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Stability assessment of agricultural tractors and self-propelled sprayers

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1 *Overview on tractor rollover accidents*

1.1 Introduction

The subject of agricultural safety has been studied for several years, as it emerges from the numerous researches conducted throughout the last decades. As a matter of fact, the average agricultural worker does not perceive the vital importance of the safety issue, despite the fatal consequences that are usually derived by agricultural accidents. Due to the nature of agricultural work, a farm can be a dangerous place for a worker, as it's a working environment with a wide range of diverse operations. Consequently, the degree of danger is increased not only because of the risky working environment but also because of the multitasking nature of working duties a worker has to perform. According to the International Labour Organization's (ILO, 2011) estimation, the agricultural sector is classified as one of the most dangerous economic sectors regarding to working activity. In a world-wide context at least 170,000 agricultural workers are fatally injured every year. Still according to ILO, considering the data on mortality rates in agriculture, these have been steadily increasing if compared to other sectors, doubling the probability of fatally injured. The official statistics produced by ILO show that work accidents with crucial consequences are mainly caused by agricultural machinery and pesticide contamination. The foresaid causes have also been noted in Italy.

In fact, ISTAT kept track of the cases of work death that have been reported for the year 2015. The recorded result was that only the construction sector, with 156 cases, precedes the agricultural sector at the ranking of deaths, which counts 147 cases. The high risk of fatal accidents is mainly caused by the particular characteristics of agricultural sector's working environment. Among the various causes that lead to a high number of deaths caused by agricultural machinery, the slope of the land on which the machinery works, negatively affecting its stability, is the main cause (INAIL, 2017).

Numerous regulations have been issued throughout the last years in Italy, but also in the European context, aiming to minimize the risk to the operator's health. In regard to the prevention of the roll-over risk, the universally accepted measure designed to reduce it (Hard & Myers, 2011) (Abubakar, Ahmad, & Akande, 2010) (Mayrhofer, Quendler, & Boxberger, 2014) is the installation of roll-over protective structures

(ROPS). A roll-over protective structure (safety cab or frame), hereinafter called “ROPS”, is a term that describes the structure that is placed on a tractor in order to avoid or limit the risks that occur to the driver, resulting from roll-over of the tractor during normal use. In Europe certain countries were pioneers. Springfeldt, (1996) in his work gives us a clear vision of what the situation was in the mid-1990s in Europe. Sweden was one of the first countries to introduce mandatory ROPS on new tractors as early as the 1950s, followed by Denmark (1967), Finland (1969), West Germany, Great Britain, Spain (1975), Norway (1977) and Switzerland (1978) (Springfeldt 1996). As expected, the frequency of rollover-related fatalities decreased. Springfeldt highlights in particular that a sample of 100,000 tractors in Sweden rollover fatalities fell from 17 to 0.3 points, in Norway the frequency was reduced from 24 to 4 (1961-69 and 1979-86), in Finland from 16 to 9 (1980 to 1987), in Western Germany from 6.7 to 1.3 (1961 to 1986). A recent study in Spain on 388 fatal agricultural machinery accidents showed that the main cause of death was the overturning of tractors without protective structures (ROPS). Among the 272 deadly rollovers detected, only one was found equipped with a certified protective structure (Arana et al., 2010).

In USA, ROPS was introduced in the first place as an optional equipment for agricultural tractors in 1971. In 1976, the Occupational Safety and Health Administration (OSHA) required employers to equip all tractors used by employees and that have been manufactured after 25 October 1976 with ROPS and driver seat belts. Although it was not made mandatory by voluntary agreements between tractor manufacturers from 1985, virtually all new tractors sold in the United States were equipped with ROPS and seatbelts (Centers for Disease Control and Prevention (CDC), 1993). In an eight-state survey (Delaware, Illinois, Indiana, Missouri, New York, Ohio, Oregon and West Virginia) on 14,000 tractors, 65% of tractors was not protected from rollover and 35% had ROPS. NIOSH estimated that the introduction of ROPS prevented more than 40% of the deaths that could potentially have occurred, accounting that more than 70% of deaths could have been avoided in case that a protective structure had been installed (Dennis J Murphy et al., 2010). Another study carried out in North Carolina on 342 tractor fatalities, covering the years 1979 to 1988, shows that in the majority of cases the main cause was the overturning of the tractor, involving only 54 % of professional operators (Bernhardt & Langley, 1999). However, Loringer and Myers, point out that between

1992 and 2005, 1412 people died in the USA as a result of tractors overturning. Whilst the recognition of ROPS as a proved alternative to decrease the rate of tractor overturn deaths on farms from 1993 to 2005, it did not manage to reduce the expected rollover mortality rate (Loringer & Myers, 2008).

