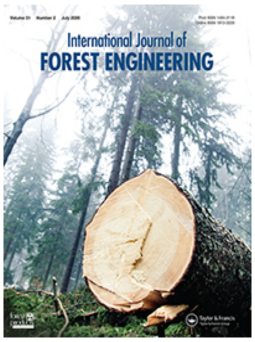

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The effect of rollover protection systems and trailers on quad bike stability

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ABSTRACT

Quad bikes are light-weight vehicles which are used for transportation of personnel, equipment, and material in forestry operations such as planning, logging, planting, and fire-fighting. With increased quad bike usage, serious injuries have become an increasing concern. The most common forms of severe incidents occur when a quad bike loses stability, causing injuries as it rolls over the rider trapped beneath. The risk of injuries during a rollover incident can be decreased by equipping the vehicle with rollover protection systems (ROPS), but since ROPS tend to decrease the stability of quad bikes, their use can be a trade-off between the risk of overturning and the outcome of any such incident. In this study, we examine the effects of approach angle, trailer load, ROPS and different hardware configurations on a quad bike's static stability. We found that approach angle and trailer configurations influenced the vehicle's stability, although the effect was difficult to quantify in a static environment. Furthermore, the quad bike's stability was negatively influenced by equipping it with a heavy (44 kg) ROPS. It reduced the static stability by an average of 5.1°, while a light (14.7 kg) prototype ROPS only reduced the vehicle's static stability by an average of 1.0°. The negative impact a ROPS has on a quad bike's lateral stability could be effectively counteracted by increasing the quad bike's track width. Increasing track width by less than 2% (20 mm) compensated for any negative impact that the light prototype ROPS had on the quad bike's lateral stability.

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ATV; All-terrain vehicle; Rollover protective structure; safety; occupational health; injury prevention; Operator protective device (OPD); Small-scale forestry

Introduction

General

Although the quad bike was originally created as a recreational vehicle, its versatile nature soon made it widely popular in many rural areas for both forestry and agricultural work (Nordfjell 1995; Fragar et al. 2005). The quad bike is a light-weight vehicle, normally weighing around 300–375 kg. Because they are designed to be ridden over rough terrain they are equipped with a narrow-track width (often less than 100 cm), four big wheels, and soft tires. They have handlebars for steering and a straddle-on seat. Quad bikes commonly have a continuously variable transmission and the higher-end models are often equipped with power steering and differential brakes. Today the quad bike has evolved into two separate types of vehicle: the work-oriented type of quad bike used in, e.g., forestry and agricultural, and a sport/recreational type of quad bike (e.g., Grzebieta et al. 2015e). The former type will here be called quad bike. We did not include the latter type in the present study, but the consequences of accidents during their recreational use are often presented in the statistics of quad bike-related injuries and deaths (Grzebieta et al. 2015c). Work quad bikes commonly have four-wheel drive, load-racks on both the front and back of the vehicle, and a trailer hitch making them a versatile tool in many occupational settings.

Quad bike usage

The quad bike is commonly used in many rural activities, such as agriculture, hunting, and forestry in many parts of the world, e.g., Sweden, Finland, Great Britain, Ireland, Canada, USA and Australia (Updegraff and Blinn 2000; Lindroos et al. 2005; Russell and Mortimer 2005; Vaughan and Mackes 2015; Grzebieta et al. 2015a). In agriculture, the quad bike is mainly used for livestock operations, transportation of goods and personnel, and crop operations (Goldcamp et al. 2006; Fragar et al. 2007; Geng and Adolfsson 2013). In hunting the quad bike is mainly used for transportation of game (Ahlm and Bylund 2008). Quad bikes are used in both small-scale and industrial forestry. In small-scale forestry, it is used to transport firewood and logs, as well as personnel and equipment over off-road terrain.

In industrial forestry, the quad bike is used in many operations, although exclusively as an auxiliary vehicle. In harvesting operations, the quad bike is foremost used for transport of personnel for planning, shift change or repairs as well as transportation of spare parts, fluids, etc., across the harvest site. In tree planting operations the quad bike is commonly used with an attached trailer for transportation of seedlings from roadside to the planting site and in pre-commercial thinning as well as clearing under power lines, it is mostly used for transportation of personnel and equipment across the site. In forest fire management, the quad bike is foremost used to transport firefighters and for deployment of hoses and water pumps to appropriate areas (Edenhamn 1990a; Nordfjell 1995; Malmeström and Millbourn 2015).

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Heavy loads such as seedlings, spare parts, fuel or fire-fighting equipment are often transported on an attached trailer, while in small-scale forestry applications transportation of logs is often carried out with either a timber trailer or with a skidding arch (Nordfjell 1995; Updegraff and Blinn 2000; Russell and Mortimer 2005). This commonly results in relatively heavy payloads. As an example, it can be mentioned that payloads of over 500 kg are common on quad bike timber trailers in Swedish small-scale forestry; they were found to be approximately 570 kg in a study by Loftäng (1991). Together with a trailer typically weighing approximately 160 kg, the total towed weight is commonly more than twice the weight of the quad bike itself. The heavy loads on the quad bike or trailer associated with occupational use introduces increased risks of rollover incidents (Moore 2002; Grzebieta et al. 2015b).

