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Forensic Engineering Analysis of a Failed ROPS

By Daniel J. Cowley, PE (NAFE 909M)

Abstract

Agricultural, commercial, and some lawn and garden tractors (tractors) have been known to tip and roll over. Roll-over protective structures (ROPS) are designed and tested to assure seat-belted occupants can survive in a zone of clearance within the structure, during and following a roll-over event. Within the laboratory testing parameters established in the current standards, energy absorption is based on tractor mass alone, apart from any other forces that may be acting on the tractor. Current standards allow tractor manufacturers to determine the "reference mass" used for ROPS testing. Most manufacturers fail to include the mass of any attached implements. Serious consideration should be given to upgrade the current standards to include the mass of large implements and spreaders in the "reference mass" used for testing. When implements remain attached to the tractor throughout the roll-over event, ROPS should still be designed to protect operators. In the past, tractors were mainly employed in soil-engaging or surface-grooming exercises. The center of gravity (CG) of these attached implements was relatively low. Today, however, tractors may tow larger, taller, and heavier implements with high CG on multiple axles, such as large liquid manure tank spreaders. The purpose of this paper is to investigate the physical issues associated with tractors towing high CG implements, such as geometrically tall, articulated steerable axle spreaders operating in sloped terrain that cause an ROPS to fail.

Keywords

Slopes, stability, tractors, ROPS, liquid manure spreader with steerable axles, articulated steering device of semi-mounted trailers, tire wear, forensic engineering, OECD-Code 4, ISO 11783, ISO 26402, ISO 3463, ISO 5700, ISO 6489-3, SAE J 1194, SAE J 2194

Introduction

Only 50 years ago, cattle grazed in the open range. Much of the pasture land across the United States was sloped. Things have changed with time, however. Unlike the past practices of cattle grazing in pasture lands, cows are increasingly confined to buildings and modern feeding methods. The pasture lands have since been converted to fields growing hay for feeding cattle, but the slopes still exist. Modern tractors and spreaders now travel the highways of the country heading from farmstead to field filled with liquid manure in nurse tanks behind semi-tractors or multi-axle spreaders to disperse on the nearby fields.

Roll-Over Protective Structures (ROPS)

Occupants operate the tractors that travel on highways and into fields. To better safeguard the operator, the industry encourages self-propelled machines to include protective structures called:

- Roll-over protective structures (ROPS)
- Tip-over protective structures (TOPS)
- Falling-object protective structures (FOPS)
- Operator protective guards (OPG)
- Overhead guards (OHG)

The ROPS is intended to protect the occupants in the tractor enclosure in the case of vehicle overturn[1] (**Figure 1**).

History of the ROPS in the United States

John Deere patented the ROPS in 1966, and turned it over to the industry shortly after that. Between 1967 and

Daniel Cowley, PE, 42671 W Anne Ln, Maricopa, AZ 85138, 520-840-1246, dan.cowley@facet-ics.com
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1976, the ROPS was optional on tractors.

Survivability was the goal for ROPS (**Figure 2**). Although the industry tries to encourage farmers to install ROPS on these vintage tractors, many are still not equipped with an ROPS. Significant efforts are being made by the industry to retrofit tractors originally sold without ROPS. Kits are provided at minimal cost to these tractor owners to retrofit their tractors with ROPS[2].

The ROPS is tested before sale, and the manufacturer certifies the testing is compliant with industry standards. The standard meant to assure the occupant of vehicle protection within a defined zone is known as the "crush clearance zone" or simply the "clearance zone." This level of protection is determined by the energy level specified in the standard for the specific vehicle.

Current standards vary only slightly on matters of testing temperature and seat belt anchor requirements, but all represent an equivalent energy level tied specifically to the mass of the tractor[3]. If the tractor were to overturn under conditions of its mass alone, this energy level should provide a safety factor to protect the operator in a roll-over event. However, this current standard allows tractor manufacturers to determine the "reference mass" based solely on tractor mass rounded to the next 500 kg, not taking into account any of the mass from an implement that may remain attached and roll-over with the tractor.

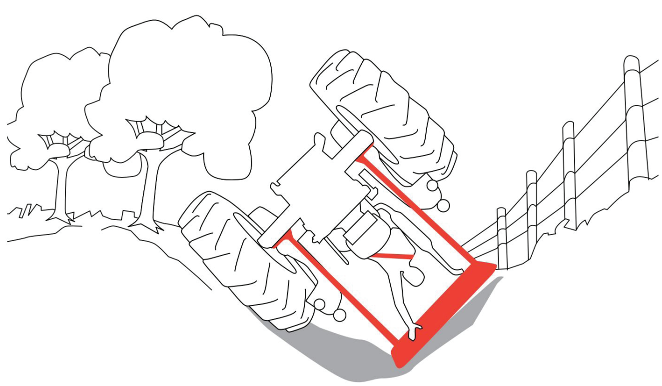

Figure 1
ROPS – operator zone of protection
from OSHA and NIOSH.

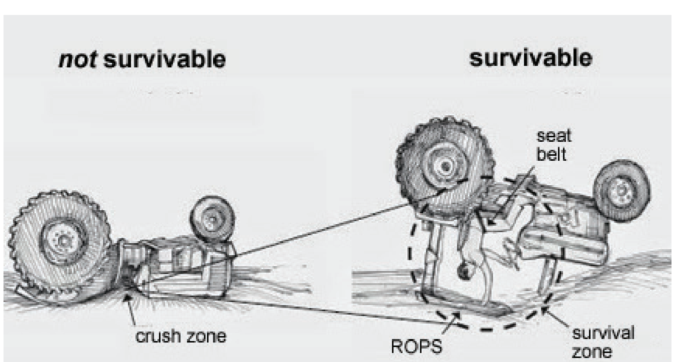

Figure 2
Crush zone and survivability[4] from an unknown source.

How an ROPS Is Tested

The ROPS is designed to absorb sufficient energy to keep the enclosure's structural members from encroaching into the "clearance zone" while still providing for sufficient visibility to the work environment. The clearance zone is defined in the standards as a safe area in the ROPS for a seat-belted operator (**Figure 3**).

Load-carrying members of the ROPS are placed in strategic locations to deflect (strain) under applied forces (stress). The absorbed energy is observed from reviewing the area measured beneath a stress-strain curve before any encroachment occurs into the clearance zone by any portion of the ROPS.

Between tests, the ROPS is examined to make sure the welds for structural member do not fracture. Cracks or tears in parent material of structural member are permissible as long as the operator's clearance zone is intact at the end of the testing cycles.

Crush loads are applied to the ROPS from the rear, top and sides in a specific sequence that are identified in the standards.

From a general understanding of the stress-strain relationship, there is an elastic (then a plastic) deformation that can take place with the ROPS. The more stress and strain added, the more the structure fails to return to the initial shape when the load is removed. Once crushed, very large and permanent deformations that intrude the clearance zone of the ROPS provide evidence of the energy absorption of the structure. If energy absorption is insufficient for the loads applied, the crushed members encroach the operator's clearance zone, and the ROPS fails the test.

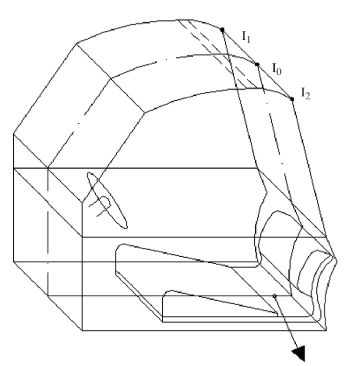

Figure 3
Clearance zone from the standard.

The current standards clearly define the energy levels proportional to a "reference mass" cited in the standards. The tractor manufacturer determines the "reference mass" used for testing based on the mass of the specific tractor to be certified. The ROPS must demonstrate that it can withstand the specific crush loads without encroaching into the "clearance zone" to be certified for a particular make and model of tractor.

Up to this point, the selection of "reference mass" is left to the tractor manufacturer and must be within the guidelines provided in the standards. In most cases, the mass is rounded to the next 500 kg above the mass of the unladen tractor. This assumes that the tractor mass is the only consideration in the roll-over event.

Why the Current Standards Are Deficient

Currently, industry standards do not generally test the combination of tractor and spreader for a roll-over event. Industry standards only consider the tractor mass and assume the decoupling of the implement during the roll-over event. For example, the standards infer chain connections between tractor and implement, as in the case of stump pulling or prior drawbar pin failure like a fuse. The inertial contribution of a spreader (or any other heavy implement that rolls with the tractor) is generally ignored in the industry standard's energy absorption and crush force thresholds for ROPS.

Based on the author's experience during the development process, there may be numerous design iterations that change the stress flow path in order to address cracked welds or to eliminate encroachment into the zone of clearance.

As a matter or conformance, manufacturers of ROPS use highly controlled processes to maintain traceability of materials for the quality of the ROPS. Continuous sampling of ROPS materials and keeping records are part of the process of manufacturing ROPS. Corrosion protection, material selection, and quality are strictly observed in the production of ROPS.

The industry has developed numerous voluntary standards that address various aspects of material utilization, manufacturing, energy dissipation necessary for worldwide use on machinery. Although standards are developed by the industry, ROPS testing is also regulated by government authorities. Since 1976, OSHA has used the ROPS standards as legal requirements for industrial uses, including agriculture and construction. Unfortunately, the standards have not remained current with industry's changing practices.

If the ROPS industry is so highly standardized and regulated, why do ROPS still fail? One would have to conclude that for an ROPS to fail, something drastically out of the ordinary must have occurred. Ruling out issues of defective material, corrosion, defective manufacturing processes, negligent misuse of the equipment, one can only conclude the equipment is misappropriated for the intended purpose; that being pulling stumps with a chain and the tractor being independent of implement when rolling into a ditch.

