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The Stability of Self-Propelled Sprayers According to the ISO 16231 Standardized Procedure

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Tractor rollover and agricultural machinery stability are subjects of interest both to manufacturers and researchers. Agricultural machines often work on rough terrain and sloping ground so instability and rollover events can easily occur. For agricultural tractors the solution adopted at international level was to provide them with Roll-Over Protective Structures (ROPS) to minimize risks for the driver in a rollover event. ROPSs are designed to absorb and sustain values of energy and forces established by the normalized OECD procedure. In the standardized tests it is necessary to evaluate the deformation of the ROPS because a clearance zone has to be maintained for the driver. Self-propelled sprayers currently have to comply with the EC 2006/42 Directive requirements and if recognized as being at risk of potential rollover a protective measure for the driver has to be defined by the manufacturer. The object of this evaluation was to assess the stability of self-propelled sprayers designed for arable crops according to the procedure in the ISO 16231-1/2 standard and evidence critical points in the provisions of the standard procedure. The standard defines a method to measure the Static Overturning Angle (SOA) of agricultural machines to be compared to a Required Static Stability Angle (RSSA) representing the limit for evaluating ROPS fitment on the machine. The measured angles allow it to be understood if such machines require ROPS installation. The stability angles measured were much higher than the required static stability angles so the rollover risk assessment produced a low risk for the sprayers and a ROPS protection was not needed.

1. Introduction

The stability of agricultural machines in field operations has been a subject of interest to the scientific community since the 1950s mainly because of the high number of fatal accidents due to tractor rollover (Arndt, 1971; Myers, 2000). Over the years studies have been conducted in many countries for improving tractor stability (Franceschetti et al., 2014, 2016). Contemporarily the approach of passive protection of the driver to mitigate the adverse effects in case of machine overturning was adopted (Moberg, 1964; Manby, 1970). A Roll-Over Protective Structure (ROPS) became mandatory in Europe for tractor road circulation in 1974 and led to a sharp decrease in severe injuries and fatalities due to rollover accidents (EC Directive 74/150/EEC, 1974). A mathematical model was developed based on geometrical and inertial characteristics of the tractor (Schwanghart, 1984) and included in the normalised procedures for narrow-track tractors (OECD Code 6, 1990); it allows tractor stability performance to be analysed with respect to a slope of 34° before performing the ROPS strength tests. Over the years the ROPS approach was not restricted only to tractors because the same protective solution, together with standard procedures for strength evaluation, has been adopted for earth moving and forestry machines all around the world (ISO 3471, 2008; ISO 8081, 1985). A recent debate in Europe was addressed to evaluate the potential rollover risk for agricultural self-propelled machines (ASPM) by analysing their static stability conditions. A European standard was therefore defined to assess the static stability angle of ASPM with the aim of comparing it with a codified angle considered for each ASPM category as the limit to decide if a ROPS protection has to be provided for the driver (ISO EN 16231-1/2, 2015). Clearly tractor rollovers are the most frequent accidents recorded in national agriculture databases by reason of the huge number of tractors in the world (Springfeldt, 1996; Thelin, 1998). Nevertheless, accidents with fatal outcomes are documented internationally mainly for self-propelled mowers, sprayers, grape harvesters and combines (Scarlett et al., 2006). Referring to European safety requirements for machinery (EC Directive

2006/42/EC, 2006), self-propelled sprayers must be fitted with an appropriate protective structure where there is a recognized risk of rolling or tipping over, unless this increases the risk. It was therefore of interest to analyse the stability conditions of self-propelled sprayers. The object of our evaluation was to assess the stability of self-propelled sprayers designed for field crops according to the procedure indicated in the standard ISO 16231-1/2 in order to calculate the Static Overturning Angle (SOA), compare the SOA with the Required Static Stability Angle (RSSA) stated in the procedure and evidence critical points in the provisions of the standard procedure.

2. Materials and Methods

2.1 Machines and equipment

Two self-propelled sprayers for field crops, manufactured by Grim Ltd (Jesi, AN, Italy) (Figure 1) were considered for the tests. Both sprayers had a front cantilevered cab, water tank in a central position and engine positioned at the rear. The main technical features of the two machines are summarized in Table 1. The two models (identified as type 1 and type 2) were equivalent in design; they differed mainly in the total mass, wheelbase and water tank overall capacity. Tests were performed with the boom-sprayer in the transport position, i.e. folded against the sides of the machine.

Table 1: Technical features of the sprayers.

Feature	Parameter	Unit	Type 1	Type 2
Mass	M	kg	5730	7360
Wheelbase	W	m	2.90	3.30
Track-width	T	m	2.05	2.00
Tyre Index Radius	R	m	0.70	0.75
Tyre-width	P	m	0.25	0.30
Water tank	m_s	kg	2500	5000
Swivelling Axle Height	U	m	0.70	0.75


Type 1


Type 2

Figure 1: Sprayers tested at Grim Ltd plant.