Quad bike injuries

Despite the quad bike's relatively heavyweight and four wheels, in its design, it is more like a motorcycle than a tractor with its straddle-on seat, handlebars and lack of cabin or any type of rollover protective structure (ROPS). The rider is consequently largely unprotected and exposed to high risk of injury in any situation where there is a loss of control. As quad bikes have become more widely used, the incidence of serious and fatal injuries has also increased (Dahle 1987; Bansal et al. 2008; Persson 2013; Topping and Garland 2014). In Sweden, for instance, the number of casualties resulting from quad bike accidents increased from a total of seven during the five years 2003–2007 to a total of 23 fatalities during the five years 2013–2017. In New Zealand and Australian farming, quad bike incidents are a major cause of injuries, while deaths from their occupational use are frequent, with about half of all quad bike-related fatalities in Australia being occupational (Fragar et al. 2005; Basham et al. 2006; Grzebieta et al. 2015c). According to Topping and Garland (2014) the number of deaths per 100,000 quad bikes has been reasonably stable over time, as have the relative numbers of serious injuries per quad bike (Axelband et al. 2007; Bansal et al. 2008). These studies indicate that the increase in quad bike-related injuries is closely related to the rapidly growing numbers of quad bikes in use.

The most common types of incidents that result in injuries are rollover incidents (e.g., Hall et al. 2009; Krauss et al. 2010; Milosavljevic et al. 2011; Jennissen et al. 2017). Quad bike incidents on public roads, as well as off-road, are commonly single-vehicle crashes (Persson 2013; Williams et al. 2014). Due to its inherent instability, combined with the high friction between the tires and the ground, the quad bike is more likely to tip over than to slide in any situation where there is a loss of control either off-road or on-road (Moore 2008). Fatalities from rollover incidents usually arise when riders fail to separate themselves safely from their vehicles, and are then crushed or pinned beneath the quad bike as it rolls (Fragar et al. 2009; Hall et al. 2009). As the quad bike rolls, approximately half of the riders are thrown clear, while the other half is either hit, crushed or entrapped (Moore 2008).

In a substantial proportion of incidents where there is a loss of control, a trailer or other towed attachment is also involved (Moore 2008). Certain circumstances exacerbate risk of injury while towing, such as going downhill with heavy loads. Since the towed trailer is normally without brakes, and can weigh more than twice as much as the quad bike, any attempt to brake while on an incline can result in the trailer folding around the quad bike – i.e., it jack-knifes – and the rider is at risk of being struck, hit or pinned by or between the quad bike and the trailer or its load during the incident.

Injury prevention

Interventions that by engineering aims to eliminate or control the dangers from relevant hazards are considered to be the most effective ways of preventing injuries (Grzebieta et al. 2015f; Donham and Thelin 2016). Rollover protection structures (ROPS) are a collective term for structures such as roll bars or roll cages that serve to create a safe space for the driver in the event of a rollover (Hallman 2005; Lower and Trotter 2014). Nowadays such equipment is standard on most heavy equipment in forestry, farming, landscaping, and construction (Stockton et al. 2002). Effective ROPS must create a safe zone around the driver in a rollover situation and should be equipped with a restraint system to contain the driver within it (e.g., Stockton et al. 2002; Lower and Trotter 2014). ROPS with seatbelts, or safety cabs where the driver is securely held inside the ROPS have been found to be very effective in farm tractor rollover incidents. For example, the legal requirement for there to be ROPS on all farm tractors has reduced deaths in rollover incidents by 99% in Sweden (Springfeldt 1996; Loringer and Myers 2008; Cavallo et al. 2014). Indeed, even the simplest ROPS without any additional driver restraining device have been shown to increase the safety for the operator in the event of a rollover with farm tractors (Ayers 1997; Reynolds and Groves 2000).

The use and sales of ROPS for quad bikes are, however very low, despite that it has long been proposed by researchers, and despite that several models have been developed over the last thirty years (Dahle 1987; Edenhamn 1990b; Rizzi 2010; Shulruf and Balemi 2010; Grzebieta et al. 2015f; Myers 2016; Khorsandi et al. 2019; Strohfeldt 2019). Some recent changes are, however, occurring; quad bike ROPS are today a legal requirement in Israel and the Australian Competition and Consumer Commission suggests it to be a legal requirement in Australia as well. In occupational settings, Quad bike ROPS are already requirements in parts of Australia and a rebate programs have been in action to increase the ROPS adoption (Australian Competition and Consumer Commission 2018, 2019). Quad bike ROPS are available in different designs and sizes from four-post roll cages with roof and windshield, to simple one-post rear-mounted ROPS, or Operator Protective Devices (OPDs) as they are often called. One problem of designing a quad bike ROPS is to create a protective space for the rider during a rollover without significantly decreasing the vehicles stability, and thus creating a higher risk of rollovers occurring (Lower and Trotter 2014; Grzebieta et al. 2015b).

A vehicle's stability or propensity to roll is primarily a function of the vehicle's track width and center of gravity (CoG). The vehicle will overturn when the CoG vector travels outside the quad bikes farthest point of contact with the ground. Static stability is a measure of a vehicle's stationary stability and is defined as the angle at which the vehicle's stationary tipping point is reached (the static tilt angle). In practice, other aspects also influence the maximum angle of an inclined slope that it is possible to drive along without over-turning. For instance, the dynamic force generated when passing over obstacles in the terrain as well as the centrifugal force when negotiating a curve have an important influence (Nordfjell 1998). The narrower the track width that a vehicle has, the more sensitive the vehicle is to obstacle height (Nordfjell 1998). Due to the quad bike's narrow-track width and high CoG, obstacles with a height of as little as 100 mm can result in a rollover incident when riding on off-road terrain at typical speeds of perhaps 20 km/h and characteristic slopes of 12.5° (Hicks et al. 2018). However, even though dynamic forces have a significant influence on a vehicle's stability, its static and dynamic stability are closely related. Indeed, vehicles with a low static stability have been shown to be closely associated with a higher risk of rollover incidents and the measurement of static stability through, e.g., static stability factor (SSF) is a common metric for measuring a vehicle's rollover propensity (Mengert et al. 1989; Grzebieta et al. 2015e).