Tractor manufacturers simply fail to take into consideration the additional energy that an implement (such as an articulated steer axle spreader that remains attached to the tractor) contributes during a roll-over event. They simply hope or assume the implement breaks free in the roll-over. As we know now from failed ROPS, the standards must be updated to account for the inertia increases of added implement mass when the tractor and implement remain coupled through the roll-over.

Current Requirements in Standards

Numerous industry standards apply to the design of tractors and spreaders individually. ROPS testing standards all contain diagrams of the test apparatus and application of loads used for testing. The documents that impact this analysis most directly include:

A. ROPS - Applicable Standards

- Code 4 - OECD Standard Code for the Official Testing of Protective Structures on Agricultural and Forestry Tractors (Static Test - Like ISO 5700).

- ISO 3463 - Tractors for agriculture and forestry - Roll-over protective structures (ROPS) - Dynamic test method and acceptance conditions.

Figure 4 demonstrates the dynamic testing apparatus. Tests incorporate a large pendulum weight dropped on a chain onto the ROPS structure while the tractor is lashed to the ground. The energy the structure must absorb from the side impact is described in the following equation appearing in the standard, where E is the energy in kilojoules absorbed from the side impact loads, m_t is the "reference mass" of the vehicle in kilograms, and H is the raised height of the pendulum specified in the standard.

$$E = 19.6\ H,\ \text{where}\ H = 0.125 + 0.15m_t \qquad [1]$$

$$\text{therefore,}\ E = 2.45 + 2.94m_t \qquad [2]$$

This equation takes into account the energy absorbed by the tires, so it is significantly larger than the energy described in the static test method of ISO 5700.

- ISO 5700 - Tractors for agriculture and forestry - Roll-over protective structures -Static test method and acceptance conditions.

The ROPS is mounted to the vehicle fixed components, which may include the rear axle housing, the transmission case, the tractor frame or the clutch housing, throughout the test. The tires are removed and the components are mounted solid to keep them from moving.

An actuator, generally a large hydraulic cylinder is used to apply the loading to the ROPS. The energy the ROPS must absorb from the side impact is described in the following equation appearing in the standard, where E_{si} is the energy in kilojoules absorbed from the side impact loads and m_t is the "reference mass" of the vehicle in kilograms.

$$E_{si} = 1.75\ m_t \qquad [3]$$

E is larger than E_{si} because it takes into account the energy absorbed by the tires, so E_{si} is significantly less than the energy described in the dynamic test method of ISO 3463.

Both ISO 3463 and ISO 5700 subject the ROPS to a vertical crush after the side impact testing. The magnitude of the force used for crush is described in the following equation appearing in the standard.

$$F = 20\ m_t \qquad [4]$$

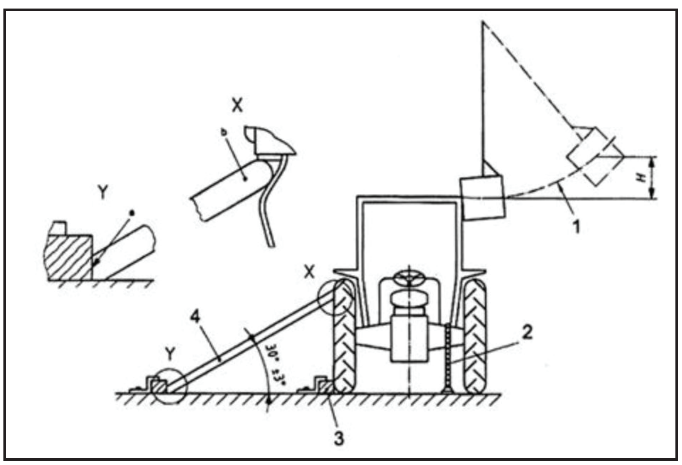

Figure 4
Tractor side impact tests from the ISO 3463 standard.

- SAE J 1194 - Roll-over Protective Structures (ROPS) for Wheeled Agricultural Tractors

The standard states, "Fulfillment of the intended purpose requires testing as follows:

A laboratory test, under repeatable and controlled loading, to permit analysis of the ROPS for compliance with the performance requirements of this SAE Standard.

- Either the static test (6.1) or the dynamic test (6.2) shall be conducted.
- A crush test to verify the effectiveness of the deformed ROPS in supporting the tractor in an upset attitude
- An upset field test under reasonably controlled conditions, both to the rear and side, to verify the effectiveness of the protective system under actual dynamic conditions (See 6.4.1.1 for requirements for the omission of this test).

In addition to the laboratory and field loading requirements, there is a temperature-material requirement."

- SAE J 2194 - Roll-Over Protective Structures (ROPS) for Wheeled Agricultural Tractors

The standard states: "Any ROPS meeting the performance requirement of ISO 5700 (Static ROPS Test Standard) or ISO 3463 (Dynamic ROPS Test Standard) meets the performance requirements of this SAE Standard if the ROPS temperature/material and seat belt requirements of this document are also met."

The energy absorption and crush force thresholds, as defined in these standards, depend strictly on the "reference mass" of the tractor, without consideration for attached implements.

In addition to the direct ROPS issues, if the vehicle fixed components fail during the roll-over event, the ROPS itself becomes more vulnerable to failure since it loses its anchoring base. For instance, an overloaded drawbar can cause a transmission case to break. The transmission case breakage may cause the cab mounts to leave their anchored positions and affect the stress flow through the ROPS, ultimately causing complete ROPS failure.

There are standards for vertical drawbar loads that do not take into account the roll-over event. For example, as long as most of the implement's weight is supported on a series of axles, the tongue load may meet the vertical loads on the drawbar of the tractor. However, in a roll-over event, the tractor may be suspended from its drawbar and exceed the maximum vertical loads of the standard. Tractor manufacturers may not have considered dangling the tractor from its drawbar as a prerequisite to ROPS testing, as may be the case with the spreaders. The tall structure of the spreader fails to collapse in the roll-over event and can suspend the tractor from its drawbar.

Currently, the integrity of the ROPS mounting points is considered a given by tractor manufacturers. There appears to be little awareness or interaction between technical committees for connecting ROPS and tractor/implement interface standards. Each committee works in its own silos on projects within a limited scope. Therefore, ROPS testing standards do not currently consider drawbar vertical overload conditions in the testing process, which may compromise the ROPS mounting points in actual practice. The drawbar vertical load is only one example, but there are others; ISOBUS is another area of interest.

In the past when approached on these issues, both ROPS and tractor/implement interface standards committee members have pointed to external trade organizations for this coordination. The trade organizations, they say, provide educational resources, safety, and otherwise, for the industry as a whole, since every tractor manufacturer is not always aware of the equipment that may be used with their product.

Trade organizations do play an important role. Educating the users of equipment may provide some assistance; however, more technical solutions, such as new ISOBUS standards, may ultimately need to be called upon to control the tractor implement compatibility issues. Safeguards should be put in place that specify if the implement has not yet been approved by the tractor manufacturer, it simply will not operate with that tractor.

B. Equipment Applicable Standards

- ISO 26402 - Agricultural vehicles - Steering systems for agricultural trailers - Interface for articulated steering device of semi-mounted trailers

- ANSI/ASABE AD6489-3, Agricultural vehicles – Mechanical connections between towed and towing vehicles – Part 3: Tractor drawbar

Current OSHA regulations in Agriculture (29 CFR 1928) Subpart C – Roll-Over Protective Structures were derived from the standards listed above.

C. OSHA Regulations

- 29 CFR 1928.52 - Protective frames for wheel-type agricultural tractors - test procedures and performance requirements.

- 29 CFR 1928.53 - Protective enclosures for wheel-type agricultural tractors - test procedures and performance requirements.

- 29 CFR 1926.1001 - Minimum performance criteria for roll-over protective structures for designated scrapers, loaders, dozers, graders, and crawler tractors.

- 29 CFR 1926.1002 - Protective frames (roll-over protective structures, known as ROPS) for wheel-type agricultural and industrial tractors used in construction.

Examples of Equipment and ROPS Failure Risk

One of the by-products of raising cattle in confined space is the concentrated nitrogen-rich supply of manure that is produced from cattle production.

Getting the most value from the manure on the farm, as well as minimizing the potential for water pollution requires careful management of the manure resource. Manure management equipment has grown in dimensions and capacity to meet these challenges. Tractors and spreaders[5] now make up the bulk of the equipment used to dispense liquid manure on the nearby fields (see **Figure 5** for a typical tractor with spreader).

The more common method to spread liquid manure is to use an agricultural tractor to pull a spreader (equipment). Today, the spreader can weigh 72,000 lb or more. Usually, when the terrain is sloping, the tractor is ballasted according to the tractor manufacturer's recommendation and equipped with dual liquid-ballasted tires. The fully ballasted tractor with enough power to pull the load is generally less than half the mass of the full spreader[6] (**Figure 5**).

Articulated steering spreader axles reduce tire scrub in the field that disrupts turf and increases axle loading. Although implement articulated steering appears to work properly on level operations, where tire sideslip is not a factor, catastrophic events can quickly develop when equipment operates on steeper slopes. Sideslip on sloping terrain occurs more readily when the implements, having low stability characteristics, are combined with conventional implement articulated steering functions.

On flat land, the force of gravity on the tires is normal to the ground. Unless the equipment is performing an unusual maneuver at higher speeds, the equipment remains relatively stable since the CG remains within the footprint of the tires, even in reasonable speed transport modes. On occasion, however, a spreader overturns along a roadway as a result of slippery weather, shoulder conditions, and a high CG[7].

