Engineering Control Technologies to Protect Operators in Agricultural All-Terrain Vehicle Rollovers

Review

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HIGHLIGHTS

- Rollovers are the leading cause of injury and fatality in farm all-terrain vehicle (ATV) incidents.
- Engineering technologies to prevent rollovers or protect the operator in ATV crashes were reviewed in this study.
- The advances in safety for ATVs are correlated with improvements in stability, handling, and crashworthiness.
- Operator protection devices and crash notification systems can protect the operator in ATV rollover incidents.

ABSTRACT. *All-terrain vehicles (ATVs) are the second most common source of injury, following tractors, in U.S. agriculture. Rollovers are the leading cause of death in farm ATV incidents, constituting about 85% of ATV-related deaths. There is neither a significant practical solution for ATV rollover crashes in the U.S. nor standards and rules for implementing such a solution. Behavior-based control methods have been used for several decades but have reached their limit of success. Hence, engineering controls are needed to significantly decrease the severity of injuries in ATV rollover incidents (as in tractor incidents). In this study, engineering technologies to protect the operator in agricultural ATV crashes were reviewed. The discussion includes improving crash testing and stability ratings, evaluating static stability of ATVs, dynamic handling tests of ATVs, using automatic systems to notify first responders of a crash, and testing and applying operator protection devices. The available standards, rules, and recommendations related to these technologies around the world are also discussed.*

Keywords. *Agriculture, All-terrain vehicle, ATV, CPD, Crush protection device, OPD, Quad bike, Safety.*

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According to the U.S. Consumer Product Safety Commission (CPSC), an all-terrain vehicle (ATV) is an off-road, motorized vehicle having three or four low-pressure tires, a straddle seat for the operator, and handlebars for steering control (Topping, 2017). ATVs are also referred to as quad bikes, three-wheelers, four-tracks, four-wheelers, and quadricycles. The CPSC Improvement Act of 2008 placed a permanent ban on three-wheel ATVs in the U.S. (CPSC, 2008).

In 1985, the CPSC declared that ATVs are an "imminently hazardous consumer product" (CPSC, 2006). ATVs are unstable vehicles due to their narrow track width, short wheelbase, and high center of gravity, which increase the risk of rollover incidents on steep, rough, or uneven terrains, which are common on farms (Grzebieta et al., 2017; Moore, 2002, 2008; Moore and Bentley, 2004; Murphy and Yanchar, 2004).

ATVs are used in different occupational sectors and activities, including agriculture, the oil and gas industry, the military, and search and rescue operations. Three out of five occupational ATV fatalities occur in the agriculture sector (OSHA, 2015). ATVs are commonly used on farms to apply fertilizer and chemicals, inspect livestock and crops, supervise workers, mow grass, and carry and tow implements (Fragar et al., 2005; Moore and Bentley, 2004). According to Weichelt and Gorucu (2019), ATV incidents were the second most common source of injury in agriculture, across all ages, causing 190 injuries or deaths (63% fatal), and ATVs were the leading cause of injury in agriculture among youth.

Differences between recreational and agricultural ATV crashes include the type of incident and resulting injuries, riding speed, and added loads or attachments. McIntosh et al. (2016) reported a clear pattern of farm work-related deaths: ATV rollovers (farm worker, 85%; recreational rider, 55%), with the operator pinned under the ATV (farm worker, 68%; recreational rider, 30%), and death by asphyxia (farm worker, 42%; recreational rider, 11%). In contrast, recreational riders suffered impact injuries to the head and chest when riding fast, losing control, being ejected, and crashing into a stationary or moving object (McIntosh et al., 2016). Grzebieta et al. (2015a) reported chest injuries as the main cause of death for farm workers (59%) and head injuries (49%) as the leading cause of fatality for recreational ATV riders (Grzebieta et al., 2015a).

In the study by McIntosh et al. (2016), most farm workers (~50% to 75%) had one or more attachments on their ATV, while only a few of the recreational riders (~25% to 33%) had an attachment on their ATV. Those attachments (such as carrying racks and pulled equipment) affected the ATV's performance. Furthermore, farm workers were less likely than recreational riders to carry a passenger (McIntosh et al., 2016). The most common causes of fatal ATV crashes in Australian workplaces included riding on a slope (26%) and riding over bumps (21%) (McIntosh et al., 2016). In other studies, other surface irregularities (such as tree stumps, rocks, and grass tufts) were reported as causing occupational ATV crashes (Schalk and Fragar, 1998; Wundersitz et al., 2016).

Rollovers are the leading cause of death in farm ATV incidents, constituting about 85% of deadly crashes (McIntosh et al., 2016). There is neither a practical solution for ATV rollover crashes in the U.S. nor standards for implementing such a solution. Behavior-based control methods have been used for several decades to varying degrees, as reviewed by Khorsandi et al. (2020), but have reached their limit of success. Therefore, this study focuses on engineering controls as a solution to significantly decrease the severity of ATV crashes, similar to tractor rollover incidents. A hierarchy of controls is used to determine how to implement effective and feasible control solutions. Wogalter (2006) established three categories of this hierarchy in terms of effectiveness: (1) eliminate hazards, (2) guard against the hazard when eliminating the hazard is not possible, and (3) warn against the hazard if other controls are inadequate (fig. 1). Controlling exposures to agricultural ATV hazards is a fundamental method for protecting farmworkers in rollover incidents.

In this study, engineering control technologies to protect farm workers in agricultural ATV crashes were reviewed. Engineering control is within the second category (guard against the hazard) of the hierarchy of controls. The discussion includes improving crash testing and stability ratings, evaluating the static stability of ATVs, dynamic handling tests of ATVs, using automatic systems to notify first responders of a crash, and testing and applying operator protection devices. The available standards, rules, and recommendations related to these technologies around the world are discussed in the Administrative Authority section. Administrative authority is within the third category (warn against the hazard) of the hierarchy of controls.

Engineering Controls

Engineering controls include improving crash testing and stability ratings, evaluating static stability, dynamic handling tests, automatic systems to notify first responders of a crash, and testing and applying operator protection devices.

Static Stability Tests for ATVs

To evaluate ATV stability, static and dynamic handling tests must be conducted. The static stability angle is the critical angle at which an ATV begins to roll. Lateral (side) and longitudinal (rear) stability angles are important measures of the relative stability of an ATV. Stability angles have been used to describe the rollover propensity of specific vehicles. Understanding the static stability angles of an ATV can help define its tendency to roll over during operation. These angles are generally determined through tilt table tests or using the axle lift method.

A calculation method using the axle lift method is described by ISO Standard 16251-2 (ISO, 2015). The axle lift method is essential for finding the vertical height of the center of gravity (Liljedahl et al., 1989). The standard also describes the need to consider the weight shift caused by moving fluids inside the vehicle. However, an investigation found that normal amounts of fluids (fuel, oil, coolant, etc.) do not have a significant effect on the center of gravity and static stability angle calculations (Khorsandi et al., 2018).

ANSI/SVIA Standard 1-2017 describes a balancing angle for ATVs for which the calculated pitch stability coefficient (K_p) must be greater than 1.0 (ANSI/SVIA, 2017). However, K_p is different from the tilt ratio (tangent of the tilt angle) determined by the tilt table

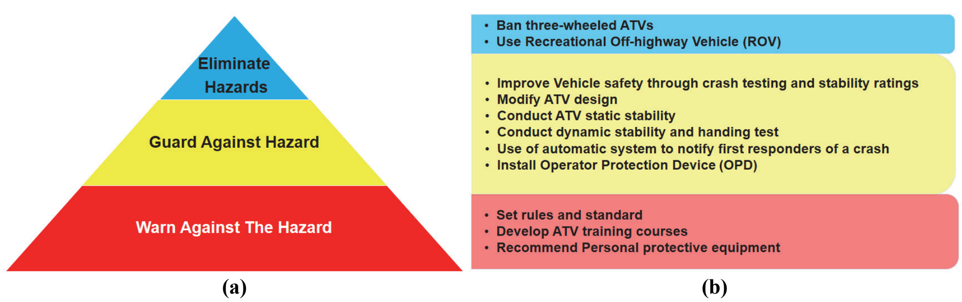


Figure 1. (a) Hierarchy of controls and (b) possible solutions based on hierarchy of controls for ATVs.

stability test (Grzebieta et al., 2015c). This is because the balancing angle places the ATV's center of gravity over the rear axle, which is free to rotate. If the rear axle was not free to rotate, the center of gravity would balance over the contact point of the rear tire and terrain.