Among other countries, Australia had a high level of awareness of the subject as well. A study in Victoria examines fatal accidents between 1985 and 2010, from a sample of 121 tractor fatalities, claiming that 55 of these were caused by rollovers. It also claimed that after the introduction of mandatory ROPS, the result was a significant decrease in mortality, estimated at 7 percentage points per year. However, it was not possible to demonstrate that the equipment of tractors with ROPS reduced the rate of fatal accidents as other variables would come into play. (Jones, Day, & Staines, 2013) (Lower, Rolfe, & Monaghan, 2017).

Furthermore, studies have been conducted in other countries as well, such as Turkey. As a matter of fact, when it comes to Turkey the statistic data concerning safety issues related to agricultural tractors and machinery are very limited. Nevertheless, a sample of 101 accidents was examined, in the province of Hatay that demonstrates that the majority of accidents is caused by the overturning of the tractor (65.4%) and among these 25.7% ended up to fatalities while 45.5% of accidents caused non-fatal injuries. Tractors with ROPS protection accounted for 19.6% of the total, while 41.3% of tractors had a sunshade protection and 33.6% had no protective structure (Görücü Keskin, Keskin, & Soysal, 2012). Another study conducted in India on the safety of agricultural machinery in the period 2004-2007 shows that from the total number of accidents, about 30.5% were caused by agricultural machinery, 34.2% by hand tools and 35.3% by other sources. In the agricultural machinery category, the largest number of accidents is caused by tractors and tractor-operated implements (31%) followed by animal-drawn implements (22%), threshers (14%), electrical equipment/pumps (12%), miscellaneous implements (15%) and sprayers (4%). Among these accidents, 5.6 % were fatal (L.P. Gite, 2009).

An international overview of the tractor accident rate is shown in a recent study carried out by (Valda Rondelli, Casazza, & Martelli, 2018), as it is evidenced in Table 1.1.

Reference	Rate	Country	Data source years
Tractor fatalities with respect to total fatalities in agriculture (%)			
Bunn et al., 2008	48	Kentucky, USA	1994-2005
Day, 1999	72	Victoria, Australia	1985-1996
Jones et al., 2013	56.5	Victoria, Australia	1985-2010
Murphy and Yoder, 1998	32.1	USA	1992-1995
NHIOS, 2010	36	USA	2003-2007
Pickett et al., 1999	47.5	Canada	1991-1995
Present study[a]	10.6	Italy	2002-2014
Present study[b]	43.7	Italy	2000-2012
Tractor rollover fatalities with respect to total fatalities in agriculture (%)			
DeGroot et al., 2011	20.4	Canada	1990-2005
Jones et al., 2013	23.7	Victoria, Australia	1985-2010
NHIOSH, 2010	16.4	USA	2003-2007
Present study[b]	25.1	Italy	2002-2012
Tractor rollover fatalities with respect to total tractor fatalities (%)			
Arana et al., 2010	70.1	Spain	2004-2008
Bunn et al., 2008	52.2	Kentucky, USA	1994-2004
Day, 1999	61	Victoria, Australia	1985-1996
Dogan et al., 2010	37.2	Turkey, Konya	2000-2007
Jones et al., 2013	42.0	Victoria, Australia	1985-2010
NHIOSH, 2010	45.2	USA	2003-2007
Present study[b]	57.4	Italy	2002-2012

Rollover fatalities referred to ROPS equipped tractors with respect to total rollover fatalities (%)			
Arana et al., 2010	0.4	Spain	2004-2008
Day, 1999	17	Victoria, Australia	1985-1996
Myers et al., 2009	4	Kentucky, USA	2002
Present study[b]	18	Italy	2002-2012

Table 1.1 Tractor accidents rate, an international overview. Authors' elaboration based on a) INAIL, Operational Archives and on b) INAIL_ASL Surveillance System

1.2 The Italian case

Accident data are traditionally provided by the INAIL Operational Archive, which used to collect accident reports from workers covered by compulsory insurance against accidents at work. Less serious accidents are also included in this archive, so this database represents a very broad source of data. However, in June 1993, with the Italian law 243/1993, self-employed workers were excluded from compulsory insurance. Since I'INAIL only took into account professional workers, there was a sharp drop observed in the data recorded in the INAIL historical series. According to Figure 1.1 between 1992 and 1994, there was a sharp reduction of around 40% in agricultural accidents and 53% in deaths (INAIL, historical statistics). As can be seen there was a marked inversion of the tendency in the two-year period 1993-1994. This is mainly attributable to the entry into force of Art. 14 of the Decree Law. May 20, 1993 n.155, which excludes from the compulsory insurance INAIL all self-employed workers habitually for whom agricultural activity is not prevalent. In this way a large part of accidents in agriculture were excluded from the total count. All those workers are hobbyists or are not self-employed, even though they are agricultural workers. Indeed, they are not included in the INAIL statistics. Even if the INAIL database is wide, it is unable to create an exhaustive database relevant for all accidents. The only solution is to allow the information contained in the database to intersect with other information from other sources.