Articulated steering, a slight berm along the side of the road and high CG contributed to the overturn of the spreader shown in **Figure 6**. Clearly, the spreader has a high propensity to roll-over due primarily to its high CG, but there are other contributing factors as well.

Equipment Stability

The static stability angle testing is conducted by the vehicle manufacturer on a tilt table under controlled conditions. The vehicle is blocked and chained to the tilt table with sensors placed under the up-slope tires to determine when lift-off occurs. The tilt table is slowly raised, and the angle of the table is measured along the way. At lift off of the up-slope tires, the angle of the tilt table is recorded.

Since some vehicle are used in various configurations (e.g., decks up or decks down in the case of commercial mowers), the angle is measured and recorded for each. The worst configuration is recorded, and then published in tractor certifying test results. However, the static stability angle limit information is generally not provided to the equipment user in the operator's manual. There are currently no known requirements for the implement manufacturers to conduct static stability angle testing of their equipment.

How the Equipment Rolls Over

The geometry of the multi-axle tires in turning maneuvers tends to increase axle stresses and cause tire scrub that forms ruts or disturbs the sod. Steering the spreader allows it to follow the path of the tractor more closely. Numerous methods are employed to articulate the spreader's axles. One such standardized method senses the differential angle between the tractor's drawbar and the longitudinal plane of the trailing spreader and adjusts the lead and trailing axles' tire steering angles accordingly.

By design, due to the mass of the full spreader in the field, the spreader's tires are generally articulated to follow more closely in the tracks of the tractor[8] (**Figure 7**). Steering the spreader tires reduces axle stresses in the field and reduces turf damage from tire scrub.

The dual, tridem, and quad-axle spreader steering systems vary by manufacturer. Some are now providing more elaborate electronic-sensing steering systems that allow the spreader to crab or offset the spreader's tire tracks from those of the tractor[8]. However, consistent with ISO 26402 but slightly different in design, the U.S.- and Canadian-made spreaders are steered with proprietary designed mechanical linkage that senses the differential angle between the tractor's drawbar and the longitudinal plane of the trailing spreader and adjusts the lead and trailing axles' tire steering angles accordingly (**Figure 8**).

Although most implement manufacturers utilize

Figure 5
Tractor with a spreader in the field
From Valmetal (2018). Reprinted with permission.

Figure 6
Overturned spreader along the roadway due to icy road conditions
from The Sentinel (2013). Reprinted with permission.

hydraulic pressure assist, they apply the same general principles of ISO 26402. This means the mechanical linkage senses the differential angle between the tractor's drawbar and the longitudinal plane of the trailing spreader to determine the proper tire steer angles for the spreader. Mechanical sensing may be accomplished in different ways than the one described in the standard, but still has the same result.

There are numerous spreader designs on the market that include articulated steering utilizing some method for mechanical sensing of the differential angle to affect "… the movement of the steered trailer wheels… [are] firmly linked to the relative angle between the longitudinal axis of the towing vehicle and that of the trailer" as outlined in the ISO 26402 standard.

The following not-to-scale graphic shows the events that transpire during an equipment roll-over event that occurs while traversing a slope. On sloping terrain, the gravitational pull on both the tractor and implement provide lateral forces that cause the equipment to ease its way down-slope (**Figure 9**). The spreader tracking follows the tractor on flat ground; the spreader tires follow the steering lead of the tractor front tires (**Figure 10**). The operator must generally steer the tractor slightly up-slope to compensate for this tendency. The tractor is forced to retain or maintain the implement's position on the slope. The tractor's steering tires are directed up-slope to compensate for the gravitational pull of both the tractor and implement.

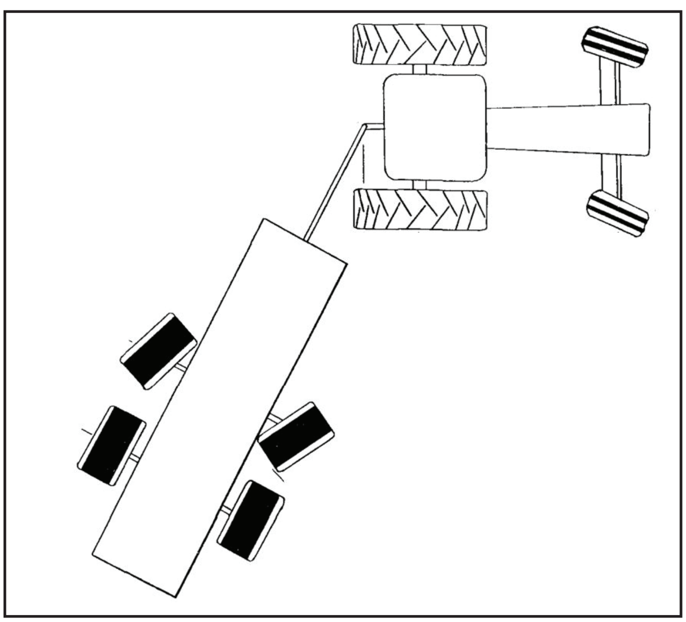

Figure 7
Trailer articulated steering (dual-axle is shown) from Laguë (1991). Reprinted with permission.

But the equipment follows a more direct path across the slope, so long as the tractor has enough power to compensate for the force of gravity on the equipment.

Furthermore, as the angle steepness of the side-slope increases, the CG for the equipment moves toward (and often over) the down-slope tires, increasing the weight they must carry. Operating in this fashion over long periods causes more rapid wear of the tread on the down-slope tires, even more than when compared to the up-slope side. Tread-worn tires provide less resistance to side forces and slide down-slope more readily than tires with full tread. In

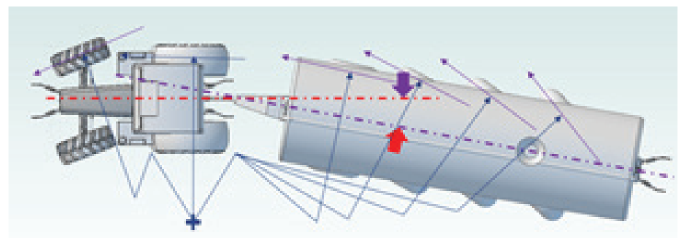

Figure 8
Spreader tires steer depending on the tractor front tires on the flat ground, but independent of tractor front tires on a slope.

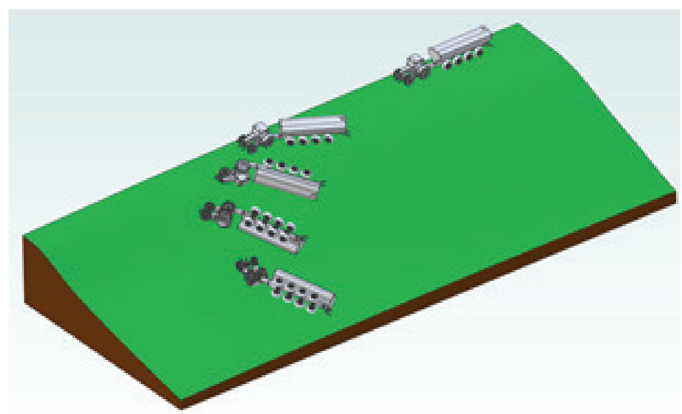

Figure 9
Sequence of the roll-over event.

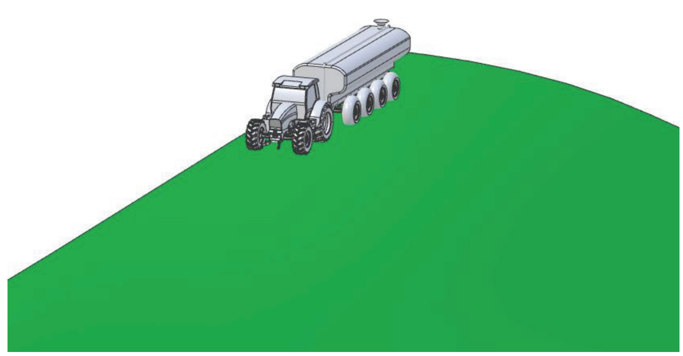

Figure 10
Equipment traverses the slope.

addition, as the side-slope angle increases, both the tractor and the implement may approach their static stability angle.

Role of Inertia in ROPS Failure

When a spreader filled with liquid manure tips over, the results are different than when an open wagon filled with silage tips over, for example. When an open wagon tips over, the mass the wagon is carrying dumps out, and is no longer part of the inertial mass that is revolving around the longitudinal axis of the vehicle.

In the case of a spreader or nurse tank, the mass of the content is contained and acts in a manner that contributes to the roll-over inertial loading. Unless the spreader or nurse tank breaks free (and is jettisoned from the drawbar pin during the roll-over event), some of the implement's inertial energy, which can be significant, will more likely than not be dissipated into the ROPS.

Role of the Articulated Steering System in ROPS Failure

By far the largest issue causing the roll-over event is with the conventional articulated steering system on the implement (**Figure 11**). When the implement slides down the slope, the conventional articulated steering function does what it is designed to do: It senses the differential angle between the tractor's drawbar and the longitudinal plane of the trailing implement and adjusts the lead and trailing axles' tire steering angles accordingly. Unfortunately, the implement's articulated steering tires are turned in the wrong direction to assist the operator with maintaining position of the equipment on the slope. The force vectors are reversed as the implement attempts to turn down-slope quickly because of its mass, increasing the lateral force on the equipment's articulated tires due to the force of gravity (**Figure 12**).

