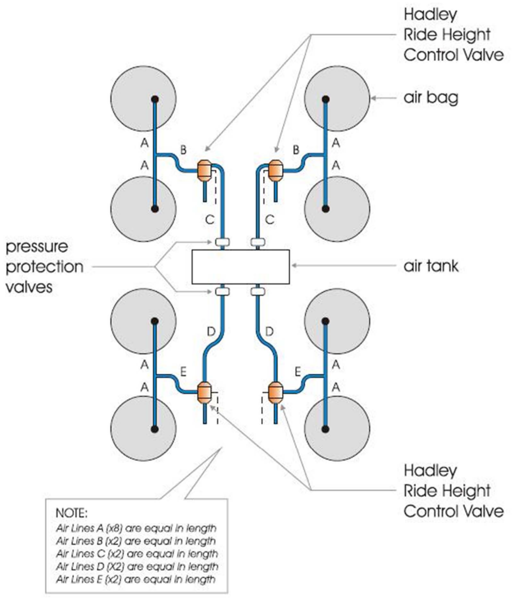

Figure 9: BASE suspension air-bag control system 4 axle.

TESTING

Comparative testing was conducted:

1. At the Australian Automotive Research Centre (AARC) Anglesea, Victoria using the 4.2km long highway circuit. Using both a fuel tanker (prime mover and trailer) and a concrete agitator; and
2. On road using two concrete agitators.

AARC testing

A series of comparative ride and handling tests were conducted on the oval course at Australian Automotive Research Centre (AARC). Two short and two long lane change manoeuvre test sites were positioned on the straight sections of the test course. The exits from both curves at either end were used to evaluate the effect of exiting from a sweeping bend. The vibration tests included the travel to and from the compound to the highway circuit and handling tests on the highway circuit.

Data was collected using:

1. RT3000, a tri-axial accelerometer, velocity, displacement, yaw rate and yaw instrument;
2. Pressure and displacement transducers on the drive axles of the truck and the axles of the trailer;
3. Accelerometers fitted to the drive axles of the truck and the axles of the trailer; and
4. Whole of body vibration was collected using a Svantek SV100.

The dynamic handling tests conducted were:

1. Four (4) modified ISO lane change manoeuvres (2 to the left and 2 to the right); and
2. Exit from sweeping bends at high speed.

The testing methodology used was to activate the instrumentation within the compound of the AARC and record the mass of the truck axle combinations. The trucks were then driven the 4km to the highway circuit over a dirt/gravel road. At the highway circuit the vehicle was then driven in an anti-clockwise direction through the lane change manoeuvres at sequentially increasing speeds. After the data for the lane change manoeuvre was captured, the vehicle was driven around the test course at 80km/h to 110km/h to evaluate the performance of the trucks exiting the sweeping bend. The vehicle was driven back to the compound and either the load and/or the suspension control system was changed. The fuel tanker was tested empty (13,920kg), half loaded (28,970kg) and fully loaded (43,640kg), whereas the concrete agitator was tested empty (17,600kg) and fully loaded (29,260kg).

The lateral acceleration was limited to approximately 60% of the vehicle's estimated limit of lateral acceleration to ensure the safety of the personnel and vehicles used in the testing.

The fuel tanker was provided by Linfox (refer to Figure 10).

Figure 10: The fuel tanker.

The prime mover details were:

1. Manufactured by Freightliner LLC (for DaimlerChrysler Australia/Pacific Pty Ltd);
2. Vehicle Identification Number (VIN) 1FVJF0CV68L999121;
3. Manufactured 10- 2007;
4. Model CL112;
5. GVM 24000 (GCM 50000); and
6. Fitted with RF2013 Airliner suspension.

The trailer details were:

1. Manufactured by Marshall Lethlean;
2. VIN 6D9125RTAM2057066;
3. Manufactured in 1991; and
4. Fitted with a BPW Transpec air-bag suspension.

The concrete agitator was provided by XL Concrete, refer to Figure 11.

Figure 11: The XL Concrete Agitator.

The concrete agitator details were:

1. Manufactured by Kenworth Trucks (for Paccar Australia Pty Ltd);
2. VIN 6F5000000AA443511.

The fuel tanker was driven by a Linfox employee. The concrete agitator was driven by an XL Concrete employee.

