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## **Continuous overturn control of compactors/rollers by rollover protective structures**

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**Abstract:** The objective of this article is to report on the effectiveness of Rollover Protective Structures (ROPS) in preventing continuous overturns of compactors/rollers. This study is a case-based analysis of government investigation reports of injury-related overturns of compactors/rollers. The overturns were predominately on construction sites including road and embankment construction in the USA. Other sites included driveway and roadway maintenance or repair and transporting of compactors/rollers either by driving or when loading on or unloading from trailers. The principle intervention observed in controlling a continuous overturn (a roll beyond 90° relative to the impact surface) was the presence of a ROPS on a compactor/roller that serves as an anti-roll bar. The main outcome measures are cases of compactor/roller overturns that are restricted to a 90° roll or are continuous (exceed a 90° roll.) All cases of an overturn in which a ROPS was present resulted in no continuous overturn, and the cases involved with no ROPS averaged an overturn of 301°, showing a propensity for a continuous overturn. This case-based analysis identified a ROPS on compactors/rollers as an effective control for reducing the risk of an overturn to 90° relative to the impact plane.

**Keywords:** continuous roll; overturn; rollover protective structures; ROPS.

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## 1 Introduction

The function of Rollover Protective Structures (ROPS) on off-road motorised equipment has historically met a criterion for restricting a vehicle rollover to not more than 90° relative to the initial impact plane. In recent years, this criterion for ROPS design has waned, but international standards have brought this criterion to the fore once again (Wang, Ayers and Comer, 2005; Wang and Ayers, 2006). A case-based study of the effectiveness of ROPS on roadway compactors/rollers offers an opportunity to describe their effectiveness in restricting vehicle overturns to 90°.

Compactors – known historically as steamrollers – are self-propelled vehicles used to increase the density of soil and roadways, and to seal and smooth asphalt surfaces. They have been indispensable in the construction of roads, streets, air strips, earthworks, parking lots and dams as well as levees and railroad beds. Compaction has been applied in ways that include pressure, kneading, impact and vibration (Galion Iron Works and Mfg. Co, 1959; Church, 1981).

In 1973, the Society for Automotive Engineering (SAE) described three types of compactors also called rollers: pad or tamping foot compactors (sometimes called sheepsfoot), rubber-tyred rollers (also called pneumatic), and smooth steel rollers (SAE, 1973). Both the tamping-foot and smooth steel types were manufactured as a double drum or single drum compactors, and some had a vibration mechanism designed into the drum wheels to assist in the compaction process. These were known as dynamic compactors, whereas, units lacking the vibration feature were called static compactors. In 1975, the SAE classified compactors as earthmoving construction equipment (SAE, 1975a), but in 1981, they reclassified them as other than earthmoving machines (SAE, 1981). Nonetheless, some tamping foot compactors are equipped with a blade for moving earthen or landfill material.

In certain operations, compactors have a propensity to overturn. An unstable embankment foundation has been identified as unable to support the weight of a compactor (Ritter and Paquette, 1960), and operating compactors at the edge of high fills has been described as dangerous (Baker, 1957). The U.S. Navy wrote in 1973 that a ‘roller is easier to overturn than most other equipment’. They warned that rolling a shoulder presents a risk of an overturn into a ditch (U.S. Navy, 1973).

Many workers have been fatally injured as the result of compactors overturning. The State of California reported 14 compactor overturn-related fatalities between 1965 and 1972 (White, 1973). Woodward Associates (1974) reported 13 compactor overturn-related injuries during 1971 and 1972 in California. Furthermore – though unsolicited – they felt compelled to refer to a myth of compactor safety:

“A description of the work practices of a roller would seem, on paper, to indicate work conditions that are very unlikely to allow rollovers. But rollers do overturn! And operators are injured and killed.”

The Construction Industry Manufacturers Association (CIMA) alerted the public in 1978 to the hazard of operating compactors on slopes (CIMA, 1978; Construction Digest, 1979):

“The danger of sliding and/or tipping on steep slopes is always present regardless of how heavy or stable your machine may appear to be.”

They also recommended always wearing a seatbelt on ROPS-equipped machines and avoiding operating the machine too close to an overhang, deep ditch or hole, and always travel slowly over rough terrain and hillsides. They identified the potential of caving edges.