Tests were addressed: to measure the weight of the two sprayers to calculate the position of Centre of Gravity (CoG); to measure the parameters in Table 1; and to define the CoG position of the water tanks to account for the laden machines. Four wheel scales and a laser measuring device with inclinometer were used. The sprayers were lifted and held in the measurement position by means of a crane with a hoist. The tests were performed according to the ISO Standard 16231 to evaluate the stability of the two sprayers, unladen and laden, by calculating the Static Overturning Angle (SOA) in case of roll and tip-over. CoG position of the sprayers with empty and full tanks was determined in order to calculate the SOA. The SOA obtained were compared with the Required Static Stability Angle (RSSA) defined by the ISO Standard for the risk assessment of self-propelled sprayers in the case of rollover and tip-over.

2.2 CoG determination of unladen and laden sprayer

The Centre of Gravity (CoG) of the unladen machines was determined by means of four scales, one for each wheel, and a hoist as support stands. As indicated in the procedure outlined in ISO Standard 789-6 (1982), adopted as reference by the stability standard, the CoG was defined by the suspension and ground reaction method. The ground reactions with the sprayers in a horizontal position allowed the horizontal CoG position (*x-y* coordinates) to be calculated. The machine was then tilted at one end, increasing the load on the resting axle. The lifting angle (α) and increased load on the scale allowed the height of the CoG (*z* coordinate) to be defied. The horizontal fore-and-aft coordinate (x) was obtained measuring the axle loads, with the brakes off, and calculating x from the mass (m) and wheelbase (w) of the machine by equation (1), where F_2 is the ground reaction at the front axle due to the machine mass (Figure 2 (1)). The lateral coordinate in the horizontal plane (y) was determined measuring the left-hand (F_4) and right-hand (F_5) wheel loadings (Figure 2 (2)).

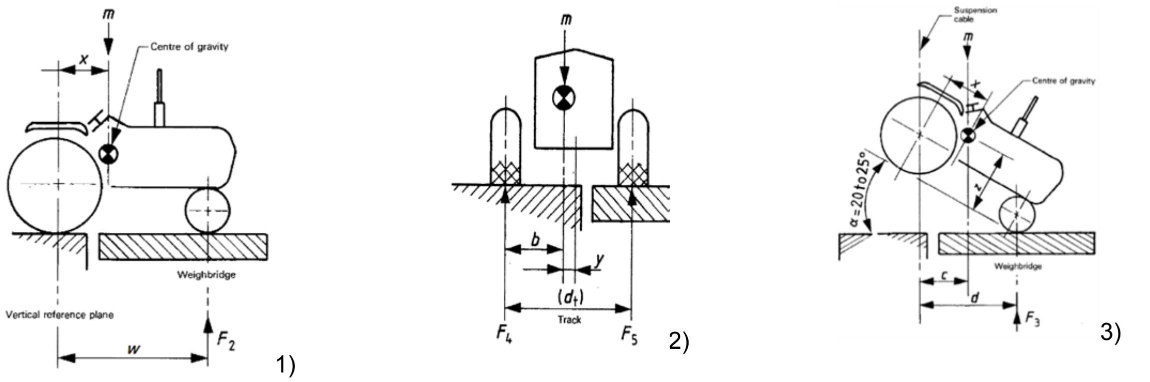

Figure 2: Reference for the determination of the coordinates of CoG: 1) horizontal fore-and-aft (x), 2) lateral (y) and 3) vertical (z).

The offset (b) of the CoG was obtained using the wheel track (d_t) as the moment arm (Eq 2); the lateral coordinate y was given by Eq (3). The vertical coordinate (z) was obtained measuring the reaction (F_3) at the ground contact on the scale. The horizontal distance (d) from the ground contact to the line of suspension was measured (Figure 2 (3)). The horizontal distance (c) from the CoG to the line of suspension was calculated (Eq 4-5). When the machine was in a horizontal position the vertical distance (e) was measured from the centre of the axle in contact with the ground to the axis of suspension. The vertical distance (h) from the centre of the axle in contact with the ground to the CoG refers to Eq (6) and the height of the CoG with respect to the ground (z) became the sum of h and the index radius of the wheel (r in Table 1) in contact with the ground (Eq 7). If the index radius of the suspended wheel is higher than the wheel in contact with the ground “minus” instead of “plus” is required in equations 5 and 6.