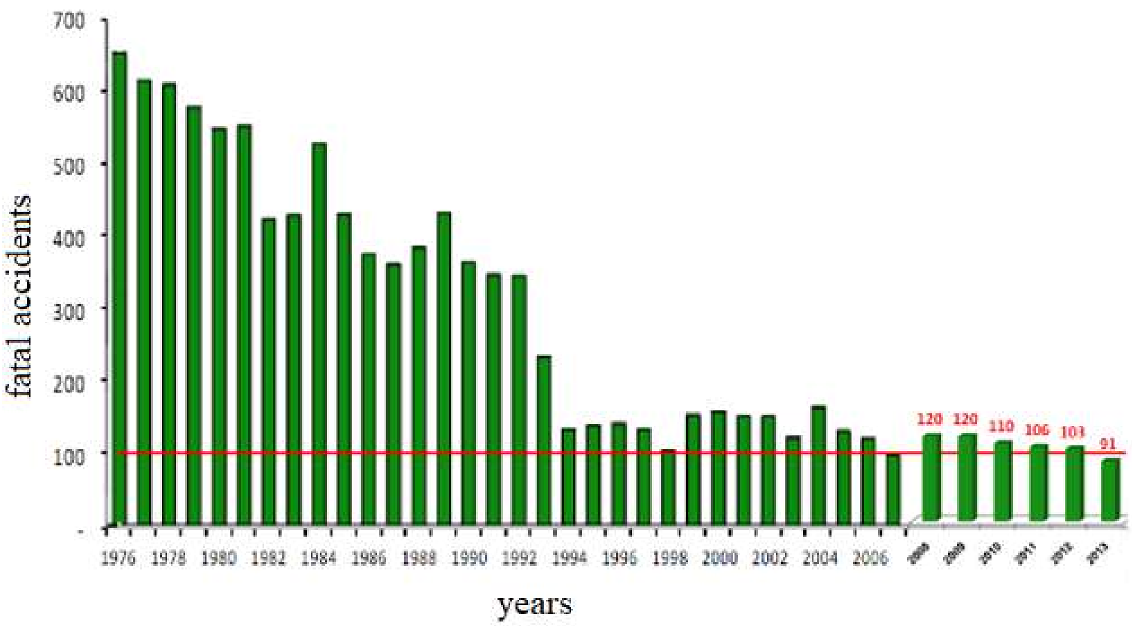

Figure 1.1 Fatal accidents in agriculture subject to compulsory insurance by INAIL (INAIL Annual Report).

In 2002 a further system for recording accidents at work place was published in Italy: the INAIL_ASL surveillance system for fatal and serious accidents at work. In the filing of accidents, a process of backward reconstruction is adopted as in legal procedures, identifying the factors that lead to the accident and those that influence its severity. Thanks to the web tool Infor.MO., some incident reports are available online even if it remains some incomplete descriptions (Lombardi & Rossi, 2013).

Since the INAIL database was available but failed to create a comprehensive and complete database, the only solution is to intersect the information contained in the database with the information from other sources. The VIII functional unit of the Department of Technological Innovation and Safety of Installations, Products and Human Settlements of INAIL then created in 2008 an observatory aiming to provide the most complete and relevant data both in terms of valid numbers and of descriptive characteristics of serious or fatal accidents. The information comes from the territorial surveillance bodies (ASL), from the news present in the main media (newspapers and press agencies), from the communications of the judicial authority, from the first aid of the hospitals and obviously from the INAIL database. In this way it is possible to limit the field and have a much more relevant picture of the real facts.