Figure 12 illustrates the lateral acceleration data collected during the short course lane change with a fully loaded fuel tanker at speeds of approximately 60km/h.

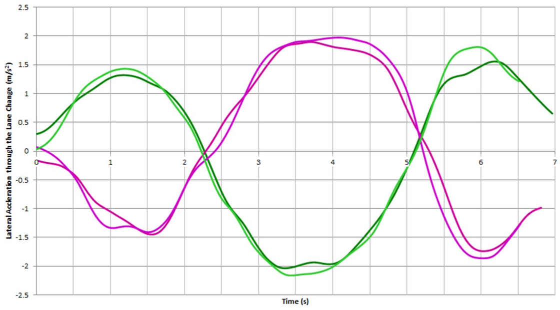

Figure 12: A representative plot of lateral acceleration vs time of four lane change manoeuvres (two turning left/right/left and two turning right/left/right) for the short course lane change with a fully loaded fuel tanker at a speeds of approximately 60km/h. The peak lateral acceleration was extracted from each individual set of test data.

Figure 13 to Figure 24 illustrate the fuel tanker testing for both the short and long lane change manoeuvre courses:

1. The blue lines are the OEM suspension control system on both the prime mover (PM) and trailer (T).
2. The brown lines are the prime mover with the BASE and trailer with the OEM suspension control system
3. The light brown lines are the BASE control system on both the prime mover and trailer.

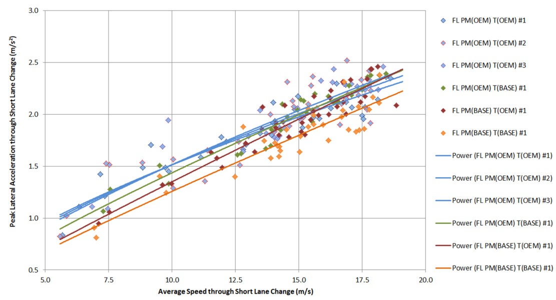

Figure 13: Fully loaded fuel tanker –Peak Lateral Acceleration (Short Lane Change).

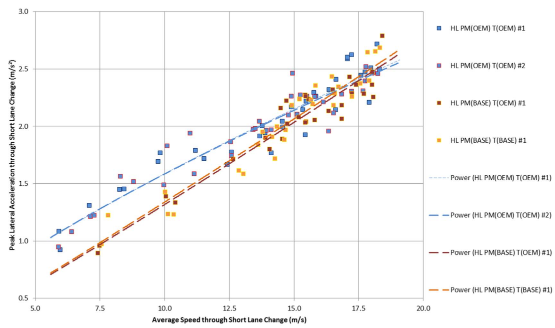

Figure 14: Half loaded fuel tanker –Peak Lateral Acceleration (Short Lane Change).

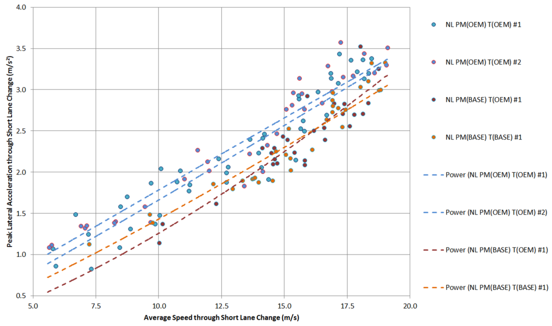

Figure 15: Empty (no load) fuel tanker –Peak Lateral Acceleration (Short Lane Change).

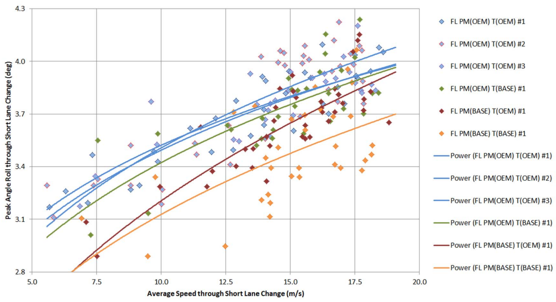

Figure 16: Fully loaded fuel tanker – Peak Roll Angle (Short Lane Change).