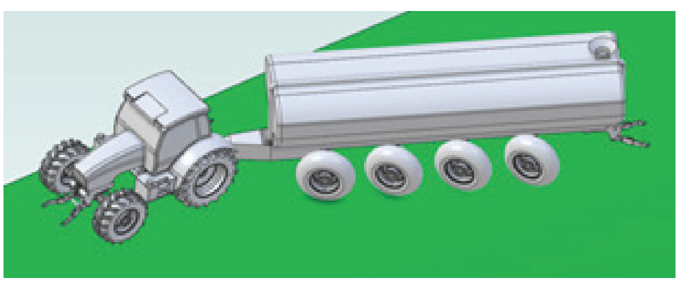

Figure 11
Spreader accelerating down slope as a result of articulated axle steer of the spreader.

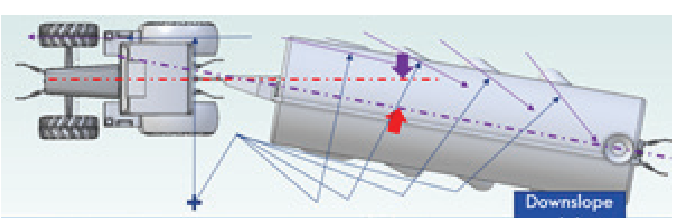

Figure 12
On a slope, the spreader mass pulls the spreader downslope in the direction of the articulated tires, loading the tractor drawbar.

A free-body diagram of the spreader would demonstrate an increasing longitudinal force on the tractor at the height of the drawbar as a result of the lateral forces on the articulating tires of the spreader. The largely resistive forces of the articulated tires would eventually initiate a counter-clockwise roll of the implement. The up-slope tires of the tractor are raised off the ground when the spreader starts to tip over as shown in **Figure 13**.

The tractor operator may react by increasing the up-slope angle of the tractor's steering tires to compensate for the error, and in moments, due to the accelerating slide of the implement, the tractor quickly loses enough power to overcome the additional force, as a result of misdirection of the implement's steered tires.

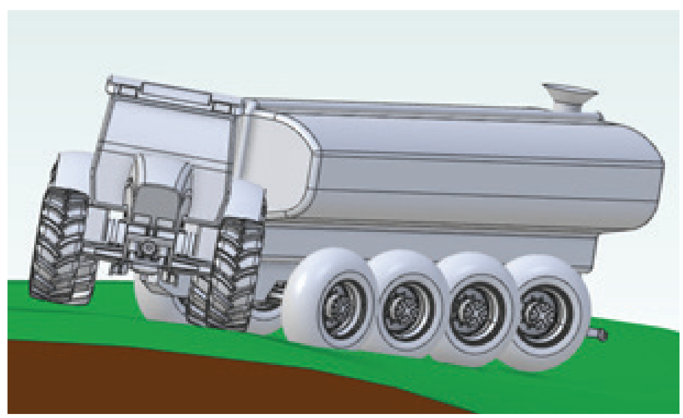

Figure 13
Spreader accelerating down slope as a result of articulated axle steer of the spreader.

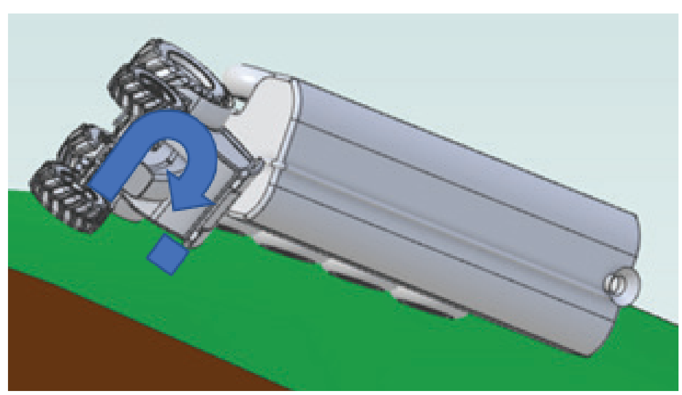

Figure 14
Spreader tips and drives the tractor roll, which applies the enormous side impact to the ROPS.

Once the implement slides far enough down-slope from the tractor, the moment generated by the draft force applied by the drawbar to the spreader's tongue, tips the spreader over (**Figure 14** and **15**). When the hitch pin connection remains intact and the implement is a spreader, the rotational inertia properties contribute greatly to the energy the ROPS must absorb in the roll-over event. The spreader tongue lifts and rolls the tractor's drawbar. This additional rotational inertia contributed by the spreader is extremely significant, adding much more energy that the cab must absorb. This will be discussed further in the analysis section of the paper.

The incident demonstrated in **Figure 16** and **17** shows a liquid manure spreader overturned on a roadway in Landcaster, Pennsylvania in September of 2017.

Even though the terrain is only slightly sloped, the rear of the tractor is clearly elevated from the ground. The tractor would have continued to roll if it had not been obstructed by a tree. Clearly, the liquid manure tank is of sufficient mass to raise the rear of the tractor by its drawbar (**Figure 18** and **19**).

In the worst scenario, the ROPS is crushed to the height of the hood and rear wheels in the overturn (**Figure 20** and **21**). There is no room left in the crush zone for operators, especially if they are properly wearing their seat belt. The roll-over event under these circumstances is catastrophic, and survivability is low (**Figure 2**). The resulting crush is unreasonably dangerous to the operator and

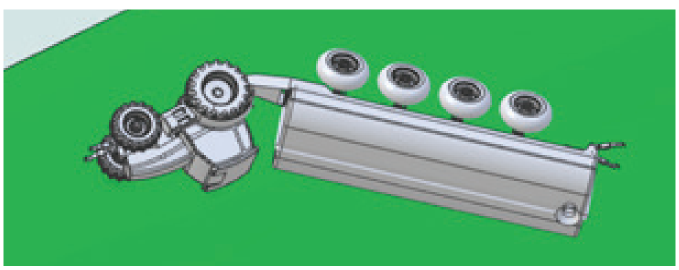

Figure 15
Spreader tips and drives the tractor roll,
which applies the enormous side impact to the ROPS.

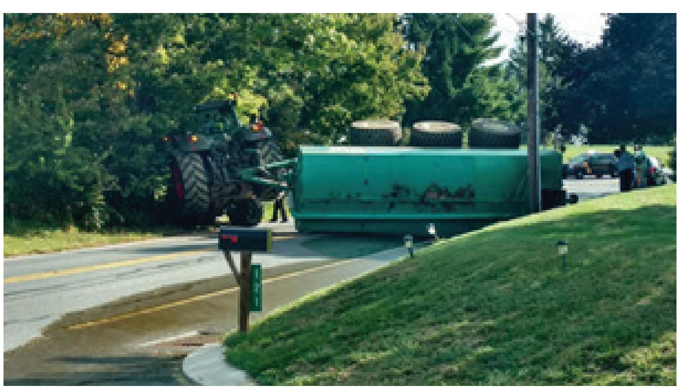

Figure 16
Overturned spreader along the roadway.
LNP – Lancaster Online (2017)[9]; reprinted with permission.

Figure 17
Overturned spreader along the roadway.
LNP – Lancaster Online (2017)[10]; reprinted with permission.

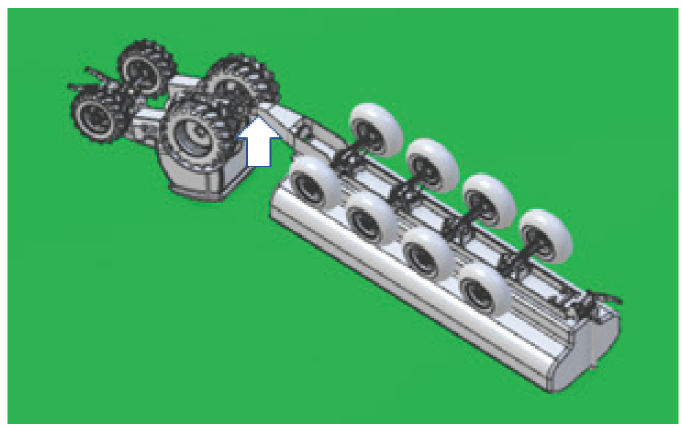

Figure 18
Spreader lifts the tractor up by the drawbar,
causing tractor frame damage.

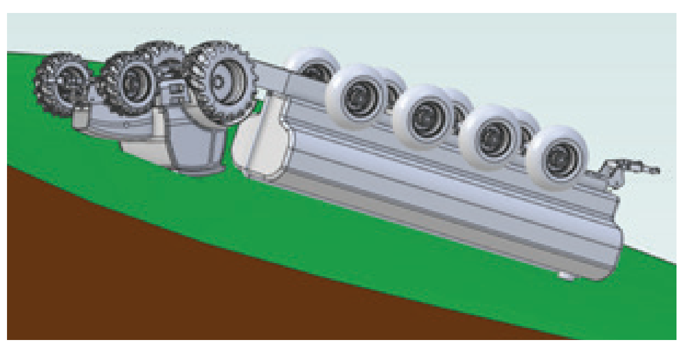

Figure 19
Spreader lifts the tractor up by the drawbar,
causing tractor frame damage.

the occupants of the ROPS. When the tractor and spreader remain coupled (**Figure 22**), high vertical forces (**Figure 23**) are introduced to the tractor by the spreader.

ROPS That Have Been Known to Fail

In addition to the case the author investigated, authorities from Workplace Health and Safety Queensland, Australia, recognize the limitations of ROPS under the special circumstances and issued a bulletin in 2010 titled, "Tractor roll-over protective structure (ROPS) limitations," which stated that use of large spreaders are not permissible with the ROPS standards in place today. They showed a tractor whose ROPS had failed as a result of a roll-over event with an articulated spreader (**Figure 24**).