In 2004, Myers reported on a study of compactor overturns and ROPS. In his study, he analysed 58 compactor overturns, 50 of which resulted in a fatal injury of the operator. He found that a ROPS controlled the overturn to no further than 90° relative to the ground plane. This control has been cited as inherently safer than a continuous roll beyond 90° (Bittner et al., 1974). Even though the injury data associated with ROPS-equipped motorised vehicles has shown their effectiveness – whether the overturn was continuous – no overturn data supporting this intuitive assumption has been reported. The specific aim of this article is to report on the results of an analysis of the continuous overturn problem related to several overturn cases of compactors/rollers. A literature search was conducted on the history of ROPS protection for compactors and on the evolution of the control of continuous overturns with a ROPS. An analytical method was then described and applied to 45 cases of compactor overturn cases regarding the effectiveness of ROPS to control continuous overturn.

## 2 Literature review

Protective canopies for crawler tractors and anti-roll bars for agricultural tractors had emerged in the 1950s (Myers, 2002), and construction equipment canopies were available from several manufacturers in 1958 (MacCollum, 1958). Protective structures have been demonstrated to be effective as early as 1956 by the U.S. Forest Service in overturn tests conducted on crawler tractors (E&R, 1956). The first patent for an agricultural tractor protective frame was issued in 1954, and the first use on an anti-roll bar of roadside mowing tractors was used in 1958 (Skromme, 1986). These bars were designed to prevent a roll beyond 90°, which proved to significantly reduce fatalities from this type of work. These mowing tractors experience slope exposures similar to the edge work of compactors. In 1967, Hansen drafted a recommendation for a test procedure of protective frames for tractors in which he wrote that most vehicle configurations for field performance, but lacking rollover protection, will roll 180° or more in an overturn and crush the occupant. He stated that a properly made protective device will usually limit the roll to less than 180°. Table 1 shows a chronology of contributions by different entities to the development and effectiveness of anti-roll bars.

The use of ROPS on agricultural tractors has proven to be effective in reducing fatality rates from 17/100,000 tractors in 1960 to 0.3/100,000 tractors in Sweden with a 98% compliance in 1990, and seatbelts that have been used can save additional lives (Myers, 2000). In addition, where ROPS have been required in mining (Woodward, 1980) and in construction (MacCollum, 1984), they have proven to be life-savers.

The ROPS can be designed with two posts or four posts, and can have a canopy overhead to provide shade; these canopies may also be designed as part of the ROPS system. Some modern compactors use a single post centre-mounted ROPS with a canopy extending to the sides to absorb the impact of an overturn.

**Table 1** Chronology of contributions to anti-roll bar development and effectiveness

Year	Contribution	Source
1952	A patent was applied from Kentucky for a guard mounted on a tractor to prevent a tractor from rolling completely over in a sideways overturn	Skromme (1986)
1958	A logging tractor outfitted with a canopy provided the germ of the idea to the car and safety coordinator of the North Dakota Highway Department for an anti-roll bar on the tractors used to mow roadsides	Skromme (1986)
1959	The North Dakota Highway Department built 14 prototype designs for anti-roll bars	Skromme (1986)
1960	The North Dakota Highway Department equipped all of their road-side mower tractors with anti-roll bars	Skromme (1986)
1961	The Illinois Department of highways tested an anti-roll bar in lateral overturns in which the roll was limited to 90°	Kuhns (1966)
1962	A roll bar design was tested in Michigan to limit a lateral overturn of a tractor to the 'on-side' position	Buchele (1962)
1963	Great Britain issued an application for a patent for an anti-roll bar designed to prevent a tractor rolling beyond an overturn onto its side	Duncan (1966)
1963	The Chairman of the ASAE Farm Safety Committee (also from Deere & Co.) expressed a belief that the concept of limiting the roll in an overturn to 90° for tractors was more acceptable than the protection assumed for racing cars with an indefinite roll	Zink (1963)
1965	The Illinois Department of Highways experienced 29 tractor overturns in which 16 had anti-roll bars with a total of six days of lost time injuries and 13 tractors (eight rented) with no anti-roll bars overturned with a total of 410 days of lost time injuries	Kuhns (1966)
1966	A general requirement to reduce serious injury or death in a tractor overturn is to limit the roll to 90° with 'rather simple devices'	Stephanson (1966)
1966	An engineer from John Deere stated that tractor with no rollover protection will roll more than 90°, a roll more than 180° or more will 'invariably' crush the operator, and a roll guard will usually limit the vehicle roll to 90°	Hansen (1966)
1966	A demonstration involving straw dummies in Nebraska of lateral overturns by a non-ROPS tractor that rolled onto its top and a safety frame equipped tractor onto its side showed the protective value of the frame	Anon (1966)
1966	The Chairman of the ASAE safety committee wrote that various studies show that when overturns are limited to 90°, they seldom result in serious injury	Zink (1966)
1966	A development engineer from John Deere stated under design considerations for rollover protective devices that in most cases they will limit a tractor overturn to 90°	Bucher (1966)
1966	The National Safety Council defined the anti-roll bar as essentially a frame installed on a tractor to prevent the machine from turning over past 90° in case of an upset.	Suino (1966)
1967	In many cases, a protective frame will limit the roll of a tractor to 90° rather than at an upside-down position	Berge and Swanson (1967)