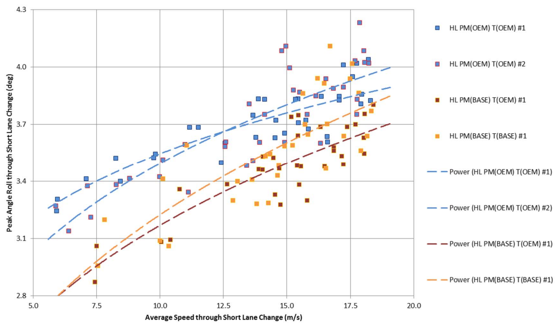

Figure 17: Half loaded fuel tanker – Peak Roll Angle (Short Lane Change).

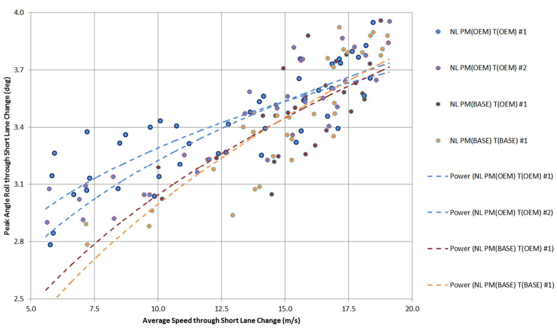

Figure 18: Empty (no load) fuel tanker – Peak Roll Angle (Short Lane Change).

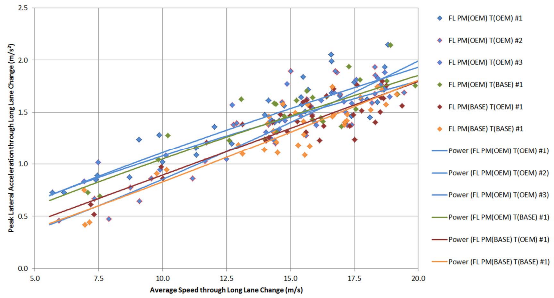

Figure 19: Fully loaded fuel tanker – Peak Lateral Acceleration (Long Lane Change).

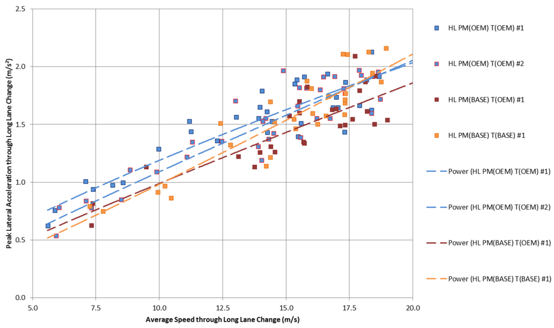

Figure 20: Half loaded fuel tanker – Peak Lateral Acceleration (Long Lane Change).

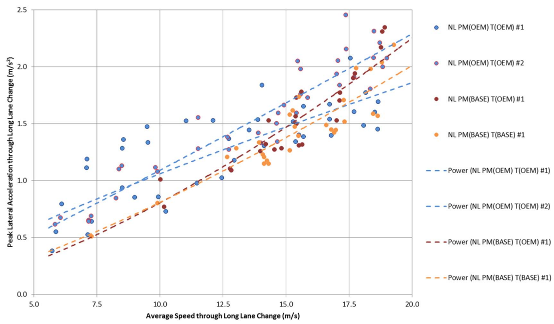

Figure 21: Empty (no load) fuel tanker – Peak Lateral Acceleration (Long Lane Change).

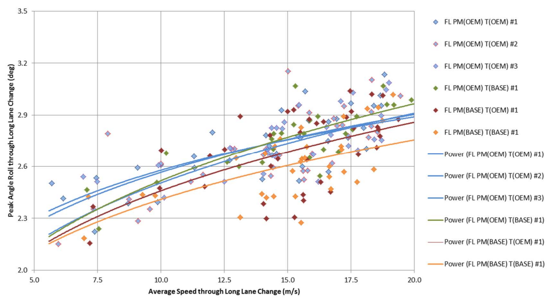

Figure 22: Fully loaded fuel tanker – Peak Roll Angle (Long Lane Change).