They state that:

"Calculations have shown that the energy of ***the combined masses of the tractor and trailer*** *... would be*

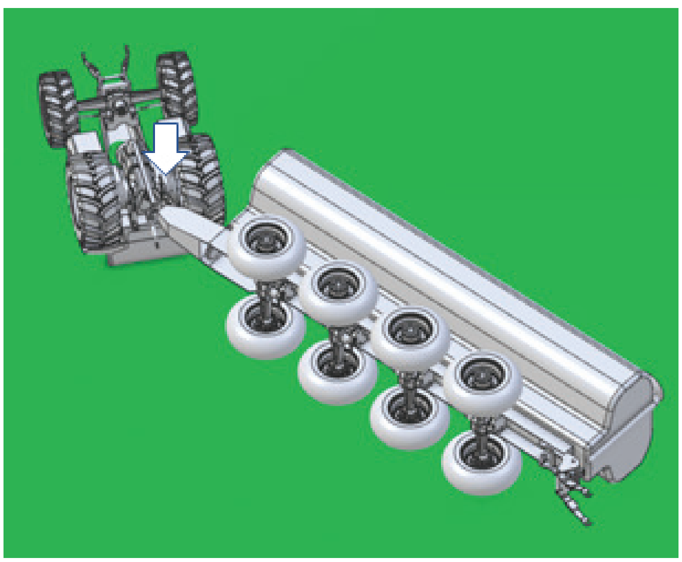

Figure 20
Spreader tongue crushes the tractor down
by the drawbar causing further damage to the ROPS.

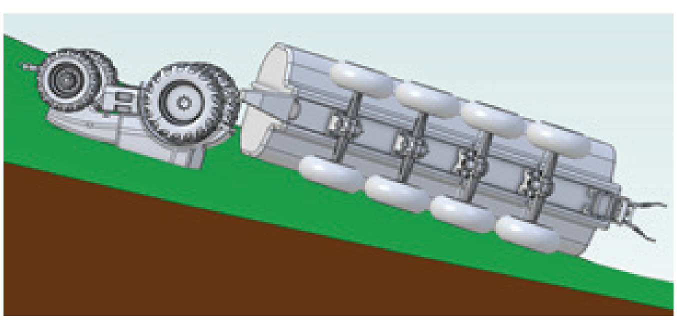

Figure 21
Spreader tongue crushes the tractor down by the
drawbar causing further damage to the ROPS.

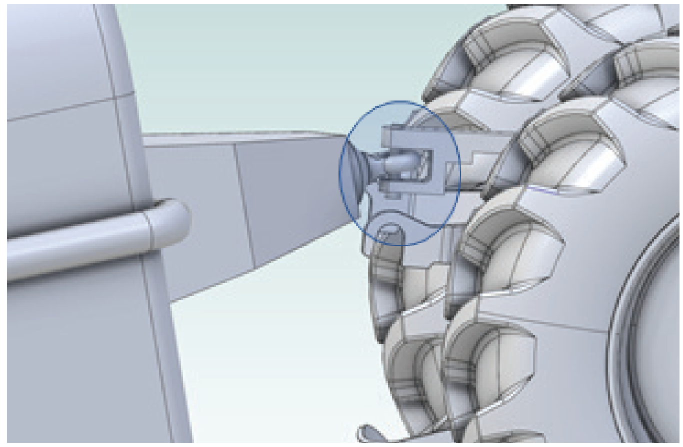

Figure 22
Hitch pin connection remained intact after the roll-over event.

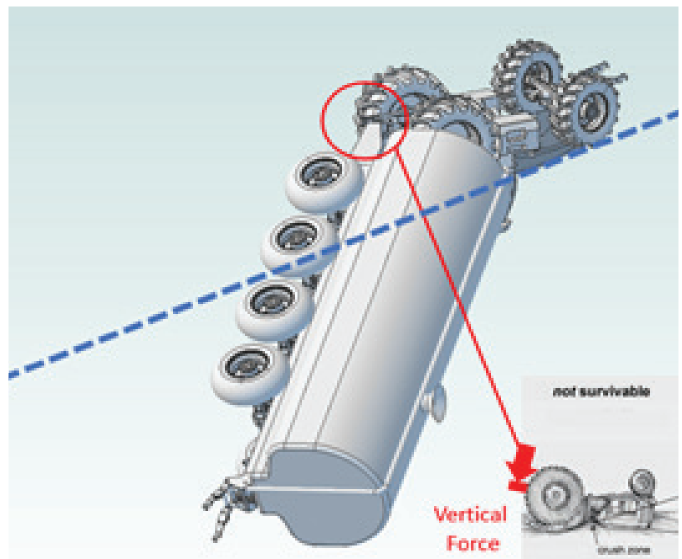

Figure 23
Final position tractor and spreader after the roll-over event.

Figure 24
Exemplar photograph of failed ROPS From
WorkCover Queensland (2010). Used with permission.

Figure 25
Exemplar photograph of failed ROPS.
From WorkCover Queensland (2010); reprinted with permission

more than that required by the code and could not be dissipated by the ROPS.

Significant contributing factors to this incident were the speed and mass of the tractor and trailer combination, as well as the use of [articulated steering] on the front axle of the trailer (emphasis added)[9]*."*

Manufacturers set the "reference mass" for testing. Industry standards do not directly specify "the energy of the combined masses of the tractor and trailer," as the Australian authorities would suggest. The manufacturer of the tractor determines the "reference mass" for ROPS certification (**Figure 25**). The only criteria in the standards, the "reference mass" needs to be greater than the tractor mass.

All other energy sources, except for the mass of the tractor, are largely ignored by most tractor manufacturers, but probably should not be. Manufacturers often set the "reference mass" by rounding up to the nearest 500 kg above the tractor mass of the largest tractor in the tractor line up that is named on the test certificate.

Summary of Causes for ROPS Failure

ROPS are tested according to industry standards. However, simply meeting the requirements of a standards does not absolve a manufacturer from producing a safe product. Furthermore, some standards are more stringent than others. In a study of 300 tractors overturn tests, C. Jarén, et al. concluded that "[SAE J2194] is less aggressive than SAE J1194 in side-load comparisons[10]."

Energy levels differ as a result of the tire interaction in the dynamic testing. There are known cases when the tractor's ROPS failed due to excessive side and crush loads applied during an overturn with a spreader. The operators of the equipment were seriously injured or killed.

Weight of Responsibility for ROPS Failure

The tractor and spreader manufacturers knew (or should have known) that a spreader can weigh almost double or more than the weight of the tractor. Furthermore, spreaders are becoming larger than standards have accounted for in the past. A review of the operator's manuals (OMs), however, shows that none of the manufacturers appears to provide proper warning or instructions precluding the operator from simultaneously operating the equipment across slopes — and if a warning for not traversing slopes is stated, the nature of the slopes are not defined.

The tractor and spreader manufacturers knew (or should have known) that the mass and the geometry of the spreader, including its liquid cargo, can contribute significantly to the forces imposed on the tractor's ROPS during the overturn. While the hitch components stay together, forces imposed by the tipping and rolling of the spreader are directed to the tractor drawbar — then into the ROPS.

Spreader Characteristics Causes for ROPS Failure

Considering the mass of a spreader, the tall shape of the tank and the low attachment point of the hitch, the tongue on the spreader acts like a crane when the spreader starts to tip, lifting the rear of the tractor (**Figure 26**). As the spreader rolls, the swiveling clevis and tongue of the spreader follow the contour of the upper tank (since the tank is full of liquid, little apparent deformation of

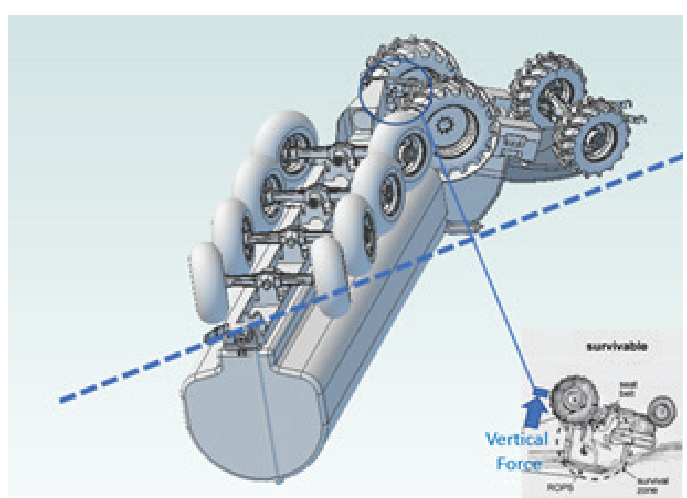

Figure 26
Spreader tongue acting like a crane raises the rear of the tractor.

the tank shape occurs).

The spreader's tongue first lifts the rear of the tractor by the drawbar, yielding a rotational acceleration of the tractor into the side impact with the ground that is greater than anticipated by the standard. The drawbar and spreader tongue then acts like a cam follower, applying downward forces again to the tractor drawbar. This adds crushing forces larger than the forces anticipated in the standards to the ROPS structure with the tractor turned completely upside down.

During the lift described above, the spreader's tongue also introduces a very large vertical load on the drawbar that jeopardizes the integrity of the ROPS mounting points. The vertical load physically lifts the tractor off the ground by the drawbar and can cause tractor chassis components that provide ROPS mounts to fail. ROPS standards should be revised to introduce spreader induced drawbar vertical loading consist with a roll-over event in future testing procedures. Additionally, the logic used to steer the spreader on relatively flat ground works well (**Figure 27**). However, when on slopes, this logic is flawed — making the problem of controlling the position of the spreader on a slope worse, if not impossible, for the tractor operator to maintain control.