Previous studies of the static stability of quad bikes show tilt angles for a lateral roll without a rider to be on average 40.6° (SD 3.2°) (Table 1). With a rider on the quad bike, the stability is reduced by an average of 6.7° (Table 1). The static stability of a quad bike with an attached trailer depends very much on the load, e.g., the lateral static tilt angle of a bogie trailer with a load of 227 kg was 39° whilst with a load of 424 kg the stability was reduced to a static tilt angle of 34° (Nordfjell 1989).

By adding weight low on the vehicle, the CoG will be lowered and the vehicle's lateral stability will increase. This is in contrast to adding a ROPS, which adds weight above the vehicle's CoG so decreasing the vehicle's stability. Thus, adding skid plates or wheel weights low on a vehicle will improve a quad bike's lateral stability and can potentially compensate for any negative impact a ROPS might have on a vehicle's stability. Increasing a vehicle's track width will also increase the vehicle's lateral stability as wells as improve its off-road terrain driving properties in regard to driving along a side-slope. An increase in track width makes a vehicle capable of passing over bigger obstacles before reaching its tipping point whilst driving along a side-slope (Nordfjell 1998). Other factors affecting a quad bike's stability are tires and suspension (Grzebieta et al. 2015e). Although a quad bike's large, low-pressure tires and soft suspension result in good traction, they also affect its stability. As a quad bike's tilting angle approaches the tipping point, the load on the wheels on the downhill side increases whilst it decreases on the uphill side. This causes tire deformation and suspension compression, which increase the vehicle's inclination and, thus, negatively influence its stability.

When towing a trailer without brakes, additional forces affect the vehicle's stability. Stability can vary dramatically with a trailer and load, and by how the load is distributed, e.g., if the load on the quad bike hitch is negative, with the trailer pushing forward on to the quad bike, either in a slope or during braking, the risk for jack-knifing increases substantially. In situations where the trailer either jack-knifes or rolls over, there is a much higher risk of the quad bike rolling over as well. Moreover, the angle at which the vehicle is driven on the slope (the approach angle) may substantially influence a vehicle's stability as well as its disposition to jack-knife.

Objective

As indicated above, rollover incidents are a major hazard when driving quad bikes in forestry, as well as in other

Table 1. Static lateral roll tilt angle for work-type quad bikes.

Study	Model	Weight (kg)	Track width (cm)	Static tilt angle, roll (°): Quad bike, no rider	Static tilt angle, roll (°): Quad bike with rider	Diff. (°)
Grzebieta et al. (2015b)	Honda TRX250	199	79	39.2	27.2	12.0
	Honda TRX500FM	293	93	37.7	29.9	7.8
	Yamaha YF M450FAP Grizzly	290	86	36.6	27.4	9.2
	Polaris Sportman 450 HO	327	98	37.6	30.8	6.8
	Suzuki Kingquad 400ASI	276	89	37.9	29.6	8.3
	Kawasaki KVF 300	246	84	38.1	28.2	9.9
	Kymco MXU300	229	80	35.7	24.5	11.2
	Cf Moto CF500	372	91	36.8	30.9	5.9
Bagdadi and Warner (2015)	Can Am 500	368	96	41.2	40.8	0.4
	Can am 400 Xt	371	92	42.6	37.4	5.2
	Goes 520	351	91	43.6	37.9	5.7
	Polaris 570	341	101	43.8	38.0	5.8
	LinHai	340	-	44.6	38.9	5.7
	Kazuma	373	92	44.9	39.3	5.6
	Dinli 700	368	97	45.3	40.2	5.1
Nordfjell (1989)	Polaris Trail Boss 4x4	250	86	42.5	38.0	4.5
	Yamaha 350 4 × 4 Big Bear	285	87	42.5	37.5	5.0
Ayers et al. (2018)	Honda Rubicon TRX 500	288	-	-	41.3	-
	Yamaha Grizzly Ultramatic 660	286	-	-	38.6	-
	Polaris 700 Sportsman	355	-	-	36.9	-
	Kawasaki Prairie 650	297	-	-	39.4	-
Swedish Machinery Testing Institute (1989)	Yamaha YFM 350 F	285	-	-	36.0	-
All models pooled, mean with standard deviation in parenthesis		**309 (50)**	**91 (7)**	**40.6 (3.2)**	**34.9 (5.1)**	**6.7 (2.7)**

activities. ROPS have proven effective to mitigate the hazard for other vehicles, and there has been recent focus on making legal requirements of quad bike ROPS. However, some efforts to prevent injuries by using ROPS might actually increase the risk of overturning. Hence, using ROPS can be a trade-off between increasing the risk of overturning and reducing the risk of injury if such an incident were to occur. However, the extent by which quad bike stability is decreased by ROPS and how this could be counteracted has not been well studied. Such information could contribute to improved machine development that both reduce the risk of occurrence and the effect of such an incident. The overall aim of the present study was therefore to investigate those mechanisms that affect the static stability of a quad bike, and to test ways of increasing a vehicle's stability. More specifically, the objective was to quantify how the static tilt angle was affected by approach angles, trailer towing, adding weight above or below the CoG (e.g., by use of ROPS, a heavier operator, and counter-weights), track width, tire pressure, and suspension stiffness.