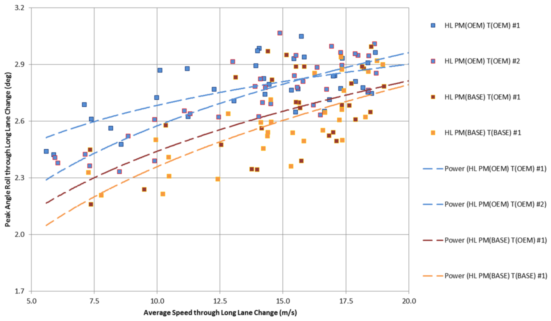

Figure 23: Half loaded fuel tanker – Peak Roll Angle (Long Lane Change).

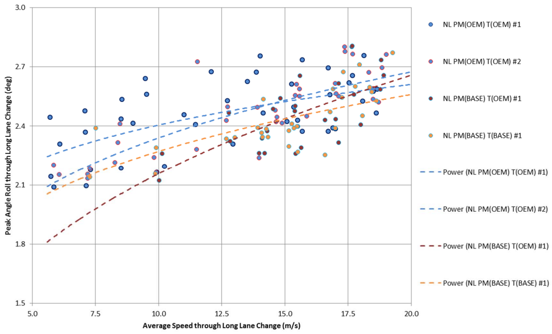

Figure 24: Empty (no load) fuel tanker – Peak Roll Angle (Long Lane Change).

Figure 25 to Figure 32 illustrate the concrete agitator testing for both the short and long lane change manoeuvre courses:

1. The purple lines are the OEM suspension control system.
2. The green lines are the BASE suspension control system.

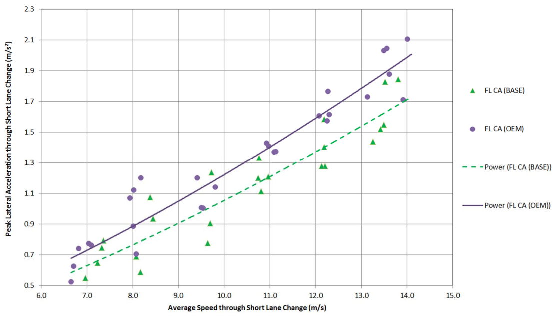

Figure 25: Fully loaded concrete agitator – Peak Lateral Acceleration (Short Lane Change).

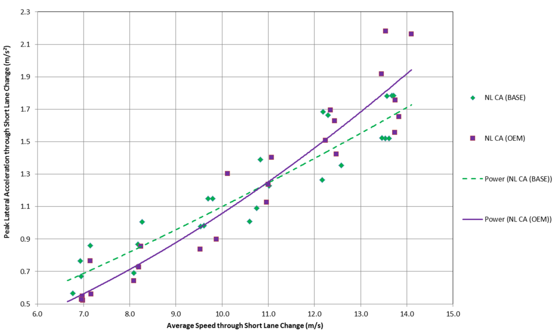

Figure 26: Empty (no load) concrete agitator – Peak Lateral Acceleration (Short Lane Change).

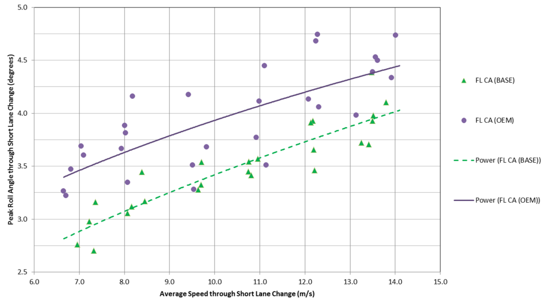

Figure 27: Fully loaded concrete agitator – Peak Roll Angle (Short Lane Change).

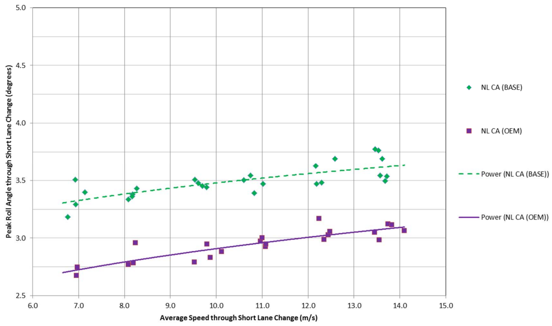

Figure 28: Empty (no load) concrete agitator – Peak Roll Angle (Short Lane Change).