Crab Steer to Compensate for Slopes

With limited effectiveness, some manufacturers in the spreader industry recognize the safety implication of drawbar differential angle sensing and are beginning to design sensors that detect slope angles as the vehicle crosses a slope. Some of these systems use electronically controlled steering systems to compensate for slope by steering the tires of the spreader up-hill (**Figure 28**) especially in sloped conditions (referred to as "crab steer mode")[11].

One such manufacturer states in its brochure that, "Optional Crab Steer Mode [is] available which steers the front and rear axle the same direction to steer up the slope [emphasis added][11]." In this mode, the steering of the spreader is set to systematically and continuously climb the hill at the appropriate speed and thus maintain its position on the slope.

Although the spreader can still slide downslope with crab steering, the tire angle remains fixed and does not accelerate the spreader into a sharper turn, as does articulated steering. This gives the operator a little more time to respond. Unfortunately, this option has not yet become standard equipment for all spreaders. Furthermore, along with crab steering, it is foreseeable that ISOBUS has the potential to assist with vehicle-to-vehicle controls necessary to properly trail vehicles in slope conditions.

The spreader's conventional power-steering logic flaw with mechanical drawbar angular sensing causes the spreader to accelerate the down-slope slide, making it difficult or impossible for the operator to control or recover the position of the spreader on the slope by maneuvering the tractor alone.

Operator Attentiveness and Skills

Caught up in the moment and from the awkward position of the tractor holding the jack-knifed spreader on the hillside, the operator runs out of obvious options, so he decides to continue moving the tractor forward. The operator's decision to proceed only causes the side load and increasing tipping moment on the implement tongue that rolls the spreader followed quickly by the tractor.

Probably the safest, yet least obvious maneuver is to slowly stop the tractor, shut off the spreader's discharge pump, put the tractor into reverse, and slowly ease the

Figure 27
Comparison of regular and crab steer modes on flat ground.
From Nuhn (2017); reprinted with permission.

Figure 28
Comparison of regular and crab steer modes on flat ground.
From Nuhn (2017); reprinted with permission.

spreader down the slope onto flat ground. Such a maneuver allows the heavier vehicle (the spreader) to take the lead down the hill. With proper maneuvering, the tractor would follow right behind the spreader to safer ground. Such a maneuver, however, would necessarily require a great deal of user training to help develop the skills to recognize the onset of the implement slide.

Equipment manufacturer associations develop information and training to assist the industry with safety and compliance. Thus far, there has been no training materials published by these associations on proper use or misuse of articulated steering spreaders.

Analysis

There are several reasons ROPS fail. They include:

- Vertical loading of the drawbar hitch pin exceeds the industrial standard vertical drawbar design load for the tractor, causing chassis component failure eliminating the solid connection between the tractor chassis and the ROPS.

When the ROPS mounting points fail, the ROPS no longer performs as designed.

- When the drawbar hitch pin remains intact throughout the roll-over event, the energy from the inertia induced by the spreader is unaccounted for and must be considered in the ROPS design to prevent failure from occurring, especially during crush loading conditions.

Spreaders are designed to be transported on highways as well as operate in soft field conditions. The spreader is therefore designed with large flotation tires. The bulk of the tank is raised to clear the tires, which increases the height of the CG.

Although most of the USA/Canadian spreaders do not use control linkage connection described in the ISO 26402 standard directly, the principle for the control link between tractor and implement is very similar. The connection between the drawbar and the trailer generally includes a proprietary articulated sensor device connecting some part of the tractor drawbar to some part on the spreader. Hydraulic assist on the mechanical sensor is used to steer the spreader tires. The logic used to turn the multi-axle steer wheels is conventionally based on the angular difference between the drawbar of the tractor and the tongue of the spreader. Furthermore, the equipment is often used in old grazing land to spread liquid manure on a field as it traverses across slopes on hill farms; some of the terrains being significantly steep.

Since the tread on the spreader tires is designed for flotation and not necessarily for traction, the tires are more prone to sliding. Specific surface coverage from manure dispensed from the tank can cause an even further reduction of coefficient of friction between the tires and grass surface from subsequent passes across the field. If the tires have excessively worn tread, this may also increase the likelihood of slide on a slope in steeper terrain conditions.

The CG of the spreader is high; therefore, the spreader rolls first, followed shortly after that by the tractor through its direct coupling with the drawbar. The dimensions of the spreader tank and the location of the spreader tongue produce a cam action that transfers the inertia of the spreader to the tractor from the onset of the overturn. The spreader coupler, working as a crank, accelerates the tractor's roll. The mass of the tractor and the spreader are virtually combined and exceed the "reference mass" (m_t) determined by the tractor manufacturer. The tractor and spreader do not necessarily separate during the roll-over event with the spreader tongue hook is design to swivel 360 degrees.

Furthermore, the roll event abruptly suspends the tractor from the spreader tongue, imposing loads greater than half the mass of the tractor. Industry standard ISO6489-3 limits the vertical drawbars loads for various categories of tractor based on horsepower, but in all cases they are well under half the mass of a fully ballasted tractor.

The suspension of the tractor from its drawbar hitch pin produces an unreasonably dangerous condition that causes the failure of chassis components that support the ROPS attachment. When the spreader tongue is at its apex in the roll-over event, it imposes large forces on the drawbar hitch pin (**Figure 19**) that exceeds the tractor's industrial standard vertical drawbar design load[12].

Spreaders can range from 1.5 to 4.5 times the mass of the tractor, depending on whether the spreader is equipped with brakes[13]. There are studies to identify ways to determine the moment of inertia of mass for tractors[14]. The same methodologies could also be extended to equipment.

When the tractor and spreader remain connected, the inertial loads of the spreader must be accounted for and included in the ROPS testing. The connection between the tractor and the spreader are coupled together by the spreader's tongue connected to the tractor's drawbar. During the roll process the axis of rotation is generally aligned through the tractor and spreader with the coupling offset to the height of the hitch, much like a piston throw on an engine crankshaft.

In broad concept, however, the energy to stop a rotating equipment is dependent on moment of inertia of mass and the angular velocity of the body. We know from basic course work in kinematics and dynamics of machines that energy (E),

$$E = \frac{1}{2} J_M \omega^2 \quad [5]$$

where "J_M" is the moment of inertia of masses and is generally dependent on the geometry and the mass of the rotational object and "ω" is the angular velocity of the body.

The moment of inertia, J_M, for a cylinder with reference to the longitudinal axis of that cylinder is:

$$J_{M \text{ for a cylinder}} = \frac{1}{2} m_{\text{cylinder}} r^2 \quad [6]$$

The tractor could be approximated by a cylinder as shown in **Figure 29**. The cylinder for the combination tractor and spreader is only longer to include the spreader (**Figure 30**). Since the tractor and spreader do not separate at the drawbar, the equipment rolls together, and the spreader has much the same shape as the tractor.

Assuming the tractor and the spreader are about the same diameter. Radius r, is roughly half the height of the tractor (**Figure 30**) and the same for the spreader. If the distribution of mass is homogeneous within the approximated cylinder, then the value of JM equipment is proportional to the total mass of the equipment as compared to the tractor for JM tractor to the "reference mass."

Adding the "reference mass" of the tractor (m_t) to the mass of a full spreader (1.5 mt to 4.5 m_t) can yield the mass of the equipment as much as 5.5 m_t (1 m_t + 4.5 m_t) times the "reference mass" of the tractor alone.

Rewriting the energy equations [2] and [3] from the current standards, but substituting 5.5m_t to account for the equipment in place of m_t for the tractor alone, the maximum energy requirements for side impact when the spreader inertia is accounted for could be roughly 5.5 times larger and expressed as follows:

$$E = 2450 + 16.17\, m_t \quad [7]$$

$$E_{is} = 9.625\, m_t \quad [8]$$

The crush force should also reflect the additional load imposed by the spreader.

$$F = 55\, m_t \quad [9]$$

When the hitch pin stays intact during the roll-over event, adding the spreader's mass increases the testing "reference mass" by 2.5 to 5.5 times. Failing to include the spreader in the calculation of test "reference mass" produces an unreasonably dangerous condition. Rearranging terms and solving for ω from equation [5],

$$\omega = (2 * E_{is} / J_{M \text{ equipment}})^{0.5} \quad [10]$$

Substituting $J_{M \text{ equipment}}$ from equation [6] and E_{is} from equation [8] in equation [10] yields the following:

$$\omega = 2.65 * r \text{ (rad/s)} \quad [11]$$

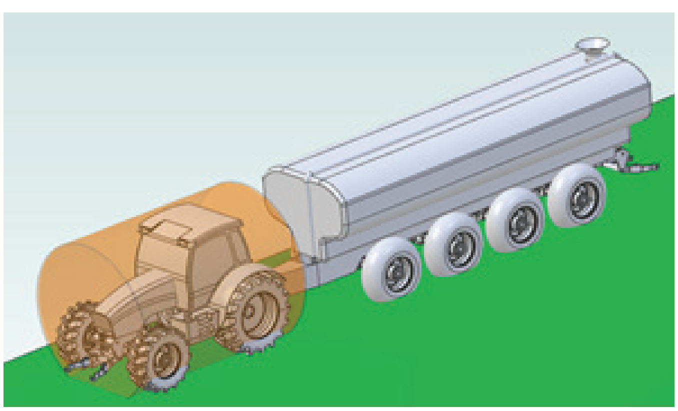

Figure 29
Tractor approximated by a cylinder of vehicle length.