Materials and methods

General

This study was conducted in two parts: Study A during the autumn of 2015, and Study B in the autumn of 2017. Study A focused mainly on three aspects: measuring the effects on static stability of (i) an attached towed trailer, including trailer load sizes and load distribution; (ii) the approach angle of a quad bike and its trailer to a slope; and (iii) mounting a heavy ROPS to the quad bike (Table 2). Based on the results from Study A, a light prototype ROPS was used in Study B. The prototype ROPS was developed partly based on the results of Study A and partly based on results from previously published studies (Edenhamn 1990b; Nordfjell 1995; Grzebieta et al. 2015b). The main focus of Study B was to investigate the effects of(i) mounting the light prototype ROPS to the quad bike; and (ii) different hardware configurations aimed at increasing the static stability and thus counteracting the negative impact of retrofitting a ROPS (Table 2).

To measure the static tilt angle, a tilt table (510 cm long by 390 cm wide) designed for testing heavy machines was used (Figures 1 and 2). The table had the capacity to tilt up to a maximum angle of 48.5° at maximum speed of 10.5° per minute. It was, however, tilted at a substantially lower speed when approaching the tipping point. Before raising the tilt table, the quad bike was positioned and secured with safety lines attached to the front and rear load racks as well as to the trailer (when one was attached) in order to prevent a complete overturn (Figure 1). The quad bike's brakes were mechanically locked by inserting a bolt through the ventilation holes on the brake discs. Sliding was prevented in both Study A and Study B, but by different means (for details see

Table 2. Factors investigated in Studies A and B as well as names and values for each factor and level.

Study	Factor	Unit	Value	Name
A	Rider weight	kg	0	No Rider
			97	Rider
			117	Heavy Rider
	ROPS	kg	0	No ROPS
			44	Heavy ROPS
	Trailer gross weight	kg	0	No trailer
			385	Light Trailer
			731	Heavy Trailer
	Approach angle	°	0	0°
			15	15°
			30	30°
			45	45°
	Hitch load	kg	14	Rec. load (Recommended)
			−20	Neg. load (Negative)
B	Rider weight	kg	0	No Rider
			97	Rider
	Tire pressure	kPa	20	20 kPa
			25	25 kPa
			35	35 kPa
			50	50 kPa
	Suspension stiffness	-	Hard	Hard
			Soft	Soft
	ROPS	kg	0	No ROPS
			14.7	Light ROPS
	Counter-weights	kg	0	No weights
			14.9	Skid plates
			20 (4*5 kg)	Wheels weights
			34.9 kg	Skid plates + Wheel weights
	Track width increase	mm	0	0 mm
			21.6	21.6 mm
			43.2	43.2 mm
			64.8	64.8 mm
			86.4	86.4 mm

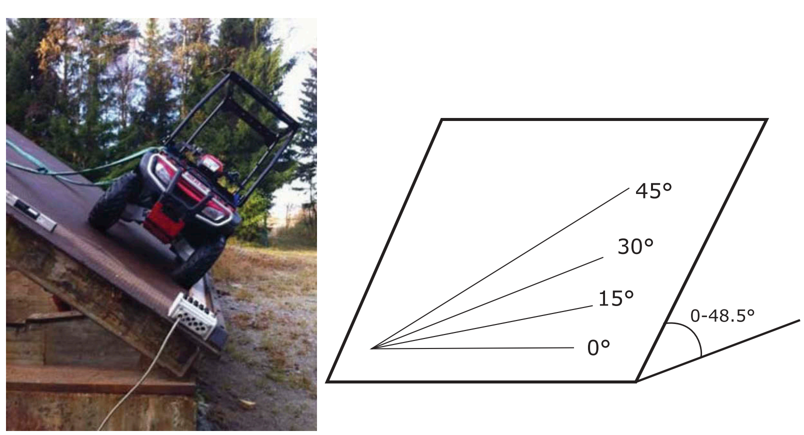

Figure 1. Tilt table with quad bike 1 mounted with the heavy ROPS and positioned at a 0° approach angle (left). Schematic of the tilt table and the four different approach angles tested: 0°, 15°, 30°, and 45°. The tilt table´s tilting angle ranged from 0° to 48.5° (Right).

Figure 2. Example of the set-up of Study A, with the quad bike and the trailer (385 kg). The quad bike is positioned at a 30° approach angle (Left). The quad bike and the timber trailer positioned at an approach angle of 0° (Right).