The lateral and longitudinal static stability angles for 12 different ATVs were calculated using track width and center of gravity calculations (Heydinger et al., 2016). The researchers found that the calculated stability angles were 5° to 8° greater than those measured using tilt tables. Adding loads to the ATVs decreased the lateral and longitudinal stability angles by 4.0° and 7.0°, respectively. The researchers attributed this increase to suspension and tire flexibility not accounted for in the calculations. However, they did not specify whether the tire tread width measurement was center-to-center or outside-to-outside.

Ayers et al. (2018) determined the lateral and longitudinal static stability angles for ATVs in loaded and unloaded conditions. The unloaded lateral stability angles ranged from 36.9° to 41.3°, while the unloaded longitudinal stability angles ranged from 45.3° to 51.6°. When the ATVs were loaded (890 N operator), the lateral and longitudinal stability angles decreased by 17.2% and 20.9%, respectively. Compared to other off-road utility vehicles, ATVs had the lowest static lateral stability angles.

Grzebieta et al. (2015c) conducted tilt table static stability tests on eight agricultural ATVs and five recreational off-highway vehicles (ROVs) or side-by-side vehicles (SSVs). The lateral stability angles with an operator ranged from 24.5° to 30.8° for the ATVs and from 32.9° to 43.8° for the ROVs. The longitudinal stability angles with an operator ranged from 37.9° to 43.6° for the ATVs and from 46.0° to 56.2° for the ROVs. Loading an ATV (front and rear) decreased its lateral stability angle by about 2.0° and decreased its longitudinal stability angle by about 3.5° (fig. 2a) (Grzebieta et al., 2015c). Each ATV was loaded with a motorcycle anthropomorphic test dummy (MATD) and a test mass of 103 kg on the front and rear of the ATV (fig. 2b) (Grzebieta et al., 2015c).

Dynamic Stability and Handling Tests

Vehicle control and handling are evaluated using dynamic stability and handling tests, which are intended to improve the vehicle's path control and resistance to rollovers. Grzebieta et al. (2015b) conducted dynamic stability and handling tests on eight agricultural ATVs and five ROVs or SSVs. The dynamic stability and handling tests included steady-

(a) (b)

Figure 2. (a) Static ATV stability tests with a single-axis tilt table and (b) typical ATV setup with test dummy, front load, and rear load (Grzebieta et al., 2015c).

state circular driving tests, lateral transient response tests, and bump obstacle perturbation tests (Grzebieta et al., 2015b).

Steady-state circular driving tests are conducted to determine a vehicle's limit of lateral acceleration and the understeer and oversteer of the vehicle (ANSI/ROHVA, 2011; ANSI/SVIA, 2017; Grzebieta et al., 2015b; ISO, 2012). The steady-state circular driving test consists of driving in a circle with a radius of 7.6 m with slow acceleration (figs. 3a and 3c). The vehicle is accelerated until two wheels are lifted off the ground, the vehicle slides out causing the vehicle to point toward the inside of the circle, the vehicle can no longer stay in the circle, or the vehicle cannot travel any faster (Grzebieta et al., 2015b).

Steady-state circular driving tests were conducted for the eight ATVs (Grzebieta et al., 2015b). For all the ATVs, the limit of lateral acceleration occurred with the ATV tipping up onto two wheels. This situation can be controlled by applying active riding techniques that include shifting the operator's body weight to increase the vehicle stability. Active riding can increase the stability by up to 30% (Shortland, 2013). By increasing the ATV's stability, the possibility of rollover or loss of control will be decreased. The overall results showed that most of the ATVs had an oversteer characteristic, which is not favorable for most situations (Grzebieta et al., 2015b).

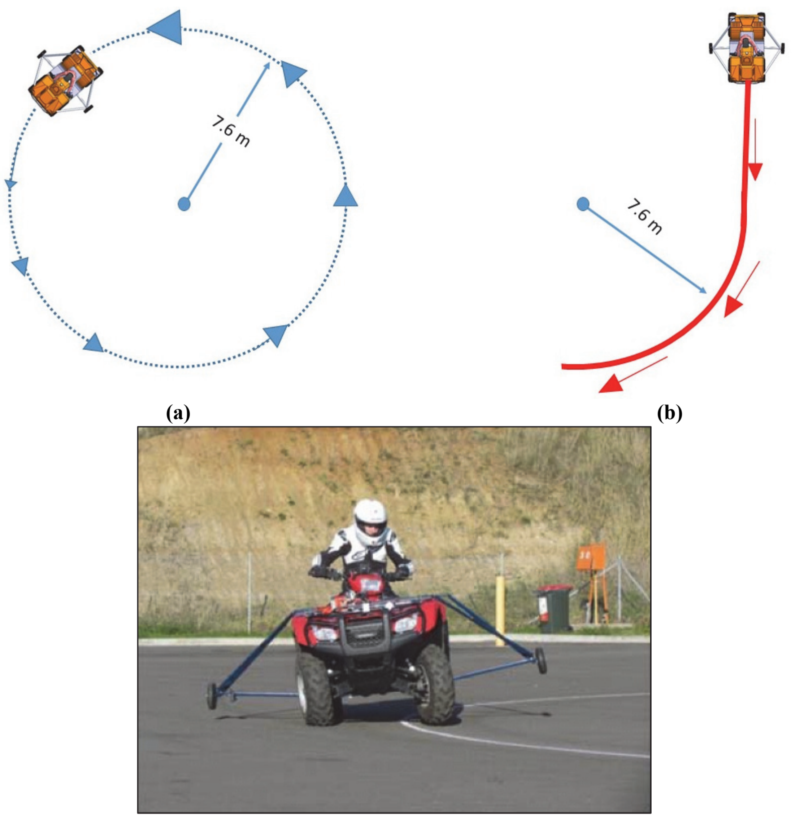


Figure 3. (a) Steady-state circular driving test, (b) lateral transient response (or J-turn) test, and (c) ATV safety setup for circular driving test and J-turn test (Grzebieta et al., 2015b).

Three of the ATVs were tested with steady-state circular driving tests on asphalt and grass. The results showed similar handling characteristics on both surfaces, and the ATVs tipped up at similar lateral acceleration values. The five SSVs were also evaluated in steady-state circular driving tests. Results showed that the SSVs had higher lateral stability compared to the ATVs (Grzebieta et al., 2015b).

Lateral transient response tests, or J-turn tests, are conducted to determine the time required for a vehicle to respond to a rapid steering input (Grzebieta et al., 2015b). These tests use a near-instantaneous steering change while maintaining the vehicle speed and steer angle to measure the yaw rate. The test consists of driving the ATV in a straight line at a 20 kph and then rapidly initiating a steering change to generate a lateral acceleration of $0.4 \times g$ (ISO, 2011; Rechnitzer et al., 2013) (figs. 3b and 3c). Based on previous studies and standard testing methods, this test is used to detect lateral transients. The response time is part of the vehicle's steering control and is a measure of the time from the application of steering input until the desired steering angle, wheelbase, and vehicle speed can produce a constant yaw rate (Weir and DiMarco, 1978).

All vehicles (eight ATVs and five SSVs) were tested in J-turn tests on asphalt and had steering response times of less than 0.3 s. Considering that a significant number of the vehicles had steering response times of less than 0.2 s, the results for the ATVs and ROVs were generally satisfactory (Grzebieta et al., 2015b).

