ANALYSIS OF QUAD-BIKE LOSS-OF-CONTROL USING EXPERIMENTAL AND SIMULATED DYNAMIC BUMP TESTS

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ABSTRACT
Quad-bikes, also known as all-terrain vehicles in the United States of America, continue to be a major contributor to fatal and serious injuries in Australia as well as in many other countries all over the world, both for recreational use and in the workplace. There have been over 150 fatalities caused by quad-bike incidents in Australia since 2000 with around 70 percent of these attributed to rollovers. In 2011, quad-bikes overtook tractors as the leading cause of injury and death on Australian farms.

There is a significant portion of quad-bike fatalities that are identified as being caused by riding over a raised obstacle (i.e. bump, log, tree stump, etc.), which causes the vehicle to lose control and rollover. However, the authors are not aware of any research that has been published to date in regards to identifying the mechanism that causes this loss-of-control situation in the case of quad-bikes. This paper details a novel method used to identify this mechanism.

Preliminary testing conducted with a human test rider, identified that a rider can be significantly displaced across the seat when riding a quad-bike over a semi-circular raised obstacle placed on one side of the vehicle wheel track. A formal test procedure was then developed to measure the pelvis kinematics of an Anthropomorphic Test Device mounted on a quad-bike moving over a 150mm high bump obstacle placed on one side of the vehicle wheel track. This procedure was then simulated using a Finite Element (FE) model of a quad-bike that was validated against experimental tests. The analysis of both experimental and FE simulation results presented here clearly demonstrate how a quad-bike loss-of-control event, leading to rollover, can be triggered by a bump-like raised obstacle.

INTRODUCTION

Background
Small vehicles including two-wheeled motorcycles, four-wheeled quad-bikes and Side-by-Side Vehicles (SSVs) are now being used for a variety of applications on Australian farms. Over the last decade, there has been a steady increase in the number of quad-bikes in use in the agricultural and recreational sectors both in Australia and in many other developed countries [1]. The increasing popularity of quad-bikes can be attributed to their ability to undertake, in a more efficient manner, activities previously performed using horses, tractors or two-wheeled motorcycles.

It is well known that an improperly negotiated raised obstacle can be dangerous to a rider and potentially cause a loss-of-control event [2].Quad-bike stability and manoeuvrability can be improved through active riding techniques, i.e., requiring the rider to actively change their body position on the quad-bike according to any specific situation where there is a risk of loss-of-control [3]. Due to the need for vigilant active riding, quad-bikes may become particularly unstable if the operator begins riding in a passive mode or performs active body movements counter to the stability of the vehicle. To maintain full control of the vehicle, it is suggested by manufacturers that when traversing a raised obstacle with a quad-bike, active riding from a standing position should be used [1]. However, *Grzebieta et al.* [4] highlighted that often in a loss-of-control situations where riders are injured they may not necessarily be aware of the obstacle. Moreover, riding continuously in an 'active mode' is unrealistic particularly in farming environments, and especially with older riders.

There has been a growing concern over the number of fatalities and serious injuries caused by quad-bikes, both in Australia and overseas [5,8]. A recent study of the Australian National Coroner's Information System (NCIS) data of 109 fatalities that occurred in the twelve-year period between 2000 and 2012 identified that in an estimated twenty six percent (n=29) of fatalities, the rider lost control of the vehicle as a result of riding over an obstacle. In most of these loss-of-control cases the quad-bike also rolled over [6].

In regards to the United States of America (USA), an analysis of 2,718 quad-bike fatalities that occurred between the years 2000 and 2010 [6], thirty-four percent (n=916) of the fatalities noted the initiator as 'hit stationary object'. In around half, forty-six percent (n=409) of these fatalities, the quad-bike rolled over as a result of hitting the stationary object. Unfortunately, a more detailed description of the types of object (e.g., tree, rock, etc.) that was hit and whether a collision occurred or the object was riden over was not available. However, these statistics suggests that riding over a raised obstacle is one of the significant causes of quad-bike fatalities in the USA.