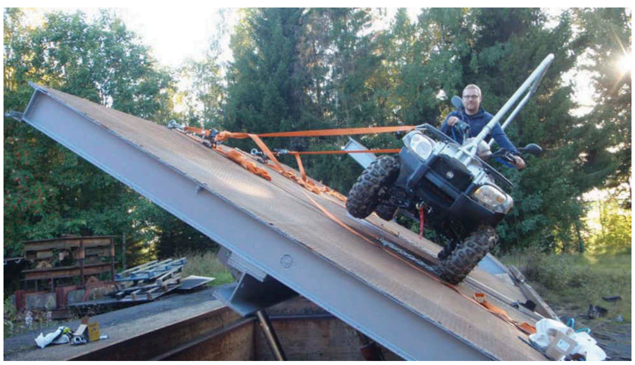

Figure 3. Example from the set-up for Study B, in which the quad bike has been tilted and is held up by the safety lines. The quad bike is equipped with the prototype light ROPS and the rider is simulating normal rider technique, leaning into the slope whilst keeping hands and feet in contact with the handlebars and footrests.

the sections below for each Study). The static tilt angle was defined as the angle at which the table had to be raised for two of the quad bike's or trailer's wheels to be no longer in contact with the tilt table's surface. The angle was measured with an inclinometer with a scale of 360° per turn, and with a 0.25° accuracy.

The same rider, weighing 97 kg including clothes and shoes, was used in both Study A and Study B. The rider simulated normal riding by leaning into the slope but with both feet in contact with each footrest and both hands on the handlebars (Figure 3). For one test, the rider's weight was increased by strapping 20 kg to the rider's upper torso in order to investigate any influence on stability.

Study A – effects of approach angle, heavy ROPS, and trailer load

The quad bike used was a Honda TRX500FA Foreman (Figure 1), with a weight of 301 kg and the tire pressure set to 25 kPa. The trailer was a Honda LT10 bogie timber trailer (Figure 2). The trailer weighed 161 kg without load, and its tire pressure was also set to 25 kPa. The vertical hitch load was set to the manufacturer's recommendation, a vertical force of 137 N (14 kg). This was used in all trials except where the effect of a negative hitch load was tested. In the negative hitch load tests, the load was set to a vertical lifting force of 196 N (−20 kg). The trailer load consisted of conifer pulpwood cut to a length of 380 cm, with log diameters ranging from 9 cm −18 cm. Two different load sizes were used in this study: recommended (224 kg, 0.3 m^3) and normal (570 kg, 0.7 m^3). This resulted in, respectively, a total towed weight (trailer and load) equal to the maximum towing weight recommended by the manufacturer (385 kg), and a total towing weight of 731 kg.

The ROPS used was the heavy 44 kg *Atvbow* (ATV-Bågen AB), one of the very few quad bike ROPS sold in Sweden (Figure 1). The ROPS consisted of a four-posted cage attached to the quad bike's front and rear loading racks. The total height of the ROPS from the attachment points was 100 cm, which resulted in an approximate height of 185 cm from the ground. The ROPS was certified according to the EU directive for rear-mounted rollover protection structures of narrow-track wheeled agricultural and forestry tractors (86/298/EEC 1986).

To prevent the quad bike and trailer from sliding as the table was lifted, a 45 mm thick board was mounted to the tilt table in front of and to the side of the vehicle (Figure 2). Four different approach angles were tested: 0° (perpendicular to the slope), 15°, 30° and facing the slope at a 45° approach angle (Figures 1 and 2).

Study B – effects of hardware configuration and a light ROPS

The quad bike used was a GOES 320 (Figure 4), with a weight of 345 kg. It was equipped with adjustable suspension for all wheels and the hardest and softest settings for suspension stiffness was used in this study. The ROPS studied was an experimental two-post prototype, center mounted to the front and rear loading racks as well as to the hitch. It weighed 14.7 kg and was 94 cm above the loading rack giving it a maximum height of 205 cm above the ground.

The quad bike was placed perpendicular (approach angle 0°) to the slope in all trails. To prevent the quad bike from sliding, chains were attached to the wheels of the quad bike. This method was developed based on the experience from Study A; it allowed the quad bike to overturn while causing negligible interference to the stability of the vehicle. The

Figure 4. The quad bike and the light ROPS used in Study *B*.

Figure 5. During Study B, chains were attached to the wheel rims to prevent the quad bike from sliding, but with a minimum of interference with stability.

chains were placed under the tire and were attached to the outside of the rim (Figure 5).

Analysis

Since the experimental setup was expected to result in minimal variation in static tilt angles for a given combination of factors, replicate tests, with up to five repetitions, were only applied to the key combinations under investigation. For combinations with repetitions, arithmetic mean values and standard deviations were calculated. The effects of the fixed factors quad bike weight and approach angle were evaluated by the use of a full two-way Anova model, for five levels of weights and two levels of approach angle. Pairwise differences were analyzed with Tukey's simultaneous test of means. The effect of the fixed factors quad bike weight and track width were also evaluated by the use of a two-way ANOVA and Tukey test, again with five weight levels, and two width levels. Linear regression was used to establish the relationship between track width and static stability, which was best described as a quadratic model. The critical level of significance was set to 5%.

Results

Study A

The quad bike's static stability increased with increasing approach angle (Table 3). When changing from a position perpendicular to the slope (0° approach angle) to facing the slope at a 45° approach angle, the static stability increased by between 5.8° and 7.7° (Table 3). However, increasing the approach angle from 0° to 15° had only a marginal effect on static stability. Equipping the quad bike with the heavy ROPS and a rider reduced the static stability by between 4.8° and 5.8°. Increasing the rider's bodyweight by 20 kg (from 97 kg to 117 kg) reduced the quad bike's static stability by between 1.8° and 2.2° (Table 3).