Data analysed showed that the actual number of accidents in the different reporting systems is clearly influenced by the origin of the database (Rondelli et al., 2018). Without matching cases, it may be totally inappropriate to mix data from different sources to overcome the incompleteness of each data set. However, an in-depth analysis of the different systems could allow information from the various databases to be used as a stand-alone source. (FIGURE 3)

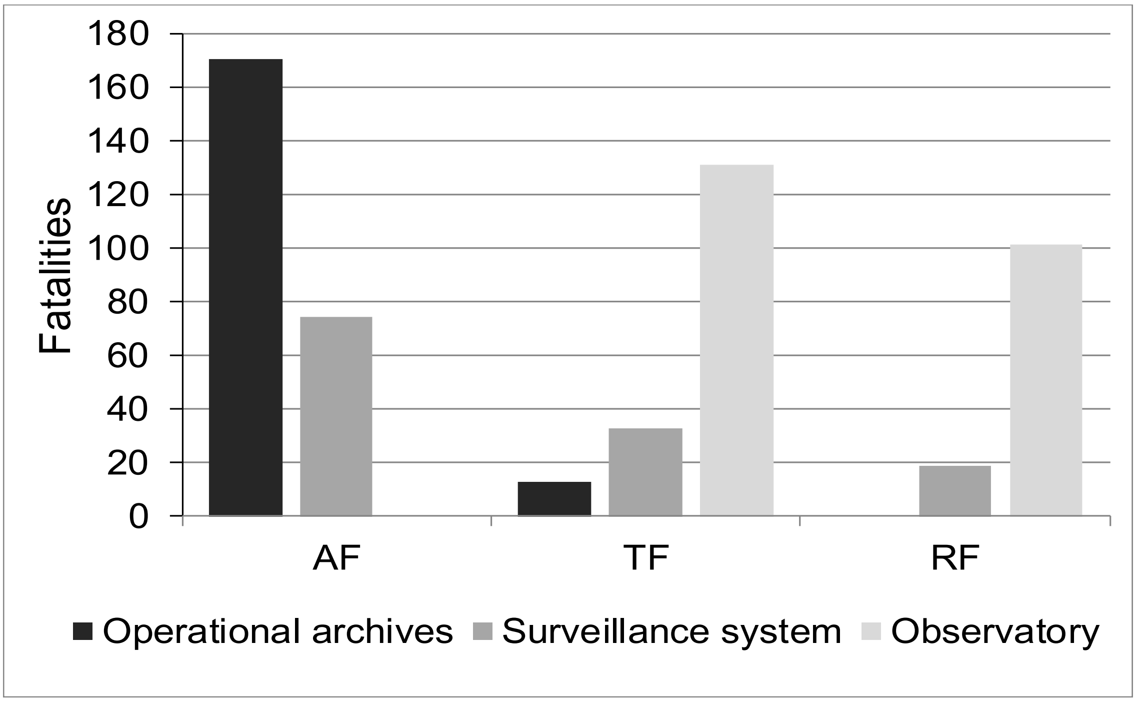

Figure 1.2 Work-related fatalities in agriculture, yearly average (2009-2012), in the three Italian reporting systems. Total fatalities in agriculture (AF), tractor-related fatalities (TF), tractor rollover fatalities (RF).

Table 1.2 shows the main causes of mortality in agriculture recorded for the period 2002-2012. A total of 205 fatal accidents occurred because of tractors overturning. An assessment of the accidents' text reports was made for the safety systems fitted to tractors at the time of the accident.

Fatalities	Frequency	%
Tractor rollover	205	25.1
Fall from height	124	15.2
Hit by falling object	88	10.8
Change in the vehicle direction (rollover excluded)	79	9.7
Contact with objects, equipment or vehicles in motion	78	9.5
Accidental starting of the vehicle	63	7.7
Contact with moving parts	69	8.4
Projections of solids	21	2.6
Direct electrical contact	19	2.3
Other fatalities	71	8.7
Total	817	100

Table 1.2 Fatalities in Italian agriculture between 2002 and 2012, source Infor.MO web tool

The main fatalities cause, with 25.1 %, is tractor rollover confirming the tendency described above.