$$x = \frac{w\, F_2}{m} \tag{1}$$

$$b = \frac{d_t\, F_5}{m} \tag{2}$$

$$y = \frac{d_t}{2} - b \tag{3}$$

$$c = \frac{d\, F_3}{m} \tag{4}$$

$$c = (d - x)\cos\alpha \pm e\ \sin\alpha + h\ \sin\alpha \tag{5}$$

$$h = d\, cot\, \alpha \left[\frac{(F_3 - F_2)}{m}\right] \pm e\ \left[\frac{F_3 - m}{m}\right] \tag{6}$$

$$z = h + r \tag{7}$$

Weighing a laden machine at an angle was not practical and unsafe, consequently the CoG of the laden machines was obtained by an alternative method. The weight and CoG of the tank were assumed taking into consideration the location of the tank with respect to the other parts of the machines. CoG coordinates of the laden machines were calculated using equations 8-9-10 as the centre of mass of a system of particles having m_i masses. M is the laden machine mass and m_i are the unladen machine mass and the full tank mass respectively.

$$x = \frac{\sum_{i=1}^{2} m_i x_i}{M} \tag{8}$$

$$y = \frac{\sum_{i=1}^{2} m_i y_i}{M} \tag{9}$$

$$z = \frac{\sum_{i=1}^{2} m_i z_i}{M} \tag{10}$$

2.3 SOA determination for lateral rollover and tip-over

The Static Overturning Angle (SOA) was evaluated for both the laden and unladen machine. In order to maintain a continuous contact between the wheels and the ground, many self-propelled machines have one swivelling and one fixed axle. Following the provision of ISO Standard 16231-2, the rolling line of the tyres on the fixed axle, when the machine rolls laterally, was assumed at 75% of the tyre width. It is hypothesised that without the axle swivel limiting device, when placed on a tilting platform, the machine reaches, then exceeds the SOA_α (as assumed in ISO 16231-2 method), and rolls over when the vertical projection of the CoG falls outside the triangular surface formed by ABC (Figure 3a).

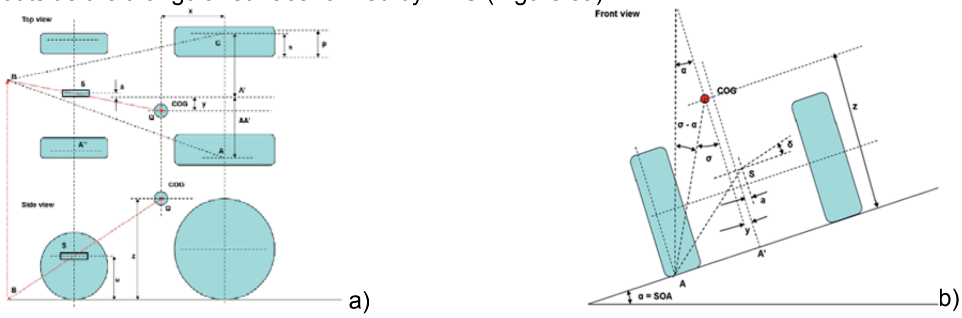

Figure 3: Determination of the stability: a) Graphical determination of the stability triangle, b) COG during roll-over around line AS and angles in the same transversal plane.

The tested sprayers were equipped with a swivel angle limiting device on the swivelling axle, which acts during lateral rollover because it restricts the swivelling of the axle prior to the complete overturn of the machine. The wheel of the fixed axle, opposite line AB (Figure 3a), loses contact with the ground and lifts up. The body of the machine rolls around the line AS and stops when the swivelling axle hits the stroke limiting device. At that point, the stability line is formed by the contact points of front and rear tyres. In this configuration, the SOA can be considered equivalent to the angle provided by Eq (11). The stroke limiting device is effective only when the angle of the swivelling axle keeps the vertical projection within the stability line formed by the tyres, in order to absorb the dynamic effects of rolling around line AS. However, ISO 16231-2 states that assessing whether the inertia of the machine rolling around line AS would result in a complete tip-over, in spite of the new stability line, is difficult to predict. In order to avoid the risk of rollover, the stroke limiting device seems effective only if an assumed safety margin is defined. ISO stability standard assumed a margin of $1.25 \cdot \delta$, otherwise the SOA will correspond to SOA_α (Eq 12). Angles α, σ, and δ are illustrated in Figure 3b. The SOA_σ (Eq 13), with respect to the line formed by the front and rear wheels, according to Eq (11) denotes AA' as the base line of the stability triangle (Figure 3a) and Δo is the difference in track width between front and rear tyre.

$$SOA_\sigma = tan^{-1}\left(\left(AA' - y - \left(\Delta o\ \frac{x}{w}\right)\right)\frac{100}{z}\right) \tag{11}$$

$$\sigma - \alpha < 1.25 \cdot \delta \ \Rightarrow \ SOA = \alpha \tag{12}$$

$$\sigma - \alpha \geq 1.25 \cdot \delta \ \Rightarrow \ SOA = \sigma \tag{13}$$

The machine tips forward when the vertical projection of the CoG crosses the line of the contact point of the front wheels with the ground. In this case, the SOA was calculated as the ratio between the horizontal position of the CoG (x) and height of the CoG (z) (Eq 14). The machine tips rearward when the vertical projection of the CoG crosses the axle line of the rear wheels. The SOA was the ratio between the horizontal position of the CoG (*w – x*) and the height of the centre of gravity (*z*) (Eq 15).