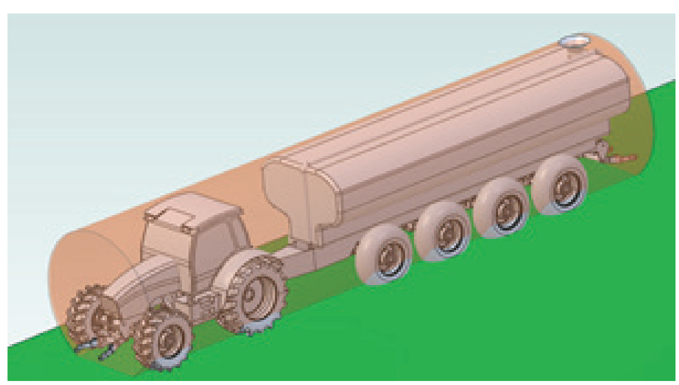

Figure 30
Equipment approximated by a cylinder is longer but as the same radius.

Stated another way, instead of lashing the tractor to the ground, one could visualize testing the tractor at the current "reference mass" by rotating it about its longitudinal axis at a constant speed ω, into the pendulum drop of the current dynamic test (see **Figure 31**). The timing of rotation would necessarily be such that the impact occurs when the tractor is vertical. This would be much like what actually occurs in practices as demonstrated in **Figure 14**. The ROPS' initial impact with the ground includes the inertial loads of the spreader in addition to the tractor.

Currently, tractor manufacturers grossly understate required energy absorption levels by only selecting "reference mass" representative of the tractor mass, ignoring the contribution of inertia induced by attached implements. They generally do not account for the combined mass of the tractor and spreader, assuming (hoping) the tractor and implement break free from each other during a roll-over event. Standards should be updated to reflect significant larger inertial loads on the ROPS structure when a roll-over event occurs with a spreader attached or a spreader should be prohibited from use on slopes that could result in a tractor roll-over.

Foreseeable Use and Misuse of the Equipment

Some of the significant questions the analyst must address are as follows:

- Was the tractor maintained and operating properly?
- Was the spreader maintained and operating properly?
- Did the information in the owner's manuals (OMs) address the circumstances and situation?
- Were there any errors or omissions from the instructions by the manufacturer?
- Were all the instructions and warnings in the OMs followed?
- Was the operator using the equipment properly?

Safety Engineering/Risk Management

As a means of mitigating this risk, vehicle manufacturers' compatibility study groups and industrial standards committees with oversight of tractor/implement interfaces should employ standardized risk assessment techniques such as the one proposed by ANSI/AIHA Z10-2012 section 5.1.2, i.e., "Hierarchy of Controls" and explained by Fred Manuele in his book "Advanced Safety Management[15]." The preferred order of control is as follows:

- Risk avoidance
- Elimination
- Substitution
- Engineering controls
- Warning systems
- Administrative controls
- Personal protective gear

As pointed out by Manuele in chapters 14 "Hierarchy of Controls: Section 5.1.2 of Z10" and 16 "Prevention through Design: Section 5.1.1 to 5.1.4 of Z10," this order of application is important and leads to the most effective way to minimize risk.

Many perceptive vehicle manufacturers conduct equipment compatibility studies to understand the interfaces and interactions of their vehicle with other vehicles in the same power class to determine vehicles that are free

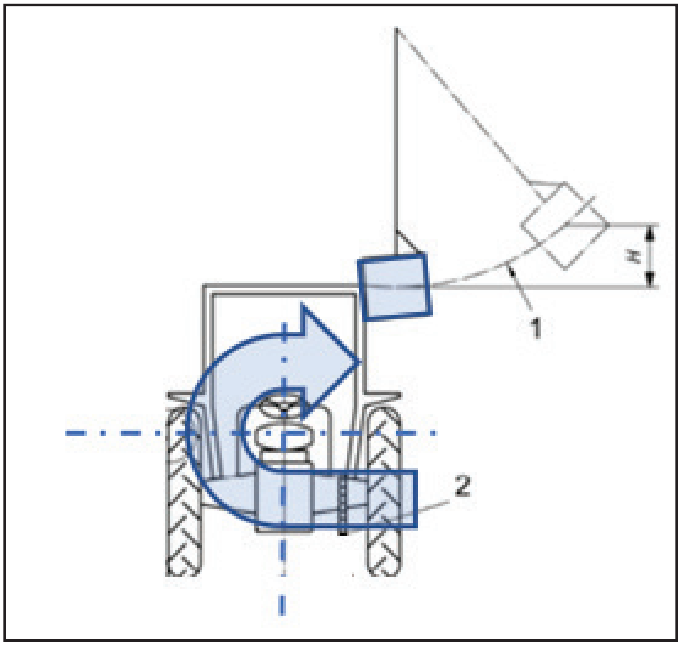

Figure 31
The additional inertia contributed by the spreader must be included, much like rotating the vehicle into the pendulum drop.

of interferences and can work safely together. The ISOBUS, described in the ISO 11783 standard, for instance, requires the combined efforts between vehicle manufacturers that incorporate significant testing before a specific farm implement is permitted to control the tractor's functions, such as ground speed, steering, and braking.

Risk avoidance is the most effective approach and must be undertaken by the manufacturers in cooperation. The interface between tractor and implement requires a group effort, so the occupants of the tractor are safe while operating this equipment. Standards for tractors and implements were generally appropriate for individual use, but ROPS may still fail when tractor and spreader are used together on steeper slopes due to the inertial contribution of the attached spreader during the roll-over event.

Safer Alternatives Exist for Spreading Liquid Manure

There are several known methods for applying nitrogen-rich slurry to the land[16,17]. A couple of methods require the liquid manure to be pumped from a lagoon into transport vehicles. These vehicles could be spreaders with tanks in the size of 1,000 to 12,000 gallons or truck-mounted tanks in the size of 3,000 to 6,000 gallons or more. They use the public road systems to carry the manure in its liquid-slurry form to the field. Over time, the size of tank trailers has increased to reduce the number of trips from the lagoon to the field.

One method to spread liquid manure includes a tractor-mounted implement that pulls a length of hose across the field (**Figure 32**)[18]. A nurse tank and pump provide the source and power to move the slurry across the field, but the nurse tank and pump are static and located at one end of the field. In such cases, the CG of the implement remains low and is not a significant factor in the tractor/implement interface for slurry distribution.

Rather than spray, some choose to knife the liquid manure in to the ground (**Figure 33**). This practice of direct injection keeps the turf from becoming slippery on subsequent passes.

More Attention to the Tractor/Implement Interface

Standards committees should also continuously examine the broader scope and implications of standards they approve to be sure all the known issues have been addressed and mitigated to the greatest extent possible; meaningful oversight of standards at the equipment level

Figure 32
Drag-line application of liquid manure from the Livestock and Poultry Environmental Learning Center (2019); used with permission.

is imperative. It is the author's belief that ROPS and tractor/implement interface standards committees must interact with each other more than they do today to make sure the combination of vehicles and implements is also safe and appropriate for public use.

Compared to the tractor industry, the spreader industry has fewer industry standards and regulations, such as hitch pin sizing and type, tow chains, performance brakes, and road lighting. One such voluntary standard is the ISO 26402, which regulates the size and location of a ball used to steer semi-mounted trailers[19]. This standard presumes the semi-mounted trailer uses an attachment to the drawbar frame itself or on the rear of the tractor to mechanically steer the trailer[20].

Figure 33
Direct injection of liquid manure from the Livestock and Poultry Environmental Learning Center (2019); used with permission.

The industry makes use of steering axles on multi-axle spreaders because of the high stresses that would otherwise be induced into the axle components when the laden spreader turns in the field. The spreader steering system is sold to customers as a means of preventing rutting, smearing, and tearing up the sod in their grasslands. The operator turns the trailer steering on when working in the field. The trailer steering is generally locked out in road transport.

ISOBUS is also being used to interface implements with tractors logically and electronically. This technology is important going forward to determine what functions are possible, given a specific tractor/implement context. More use will be made of this interface on new products reaching the market.

Symbols, Warnings, Displays, and Manuals

Warnings are placed on vehicles to identify known hazards and how to avoid them. Manuals provide the operator with the proper way to select and use the equipment he is using. It is incumbent on the manufacturers to describe limitations and the dangers of using the equipment. The warnings are further explained throughout the manuals to assist the operator with background and knowledge for the directive.

Numerous standards have been written and provide direction for manufacturers to follow[21]. The Association of Equipment Manufacturers (Agricultural) has compiled a list of those standards which may affect the vehicles used by their constituents. Proper instructions must be documented, and warning alerts must be placed in such a manner that the operators are aware of the limitation of the vehicles they are operating. The operator's manual states how to use the vehicles from a manufacturer's independent perspective but fails to identify the issues with the combined vehicle and implement or at the equipment level of use.

Summary and Recommendations

To prevent ROPS tragedies from occurring, it is recommended that authorities having jurisdiction and industry standards committees include requirements that more closely represent the loads spreaders induce into the tractor in a roll-over event. A vertical load, based on gross vehicle weight (GVW) should be applied to the drawbar to determine if the chassis is capable of being lifted off the ground by the spreaders tongue, attached to the tractor's drawbar, while the spreader remains connected to the tractor. ROPS standards should reflect this added step in the standard ROPS testing process.

Industry, in general, encourages operators to depend upon the protection of ROPS during roll-over events and wear their seat belts. Although the frequency of accidents resulting from ROPS failure may seem low, exposure is rising with market growth of the subject equipment. Sales of liquid manure spreaders have increased year by year; liquid manure is being applied by spreaders onto sloped hill farms across the country. Most importantly, the severity of ROPS failure is high under these conditions, resulting in a level of certainty for serious injury and fatality if the spreader rolls over.

With market growth trends toward larger equipment, OSHA should reconsider minimum energy thresholds incorporated in 29 CFR 1928.52, 1928.53, 1926.1001 and 1926.1002 and increase the energy absorption levels for ROPS to accommodate implements like spreaders.