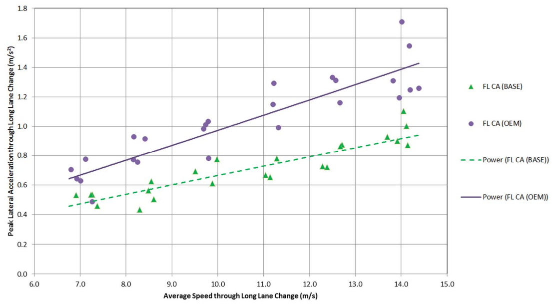

Figure 29: Fully loaded concrete agitator – Peak Lateral Acceleration (Long Lane Change).

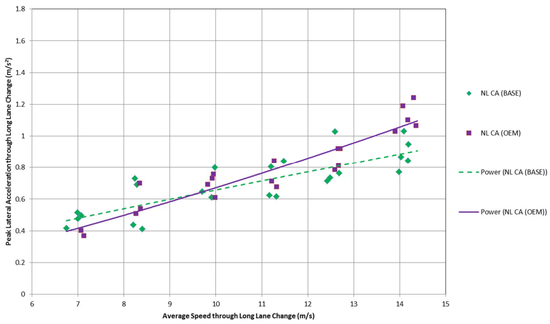

Figure 30: Empty (no load) concrete agitator – Peak Lateral Acceleration (Long Lane Change).

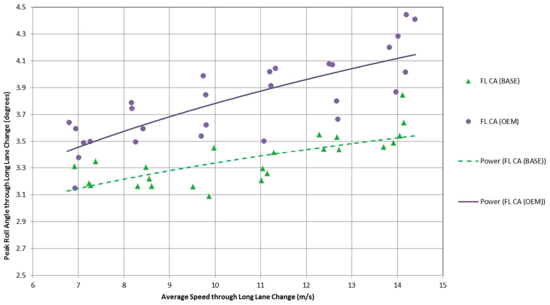

Figure 31: Fully loaded concrete agitator – Peak Roll Angle (Long Lane Change).

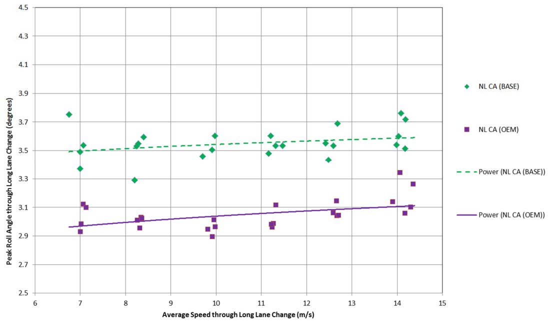

Figure 32: Empty (no load) concrete agitator – Peak Roll Angle (Long Lane Change).

Figure 33 and Figure 34 are extracted from the 70km/h testing of the rear drive axle of the fuel tanker prime mover manoeuvring through the test course. They show a circuit with OEM suspension control (refer to Figure 33) and BASE suspension control (refer to Figure 34) on both the prime mover and tanker.

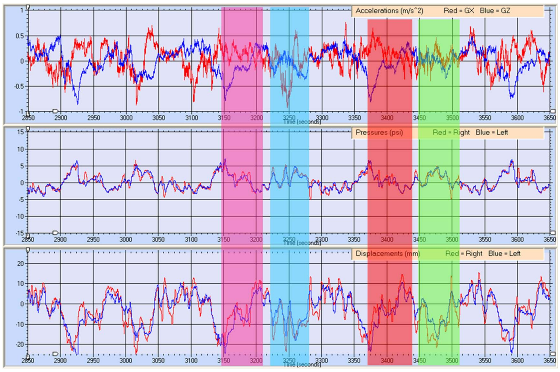

Figure 33: Accelerations, pressures and displacements of the fuel tanker rear drive axle with the OEM single ride height control valve air-bag suspension controller on the prime mover.