**Table 1** Chronology of contributions to anti-roll bar development and effectiveness (continued)

Year	Contribution	Source
1967	The National Safety Council recommended that a protective frame should limit an overturn to 90°	Suino (1967)
1968	The National Safety Council launched a tractor overturn protection programme with a premise that a tractor operator must be protected with some kind of device to restrict an overturn to 90°	National Safety Council (1968)
1968	A demonstration illustrated the protective value of a safety frame by arresting the roll at 90° rather than the typical overturn without protection at the upside-down position which crushes the operator	Knapp (1968)
1972	The National Safety Council issued a data sheet that stated that the design of a protective frame should tend to limit an overturn to 90°	Anon (1972)
1974	Deere & Co. published a manual that stated that ROPS were designed to limit overturns to 90°	Bittner et al. (1974)
1978	The National Safety Council updated a data sheet that restated that the design of a protective frame should tend to limit an overturn to 90°	National Safety Council (1978)
1987	Deere & Co. published a manual that restated that ROPS were designed to limit overturns to 90°	Bittner et al. (1987)
1994	Deere & Co. published a manual that restated that ROPS were designed to limit overturns to 90°	Bittner et al. (1994)
2003	A tip-over protective structure must prevent a roll onto its top	ASAE (2003)

Between June of 1973 and 1974, Woodward Associates conducted a study for the U.S. Occupational Safety and Health Administration (OSHA) on the feasibility of retrofitting construction equipment with ROPS (Woodward Associates, 1974). They concluded that ROPS clearly reduced injuries and deaths related to vehicle rollovers. Moreover, they found that ROPS designs were available for most heavy construction equipment manufactured after 1960 and that rollovers occurred in all types of terrain and to all types of vehicles. OSHA asked them to evaluate the retrofit feasibility regarding seven types of equipment, which excluded compactors. Nonetheless, the fatality data that they analysed from California and the U.S. Corps of Engineers (CoE) design included compactors.

From the 1950s to the 1970s, two ROPS performance standards emerged: the CoE criteria (CoE, 1967; Murphy, 1970; Zinc, 1970; Woodward Associates, 1974) and the SAE recommended practice (SAE, 1975b; Sec, 1976). Between 1950 and 1970, several government entities promulgated ROPS regulations: the State of California, State of Oregon, CoE and agencies of the U.S. Departments of Interior and Agriculture (Forest Service).

The CoE began requiring heavy canopies as rollover protection on crawler tractors in 1960. In 1967, the CoE issued their Safety-General Requirements (CoE, 1967), which required steel canopies and seatbelts on any construction equipment that presented a construction hazard including compactors. This manual required a canopy design that would support twice the weight of the machine and provide at least a 52-in. clearance from the machine's deck to the roof of the canopy.

In 1966, SAE began developing recommended practices for protective devices for mobile construction and earthmoving equipment including wheeled tractors. They

developed a standard to allow the structure to yield through deformation and absorb some of the energy of the rollover so as to lessen the violence of the overturn. The structure was designed to deform through a plastic range that would neither break nor intrude into the operator's protective zone (Sec, 1976).