Trade and standards organizations responsible for tractors, ROPS, spreaders, tractor implement interface (including drawbar and hitch pins), PTO and ISOBUS should be encouraged to find ways to work across committee boundaries to identify tractor/implement characteristics. The topics may include such items as implement stability and directionality (including steering or side slip); methodologies to mitigate vehicle incompatibilities in growing market segments; and finally considering automation where necessary to prevent high-risk exposure to unsuspecting operators. Other topics may require review and increasing the energy absorption levels in existing ROPS standards based on what implements the tractor is pulling, adding appropriate warnings for operations on slopes, and removing conflicting standards that contribute greatly to energy levels ROPS must absorb to protect the occupants in a roll-over event.

Manufacturers of both tractors and larger, heavier, and higher CG implements, including spreaders, should be encouraged to work together through tractor/implement compatibility issues along with the appropriate voluntary industrial standards committees. They should be encouraged to take oversight of this unreasonably dangerous use of the subject type of equipment on slopes. It may even require that manufacturers agree to withdraw dangerous products from the market place. This includes for example, tractor and spreader with steerable axles sensing the differential angle between the tractor's drawbar and the longitudinal plane of the trailing spreader that steer the trailer and increase the propensity to roll the equipment. Higher energy absorption levels for ROPS should be considered when designing for contributing implement inertia when it is significant in the roll-over event.

A risk avoidance approach would encourage industry manufacturers to work together to sense side slip of the spreader in slope conditions and use this information in steering logic for both vehicles. Manufacturers of vehicles should be encouraged to use electronic steering systems with crab-steer and tractor tire steer angles sensing to maintain spreader position on feasible slopes. Using ISOBUS technology, the same electronic steering systems should prevent the use of the spreader on non-feasible slopes where side slip is too extreme to operate the equipment (shut the spreader discharge pump off and warn the operator to seek more level ground).

At a minimum, a slope indicator should be mounted in the cab of the tractor, and slope limitation should be spelled out clearly in all the operator's manuals. Wherever possible, proper warnings[22] should be displayed, alerting operators of the danger of operating high CG and stee able implements on steeper slopes. All forms of educational information should be provided to operators, including the OMs of both combinations of tractor and spreader. Finally, the minimum tire tread height should be monitored more closely by the operator when this type of equipment is used on slopes. Manufacturers' recommendations should be properly documented, and maintenance should be performed to provide adequate traction on reasonably steep slopes where hill farms exist.

References

1. OSHA Agricultural Safety Fact Sheet, "Protecting Agricultural Workers from Tractor Hazards, Overturns." Internet: https://www.osha.gov/Publications/OSHA3835.pdf [12/29/2020].

2. Northeast Center for Occupational Health and Safety in Agriculture, Forestry, and Fishing (NEC). "National ROPS Rebate Program." Internet: https://www.ropsr4u.com/ [12/01/2020].

3. OECD. "CODE 4 - OECD Standard Code for the Official Testing of Protective Structures on Agricultural and Forestry Tractors (Static Test)." Internet: http://www.oecd.org/agriculture/tractors/codes/04-oecd-tractor-codes-code-04.pdf [12/01/2020]. (See paragraph 3.5.3.1).

4. Ipinaskil. "Toolbox 14- Rollover Protective Structures (ROPS)." Internet: http://desertknight-fm.blogspot.com/2014/04/toolbox-14-rollover-protective.html [12/01/2020].

5. Manure Management. "GEA delivers 10,000th liquid manure spreader" Internet: https://www.manuremanager.com/gea-delivers-10000th-liquid-manure-spreader-30698/ [12/29/2020].

6. Jamesway. "Maxx-Trac Dura-Tech." Internet: https://jamesway.valmetal.com/wpcontent/uploads/2018/11/Michigan-10200-1.jpg [12/01/2020].

7. The Sentinel. "Road reopens after manure spill in South Middleton Township Friday." Internet: https://cumberlink.com/news/local/road-reopens-after-manure-spill-in-south-middleton-township-friday/article_5dd1f6ea-7d33-11e2-956f-0019bb2963f4.html [12/01/2020].

8. Lague, C. "A Steering System for Trailers with Multiple Axles" 1991 American Society of Agricultural Engineers 0883-8542/ 91 / 0706-0649].

9. WorkSafe, The State of Queensland. "Tractor roll over protective structure limitations." Internet: https://www.worksafe.qld.gov.au/injury-prevention safety/alerts/whsq/2010/tractor-roll-overprotective-structure-limitations#lr [12/01/2020] .

10. Jarén, C., Alfaro, J. R., Arazuri, S., Ponce de León, J. L., Arana, J. I., Assessing Rollover Safety Provided by ROPS Tests Following SAE Standard J1194 versus OECD Code 4; Transactions of the ASABE Vol. 52(5): 1453-1459; American Society of Agricultural and Biological Engineers; 2009.

11. Nuhn. "Electra-Steer Vacuum." Internet: http://nuhn.ca/products/manure-tanks/electra-steervacuum/[12/01/2020].

12. ANSI/ASABE AD6489-3:2004 JUL2017, Agricultural vehicles — Mechanical connections between towed and towing vehicles — Part 3: Tractor drawbar (See paragraph 5).

13. ANSI/ASAE S365.9 NOV2011 (R2017), Braking System Test Procedures and Braking Performance Criteria for Agricultural Field Equipment (See paragraph 10.1 and 10.3).

14. Mishra. "TTS 2.6 : TRACTOR CENTER OF GRAVITY & MOMENT OF INERTIA" Internet: https://youtu.be/H2s-Zu53hVw [12/29/2020].

15. Manuele, F. Advanced Safety Management – Focusing on Z10 and Serious Injury Prevention, Hohoken, NJ: John Wiley & Sons, Inc.; 2014, Chapter 14 &16.

16. eXtension. “Liquid Manure Application Equipment.“ Internet: https://articles.extension.org/pages/8904/liquidmanure-application-and-irrigation-equipment [02/07/2019].

17. Livestock and Poultry Environmental Learning Community (LPELC). “Liquid Manure Application and Irrigation Equipment.“ Internet: https://lpelc.org/liquid-manure-application-and-irrigation-equipment/ [12/01/2020].

18. NC State Extension Publications. “Hose Drag Systems for Land Application of Liquid Manure and Wastewater.“ Internet: https://content. ces. ncsu.edu/hose-drag-systems-for-landapplication-of-liquid-manure-and-wastewater [12/01/2020].

19. ISO 26402 - Agricultural vehicles - Steering systems for agricultural trailers - Interface for articulated steering device of semi-mounted trailers; International Standards Organization.

20. Waltersheid, “Waltersheid Forced Steering Devices ZWL 50 and ZWL 30 Brochure, GKN Land Systems, ATASC1303.1400013“ Internet: https://www.walterscheidcoupler.de /out/pictures/media/ba_6.01+6.02+6.03.6.04_zwl50_zwl30.pdf [02/07/2019].

21. Association of Equipment Manufacturers (AEM). “Standards for Safety Signs and Symbols.“ Internet: https://www.aem.org/safety-and-technical/safety/standards-for-safety-signs-and-symbols [12/01/2020].

22. Association of Equipment Manufacturers (AEM). “Standards for Safety Signs and Symbols.“ Internet: https://www.aem.org/safety-and-technical/safety/standards-for-safety-signs-and-symbols [12/01/2020].

Bibliography

ANSI/AIHA/ASSP Z10 - Occupational Health and Safety Management Systems; American National Standards Institute, American Industrial Hygiene Association and American Society of Safety Professionals .

ANSI/ASABE AD6489-3:2004 JUL2017, Agricultural vehicles — Mechanical connections between towed and towing vehicles — Part 3: Tractor drawbar.

ANSI/ASAE S365.9 NOV2011 (R2017), Braking System Test Procedures and Braking Performance Criteria for Agricultural Field Equipment.

ANSI/ASSP Z590.3 - Prevention through Design Guidelines for Addressing Occupational Hazards and Risks in Design and Redesign Processes; American National Standards Institute and American Society of Safety Professionals.

ANSI/NEMA Z535 SET - Safety color code - environmental facility safety signs - criteria for safety symbols - product safety sign & labels and accident prevention tags; American National Standards Institute and the National Electrical Manufacturers Association.

OECD. “CODE 4 - OECD Standard Code for the Official Testing of Protective Structures on Agricultural and Forestry Tractors (Static Test).“ Internet: http :// www.oecd.org/agriculture/tractors/codes/04-oecd-tractor-codes-code-04.pdf [12/01/2020].

CSA B352.1 - Rollover Protective Structures (ROPS) for Agricultural, Construction, Earthmoving, Forestry, Industrial and Mining Machines - Part 2: Testing Requirements for ROPS on Agricultural Tractors (Inactive); Canadian Standards Association.

OSHA - Agriculture (29 CFR 1928) Subpart C – Roll-Over Protective Structures; U.S. Department of Labor

ISO 3463 - Tractors for agriculture and forestry — Roll-over protective structures (ROPS) — Dynamic test method and acceptance conditions; International Standards Organization.

ISO 5700 - Tractors for agriculture and forestry — Roll-over protective structures — Static test method and acceptance conditions; International Standards Organization.

ISO 11783 – Tractors and machinery for agriculture and forestry -- Serial control and communications data network; International Standards Organization.

ISO 26402 - Agricultural vehicles - Steering systems for agricultural trailers - Interface for articulated steering device of semi-mounted trailers; International Standards Organization.

SAE J 1194 – Roll-Over Protective Structures (ROPS) for Wheeled Agricultural Tractors; Society of Automotive Engineers, International.

SAE J 2194 - Roll-Over Protective Structures (ROPS) for Wheeled Agricultural Tractors; Society of Automotive Engineers, International.