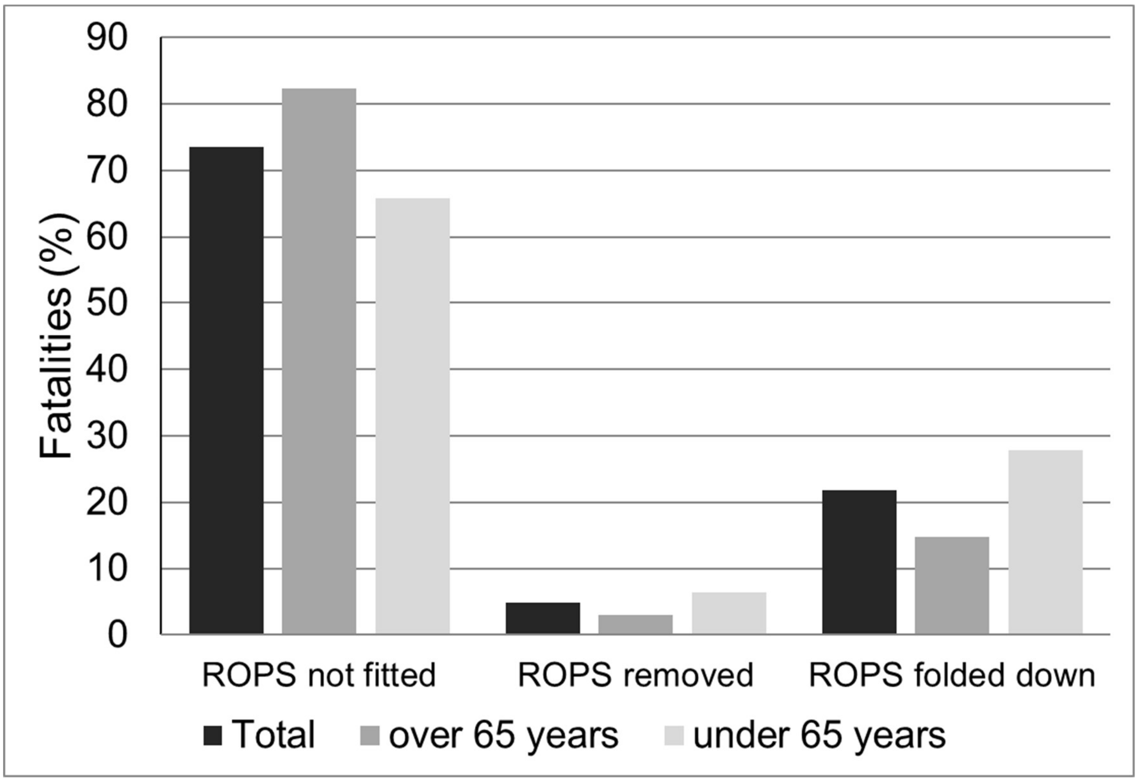

Figure 1.3 Tractor fatalities (%) related to worker age (over and under 65 years) and ROPS installation. Tractors non-ROPS equipped (no ROPS); Tractors with ROPS (ROPS); ROPS not assessed (Undefined).

From the data analysed by the various range of sources, the total average annual number of fatal accidents varies from 16 to 128 respectively for the INAIL Operational Archive and the INAIL Observatory. Even if the INAIL Observatory is the most valid source, the data it's incomplete because it doesn’t include the description of the accident. Another very interesting data is that concerning fatal accidents, in fact 71.7% involved tractor not equipped with ROPS (Figure 1.3) while for vehicles equipped with ROPS there was only one fatal accident associated with the collapse of ROPS.

1.3 Objectives of the research

Safety in agriculture is an important issue with respect to the high number of fatalities reported in the official databases. Agricultural machines certainly contribute to define the risk level in the normal operations. In view to reduce the potential risks for the agricultural operators, the machines are properly designed to minimize the risks while preserving the main features for the field operation. Generally, the design provisions are clearly defined in international standards worldwide accepted. Machine rollover is recognized as one of the most dangerous events for agricultural operator mainly because of the fatal or severe injuries. Tractor rollover has been studied since 1930th and a rollover protective structure (ROPS) was conceived as driver passive protection because it was considered nearly impossible to prevent tractor overturning during the normal operation of the machine. Nowadays the ROPS approach for the tractor is a well consolidated safety method and dedicated normalized procedures are available to test ROPS strength behaviour.

Concerning self-propelled agricultural machines, the rollover issue is a quite recent subject at the standardization level and a different approach with respect to agricultural tractors has been adopted. Indeed, the ROPS fitment on the machine becomes compulsory only if the static overturning angle (SOA) is higher than a required static stability angle (RSSA), specifically defined for each machine type.

The aim of the research carried out was addressed to analyse the stability of agricultural tractors and self-propelled sprayers.

In detail the activity performed is divided in two main themes.

1. The effect of ROPS type on the stability of narrow-track tractors was studied.
   A comparison between a front foldable ROPS and a cab ROPS was carried out for assessing the contribute of each ROPS type on the tractor stability. The interest of the evaluation raised from the international debate on the high number of rollover fatalities involving tractors mounted with foldable ROPS.
   The research carried out was presented in terms of materials and methodology, results and conclusions in the Paper “A tractor safety assessment to stress the influence of ROPS type on lateral stability” currently in the second revision for publication in the Safety Science, Elsevier Journal. The manuscript included in the thesis is the version under revision.
2. The stability of self-propelled sprayers was evaluated. The assessment was carried out 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.