Research Objectives

The objective of this research was to investigate how riding over a relatively small raised obstacle could cause a quad-bike rider to lose control. Both experimental testing and computer simulations, using both a human rider and an Anthropomorphic Test Device (ATD), were used to observe the vehicle and rider kinematics when a quad-bike moved over a relatively small raised obstacle on level terrain at low speed. Both testing and simulations were purposely designed to observe the reaction of a rider seated in a neutral and relaxed seating position, i.e., without undertaking any active riding or bracing themselves against the impact in any way. This, in effect, allowed a situation where a rider who was not anticipating riding over an obstacle, to be observed.

METHOD

Human Rider Bump Test

A preliminary qualitative investigation was conducted to identify how riding over a raised obstacle could potentially cause a quad-bike to rollover with a human rider [7]. A volunteer test rider rode a Honda TRX250 quad-bike over several obstacles varying in height from 100 mm to 200 mm and at speeds of 10, 15, 20 and 25 km/h. The raised obstacles were asymmetrically placed and in line with either the left or right front wheel of the quad-bike. A moment just before impacting the obstacle, the rider released the throttle in order to 'free-wheel' over it. As the quad-bike moved over the obstacle, the rider maintained a neutral (i.e., relaxed) seating position to replicate a rider who was not anticipating riding over the raised obstacle.

ATD Bump Test

A controlled reproducible test, was then developed using an ATD instead of a human test rider [7]. The 'ATD bump test' consisted of towing the quad-bike, a Honda TRX500, along a straight line, over a 150-mm high semi-circular obstacle, which was in line with either the left or right wheel track. The tow vehicle stopped towing before the quad-bike hit the obstacle so that the quad-bike could 'free-wheel' over it. A Hybrid III 95th percentile ATD was positioned on the quad-bike in an upright seating position. The hands were ratchet strapped to the handle bars to prevent the ATD from becoming detached from the vehicle. A visual representation of the initial test setup including the initial seating position of the ATD is shown in Figure 1.

The quad-bike was towed from a standstill to approximately 25 km/h before being released in front of the obstacle. This ATD bump test was repeated three times for the case with the obstacle placed on either side of the vehicle wheel track in order to assess repeatability. The lateral and vertical accelerations of the ATD pelvis were used to determine the consistency of any particular test. The vehicle yaw rate and roll angle were also measured at the centre of the quad-bike's rear tray. The pelvis lateral displacement was also measured using a string potentiometer. The velocity of the vehicle was measured using a Global Positioning System (GPS) device positioned on the front tray.

The ATD bump test was then simulated using previously developed quad-bike and ATD Finite Element (FE) models [9], as shown in Figure 1. The FE quad-bike model reproduces in detail a Honda TRX500 quad-bike. The model consists of a series of shell, solid and beam elements linked together to represent the main components of the quad-bike that affect its stability and handling. These include: steering and suspension control arms, frame, fairings tyres, seat and handle bars. The suspension and steering system components of the vehicle were calibrated against the physical components. A series of dynamic and static test procedures were also performed to verify and validate the static stability and dynamic handling of the FE quad-bike model.

A validated FE model of a 95th percentile Hybrid III ATD provided as a standard software component by Livermore Software Technology Corporation (LSTC) was used for the simulations [10]. A 95th percentile ATD was used instead of a 50th percentile since the former represents the worst-case scenario in terms of both ATD mass and location of the centre of gravity above the vehicle seat. The ATD model used for these simulations is shown in Figure 1.

Simulation of the ATD bump test was performed in order to validate the response of the FE quad-bike and ATD models to moving over a raised obstacle. This allowed the use of simulations to further highlight the rollover mechanism observed in the human rider bump testing. The validation procedure involved comparing the experimental and simulation results. This included comparing the lateral and vertical pelvis accelerations of the ATD as well as the vehicle roll angle and speed while the quad-bike and rider moved over the obstacle. A qualitative visual comparison of the tyre deformation and the final resting position of the ATD on the quad-bike post ATD bump test was also conducted. A comparison of the setup and initial conditions between the actual experimental tests and the simulation is shown in Figure 1.