Figure 33 is a plot of the accelerations, pressures and displacements of the fuel tanker rear drive axle with the OEM single ride height control valve controlling the suspension air-bags on the prime mover:

1. At 3145s the fuel tanker starts in the first sweeping bend of the circuit and at 3215s the vehicle exits the bend;
2. At 3215s the fuel tanker drives along the first straight section of the test track and manoeuvres through the:
   a. Short course, at 3220s; and
   b. Long course, at 3240s.
3. At 3375s the fuel tanker starts in second sweeping bend of the circuit and at 3430s the vehicle exits the bend;
4. At 3440s the fuel tanker drives along the second straight section of the test track and manoeuvres through the:
   a. Short course, at 3450s; and
   b. Long course, at 3470s.

In Figure 33 the light blue and light green bands identify the short and long lane change manoeuvers and the pink and red bands indicate the sweeping bends.

In Figure 33 both the air pressures run effectively parallel to one another indicating that air-bag pressure on the left side is similar to the right side irrespective of where the vehicle is travelling on the highway circuit; along a straight, through a sweeping bend or manoeuvring through the short or long course land change. Through a complete loop of the circuit the displacement of the drive axles to the chassis varies from +12mm to -25mm (i.e. by 37mm). Figure 33 plot of pressure and displacement is consistent with a single ride height control valve.

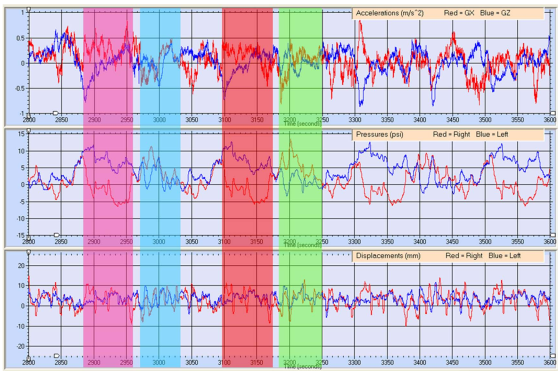

Figure 34: Accelerations, pressures and displacements of the fuel tanker rear drive axle with the BASE single ride height control valve air-bag suspension controller on the prime mover.

Figure 34 is a plot of the accelerations, pressures and displacements of the fuel tanker rear drive axle with the BASE ride height control valves controlling the suspension air-bags on the prime mover.

1. At 2880s the fuel tanker starts in the first sweeping bend of the circuit and at 2950s the vehicle exits the bend;

2. At 2960s the fuel tanker drives along the first straight section of the test track and manoeuvres through the:
    a. Short course, at 2975s; and
    b. Long course, at 3005s.
3. At 3095s the fuel tanker starts in second sweeping bend of the circuit and at 3160s the vehicle exits the bend;
4. At 3170s the fuel tanker drives along the second straight section of the test track and manoeuvres through the:
    a. Short course, at 3180s; and
    b. Long course, at 3220s.

In Figure 34 the light blue and light green bands identify the short and long lane change manoeuvers and the pink and red bands indicate the sweeping bends.

In Figure 34 there is a difference in the left and right air pressures depending on where the vehicle was on the test track. In the straight sections the pressures are parallel to one another, whereas through a sweeping bend or manoeuvring through the short or long course lane change the air pressures are different. Through the sweeping bend the there is a significant difference between the left and right sides, whereas manoeuvring through the short or long course lane change the air pressures change as the vehicle manoeuvres. Through a complete circuit the displacement of the drive axles to the chassis varies from +12mm to -8mm (i.e. by 20mm). Figure 34, a plot of pressure and displacement, is consistent with a two ride height control valves on either side.

The measured Vibration Dose Values for the suspension control systems were:

1. Fuel tanker:
    a. Fully loaded:
        i. OEM 23.5m/s$^{1.75}$;
        ii. BASE 18.7m/s$^{1.75}$.
    b. Half loaded:
        i. OEM 23.3m/s$^{1.75}$;
        ii. BASE 19.5m/s$^{1.75}$.
    c. Empty:
        i. OEM 24.0m/s$^{1.75}$;
        ii. BASE 19.4m/s$^{1.75}$.
2. Concrete agitator:
    a. Fully loaded:
        i. OEM 24.2m/s$^{1.75}$;
        ii. BASE 20.2m/s$^{1.75}$.
    b. Empty:
        i. OEM 20.3m/s$^{1.75}$;
        ii. BASE 21.4m/s$^{1.75}$.