$$SOA_F = tan^{-1}(x/z) \quad (14)$$

$$SOA_R = tan^{-1}((W-x)/z) \quad (15)$$

3. Results

3.1 CoG determination of unladen and laden sprayer

The sprayers were raised by the front axle until a slope of 15°, achieving the 20° slope not being possible because of the configuration of the machine and the height of the overhead-travelling crane. The increase in rear axle weight due to the inclination of the machine was recorded and the position of the lifting points of the machine measured. Data were used to determine the CoG by means of the alternative mathematical model. Table 2 gives the coordinates of the CoG with respect to the coordinate system represented in Figure 3.

Table 2: x, y, z coordinates of the CoG of the sprayers

		Type 1		Type 2	
	Unit	unladen	laden	unladen	laden
x	M	1.43	1.62	1.49	1.74
y	M	0.01	0.01	0.00	0.00
z	M	1.64	1.66	1.80	1.86

3.2 SOA determination for lateral rollover and tip-over

The CoG coordinates were used for determining the SOA values. The two machines had a swivelling front axle. Table 3 gives the results of the standard methodology. The differences between SOA_σ and SOA_α were always greater than $1.25 \cdot \delta$. As a consequence, the reference angle was the SOA_σ. Nevertheless, the SOA of the two machine types in both configurations, unladen and laden, were higher than 12.7°; which is the RSSA established for "Field crop sprayer" in ISO 16231. A comparison between SOA_σ, SOA_α and RSSA is depicted in Figure 4. Table 4 shows the results of Tip forward and Tip rearward angles, SOA_F and SOA_R calculated for the sprayers in unladen and laden conditions. Again the angles were higher than the RSSA stated by the ISO standard (20.6°).

Table 3: Static Overturning Angle of the sprayers

		Type 1		Type 2	
	Unit	Unladen	laden	Unladen	laden
SOA_σ	degrees	33.3°	33.0°	30.9°	30.0°
SOA_α	degrees	22.0°	19.6°	19.6°	18.7°
Margin	degrees	11.3°	13.4°	11.3°	11.3°

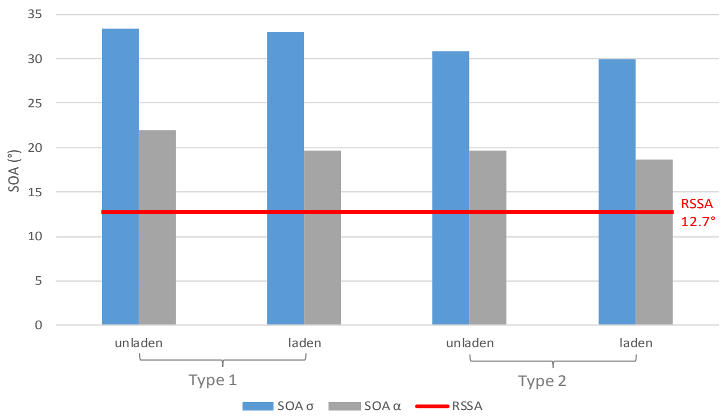

Figure 4: SOA_σ and SOA_α for the unladen and laden sprayers. Red line represents the RSSA

Table 4: Tip-Over angles of the sprayers

		Type 1		Type 2	
	Unit	unladen	laden	unladen	Laden
Tip Forward	degrees	41.1°	44.3°	39.6°	43.1°
Tip Rearward	degrees	41.9°	37.6°	38.1°	40.0°

4. Conclusions

The stability assessment on the two models of self-propelled sprayers designed for field crops, performed by determining the static overturning angles with respect to the RSSA foreseen by the ISO 16231 standard, showed that the rollover and tip-over risk is low and a ROPS fitment is not needed. Nevertheless the ROPS approach for the tractors is mandatory and allowed fatal accidents due to tractor rollover to be sharply decreased over the years (Springfeldt, 1996). In reason of this experience the compulsory installation of a ROPS on the self propelled sprayers could produce the same result over the time.

Furthermore the application of the procedure evidenced some critical points. The first objection is addressed to the provisions for the determination of the CoG. Indeed the standard has a reference to the ISO 789-6 specifically intended for agricultural tractors. Consequently an alternative mathematical model for the CoG calculation of the unladen self-propelled sprayers had to be developed. A second point needing additional explanation to properly comprehend the provisions of the procedure refers to the swivel angle limiting device for the swivelling axle of the machine because it is totally unclear how to assess the performance of the system in stopping the rollover.

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