When the quad bike had the light trailer attached, its static stability remained similar to that of the quad bike itself (Table 3). The loaded trailer even increased the stability of the vehicle slightly compared to the stability of the quad bike without the trailer. At a position perpendicular to the slope (0° approach angle) the light trailer tilted before the quad bike, but with approach angles of both 15° and 30°, the quad bike tilted before the trailer. At an approach angle of 45°, the tilt table's maximum tilting angle (48.5°) was reached before the quad bike or the trailer tilted. The heavy trailer, with a gross weight of 731 kg, reduced the vehicle's stability by between 6.6° and 9.8° compared to the light trailer (385 kg). In all trails, the heavy trailer tilted before the quad bike.

The static stability of the quad bike with rider and heavy ROPS was considerably lower than it was for the quad bike with a rider and an attached heavy trailer, which in turn had a considerably lower stability than a quad bike with an active rider but without trailer or ROPS (Figure 6).

Table 3. Static tilt angle (°) for different approach angles and quad bike configurations. Mean values and standard deviations (SD) are reported where tests were replicated. Values with different superscripted letters are significantly different (p ≤ 0.05) (Anova with Tukey test).

Treatment				Approach angle			
				0°	15°	30°	45°
Rider	ROPS	Trailer	Hitch load	mean (sd)	mean (sd)	mean (sd)	mean (sd)
-	-	-	-	43.5 (0.08)[c]	43.9	46.9	> 48.5 (0)[a]
-	Heavy	-	-	36 (0.08)[f]	36.3	38.7	43.6 (0.17)[c]
Rider	Heavy	-	-	33.5 (0.36)[g]	34.1	35.7	39.8 (0.17)[d]
Rider	-	-	-	38.6 (0.22)[e]	38.9	41.5	45.6 (0.32)[b]
Heavy	-	-	-	36.4	37.0	39.7	43.7
Rider	-	Heavy	Rec.	36.5	37.5	38.5	42.3
-	-	Heavy	Rec.	36.4	37.6	38.9	42.7
-	-	Heavy	Neg.	37.2	38.2	39.4	44.6
-	-	Light	Rec.	43.0	45.4	48.5	> 48.5

In some cases, the tilt table's maximum tilt angle of 48.5° was reached without the vehicle tipping over.
Rec.- Recommended maximum hitch load; Neg.- Negative hitch load.

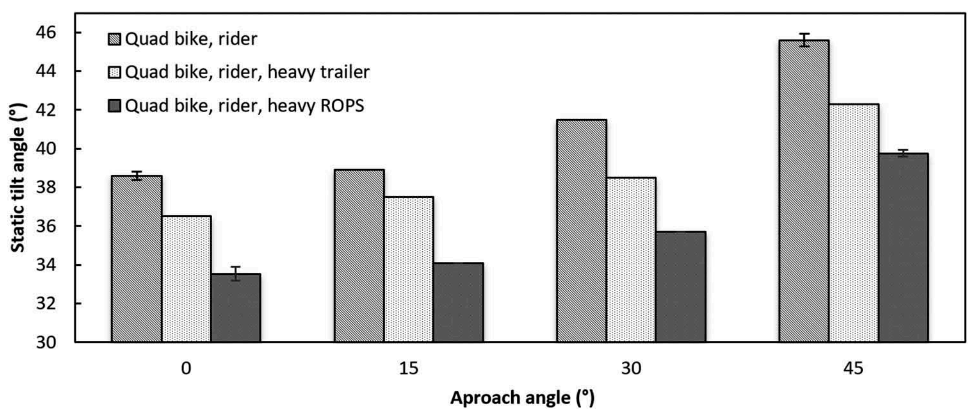

Figure 6. Static tilt angle for different approach angles for: quad bike with rider only; with rider and heavy trailer (731 kg); and, rider and heavy four-post ROPS. At 0° approach angle, the vehicle was positioned perpendicular to the slope. In all trials with heavy trailer, the trailer tilted before the quad bike.

Table 4. Static tilt angle for quad bike with a mounted rider, hard suspension and a tire pressure of 35 kPa given different weight configurations and increase in vehicle track width.

Treatment			Increase in track width (mm)			
			0		86.4	
Skid plates	Light ROPS	Wheel weights	mean	sd	mean	sd
No	No	No	31.9[a]	0.22	-	-
Yes	No	No	32.1[a]	0.22	35.3[c]	0.43
Yes	Yes	No	30.9[b]	0.14	34.7[d]	0.29
Yes	Yes	No	31.3[b]	0.27	34.6[d]	0.11
Yes	Yes	Yes	-	-	34.9[d]	0.22

Values with different superscripted letters are significantly different (p ≤ 0.05) (Anova with Tukey test).

Study B

The stiffness of the suspension had no significant effect on the vehicle's static lateral stability, whereas increased tire pressure resulted in a slight increase in lateral stability. An increase of tire pressure from 20 kPa to 50 kPa increased in general the static tilt angle by 1° both with and without a light ROPS mounted.

Neither adding skid plates alone (14.9 kg), nor skid plates plus an additional 20 kg of wheel weights (4 × 5 kg), had any significant effect on the quad bike's lateral stability (Table 4). Increase in track width by 86.4 mm resulted in a 3.8° increase in static tilt angle for the quad bike equipped with a light ROPS (Table 4).