Based on the testing conducted at AARC there is a clear and measureable difference in handling and ride between the OEM and the BASE air-bag suspension control system. The BASE system is quantifiably better optimised for ride and handling.

1. The BASE suspension air-bag control systems reduced manoeuvring peak lateral acceleration by between 4% and 43% for the full, half full and empty fuel tanker; and full and empty concrete agitator.
    a. At lower speeds the handling empty concrete agitator was not improved, but was equivalent to the OEM suspension control system.
    b. In the case of the half full fuel tanker for both the short and long lane change manoeuvre, at the majority of speeds tested the handling was improved. At higher speeds, the handling was equivalent to the OEM suspension control system.
2. The BASE suspension air-bag control systems reduced manoeuvring peak roll angle by between 3% and 19%.
    a. In the case of the empty concrete agitator, for both the long and short lane change manoeuvre at low speeds, the roll angle was not improved. However the rollover collision rates for empty concrete agitators is very low.
    b. In the case of the half full fuel tanker, for the short lane change manoeuvre at the majority of speeds, the roll angle was improved. At the highest speeds the roll angle was equivalent to the OEM suspension control system.
3. In the majority of tests the handling was improved with the BASE system fitted. Overall, the BASE suspension air-bag control systems reduced the average manoeuvring peak lateral acceleration and average peak roll angle by 16% and 10% respectively.
4. A 16% reduction in average manoeuvring peak lateral acceleration would equate to an 8% increase in the rollover tolerance i.e. an OEM truck/trailer would roll at 100km/h whereas a BASE truck/trailer would roll at 108km/h.
5. The pressure measurements of the air-bags show that for the:
    a. OEM single ride height control valve the air pressures on the left and right side of the vehicle are effectively the same.

   b. BASE dual ride height control valves the air pressure can be different and is a function of displacement.

6. The displacement measurements of the air-bags show that the magnitude of the displacement for the OEM single ride height control valve is greater than the BASE system (which is consistent with the peak roll results).
7. The ride of the trucks improved with the BASE system fitted. The BASE suspension air-bag control systems reduced VDV by between 17% to 23%.

The test data obtained from exiting the sweeping bends at speeds from 20km/h to 110km/h found no discernible oscillations or control deficiencies with either the OEM or BASE air-bag suspension control systems.

Two independent, highly-experienced truck drivers were used for the testing. The empirical observations of both drivers were that the BASE system significantly improved both ride and handling.

The following link can be used to view a short video of the testing conducted at AARC: http://www.youtube.com/watch?v=MJ_-rKDipmY.

On Road Testing

A series of comparative on-road tests were conducted by pairing two concrete agitators. One of the agitators was fitted with the OEM suspension control system and the second agitator was fitted with the BASE suspension control system.

The concrete agitators were provided by XL Concrete, refer to Figure 35. The OEM suspension control system was equivalent to Figure 4, whereas the BASE suspension control system was equivalent to Figure 5.

Figure 35: The XL Concrete Agitator.

The concrete agitators were manufactured by Kenworth Trucks (for Paccar Australia Pty Ltd), the VINs were;

1. OEM 6F50000005A430174;
2. BASE 6F5000000AA442970.

The concrete agitators were driven by XL Concrete employees, during the course of their normal duties.

Data was collected using BX1500 [5] 'Smarty Black Box' which contains:

1. A tri-axial accelerometer;
2. Global Positioning System (GPS); and
3. High Definition (HD) video.

The BX1500's were fitted to the left side chassis rail with the video camera focussed on the motion of the movement of the suspension air-bag, refer to Figure 36.

Figure 36: A video image of the concrete agitator suspension air-bag (OEM).

The BX1500 software displays the video (upper left) the speed, date and time are displayed at the bottom of the video, the source data files (upper right), the acceleration data (lower left), the heading (lower centre) and Google map (lower right), refer to Figure 37 and Figure 38.