The research carried out was presented in terms of materials and methodology, results and conclusions in the Paper "The Stability of Self-Propelled Sprayers According to the ISO 16231 Standardized Procedure" currently published in Chemical Engineering Transactions, 58, 61-66 DOI: 10.3303/CET1758011. The manuscript included in the thesis is the published version.

In order to enhance the comprehension of the research performed, an overview of the stability issue related to tractors and agricultural machines, of the rollover protective structures (ROPS) as passive protection for the driver in the event of tractor overturning and of the main content of the ISO 16231 standard for the assessment of self-propelled sprayers stability will be provided before to present the research outcomes.

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2 *Stability of tractors and agricultural machines*

2.1 Introduction

In order to comprehend a rollover event, it is essential to make certain simplifications. In this evaluation the tractor will be consider as a rigid body, as already performed in researches carried out on this issue (Franceschetti et al., 2014). According to the rigid body theory the deformation is therefore not taken into consideration. In classical mechanics a rigid body is usually considered as a continuous mass distribution, while in quantum mechanics a rigid body is usually considered as a collection of point masses. The assumption that the bodies are rigid, which means that they do not deform under the action of applied forces, simplifies the analysis by reducing the parameters that describe the configuration of the system (Franceschetti et al.,2014)

Notation

h	Height of the Centre of Gravity
m	Tractor's mass
CoG	Centre of Gravity
G	Weight force
T	Transversal force
N	Perpendicular reaction
L_1	Reaction force of the left tyre to the ground
L_2	Reaction force of the right tyre to the ground
w	Track width
a	Horizontal projection of the distance between CoG and L_1
b	Horizontal projection of the distance between CoG and L_2
O	Pivot point
α_{lim}	Lateral stability angle
ω	Angular velocity
v	Forward velocity
T_c	Centrifugal force
r	Radius of curvature
g	Force of gravity