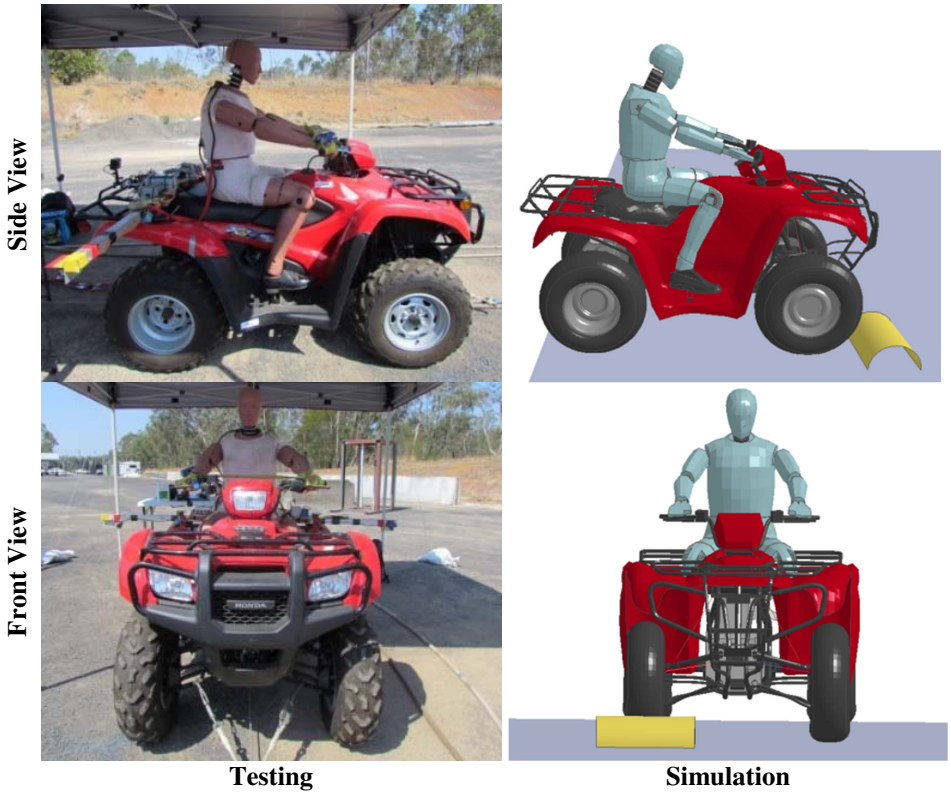

Figure 1: Initial simulations setup: testing and FE simulation using a Honda TRX500.

FE Tyre Model Calibration

The tyres of the original quad-bike model were further improved to ensure their calibration for the intended use in this research. A simplified tyre model consisting of solid elements with isotropic and nearly incompressible rubber properties were sufficient to reproduce with good approximation both the tyre deformation and damping in the radial direction. The LS-DYNA airbag modelling feature was used to simulate the tyre internal pressure, which was set to an initial value of 30 kPa (4.4psi).

Radial Compression

Radial tyre compression tests were performed to determine the vertical stiffness of the physical tyres. The calibration process, which was performed separately for both the front and rear tyres, was based on the force-versus-displacement curves obtained from the corresponding experimental tests. A constant displacement rate of 10 mm/min was applied. Adjustments to the shear modulus of the tyre material in the FE tyre model matched the experimental radial stiffness.

Radial Damping

Vertical tyre drop tests were also performed to determine the vertical damping properties of both the physical front and rear tyres. In the calibration test, the wheel was raised 750 mm from the ground and released to bounce over a smooth surface under its own weight, until it naturally came to rest. The vertical displacement of the rim was measured over time (displacement per fractions of a second) as the wheel bounced. The damping properties of the FE tyre model were calibrated such that they accurately reproduced the vertical displacement time domain response obtained from the testing.

ATD Bump Test with Increased Obstacle Height

The ATD bump test was also simulated for increased obstacle heights of 200 and 250 mm. This was in order to replicate the large displacement of the rider vertically and laterally across the seat as seen during the human rider bump test. Since the FE quad-bike model represents a larger, heavier quad-bike with greater suspension travel than the TRX250 that was used for the human rider bump test, a taller bump obstacle was required to reproduce the same rider displacement. Another difference between the preliminary testing and this simulation is the weight of the rider. The volunteer test rider used during the human rider bump test had an approximate mass equivalent to a 50th percentile adult male (approximately 78 kg) whereas the ATD bump test and simulations used a 95th percentile adult male weighing approximately 101 kg.