The concept of controlling the overturn to not exceed 90° has evolved from the principle that a restricted overturn is inherently safer than a continuous overturn beyond 90° relative to its impact surface (Skromme, 1986). This concept grew out of the development of an anti-roll bar designed and used by state highway departments (Hansen, 1966).

The anti-roll bar concept proved effective in reducing deaths and injuries as a result of tractor overturns. The anti-roll bar – which became today's ROPS – was designed to prevent a continuous overturn, and the measure of a non-continuous lateral overturn is that the vehicle will come to rest upon the side that struck the ground plane first (Standards Australia, 1996).

In addition, several highway departments specified ROPS in their purchase orders for construction and highway maintenance equipment. One type of equipment that was exposed to environments at times similar to that of compactors/rollers was the utility tractor used to mow vegetation along roadsides. This included cutting and clearing vegetation from the highway right-of-way, and this right-of-way extended from the road edge and shoulders across ditches, culverts, streams and bridges up to the right-of-way line. Side-mounted mowers on tractors were used for this job. In this sloped and at times steep roadside terrain, tractor overturns were common (Kuhns, 1966). The roadside mowing programme meant that a tractor with a side mowing bar would manoeuvre along the road edge with the mower extending into the ditches and culverts. Travelling the road edge was dangerous, for the slope of the shoulder relative to the road and the bank into the ditch would tilt the tractor to the side and lead to an overturn. When the tractor overturned, the operator would jump or would fall in the direction of the roll into the rolling tractor's path. The weight of the tractor would land on and crush him or her.

In 1958, the logging tractor outfitted with a canopy provided the germ of the idea to the North Dakota Highway Department for an anti-roll bar on the tractors used to mow roadsides (Skromme, 1986). The design concept was of a wide and high frame that would stop the roll on its side or to the rear where the overturn would stop when the frame hit the ground. This would prevent a tumble of the machine where it would roll several times by stopping it at 90°. Based upon an evaluation of several designs the department equipped all 190 tractors used to mow roadsides with an anti-roll bar. During the two years after the installation of anti-roll bars, no operators had died from a tractor rollover, although six overturns had occurred. The injuries incurred resulted in neither death nor disabling injuries – the injuries incurred resulted in 54 days of lost time. The operators were convinced that these bars, while not preventing the overturn, did protect them from serious crushing injuries (Skromme, 1986).

The Illinois Division of Highways recorded 45 injuries including three fatalities related to rollovers of their tractors for the period, 1956–1960. For every 28 tractors, one fatal rollover death would occur over a 55-year working lifetime. The division owned 941 tractors, but engaged additional mowers through contracting to help in keeping the right-of-ways clear. In October, 1961, the division used the anti-roll bar design from North Dakota as well as the safety frame design from the University of California

**Figure 1** A Rollover Protective Structures-equipped smooth drum compactor overturned no further than 90° relative to the ground plane (see online version for colours)



Source: U.S. Department of Energy.

(Lamouria, Lorensen and Parks, 1964) to make an anti-roll bar, and they tested it by pushing the tractor sideways over two different slopes. To simulate the conditions faced by tractor operators, a dummy was strapped into the operator's seat with a lap seatbelt. One of two conditions was when an operator was attempting to mow over the brink of a 2-to-1 slope, and the other condition was on a steep 1-to-1 or greater slope. The anti-roll bar successfully stopped the overturn at 90° in both experiments with no damage to the dummy or to the tractor.

After the rollover tests, the division proceeded with outfitting all of their tractors with anti-roll bars. By the 1965 mowing season, 630 of their 941 tractors had been outfitted with anti-roll bars and seatbelts. During 1965, the division had experienced 29 tractor overturns: 16 were bar-equipped, 5 were not and 8 were rented with no bars. Of the overturns with bar-equipped tractors, no fatalities occurred, but there were two cases of injury when the operators struck their head against the bar. These two injuries resulted in six days of lost time. The five overturns with tractors that were not equipped with rollbars resulted in four non-fatal injuries with a total of 201 days of lost work time. Of the eight rollovers of rented tractors, three operators were injured non-fatally with a total of 209 days of lost work time. ROPS were designed to restrict an overturn to not more than 90° relative to impact or ground plane as shown by Figure 1.