2.2 Static stability

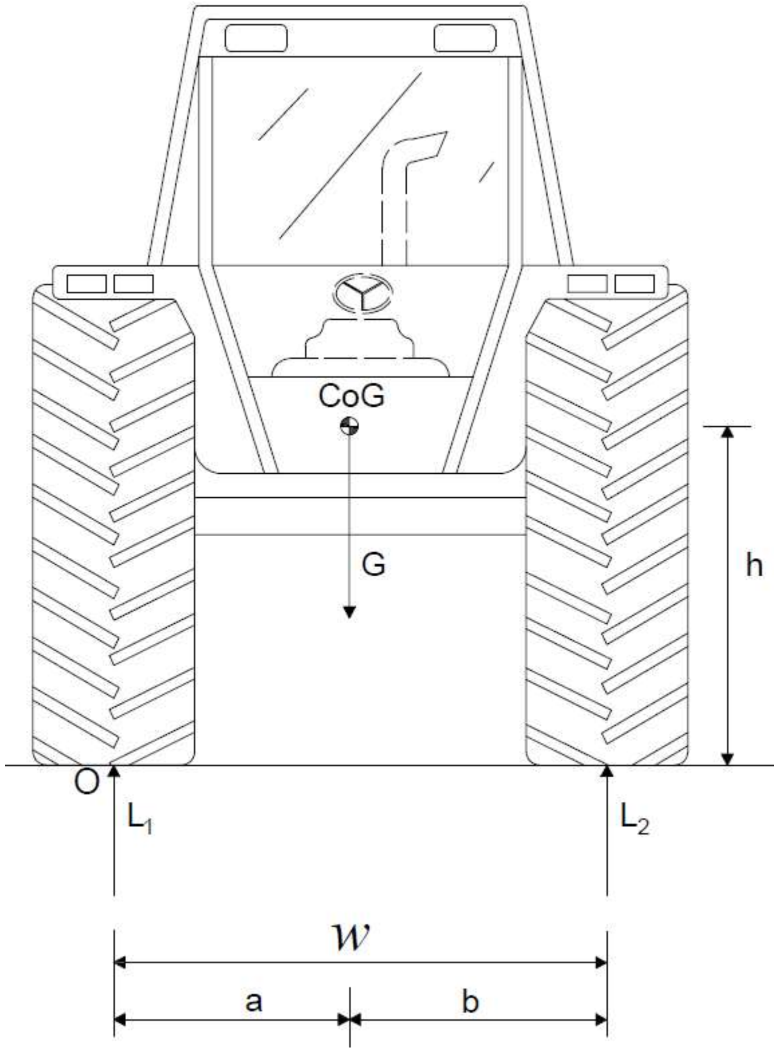

Figure 2.1 Tractor on horizontal plane

With a view to better define the concept of stability and therefore understand the theory of the rollover, we can supposing an initial situation in which the tractor is steady on a flat surface, in a context of perfect stability. Defining the tractor's mass with *m*, the centre of gravity with CoG, the mass could be considered as concentrated in the CoG. On a horizontal plane and in steady conditions (Figure 2.1), the tractor has a mass m and a weight force G=mg and the two ground reactions to the tyres, L_1 and L_2. If is h the height of the CoG and *w* the track's width, the sum of the forces L_1 and L_2 is equal to G. Taking into consideration the equilibrium of moments the relationship between L_1, L_2 and G is represented as follow:

$$\begin{cases} L_1 + L_2 = G \\ L_2\, w = G\, a \end{cases} \tag{2.1}$$

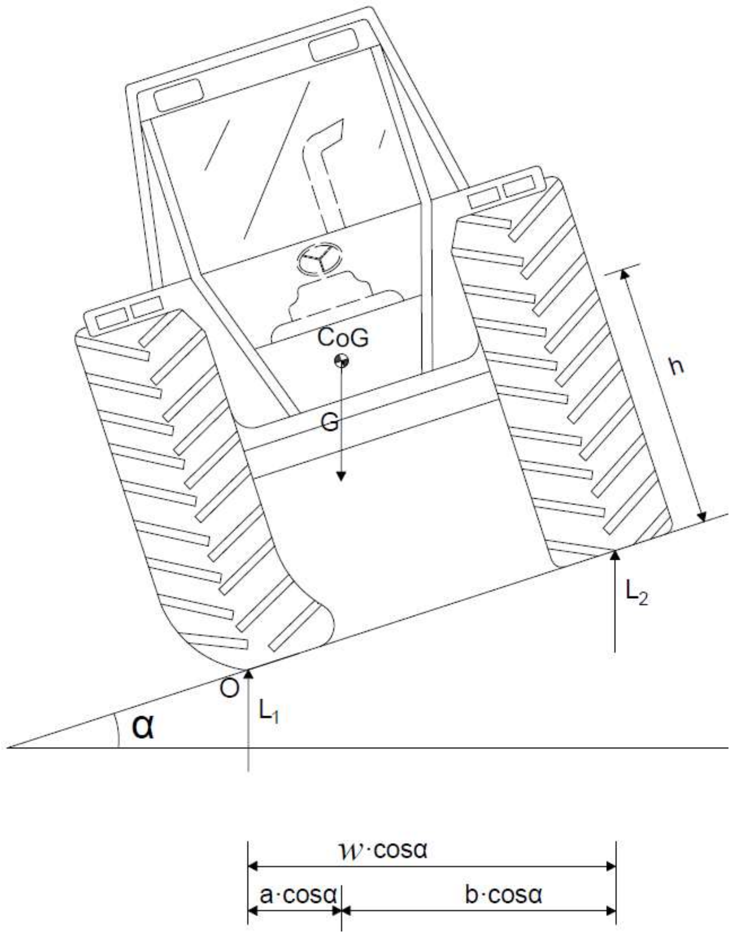

Figure 2.2 Tractor on slope

Tilting the tractor, L_2 progressively decreases. At the same time, there is a change in the direction of the resultant G, which tends to approach point O. Point O is considered as the machine's pivot point during a rollover; it is assumed as the centre of the tyre tread (OECD Codes, 2018) (Schwanghart, 1973). The tractor is still in a stable condition (Figure 2.2). In this situation the *a* decreases because the tractor is tilted. Also, the *w* changed, and the new equilibrium is:

$$\begin{cases} L_1 + L_2 = G \\ L_2\, w \cos \alpha = G\, a \end{cases} \tag{2.2}$$