RESULTS

Human Rider Bump Test

The human rider bump test demonstrated that riding over an asymmetric raised obstacle could cause the rider to become displaced laterally across the seat. It was observed that the larger the obstacle the further the rider was displaced. The sequence of events as the rider moves over the 200 mm high bump obstacle at 25 km/h is presented in Figure 2. It was observed that when the front-right wheel moved over the raised obstacle, the front suspension system allowed the quad-bike to maintain stability, which in turn allowed the rider to maintain a balanced seating position, as shown in frames 2 and 3 of Figure 2. In other words, the suspension of the front wheel and the riders arms adequately dampened the impact with the obstacle. However, when the rear-right wheel hit the raised obstacle, the rider became elevated and was thrown sideways across the vehicle seat, as shown in frames 4 through 6 of Figure 2. It is clear that suspension cannot adequately dampen the rear tyre impact with the obstacle. Using the rear tyre to absorb most of the impact energy subjects the rider to a high risk of losing control of the vehicle. This impact also caused the quad-bike to yaw at an angle towards the side of the obstacle i.e. clockwise towards the obstacle if it was on the right side. The rider's spontaneous reaction to this lateral movement was to increase the grip on the handle bars and pull on the right side of the handle bars in order to relocate their posterior squarely back on the seat. This in turn caused the rider to suddenly turn the vehicle towards the right hand side, i.e., the side where the obstacle was located. Such sudden steering combined with the vehicle yaw increased the roll rate of the vehicle and had not the rider taken a quick and active counter-response manoeuvre, rollover would have likely occurred.

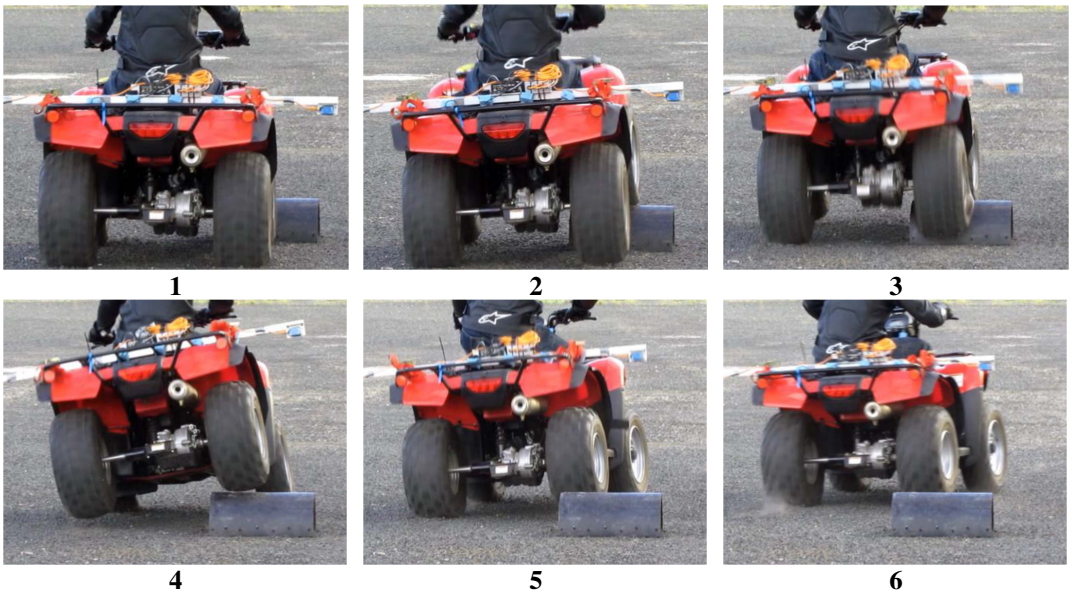

Figure 2: Rider on a Honda TRX250 moving over a 200mm high asymmetric raised obstacle at 25 km/h. <u>Note:</u> in frame 5 the rider's pelvis has lifted off the seat in response to the accelerations imparted by the bump. In frame 6, the rider's pelvis can clearly be seen relocated to the left side of the quad-bike and the rider is beginning to slide off the saddle.