### 3 Method

This study used a case-based approach that aimed to describe the effectiveness of ROPS to restrict an overturn on compactors to 90° relative to the impact surface. The first step in this analysis was to identify cases of compactor overturns through a word search of OSHA investigations, Fatality Assessment and Control Evaluation (FACE) reports from the National Institute for Occupational Safety and Health (NIOSH), and a search of personal records. A listing of OSHA accident reports was available on the internet at

www.osha.gov. With OSHA inspection numbers identified, reports were requested from OSHA Area Offices and State OSHA programmes. In addition, FACE reports were available from NIOSH at their website and were downloaded. One additional report was identified in which the U.S. Department of Energy investigated a compactor overturn. Of the 123 overturn incidents identified, reports were acquired for 58 overturns.

Of 58 cases for which an investigation report was acquired, 46 were found to provide enough data for an evaluation of continuous overturn circumstances as shown in Table 2. Non-ROPS compactors totalled 28, and ROPS-equipped compactors totalled 18. Twelve cases were not included in this evaluation. Four cases of overturns did not report the ROPS status of the compactor, and seven cases did not provide enough information to determine the extent of the overturn (four non-ROPS and three ROPS-equipped compactors). One additional compactor overturn involved a unit that had a canopy that crushed during an overturn killing the operator (OSHA Inspection No. 18576249).

The three types of compactors – pad, rubber and smooth – were described in Section 1. Data were also collected on whether the compactor was equipped with a ROPS and the type of incident, which involved five different circumstances.

Information was also collected on the type of task being performed at the time of the overturn. This included rolling soil, road shoulders, asphalt, gravel, chip-seal or rock. In addition, transport was a task in which an operator would drive the unit from one location to another between rolling jobs (called ‘tramping’ in the trade), and another task was loading or unloading a compactor onto or from a trailer.

Data were also collected on the extent of the roll measured in degrees and based upon quantitative, descriptive or photographic evidence presented in the investigation report. The degree of overturn was relative to the initial impact surface of the side of the compactor also known as the ground plane (Standards Australia, 1996).

#### 4 Results

As shown in Table 2, the analysis of 46 cases represented 28 overturns in which a ROPS was not present on the compactor and 18 overturns in which a ROPS was present. The pad type compactors overturned 12 times on soil or rock embankment edges or shoulders and once in soft, unstable soil. The rubber type compactor overturned as a result of four runaways and seven at edges in a variety of operations. The smooth type compactor overturned as a result of five runaways, 15 edges in a variety of operations, two soft soil areas, and one from a limited turning radius of a unit at a road shoulder in which the operator was unable to turn the unit parallel with the road before it went over the shoulder. Figure 2 summarises the circumstances that precipitated the overturn.

Every overturn evaluated in which a ROPS was present on a compactor resulted in a non-continuous roll. These 18 overturns involved 7 pad, 1 rubber and 10 smooth type compactors. Eleven occurred at the brink of surface edges, four in soft areas in the soil or hot asphalt that sank under the weight of the compactor, three as runaways down an inclined surface, and one when a compactor operator crossing a road diagonally and could not turn sharp enough to avoid going over the shoulder of a road.

In contrast, of those compactors in which a ROPS were not present, the unit rolled an average of 301°, ranging from 90° (three events) to 1,080° (three rotations). Of the total of 28 overturns, 25 were continuous rolls as shown in Figure 3. The extent of these 28 non-ROPS compactor overturns by their type is shown in Figure 4. A full rotation was

360°, thus, a 180° overturn meant that the unit came to rest upside-down. Fifteen of the overturns resulted with the unit coming to rest upside-down, and 10 rolled beyond the upside-down position.