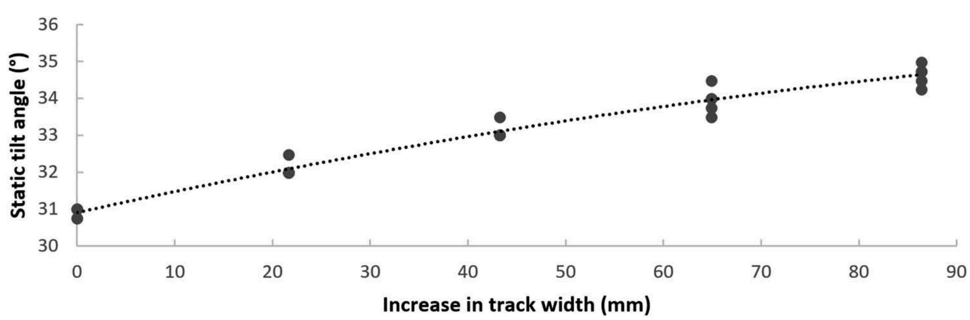

Figure 7. Static tilt angle (°) for lateral roll for quad bike alone, and quad bike with active rider and mounted light ROPS as a function of increase in vehicle track width. Curved linear relationship ($y = -0{,}0002x^2 + 0{,}0585x + 30{,}906$). $R^2 = 0.9703$, $p < 0.001$).

An increase of track width by 20 mm resulted in a stability of more than 32° (Figure 7). This compensated for the reduction in stability due to the mounted light ROPS (Figure 7)

Discussion

Due to a quad bike's narrow-track width and relatively high center of gravity, the risk of a rollover incident while riding on off-road terrain is significant. This is especially true when performing forest-related work associated with heavy loads on the quad bike or on an attached trailer and driving through difficult terrain. The relative risk of injuries in small-scale forestry has been found at high levels, and this over time. A substantial part of these small-scale forestry injuries is vehicle-related (Lindroos and Burström 2010). And an increased use of quad bikes will likely result in more quad bike-related incidents in small-scale forestry applications.

Not all quad bike incidents result in injuries; but as the statistics show, the risk of injury and death in the event of a rollover incident are substantial (e.g., Shulruf and Balemi 2010). The vehicle's configuration, which confers a high risk of rollover, together with a lack of protection for the rider, makes some sort of intervention highly desirable. Designing a ROPS for as small a vehicle as a quad bike is difficult. However, in the present study, as well as in previous studies, it has been shown that it is possible to construct a ROPS that doesn't have a major impact on the vehicle's stability, and that a minor increase in track width can compensate for the negative impact of mounting a light ROPS. It has also previously been shown that light-weight ROPS can create a protective space for the rider in the event of a rollover (e.g., Snook 2009; Grzebieta et al. 2015e; Khorsandi et al. 2019). Thus, this study corroborates previous findings that it is possible to increase a rider's safety in the event of a rollover without substantially increasing the risk of being subject to a rollover incident. The results from this study show similarities with previous studies of quad bike static stability. The static tilt angles for quad bikes with and without a rider in our study (both A and B) all lie within the standard deviations reported in other published studies (Table 1).

Study A

Static stability was tested at four different approach angles, i.e., the quad bike's stability when approaching the slope at angles of 0°, 15°, 30°, and 45°, both with and without an attached trailer. It was found that an increase in angle correlates with an increase of static stability. It was also found that the load transfer from the trailer to the quad bike had no major effect regardless of approach angle. This was somewhat surprising, since it was expected that the load transfer from the heavily loaded trailer onto the quad bike should result in jack-knifing. However, due to the experimental setup, the quad bike and trailer were hindered from sliding on the tilt table. Hence, with the trailer aligned with the quad bike, we assume that the load, by pushing in line with the quad bike, was distributed equally to both the quad bike's front wheels, thereby preventing a jack-knife. A negative hitch load did not result in a jack-knife either. In fact, it slightly increased the stability, most likely due to the fact that the set-up required a load distribution that moved the trailer's center of gravity closer to the trailer wheels, which increased its stability. However, in practice, it is well known that a negative hitch load increases the risk of jack-knifing.

When using a quad bike with an attached trailer, a lack of stability that limits its operational use can be attributed either to the quad bike or to the trailer, depending on load. In our study, we found that when following the manufacturer's maximum load recommendations, the trailer's static stability was similar to the stability of the quad bike itself. However, when increasing the load to a trailer gross weight of 731 kg, closer to what is common practice in small-scale forestry applications, the timber trailer had a considerably lower stability than the quad bike. Hence, with heavy but commonly encountered loads, the trailer is limited in use in steep terrain and will overturn earlier than the quad bike in a rollover situation. Adding the heavy ROPS lowered the static stability even more than the trailer. Thus, the results indicate that mounting a heavy ROPS to increase safety in a rollover incident, actually increases the risk of a rollover incident occurring since the quad bike's stability is then significantly reduced. Grzebieta et al. (2015e) found that a 30 kg heavy ROPS ("Life Guard") decreased static stability by between 1.0° and 4.0°, depending on load configuration and quad bike model. Those results coincide rather well with ours reported here, which show a mean reduction in static stability of 5.1° when the heavy ROPS (44 kg) was employed.

Study B

Adding the light ROPS tested in this study significantly reduced the quad bike's stability; however, the reduction was substantially less than that resulting from adding the heavy ROPS as tested in Study A. The stability reduction of 1.0° that we measured when the light ROPS (14.8 kg) was added corroborates well with the results from the light ROPS studied by Grzebieta et al. (2015e). Their 8.5 kg ROPS "Quad bar" gave results that showed very limited changes in stability ranging from an increase in stability by 1.0° to a decrease by 0.7°.