Bump obstacle perturbation tests are conducted to determine the response characteristic of a vehicle when going over bumps with minimal changes in steering and lateral and vertical acceleration of the operator (fig. 4). These tests assessed the stability of the ATVs when going over bumps, which has been reported as one of the leading causes of ATV rollovers (Hicks et al., 2018; Milosavljevic et al., 2011; Wundersitz et al., 2016). The tests consisted of towing the vehicle over a bump that was 105 mm high and lined up on the right or left vehicle track. The operator's pelvis acceleration was recorded by the MATD.

The bump obstacle perturbation tests showed that going over a moderate bump (such as a log, small rock, small mound, rut, etc.) is an important factor in losing control of an ATV. When going over a moderate bump, the operator and ATV are excessively displaced laterally. This displacement can get worse and result in a rollover when operators attempt to pull themselves back onto the seat. Operators may also pull on the handlebars, or

Figure 4. Bump obstacle perturbation test (Grzebieta et al., 2015b).

inadvertently accelerate the vehicle with the thumb throttle. All of the SSVs passed the bump obstacle perturbation tests satisfactorily, with low levels of operator or vehicle perturbation (Grzebieta et al., 2015b).

In conclusion, ROVs or SSVs are a possibly safer substitute for ATVs. The steering wheel, bucket seating, seatbelts, and rollover protective structure (ROPS) on ROVs contribute to superior static stability, dynamic handling, and rollover crashworthiness when compared to ATVs, especially for occupational uses that involve adding loads and consequently decreasing the stability of the vehicle (Grzebieta et al., 2015d; Hicks et al., 2016). The static and dynamic stability tests can also increase our understanding of the stability of current designs of ATVs. In addition, the advances in safety for all ATVs and SSVs are correlated with improvements in stability, handling, and crashworthiness.

Standardized Vehicle Safety Ratings

The New Car Assessment Program (NCAP) helps consumers decide which vehicle to purchase by providing important information on vehicle safety. Manufacturers also use NCAP test results to promote their vehicles. A similar safety program for ATVs and SSVs would encourage manufacturers to improve safety for these vehicles. The Australian Consumer and Competition Commission (ACCC) proposed a safety rating program for ATVs and SSVs (ACCC, 2017a). With the support of the Australian National Farmers' Federation, the ACCC recommended a five-star safety rating system for ATVs (NFF, 2018). A similar safety rating system for ATVs and SSVs should be developed in the U.S. and around the world.

Automatic Systems to Notify First Responders

Many ATV crashes, both on and off the road, occur in rural areas with limited access to emergency medical services (Qin et al., 2017). Off-road crashes are especially problematic because of the difficulty for first responders in locating and accessing the crash site, which may be in rough terrain or dense woods, rendering aid to the injured, and then transporting the injured to the nearest hospital. Considering travel time alone, most ATV crashes occurred beyond the distance that an ambulance could drive from a Level 1 or 2 trauma center and back again within one hour, and many occurred beyond the distance that a helicopter could fly to reach a patient and return within one hour (Qin et al., 2017).

In 1997, General Motors introduced the OnStar system, which automatically dials a call center to direct first responders if a crash is detected (GM, 2019). While there is no federal mandate for the use of this technology, automakers have voluntarily added it as standard equipment. In the European Union, all passenger vehicles were required to have an eCall (emergency call) system as of 2018 (EC, 2018). Additionally, in December 2017, the European Association of Motorcycle Manufacturers created a task force to investigate installing such devices into motorcycles (ACEM, 2017).

Farm Angel, a company based in New Zealand, markets a product for ATVs and SSVs that automatically sends a signal if a crash is detected. This product can also measure the speed and acceleration of the vehicle and limit the area in which the vehicle can be ridden using its geo-fencing capabilities (Farm Angel, 2015).

Operator Protection Devices

An operator protection device (OPD) is passive control that protects the operator in the event of a rollover. OPD is a general term for both crush protection devices (CPDs) and rollover protective structures (ROPS) that protect the operator in the event of a rollover but do not prevent the rollover from occurring (Grzebieta and Achilles, 2007).

In the event of a rollover, the CPD provides a crush protection zone (CPZ) under the vehicle. In crashes that involve active operator separation or the operator hitting hard parts of the ATV, the CPD may not be effective (Grzebieta and Achilles, 2007). The CPD structure absorbs the impact energy and can prevent or decrease movement of the vehicle during the rollover. CPDs also decrease the risk of crushing and asphyxiation due to compression of the operator's chest or neck. Unlike ROPS, which need seatbelts to be effective, a CPD does not require a restraint system. ROPS protect the operator in rollover crashes by providing a clearance zone and absorbing the impact energy.

Different OPDs have been developed by researchers and industrial designers (fig. 5). Several CPDs are commercially available, such as the Quadbar, Quadbar Flexi, ATV Life-Guard, and Air-Quad (figs. 5a to 5d). The Israeli Army ATV frame has been designed and tested based on Israel's OPD standard for ATVs (Israel, 2005) (fig. 5e). Several CPDs have been designed but were not commercially successful, including the Quick-fix, ATV-bage, CFMOTO, MTV roll cage, and Pro-Tec system (figs. 5f to 5j). The successful commercial OPDs are discussed in this section.

The Quadbar is a hairpin-shaped tube that mounts on the rear tow hitch, extends vertically behind the operator, and can be telescopically adjusted at the base (fig. 5a). The Quadbar is made of aluminum tubing and is equipped with a flexible plastic cap at the top.

The Quadbar Flexi is a long, single-post CPD that mounts to the rear tow hitch and extends vertically from the rear of the ATV (fig. 5b). It is made of a single aluminum tube with a flexible spring joint in the middle and with a plastic cap that covers the top. In a rollover incident, the Quadbar Flexi deforms at the flexible joint that absorbs energy to protect the operator.

The ATV LifeGuard is a flexible arc-shaped CPD that extends vertically from the rear of the ATV (fig. 5c). It mounts onto the rear rack of the ATV. The flexible design allows deflection that spreads the weight of the ATV throughout the CPD in the event of a rollover. The dispersal of force allows the operator to easily push the ATV when overturned. It is rated to support a 1,200 kg load (ATV LifeGuard, 2018).

The Air-Quad is a triangular compact CPD that mounts onto the rear tow hitch and extends vertically behind the operator (fig. 5d). The Air-Quad has a tubular structure, a gas generator, and an electronic control unit. If a rollover occurs, the gas generator deploys the triangular tubing that extends the CPD both horizontally and vertically.

Many ATV ROPS have been developed and evaluated, such as the Dahle ROPS, Johnson ROPS, and MUARC ROPS. When a ROPS is installed, a restraint system such as a seatbelt is required. An ATV is an active riding device that responds to movements of the operator's weight on and off the seat while holding the handlebars and keeping both feet on the footrests. Some researchers have reported that active riding increases the stability of an ATV and decreases the risk of a rollover (Lock, 2015). Shortland (2013) reported that active riding can increase the stability by 10% to 30%. Active riding and operator separation are not considered reliable rollover risk-reduction strategies for agricultural ATVs (Grzebieta et al., 2015d).