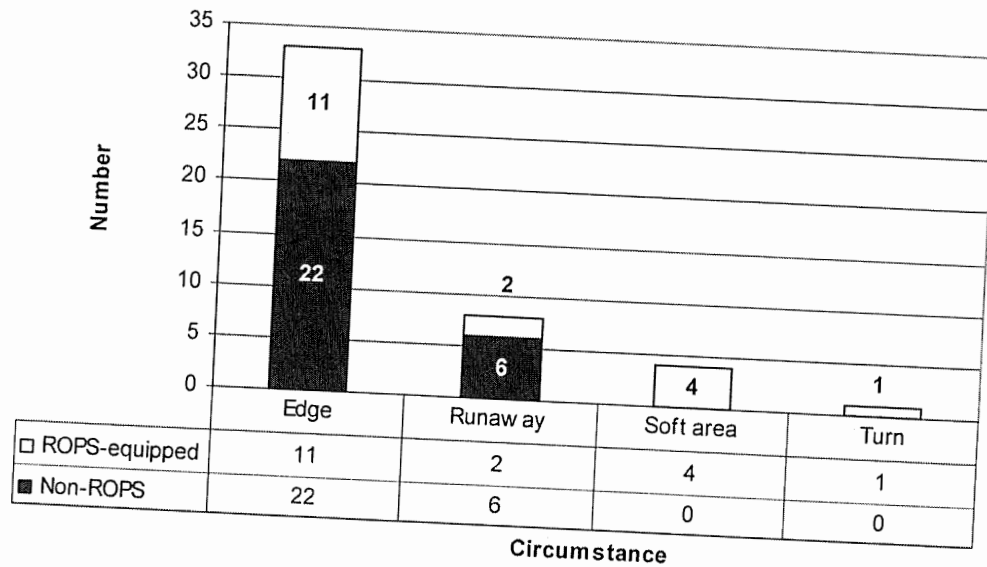
Table 2 A list of cases of compactor overturns evaluated,  $n = 46$

	OSHA inspection no.	FACE no.	Incident year	Compactor type	ROPS status	Incident	Roll angle	Operation
1	017443771		1988	Tamping	No	Edge	90°	Shoulder
2	107703563		1992	Tamping	No	Edge	180°	Soil
3	109070300		1994	Tamping	No	Edge	180°	Soil
4	101281608		1987	Tamping	No	Edge	190°	Soil
5	104557012		1987	Tamping	No	Edge	1,080°	Soil
6	300956950		1996	Rubber	No	Edge	180°	Loading
7	109257709		1995	Rubber	No	Edge	180°	Gravel
8	300675071		1999	Rubber	No	Edge	180°	Soil
9	113327894		1998	Rubber	No	Edge	180°	Shoulder
10	111609665		1990	Rubber	No	Edge	270°	Gravel
11	103609319		1986	Rubber	No	Edge	450°	Shoulder
12	102338530		1988	Rubber	No	Edge	630°	Shoulder
13	302936265	2000–2020	2000	Smooth	No	Edge	90°	Asphalt
14	103040200		1991	Smooth	No	Edge	90°	Asphalt
15	302796149		1999	Smooth	No	Edge	180°	Soil
16	103336467		1995	Smooth	No	Edge	180°	Shoulder
17	301530283		1997	Smooth	No	Edge	180°	Transport
18	115714776		1991	Smooth	No	Edge	180°	Shoulder
19	115328064		1997	Smooth	No	Edge	180°	Shoulder
20	302510367		1999	Smooth	No	Edge	220°	Asphalt
21	107298770		1990	Smooth	No	Edge	360°	Chip-seal
22	100089754		1985	Smooth	No	Edge	900°	Asphalt
23	102834579		1988	Rubber	No	Runaway	180°	Gravel
24	120400437	95MN47	1995	Rubber	No	Runaway	180°	Asphalt
25	014992093		1986	Rubber	No	Runaway	270°	Transport
26	124019019		1993	Smooth	No	Runaway	180°	Transport
27	302071550		1998	Smooth	No	Runaway	540°	Transport
28	108761438		1991	Smooth	No	Runaway	720°	Chip-seal
1	110353844		1993	Tamping	Yes	Edge	90°	Soil
2	302563101		2000	Tamping	Yes	Edge	90°	Soil
3	303378830		2000	Tamping	Yes	Edge	90°	Soil
4	002781524		1987	Tamping	Yes	Edge	90°	Soil
5	104558358		1987	Tamping	Yes	Edge	90°	Soil