As the load on the downward side of the vehicle increases to the point where the quad bike is on the verge of rolling, the vehicle's soft tires and suspensions are compressed, which reduces its stability further. Counteracting this compression could potentially be a relatively simple way to improve stability, as it does not require any major changes to the vehicle. In the current study, it was found that increased tire pressure and suspension stiffness had only marginal effect on the static stability. However, it has been shown that tire pressure and the softness of the tire and suspension stiffness together have a larger effect on the quad bike's dynamic than on its static stability (Grzebieta et al. 2015e). As the quad bike travels through rough terrain at a certain speed, the vehicle will experience dynamic forces, which in combination with slope, results in a greater risk of a rollover accident.

Adding low weight retroactively to the vehicle, to lower its center of gravity, is another possible way to improve the stability of quad bikes already in use. However, the amount of weight it might be possible to add to such a small vehicle as a quad bike is limited, and the result of the current study shows that adding a total of 35 kg, or approximately 10% of the vehicle weight, by mounting a skidding plate and wheel weights had only a marginal effect on its stability. The most effective way we found in our study, to counteract the negative effects of the mounted ROPS, was to increase the quad bike's track width. Our results show that a 20 mm increase in track width is sufficient to counteract the negative impact of the light ROPS that we tested (Table 4, Figure 7). This shows that only a small change in track width has a positive impact on the quad bike's stability. Thus the simple act of using quad bikes with a wider track width, with the same CoG would increase the quad bikes stability and thus likely increase the user's safety.

Strength and weaknesses

This study involved measuring a quad bike's static stability. Even though the situations where a quad bike rolls in practice are commonly quite far from the static environment of a tilt table, previous studies have found that static stability is closely related to a vehicle's dynamic stability and measuring a vehicle's static stability is an established method to assess its propensity to roll over (Mengert et al. 1989; Grzebieta et al. 2015f).

Tilt angles were replicated in some key parts of the study; this revealed the typical level of variation inherent in our experimental set-up. We deemed this sufficient to ensure that the variance in the wider study would reasonably fall within the same range so allowing a wide variety of parameters to be tested without replication in the limited amount of time available.

In this study, conditions differed between Studies A and B in two ways. Firstly, we used a different model of quad bike in each study. Due to the time that had elapsed between the fieldwork of the two parts of the study the first Quad bike was no longer available for the second part of the study. We were therefore unable to test differences in static tilt angles between the two quad bike models. However, Grzebieta et al. (2015b), Bagdadi and Warner (2015) and others (Table 1) have shown that differences in the stability of the various models and brands are minor. Secondly, the board used in Study A to prevent the quad bike from sliding off the tilt table might have slightly increased the apparent stability of the vehicle, due to its height of 45 mm. As the quad bike approached its tipping point the soft tires deformed around the board, which would have added some marginal level of support. Based on this observation, another method was used to prevent the quad bike from sliding in Study B. The supportive effect in Study A is thought to have resulted in only slight increases in tilting angle, and not to have influenced the comparisons of treatments within Study A.

In studies of quad bike static stability, either a human rider or an Anthropomorphic Test Device, i.e., a crash dummy, can be used. In this study, a human rider was used in all rider tests. This gave a more realistic result than could have been achieved with a crash dummy in terms of the influence a rider can have on a vehicle's static stability because the human rider can keep his body upright by leaning into the slope during a tilt. It is difficult to reproduce a realistic active rider response to side-lean using Anthropomorphic Test Devices (e.g., Grzebieta et al. 2015e); thus, it is expected that results derived from experiments with Anthropomorphic Test Devices would give lower static tilt angles than those derived from experiments with a human rider. However, using Anthropomorphic Test Devices renders results more reproducible as well as providing the basis for a standard procedure for comparisons between the different studies.

Future research

Despite the strong connection between a vehicle's static and dynamic stability, future studies should also encompass dynamic stability in order to advance our understanding of the problem of quad bike rollover events and the potential role of ROPS in preventing injuries. This could be achieved by incorporating the tests developed by Grzebieta et al. (2015d). The results of our present study highlight some of the difficulties involved in quantifying the complex relationship between the quad bike and trailer in terms of static stability. Further studies are needed to add knowledge to the dynamics of a towed quad bike trailer. Another important subject needing further study is the design and development of quad bike ROPS. As the results of our study show, although the safety of the rider in the event of a rollover might be increased by the addition of a ROPS, if it is too heavy it may decrease a quad bike's stability significantly, and so increase the probability of a rollover occurring.

Conclusions and implementation

As expected, it was found that the quad bike's lateral static stability was highly influenced by the weight of the ROPS. It was also found that when using a loaded timber trailer, the trailer normally tilts before the quad bike – especially with large loads. This suggests that a light ROPS might improve rider safety without limiting the quad bike's usefulness in forestry due to its low lateral stability. The effects on usability are important points to pass on to developers of quad bike ROPS, so that they can design ROPS that will increase the safety with a minimal impact on the quad bike's stability. As there is a movement toward legal demands of ROPS in at least occupational settings, these points are also important to pass on to actors within forestry and other sectors that are moving to retro-fit ROPS on their quad bikes. Moreover, another important finding to highlight and implement is the result that increased track width was the most effective measure to counteract the negative impact of a mounted ROPS on stability. An increase in track width by no more than 20 mm compensated for the negative impact of a 15 kg light ROPS, and maintained the quad bike's lateral stability. How these findings can be implemented in quad bike designs awaits a solution.

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