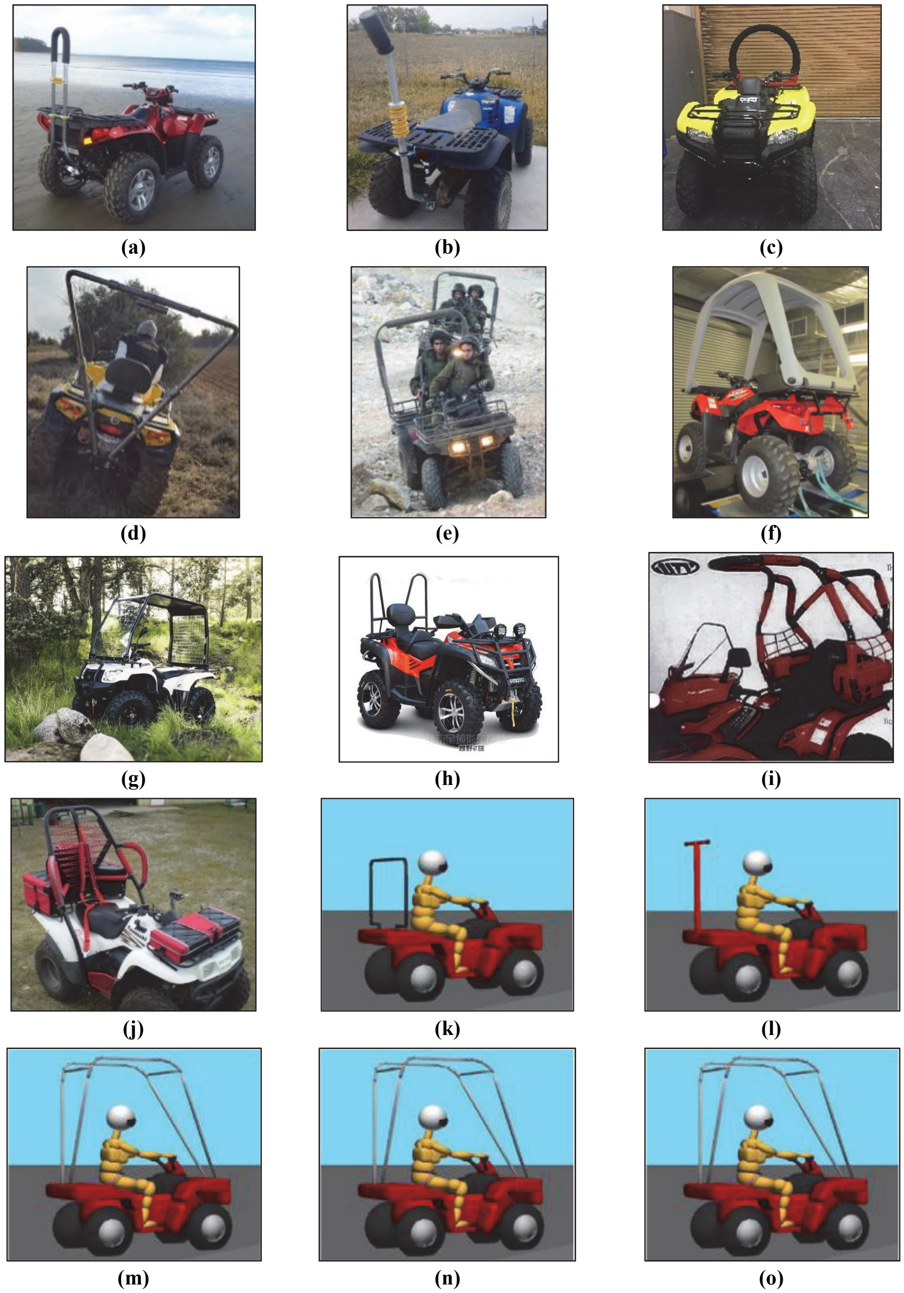


Figure 5. Operator protection devices (OPDs) and rollover protective structures (ROPS) installed on ATVs: (a) Quadbar, (b) Quadbar Flexi (photo credit: www.quadbar.com), (c) ATV LifeGuard, (d) Air-Quad in deployed position (photo credit: https://air-rops.es/), (e) Israeli Army ATV frame, (f) Quick-fix (Grzebieta et al., 2015a), (g) ATV-bage, (h) CFMOTO, (i) MTV roll cage, (j) Pro-Tec System, (k) HSE U-Bar CPD, (l) NZ T-Bar CPD, (m) Dahle ROPS, (n) Johnson ROPS, and (o) MUARC ROPS (Wordley and Field, 2012).

Test Methods for Protective Devices

Two test methods, including experimental methods and modeling, are used to evaluate the performance of CPDs in ATV rollovers. Researchers use static, dynamic, and field-upset-tests for rollover incidents. In this section, the experimental and modeling methods are reviewed.

Static Tests

Multiple studies have used static tests to evaluate the performance of CPDs in rollover incidents (Ridge, 2009; Sulman et al., 2007). Static tests include side, first crushing, rear, and second crushing tests to evaluate CPD performance and to create force-deflection and energy-deflection curves (figs. 6a to 6c). The CPD must be able to absorb a specific amount of energy without infringing on the deflection limit volume (DLV) or leaving the DLV unprotected (ISO, 2013; WorkSafe, 1998) (fig. 6d).

Ridge (2009) conducted static tests on CPDs based on ISO Standard 5700 (ISO, 2013), which was created to test ROPS for tractors weighing less than 600 kg and having a width greater than 1150 mm. Based on that standard, the Quadbar passed the static tests for ATVs lighter than 300 kg. Sulman et al. (2007) conducted static tests on ATVs based on guidelines provided by New Zealand's occupational safety and health service (WorkSafe, 1998) that were created to evaluate the performance of ATV ROPS. Based on those guidelines, the Quadbar passed the test for a 290 kg ATV (figs. 6a to 6c).

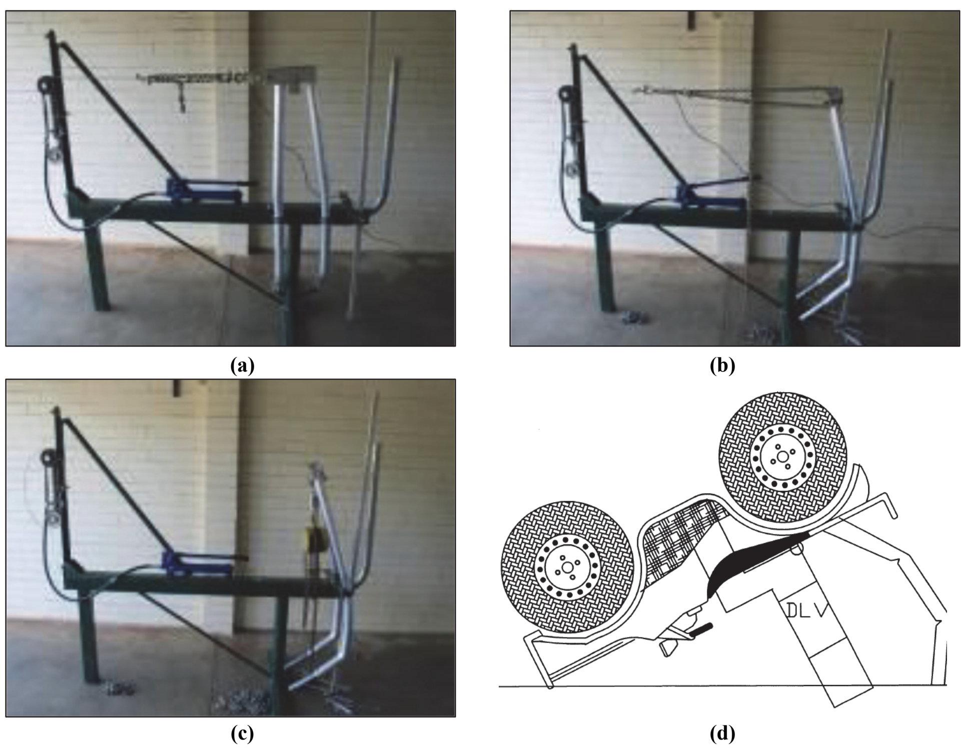


Figure 6. Static testing of Quadbar with (a) lateral, (b) longitudinal, and (c) vertical loads (Sulman et al., 2007) and (d) deflection limit volume (DLV) (WorkSafe, 1998).