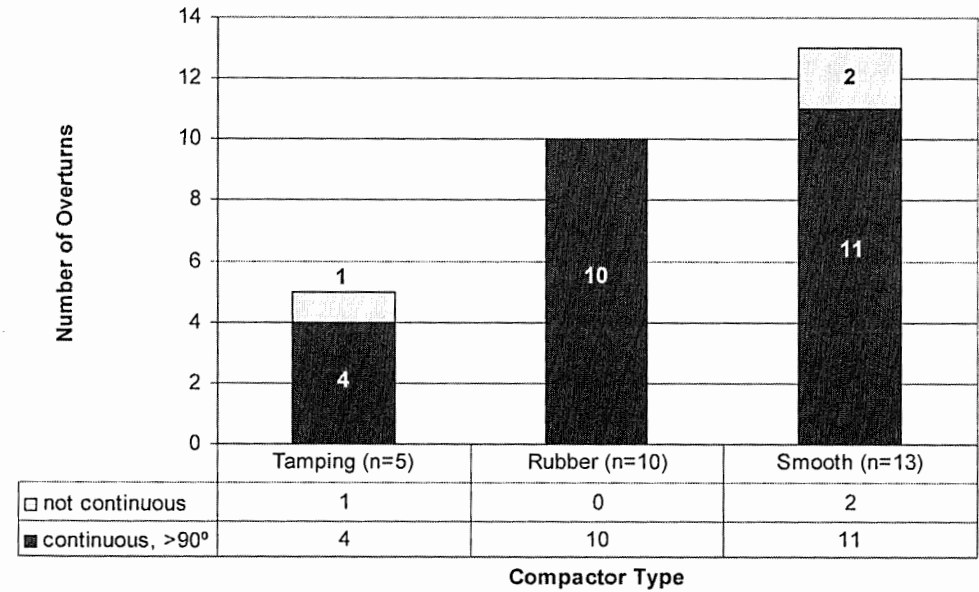
**Table 2** A list of cases of compactor overturns evaluated,  $n = 48$  (continued)

OSHA inspection no.	FACE no.	Incident year	Compactor type	ROPS status	Incident	Roll angle	Operation
6	111116166	1995	Tamping	Yes	Edge	90°	Rock
7	124096314	1997	Smooth	Yes	Edge	90°	Loading
8	111116257	1994	Smooth	Yes	Edge	90°	Loading
9	302417621	1999	Smooth	Yes	Edge	90°	Soil
10	303218817	2000	Smooth	Yes	Edge	90°	Soil
11	105201941	1988	Rubber	Yes	Runaway	90°	Transport
12	305747313	2002	Smooth	Yes	Runaway	90°	Transport
13	US Dept of Energy (2002)	2002	Smooth	Yes	Slope	90°	Soil
14	302662770	2000	Tamping	Yes	Soft area	90°	Soil
15	127378594	1997	Smooth	Yes	Soft area	90°	Soil
16	106161888	2002	Smooth	Yes	Soft area	90°	Soil
17	97MO037	1997	Smooth	Yes	Soft area	90°	Asphalt
18	109448084	1993	Smooth	Yes	Turn	90°	Transport

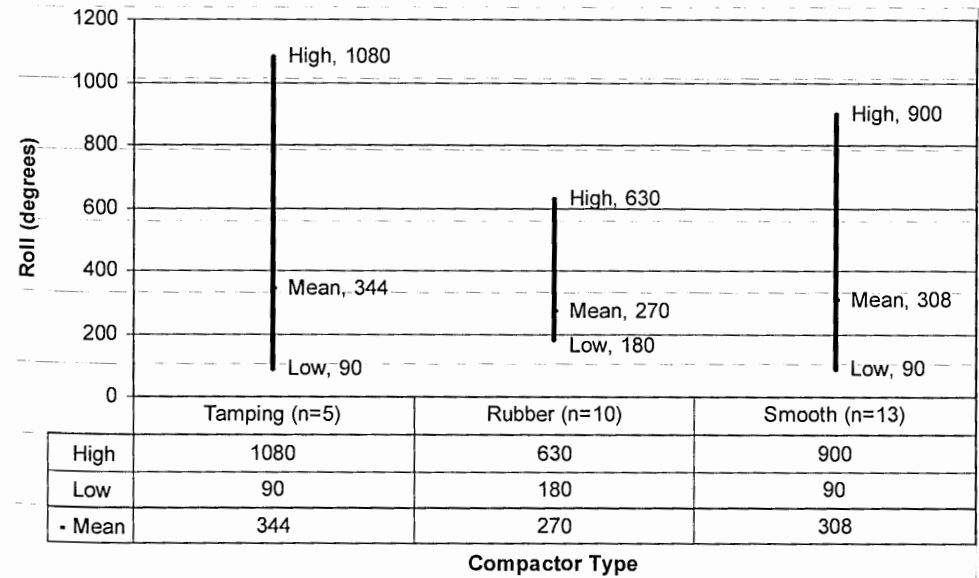
**Figure 2** Environmental circumstances preceding the overturn,  $n = 46$  (see online version for colours)