Tyre Calibration

Before the bump test could be simulated using the FE model of the quad-bike and ATD the tyres in the FE model had to be calibrated against test results first. The results of the front and rear tyre vertical stiffness tests are shown in Figure 3. The results show that good calibration of the vertical stiffness was achieved. Good calibration of the vertical damping properties of the front and rear tyres was also achieved.

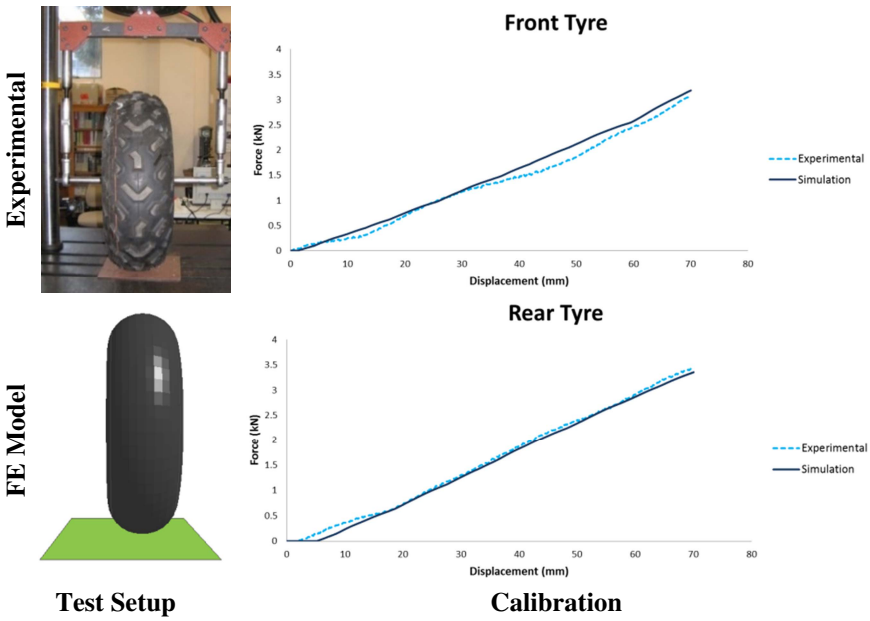

Figure 3: Vertical compression calibration of a Honda TRX500 tyre– test and model setup (left) and comparison of experimental and simulated force-displacement curves (right).

ATD Bump Test

There was sound repeatability evident between any three 'ATD bump tests' conducted on either side of the vehicle wheel track [7]. Good correlation between the experimental and simulated results was also evident. The speed at which the FE quad-bike model impacted and moved over the obstacle as well as the vehicle roll angle closely matched those observed during testing. The displacements and accelerations imparted to the ATD were similar between the tests and the simulation. The FE ATD also simulated the kinematics of the actual ATD during the tests well. In the simulation, the pelvis was displaced laterally across the seat by a similar distance as observed in the test.

During the ATD bump test, a large compression of both the front and rear tyres occurred as they rolled over the obstacle. This large deformation confirms that the tyres are absorbing a large part of the energy that would have otherwise increased the suspension travel when the vehicle moved over the obstacle. A comparison of the experimental and simulated tyre deformation is shown in Figure 4.