Both ISO Standard 5700 and the New Zealand ATV ROPS guidelines were created to test ROPS, not CPDs. In both standards, the required restraint systems allow the creation of a DLV based on the ROPS and operator locations. Because CPDs do not require a restraint system, defining a DLV is less valid, as operators may be dismounted in the event of an incident. Furthermore, ISO Standard 5700 was created based on tractor speeds and geometry, which are different from ATV speeds and geometry. Because ATVs travel faster and have lower stability angles than tractors, the energy involved in a crash may be different for ATVs than for tractors of similar weight.

Dynamic Tests

Dynamic tests are conducted using a tilt table (Grzebieta et al., 2015a) or a vehicle accelerator, which is a tilted rail. Snook (2009) developed a vehicle accelerator that could produce a range of initial velocities, slopes, and initial release heights (fig. 7) to evaluate CPDs in roll and backflip incidents. Two ATVs (250 and 400 cc) were tested by rolling the ATVs down a 20° slope onto flat ground (fig. 7). In low and high speed sideway rolls, the CPDs were found to prevent continuous rolling and pinning the operator under the ATV. The CPDs were also observed to create a CPZ under the overturned ATV, which prevents the operator from becoming trapped under the ATV (Snook, 2009).

Studies at the University of New South Wales used dynamic handling tests and rollover crashworthiness tests to evaluate the safety of eleven ATVs with three CPDs (Quadbar, ATV LifeGuard, and Quick-fix) in rollover incidents. The rollover crashworthiness tests include a single-axis tilt table and MATD to observe the CPZ and functionality of each

(a)

(b) (c)

Figure 7. Dynamics tests reported by Snook (2009): (a) vehicle accelerator test, (b) side roll test onto flat ground without Quadbar, and (c) back roll test down a 20° slope with Quadbar.

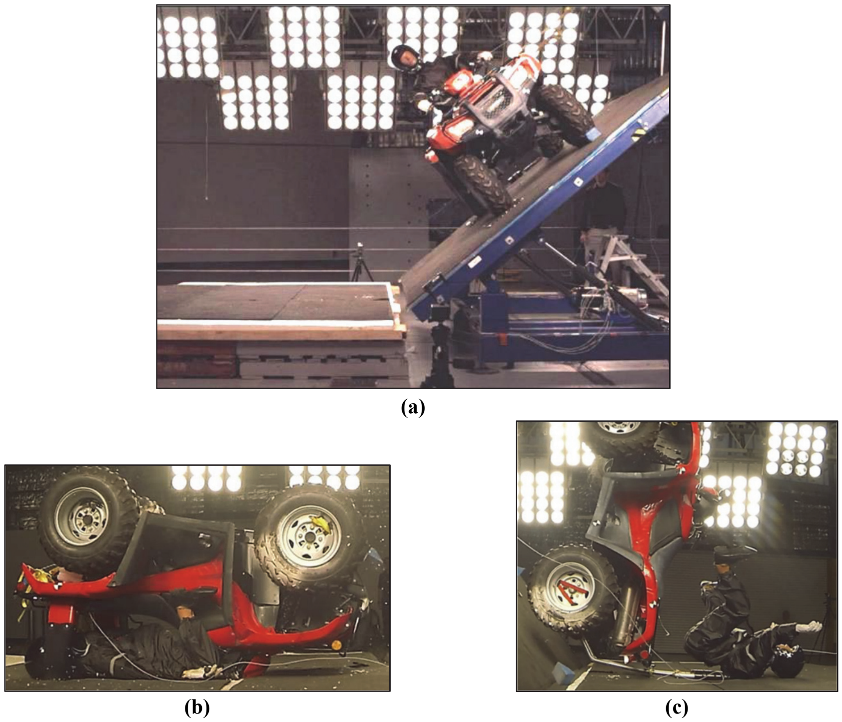


Figure 8. Dynamic tests reported by Grzebieta et al., 2015a): (a) lateral roll (just prior to release) without Quadbar, (b) forward pitch with ATV LifeGuard, and (c) rearward rollover with Quadbar.

CPD. Each ATV was subjected to nine (3 × 3) test configurations including roll direction (lateral roll, rearward pitch, and forward pitch) and CPD (none, ATV LifeGuard, and Quadbar) (fig. 8) (Grzebieta et al., 2015a). Each ATV was placed 1000 mm from the lower edge of the tilt table and then tilted to an angle 5° higher than the static stability angle. Results showed that ATVs with no CPD could not prevent injury at any speed, while the Quadbar and ATV LifeGuard could prevent serious injury in low-speed rollover crashes.

These studies may not accurately represent real-world ATV incidents. In crash worthiness tests, the lack of initial speed creates a crash that has lower energy than in a real-world incident. Furthermore, the test conditions of stability angle plus 5° and height (1000 mm) cannot be proven to represent real-world rollovers.

Field-Upset Tests

Field-upset tests are conducted by driving an ATV on slopes or irregular surfaces or making sharp turns at high speeds. A realistic experiment is created using different surface conditions, ATV speeds, slope lengths, and slope angles. Several studies have used this method to test CPD performance (Piziali et al., 1993; Zellner and Kebschull, 2015). Dynamic Research Inc. (DRI) conducted 12 full-scale field-upset tests to verify and calibrate the force-deflection of the ATV, CPD, soil surface, and MATD (Zellner et al., 2008). Tests were conducted using ATVs with and without the U-bar and T-bar (fig. 9).

Another field-upset study was conducted by DRI using a remote-control ATV (Zellner and Kebschull, 2015). Frequently reported J-turn and V-ditch rollovers were tested

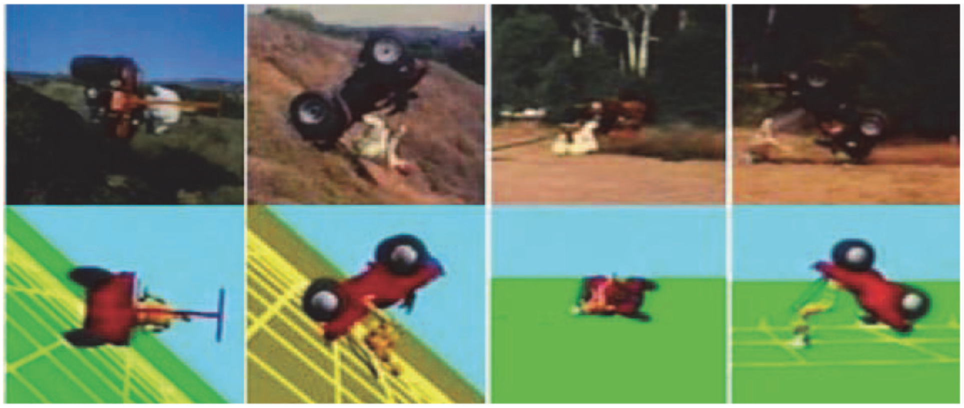


Figure 9. Photos of full-scale tests and corresponding computer simulations (Zellner et al., 2008).

(fig. 10). The J-turn tests were conducted on unpaved flat ground with a target speed of 25.7 kph. The V-ditch tests were conducted on a 30° slope at 3 m from the bottom of the ditch with a target speed of 16.1 kph. Each test used the ATV without a Quadbar (base-line ATV), the ATV with a Quadbar, and a 50th percentile adult male MATD. Accelerations, forces, moments, and displacements relating to injuries were recorded and evaluated according to ISO Standard 1323 (Zellner et al., 2013).

The ATV equipped with a Quadbar resulted in a three-quarter roll and pinned the MATD underneath the ATV, while the base-line ATV resulted in a full roll and complete separation of the MATD from the ATV. The researchers stated that the Quadbar created a larger CPZ underneath the overturned ATV. However, there was no guarantee that the operator would be pinned underneath the ATV, nor that the ATV would be at rest in the upside-down position. The researchers argued that a CPD would hinder operator separation from the ATV, increasing the chance of being pinned (Zellner and Kebschull, 2015).