**Figure 3** Number of continuous vs. non-continuous rolls by non-ROPS compactor type,  $n = 28$  (see online version for colours)



**Figure 4** Extent of roll of non-ROPS compactors that overturned in degrees,  $n = 28$



## 5 Discussion

This study identified the lack of a ROPS as a risk factor contributing to a continuous overturn. Even though early ROPS designs aimed to prevent continuous overturns, standards established by consensus and governmental organisations have not included the prevention of continuous overturns as a design criterion until recently. This recent attention to the prevention of continuous overturns has been driven by the international harmonisation of standards. This study has identified ROPS as effective in preventing continuous overturns for one type of off-road vehicle, the compactor or roller.

This study found that ROPS were effective at restricting overturns to 90°, whereas non-ROPS compactors average nearly a full revolution per event. Fatalities occur not only in the absence of a ROPS but when a ROPS is present. Investigation is needed of overturn-related injuries when ROPS are present. As Brickman and Barnett (1999) identified, the ROPS on compactors were the instrument that crushed several operators in overturns. Myers (2004) noted that in some of these cases, the canopy part of the ROPS struck the operator, and the victims were not wearing a seatbelt.

Without a ROPS, the vehicle would likely continue to roll beyond 90° resulting in the injury, nonetheless. Moreover, without the ROPS they would lack the opportunity to use a seatbelt, for manufacturers recommend not wearing seatbelts when a ROPS is not present. A principal complaint regarding the anti-roll bars in the past has been that some of the uprights were too close together and the operators would knock their heads against them on rough terrain (Hanson, 1966; Skromme, 1986). Of all overturns analysed in this study, there were 41 fatalities, four non-fatal injuries and one non-injury case (Myers, 2004), for the OSHA and NIOSH data that were used included either fatal or serious non-fatal cases. Thus, the database lacked successful protection of the compactor operators by a ROPS with the exception of the one case reported by the U.S. Department of Energy. Further research is needed to better understand the factors that make ROPS safe in the event of an overturn.

Reports on recent incidents not covered by this study indicated circumstances in which the operator was not protected from continuous overturns with the presence of a ROPS and a seatbelt. In one incident, a ROPS-equipped compactor backed off of a 25-foot high embankment and rolled 900° and came to rest on its side (NIOSH, 2004). The operator wore a seatbelt, but was killed with injuries to the head. This incident was unique in contrast with cases evaluated in this study, since the initial overturn was to the rear rather than laterally to the side. In another incident, a ROPS-equipped compactor slid sideways along a roadside, dropped over a 17-foot high underpass wall, and rotated 270° in midair before impacting the ground (KY FACE, 2002). The operator was not wearing a seatbelt and was killed with abdominal injuries. This incident was a fall over a precipitance rather than an overturn against the ground plane.

## 6 Conclusions

Compactors have been shown to overturn and cause serious injury or death to the operator. ROPS and seatbelts are proven technologies for the protection of the operator in the event of an overturn. Moreover, if the overturn can be restricted to 90°, the danger involved in an overturn has been recognised as less. A ROPS provides protection against a continuous overturn beyond 90° relative to the ground plane. International standards are

establishing criteria for ROPS design to stop a continuous roll during a vehicle overturn. The importance of this case-based study is that it affirms the tenant of the anti-roll function of ROPS and has shown that ROPS-equipped compactors are protected against continuous rollovers.

## 7 Acknowledgements

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