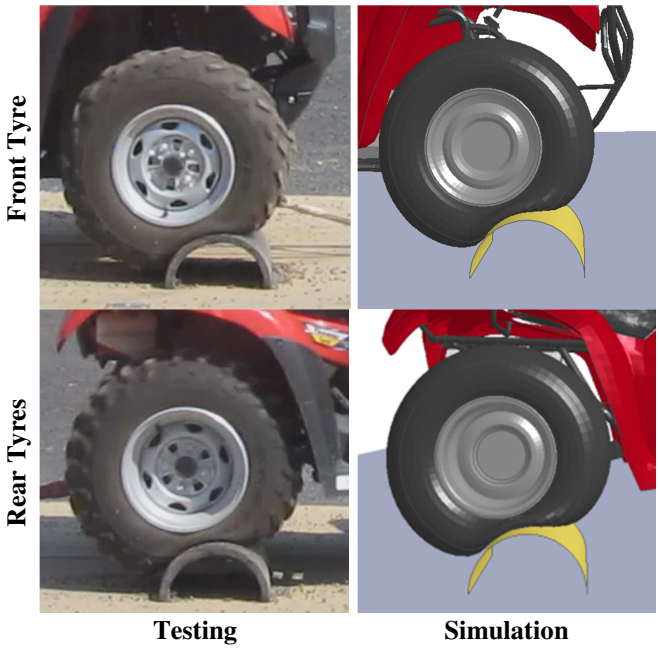

Figure 4: Comparison of a Honda TRX500 tyre deformation – testing and FE simulation.

Both the experimental and simulated kinematics of the quad-bike and the ATD as they moved over the raised obstacle are shown in Figure 5. It can be seen that, as a result of the right-front wheel hitting the obstacle, the ATD was able to maintain a stable seating position (frames 1 and 2 in Figure 5) as the ATD's arms acted as shock absorbers to manage the movement of the handlebars. The ATD's upper body adjusted by leaning back slightly against this and pulling forward again as the handlebars fell back down, but there was no significant change of location on the saddle and no resultant imbalance. However, when the right-rear wheel impacted the obstacle, the ATD's pelvis was displaced outward across the seat with respect to the obstacle (frame 5 in Figure 5). This resulted in the ATD leaning both sidewards and forwards due to the rear suspension system being unable to smoothly absorb the impact energy. The simulated kinematics was very similar to that observed in the experimental test. However, overall both the simulated ATD forward and lateral movements were slightly smaller than in the corresponding experimental test.

Figure 5: Asymmetric-obstacle test using a Honda TRX500 - sequence of events of test and simulation: rear and side views.

ATD Bump Test with Increase Obstacle Height

The 'bump test' simulation at a raised obstacle height of 250 mm demonstrated the large lateral displacement and steering effect observed during the human rider bump testing. It can be observed from the simulation that when the front wheel moved over the obstacle, the ATD maintained a balanced seating position, as shown in frames 1through 3 of Figure 6. However, when the rear wheel impacted the obstacle, the rider became elevated and thrown sidewards across the seat, as shown in frames 4 through 6 of Figure 6. This impact has also caused the quad-bike to yaw clockwise towards the obstacle. Also similar to the human rider bump testing, it can be observed in frames 6 of Figure 6 that the ATD has induced a steering input as a result of being shifted across the seat.

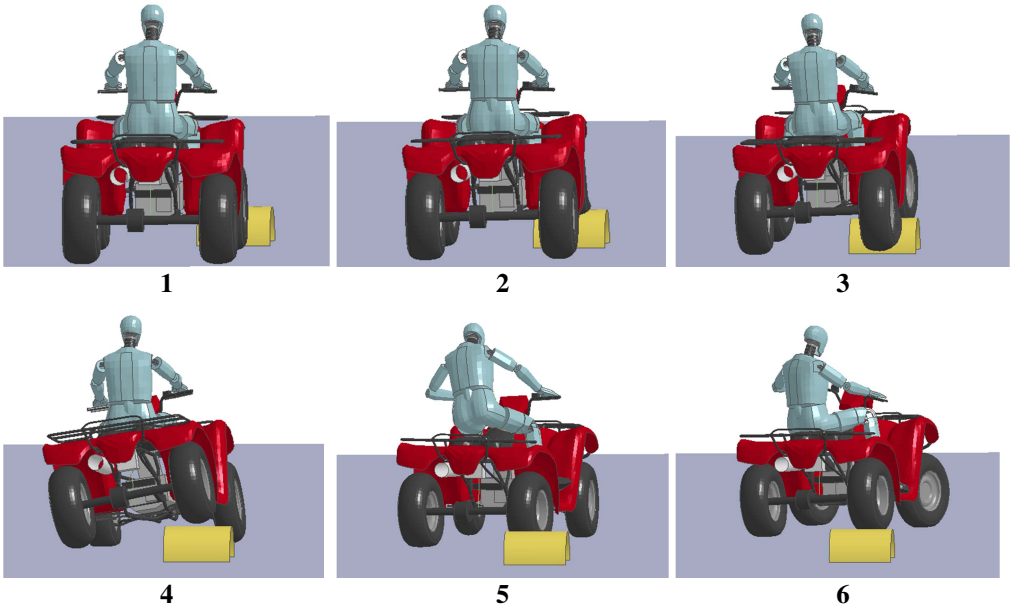

Figure 6: Modelling of quad-bike (Honda TRX500) and ATD moving over a 250mm high raised obstacle.