Because very low injuries were recorded for all rollover scenarios, no claims can be made about the effectiveness of a CPD based on injuries. Furthermore, the trajectories of the base-line ATV and the CPD-equipped ATV were not the same, and the conducted tests are not repeatable. Therefore, the researchers could not prove their previous claim that the percentage of injury risk versus injury benefit was 7% larger for the CPD-equipped ATV compared to the ATV without CPD.

Modeling Methods

Researchers have also used models to predict ATV and OPD performance. Several studies from DRI used theoretical simulations to evaluate the effectiveness of CPDs. Simulated crashes were created based on 113 reported ATV incidents from the U.S. and U.K. In addition to the base-line ATV, six OPDs were evaluated, including Dahl ROPS, Johnson ROPS, NZ T-bar, UK U-bar, MUARC ROPS, and Quadbar (Munoz et al., 2007; Zellner et al., 2004, 2008, 2013), in 791 total tests that included the 113 reported ATV incidents with each of the seven ATV variations (Zellner et al., 2008). Results from these initial tests could not predict operator death due to mechanical or traumatic asphyxia. In a subsequent study, 3080 tests were run (Zellner et al., 2013). Results showed that the OPDs had no statistically significant net injury benefit, nor that the ROPS risk/benefit percentage was much greater than the 12% allowable limit.

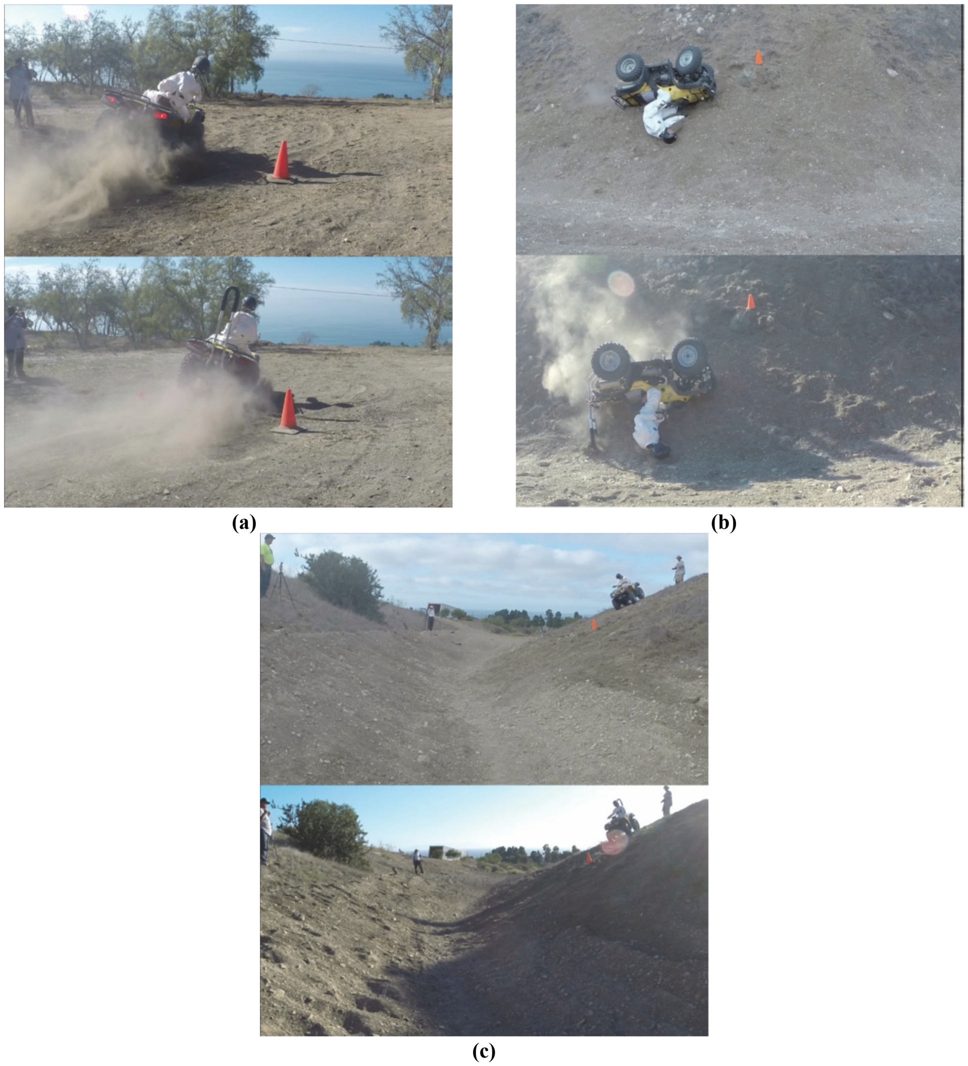


Figure 10. (a) J-turn tests with base-line ATV (top) and ATV with CPD (bottom), (b) V-ditch tests with base-line ATV (top) and ATV with CPD (bottom), and (c) the V-ditch field (Zellner et al., 2013).

Another study was conducted using a finite element model to predict combinations of speed, bump size, and slope that would cause ATV rollover (Hicks et al., 2018). Results showed that increasing speed and slope angle (e.g., 20 kph and 12.5°) sharply decreased the bump size required for a rollover incident. The researchers recommended using a safer vehicle instead of an ATV.

Computer simulations based on the Snook (2009) study were used to predict the forces on the operator's body during a rollover (Richardson et al., 2013). Four fatal rollover incidents were simulated. Results showed that a CPD could help operators survive a rollover.

A study was conducted using the MADYMO computer simulation program to compare injuries in rollovers of a base-line ATV and an ATV equipped with the MUARC ROPS (Rechnitzer et al., 2013). Results showed that the ATVs rolled more often at slow initial speeds, while the operator was ejected at high initial speeds. The MUARC ROPS significantly reduced the rates of injury and death at all initial speeds (Rechnitzer et al., 2013).

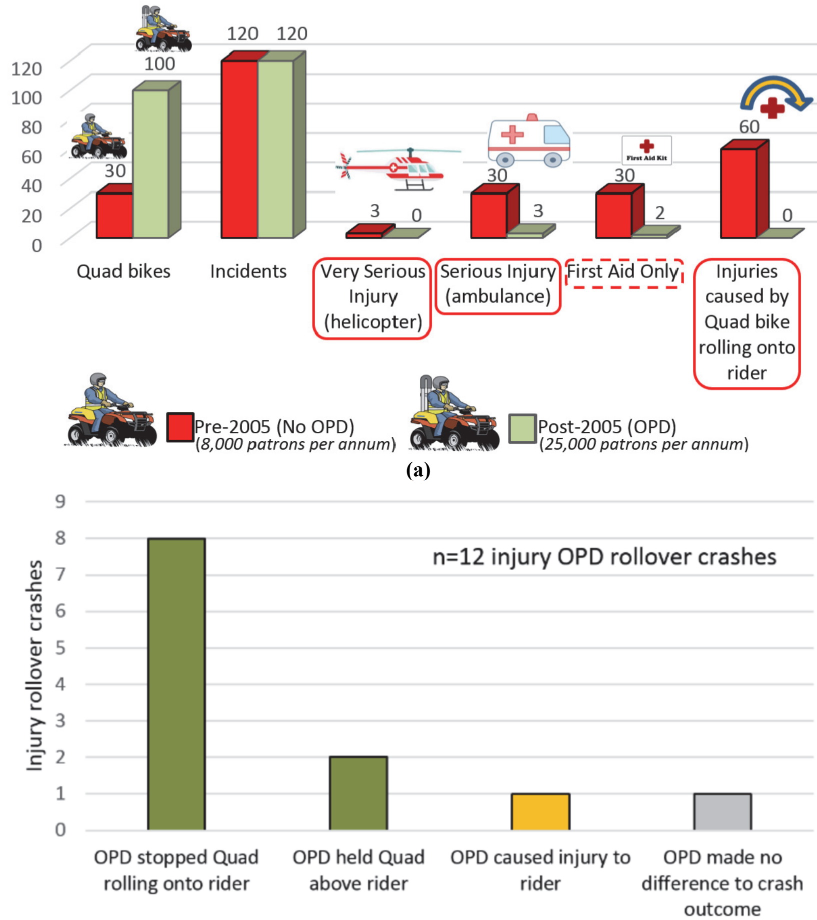
Another study used the MADYMO simulation program to evaluate the performance of the Quadbar (Grzebieta and Achilles, 2007). Ten crash cases were chosen. Results showed that the Quadbar reduced injuries in low-speed, low-slope rear rollovers. However, the Quadbar was found to potentially impact the operator in the event of a front rollover. It was also found to be ineffective in high-speed incidents. The Quadbar also created a CPZ in an overturned ATV that could prevent the operator from being crushed.