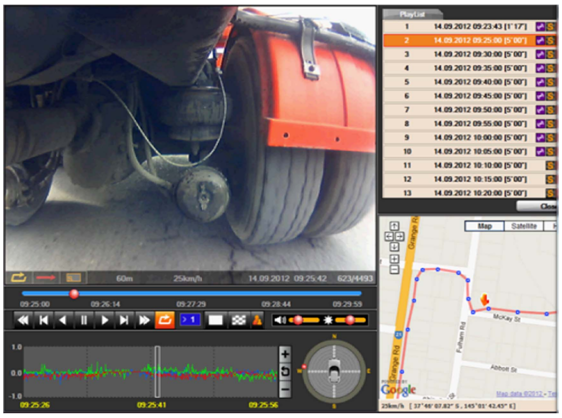

Figure 37: Concrete agitator with OEM air-bag suspension control system.

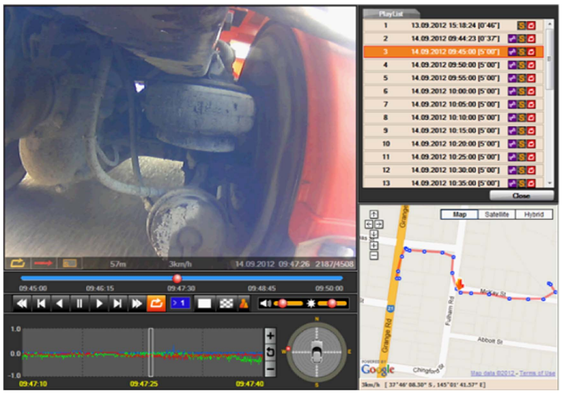

Figure 38: Concrete agitator with BASE air-bag suspension control system.

Comparing the magnitude of the green (vertical vibration) of the OEM and BASE air-bag suspension control systems, refer to Figure 39 and Figure 40, further illustrates that the BASE air-bag suspension control system reduces vertical vibration.

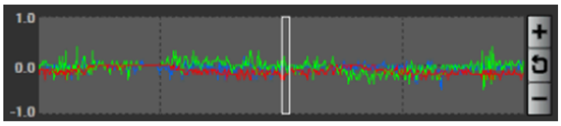

Figure 39: A section of the acceleration plot of the Concrete agitator with OEM air-bag suspension control system. Compare with Figure 40.

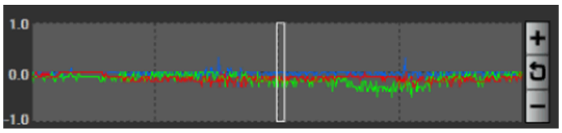

Figure 40: A section of the acceleration plot of the Concrete agitator with BASE air-bag suspension control system. Compare with Figure 39.

The following link can be used to view a short video of the comparative on road testing conducted: http://www.youtube.com/watch?v=P7h91tCDx5k&feature=plcp.

ACKNOWLEDGMENTS

Linfox supported the testing program by providing a prime-mover and trailer, a driver and access to the AARC at Anglesea. Mr Mick Best drove the fuel tanker and is an employee of Linfox.

XL Concrete (Mr Mario Amenta) supported the testing program by providing a concrete agitator and a driver. Mr Joe Montalti drove the concrete agitator at AARC and is an employee of XL Concrete. Subsequently XL Concrete has continued to support with on-road and further concrete agitator specific evaluations.

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[2] VicRoads is a Victorian State Government Authority in Australia. VicRoads key role is to help provide Victorians with safe and easy connections to the people and places that matter most to them. This includes connecting people to social activities and workplaces as well as connecting goods to domestic and international marketplaces. VicRoads manages over 22,000 kilometres of roads, 3300 bridges, 3.7 million licensed drivers and 4.9 million registered vehicles.

http://www.vicroads.vic.gov.au/Home/Moreinfoandservices/HeavyVehicles/VehicleManagementAndSafety/HeavyVehicleRolloverPreventionProgram.htm

[3] Toth G.R., Radja G. A., Thiriez K. K. and Carra J. S., Large Truck Crash Causation Study in the United States, National Highway Traffic Safety Administration, Paper No. 252. http://www.nhtsa.gov/DOT/NHTSA/NRD/Articles/ESV/PDF/18/Files/18ESV-000252.pdf

[4] Hildebrand & Wilson, Development and Intermediate Findings of a Level III Heavy-Truck Collision Study, Transportation Research Record 1595, Paper No. 971502, p. 39, 1997.

[5] http://www.d-teg.com/products/add_02_ix1000.htm