SUMMARY AND CONCLUSIONS

Both the experimental and simulated bump tests outlined the potential risks associated with riding over an asymmetric raised obstacle, even at a relatively low speed of 25 km/h. The experimental test (both human rider and ATD) demonstrated that an obstacle may cause the rider to become displaced laterally across the seat of the quad-bike when the rear wheel hits an obstacle placed asymmetrically on one side of the wheel track. Simulations further demonstrated that, in case of a bigger obstacle, hitting an asymmetric obstacle could cause the rider to steer the quad-bike into a loss of control situation. These results show the potential risk of riding over an asymmetric obstacle in a neutral seating position if the quad-bike's suspension has not been designed to dampen such rear tyre impacts that can lead to the loss-of-control situation identified in this research.

Further investigation should be done to assess what combination of speed, obstacle height and slope combined with this mechanism can cause a quad bike to rollover. Modifications to the existing quad-bike suspension setup could then be simulated to optimise the vehicle stability when moving over an obstacle with a passive seated rider. Also, a detailed model of a high-grip soil, such as sand or soft ploughed soil, would better assist in investigating the traction provided by the tyres and its causal relationship with a quad-bike rollover.

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REFERENCES

[1] FCAI (Accessed: 12/05/2013). *Australian Motorcycle Market in 2012*. Available: http://www.fcai.com.au/motorcycles/australia%27s-motorcycle-market-in-2012
[2] Elder J, Leland E. (2006). CPSC Staff Response Regarding Follow-Up Questions from Commissioner Moore after the June 15, 2006, ATV Safety Review Briefing, Consumer Product Safety Commission.
[3] SVIA. (2010). American National Standard for Four Wheel All-Terrain Vehicles, ed, 2010.
[4] Grzebieta R, Rechnitzer G, Simmons K, McIntosh A. (2015). Final Project Summary Report: Quad Bike Performance Project Test Results, Conclusions and Recommendations, TARS Research Report, Submitted to The Workcover Authority of New South Wales, UNSW, Australia.
[5] Knight S, Franklin R, Lower T. (2012). Mouint Isa Statement on Quad Bike safety, Mount Isa Centre for Rural and Remote Health (Media Release 03/08/2012).
[6] Grzebieta R, Rechnitzer G, McIntosh A, Mitchell R, Patton D, Simmons K. (2015). Supplemental Report: Investigation and Analysis of Quad Bike and Side by Side (SSV) Fatalities and Injuries, Quad Bike Performance Project, TARS Supplemental Research Report submitted to the Workcover Authority of New South Wales, UNSW, Australia.
[7] Grzebieta R, Rechnitzer G, Simmons K. (2015). Dynamic Handling Test Results, Quad Bike Performance Project, TARS Research Report No. 2 submitted to The Workcover Authority of New South Wales, UNSW, Australia.
[8] Rechnitzer G, Grzebieta R, McIntosh A, Simmons K. (2013). Reducing All Terrain Vehicle Injuries (ATVs) and Deaths - A Way Ahead, presented at the 23rd International Technical Conference on the Enhanced Safety of Vehicles, Seoul, South Korea, 2013.
[9] Mongiardini M, Hicks D, Grzebieta R, Rechnitzer G. (2014). Modeling a Quad Bike (All-Terrain Vehicle) for Simulating Rollover Events, *Journal of the Transportation Research Board,* vol. 1, pp. 50-60, 2014.
[10] LSTC. (Accessed: 15/04/2013). *Dummy Model Archive*. Available: http://www.lstc.com/products/models/dummies/H3_Adult_FAST