Conclusions for Protective Devices

Multiple studies by DRI used theoretical simulations of past fatal ATV crashes and full-scale field-upset tests to oppose installing OPDs on ATVs (Munoz et al., 2007; Van Auken and Zellner, 1996; Zellner et al., 2008). However, calibration of the ATV and dummy motion in the field-upset tests resulted in no correlation with the predicted injuries. Results of these studies showed that OPDs had no statistically significant net injury benefit, nor that the risk/benefit percentage was much larger than the allowed 12% limit (Zellner et al., 2008). Three reasons for the opposition to CPD or ROPS on ATVs are: (1) the injuries caused by impact between the CPD/ROPS and the operator, (2) the operator was caught between the OPD and the ground surface, (3) the CPD/ROPS impeded the operator's rapid separation from the vehicle (Zellner et al., 2013). Several studies have critiqued the claims made by DRI based on the assumptions made about the input data and computer simulations (Grzebieta and Achilles, 2007; McDonald and Richardson, 2011; Stevenson, 1998).

Other studies have shown that CPDs can effectively reduce injuries during rollover incidents (Grzebieta and Achilles, 2007; Snook, 2009; Myers, 2016a, 2016b, 2016c, 2017; Myers and Cole, 2016). Multiple agencies, including the National Institute of Occupational Safety and Health (NIOSH), Australian Centre for Agricultural Health and Safety, Australian Workers' Union, and Royal Australasian College of Surgeons, recommend the installation of CPDs because they can reduce ATV deaths by 40% (FCAI, 2010; RACS, 2011; Helmkamp, 2012b). The societal economic benefit of a CPD ($3,943) is eight times greater than the average price of a CPD ($478), while the cost associated with each ATV fatality is $803,100 (Helmkamp, 2012a; Myers, 2016a).

Different effectiveness rates for CPDs have been reported. CPDs were used at an Australian resort with over 100 ATVs and 3,000 tourists annually. It was found that installation of CPDs on the ATVs reduced the injury rate by 90%, as shown in figure 11a (Grzebieta et al., 2017). Additionally, a fleet manager survey of companies with ATVs fitted with CPDs (12 Australian and four New Zealand companies, with a total of 436 ATVs) found that OPDs protected operators in 83% of rollover crashes by stopping the ATV from rolling onto the operator or by holding the ATV above the operator (Grzebieta et al., 2017) (fig. 11b).



(b)

Figure 11. (a) Commercial ATV OPD efficacy and (b) fleet manager survey (Grzebieta et al., 2017).

Administrative Authorities

A properly designed and installed OPD can potentially decrease operator injuries in rollover incidents. Although many ATV OPDs are sold, to date (June 2020) there is only one officially accepted standard (in Israel) for testing OPD performance. This section discusses the rules and standards related to OPDs in the U.S. and around the world.

United States

Rollovers are the leading cause of death on U.S. farms, constituting about 85% of ATV-related deaths (McIntosh et al., 2016). Although many ATV OPDs are sold in the U.S., there is no standard or regulations for implementing OPDs.

The Consumer Product Safety Commission (CPSC), rather than the U.S. Department of Transportation (DOT), provides regulation oversight for ATVs. The DOT's primary responsibility is to provide regulation of vehicles used on public roads. The CPSC can either adopt an industry-developed standard or issue its own mandatory standard. The CPSC has adopted the 2010 voluntary standard developed by the American National Standards Institute and the Specialty Vehicle Institute of America (ANSI/SVIA, 2017), which is titled "American National Standard for Four-Wheel All-Terrain Vehicles" (CPSC, 2017).

Although there is some opposition to installing CPDs on ATVs in the U.S., NIOSH has recommended installing CPDs and has reported that CPDs can decrease the number of deaths in rollover incidents by 40% (Helmkamp, 2012b).

Several NIOSH-funded agricultural safety centers in the U.S. mention CPDs as a safety requirement for ATVs on farms, including Upper Midwest Agricultural Safety and Health (UMASH) and the National Children's Center for Rural and Agricultural Health and Safety (NCCRAHS). A farm safety checklist for ATVs was offered that included this question: "Does the ATV have a CPD designed to prevent crush injuries in lower-speed crashes (<30 mph)?" (UMASH, 2017). Based on NCCRAHS guidelines for adults to use in determining the readiness of youth (younger than 16 years) to operate a utility ATV on farms (NCCRAHS, 2018), one of the requirements is: "The ATV has a CPD designed to prevent crush injuries in lower-speed crashes (<30 mph)."

Canada

There are no national standards for ATVs in Canada. Instead, industry-developed standards for ATVs have been adopted by the Canadian Off-Highway Vehicle Distributors Council (COHV). COHV has adopted ANSI/ROHVA Standard 1-2016 for recreational off-highway vehicles (COHV, 2017) and ANSI/SVIA Standard 1-2012 for four-wheel ATVs (COHV, 2018). Although many ATV OPDs are sold in Canada; there is no recommendation or regulation regarding OPD installation. One insurance company in Canada offers a 5% discount on its ATV insurance if customers have a Quadbar installed on their ATVs (Cansure, 2019).

Europe

In Europe, enforced regulations are decided by international, European Union, and United Nations Economic Commission for Europe (EC, 2019) standards. The European Union has adopted a regulation titled: "Directives and Regulations for Two- and Three-Wheel Vehicles and Quadricycles" that sets performance requirements for ATVs (EU, 2013). There is no recommendation or regulation regarding OPDs in Europe.

In Sweden, "Safe Use of Quad Bikes, Mopeds, Tractors, and Power Tools, Version 2019" promotes rollover protection on ATVs used for occupational purposes (Persson, 2020). The previous version of this document ("Better Safety on Quad Bikes, Joint Strategy Version 1.0 for the Years 2014-2020") stated that "We do not feel ready to recommend physical rollover protection structures, as there is no research that demonstrates that they have the desired effect in the event of a vehicle overturning" (Persson, 2013).

New Zealand

New Zealand's occupational safety and health service published "Guidelines for the Design, Construction, and Installation ROPS for ATVs" for testing Quadbar performance in static tests (WorkSafe, 1998). It is not known if these guidelines have been approved. The primary workplace health and safety regulator in New Zealand is WorkSafe, which strongly recommends installing CPDs on ATVs (Aotearoa, 2019). The Accident Compensation Corporation (ACC) provides rebates for safety equipment for farmers in New Zealand, which helps pay for CPDs on ATVs that are used for farm work (ACC, 2019).

Australia

The Australian Consumer and Competition Commission (ACCC) protects consumer rights in Australia and is the equivalent of the CPSC in the U.S. The ACCC asked for public comments on a proposed safety standard and on a safety rating program for ATVs (ACCC, 2017b). Comments submitted on the proposals were posted on the ACCC website (ACCC, 2017a). In October 2019, the Australian government passed the new standard to improve the safety of ATVs (Australia, 2019).

Within 12 months of passage, all new ATVs were required to:

- Have a warning label alerting the operator to the risk of rollover.
- Meet U.S. or European standards for the performance of components such as the brakes, suspension, throttle, and clutch.
- Test for stability and display the test result on a hang tag attached to the ATV at the point of sale.

Within 24 months, all new general use (utility) ATVs were required to:

- Be fitted with an OPD or have an OPD integrated into the design.
- Meet minimum stability requirements.

The Minister for Government Services (Sukkar, 2019) developed a standard titled "Consumer Goods (Quad Bikes) Safety Standard." A section of the standard titled "General Use Quad Bikes Operator Protection Devices" reads as follows:

"*A general use quad bike must have one of the following devices fitted, or integrated into its design:*

a. An ATV LifeGuard, in the model manufactured by Ag-Tech Industries Ltd. (New Zealand) and available for supply when this instrument commences;

b. A Quadbar, in the model manufactured by QB Industries Pty Ltd. and available for supply when this instrument commences;

c. *A device of a type that offers the same, or better, level of protection for operators from the risk of serious injury, or death, as a result of being crushed or pinned in the event of a rollover, as is offered by a device of a type mentioned in paragraph (a) or (b).*"

Unfortunately, none of those documents defined "level of protection" as a performance criterion. The ACCC is working alongside Standards Australia to develop specifications for the design and testing of OPDs (Australia, 2019).

Several safety programs in Australia provide ATV safety rebates in New South Wales (NSW Quad Bike Safety Improvement Program) and Victoria (WorkSafe Victoria) for approved safety solutions to help reduce occupational ATV deaths (NSW Farmers, 2018; VFF, 2017). WorkSafe Victoria accepts OPDs as a solution to control the risk to operators in the event of a rollover (VFF, 2017). Australia's Victoria State mandates rollover protection on ATVs used in the workplace (Arnold, 2016).

Israel

The government of Israel requires that ATV owners install a safety frame, which is also called a back arch or OPD. The safety frame prevents the operator from getting crushed under the ATV in a front, side, or backward rollover (Israel, 2005). Manufacturing and installation of safety frames must be approved by the Ministry of Transport under the supervision of a qualified test laboratory (Israel, 2005).

The Standards Institute of Israel evaluated the performance of a CPD designed based on the Israeli standard (Israel, 2005). The tests included three types of rollover (front, side, and backward) while driving in a circle. Tests were conducted on ATVs with and without the CPD. Results showed that the "injuries caused to the operator during the rollover without the back arch were more severe than during the rollover with the back arch" (Israel, 1998). Technical specifications for testing and mounting of Israeli safety frames for ATVs based on the standard (Israel, 2005) are summarized in the following sections.

Structural Specifications

The OPD shall be installed on the ATV by clamps with mounting bolts and safeties, without any drilling or welding. The frame shall withstand the following loads without any plastic deformation under the following loads:

- A vertical load, equivalent to 1.5 times the weight of the ATV, should be applied.
- A horizontal load, in the direction of the ATV's longitudinal axis, equivalent to 0.15 times the weight of the ATV, should be applied.
- A horizontal load, in the direction perpendicular to the ATV's longitudinal axis parallel to the ground surface, equivalent to 0.65 times the weight of the ATV, should be applied.

Minimum Dimensions and Location

The minimum height of the internal part of the OPD, above the ATV seat (unloaded) shall be 100 cm. The minimum internal width of the OPD shall be at least 75 cm (measured at a height of 50 cm above the seat). The frame shall be constructed as one piece (for example, a bent pipe) and shall not have any sharp comers. The horizontal top part of the frame shall be coated all around with a flexible material as follows:

- The thickness of the padding material shall be not less than 20 mm.
- The hardness of the flexible material shall be between 40 and 50 units, as measured by the SHORE method.

The body of the OPD, including the mounting hardware, shall be protected against corrosion. The mounting bolts shall be high-strength (grade 80) steel bolts. The welding of the OPD shall be done only at the frame's manufacturer and by welders authorized according to Israeli Standard 127. The frame welding process, if any, shall be carried out according to a process that was approved as fully conforming to Israeli Standard 127.

Testing Requirements

The test shall include:

- Defined prototype characterized by proper technical drawings.
- Mathematical analysis.
- Defined prototype characterized by testing at an accredited laboratory including actual loading test.

Administrative Requirements

The manufacturer of the ATV frame shall have a valid production license from the Ministry of Transport, which authorizes it to produce and install safety frames. The manufacturer shall provide the accredited laboratory with detailed technical drawings, appropriate calculations, and a prototype for each model of safety frame it produces, before and after mounting it on the ATV. Following the test and authorization by the laboratory, the laboratory shall issue the manufacturer an appropriate certificate, including a signed drawing, and send copies to the homologation department.

The manufacturer must order from an accredited laboratory at least four visits per year, being made without prior notice, whereby the purpose of the visits is to ensure that the frames manufactured and installed by the manufacturer match the approved prototypes.

Should any exception be found, the manufacturer shall have to recall the vehicles on which the frame was fitted and install it appropriately.

Each safety frame shall be marked with a permanent marking, including the manufacturer's name, the frame model, the serial number of the frame, and the license (or chassis) number of the ATV on which the frame is mounted and approved with a certificate of issued by a manufacturer authorized by the Ministry of Transport and under the supervision of an accredited laboratory.

Conclusion

Rollovers are the leading cause of death in farm ATV incidents, constituting the majority of deadly ATV incidents around the world. Behavior-based control methods have been used for several decades but have reached their limit of success. Elimination of ATVs is not practical because ATVs are the preferred vehicle for many farm tasks. Hence, engineering controls are needed to decrease the severity of injuries in ATV rollovers. Engineering control technologies can prevent injuries and protect the operator in a rollover. New technologies can decrease the severity of injuries and the number of fatalities in ATV incidents by improving the vehicle stability, handling, and crashworthiness.

This study provided a critical review of the engineering controls available to improve agricultural ATV safety. The discussion included the static stability of ATVs, dynamic handling of ATVs, improving crash testing and stability ratings, automatic systems to notify first responders of a crash, and testing and installation of OPDs. Such methods are currently used in the automotive industry and have worked to improve vehicle safety.

Prevention

The advances in safety for all types of land vehicles are correlated with improvements in stability, handling, and crashworthiness. Stability angles have been used to describe the rollover propensity of ATVs. These angles are generally determined with tilt table tests or the axle lift method. Calculated stability angles have been found to be 5° to 8° higher than those measured using tilt tables. Adding loads to ATVs decreases the lateral and longitudinal stability angles, depending on the amount and location of the load. Static stability and dynamic handling tests can increase our understanding of the stability of current ATVs and improve the safety of future ATV designs. A safety rating system for ATVs has been developed in Australia and should be developed in the U.S. and around the world.

Protection

Installing safety features on ATVs (i.e., crash notification system and OPD) can protect the operator in ATV rollovers. Installing technology on ATVs to automatically notify first responders that a crash has occurred and providing information on the crash location can possibly decrease the rescue time, especially if the crash occurs off-road, and consequently decrease the severity of injuries and the number of fatalities in ATV rollovers.

An OPD is a structure that protects the operator in a rollover by providing a crush protection zone under the vehicle, absorbing the impact energy, and preventing the vehicle from continuous rolling. An OPD reduces injuries by preventing the vehicle from crushing the operator, who would otherwise be asphyxiated due to chest or neck compression.

Although many OPDs have been sold in the U.S., there is no officially accepted standard for OPD performance. OPDs are mandatory in several countries, including Australia, New Zealand, and Israel. The New Zealand government and several states in Australia provide rebates to purchase OPDs for utility ATVs. There is no regulation regarding the installation of OPDs in the U.S.

Few studies have been conducted on agricultural ATV use. Additional studies are needed for agricultural ATV safety programs. It is recommended that safety agencies in the U.S. provide funding to conduct research and initiate programs that develop engineering controls for ATV safety. In addition, there is a need for technical standards for evaluating OPD performance in protecting the operator in the event of an ATV rollover.

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