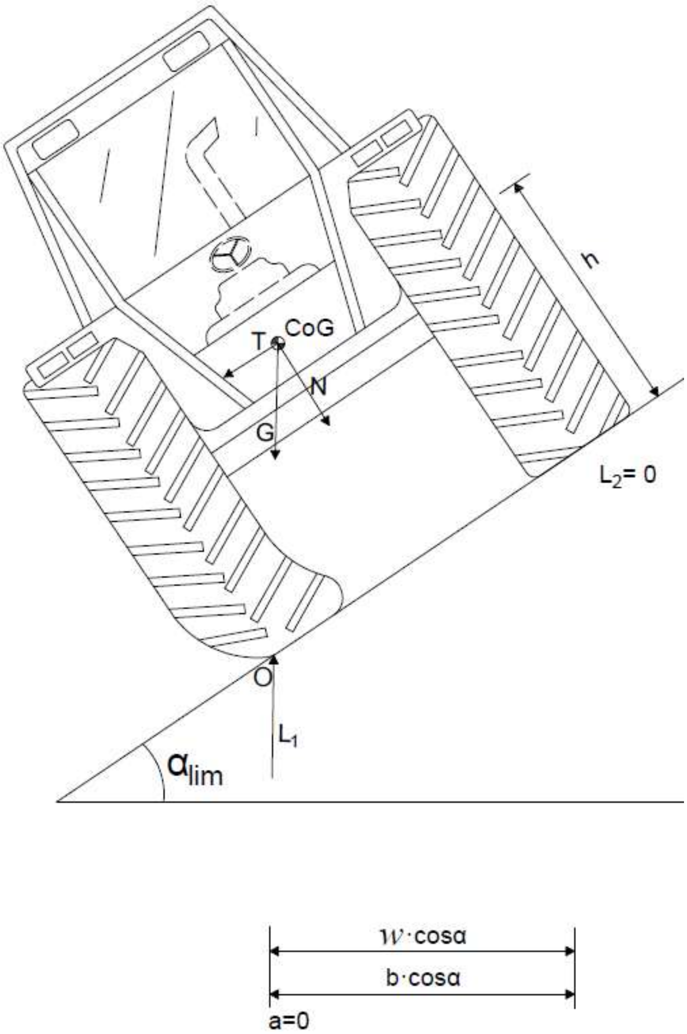

Figure 2.3 Tractor on slope in equilibrium position

Continuing to increase the sloping (Figure 2.3), until the resultant G crosses with the point O, the limit of the unstable equilibrium is reached at the α_{lim} . Due to the specific situation a, that actually is the projection of the distance between CoG an O, tends to 0 and the L2 force is 0 too. The resultant G can be represented by the components T and N where T is the transversal force and N is the reaction to the ground (Figure 1.3). When the CoG is in the median plane of the tractor, the equation of the moment's equilibrium is:

$$T\ h = N\ \frac{w}{2} \text{ (Biondi, 1999)} \qquad (2.3)$$

Where $\frac{w}{2}$ correspond to the arm a.

In this unstable equilibrium α_{lim} (Figure 2.3), that is also the maximum tilting slope before the rollover, can be obtained according to the following steps.

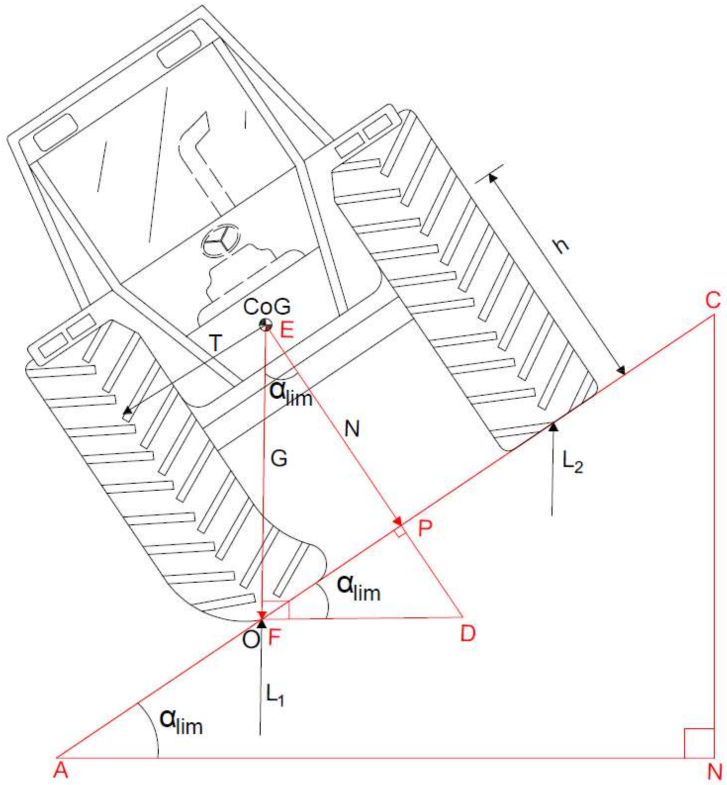

Figure 2.4 Tilting limit angle for tractor unstable equilibrium

In Figure 2.4 and the triangle FEG, the α_{lim} is:

$$\tan \alpha_{lim} = \frac{\sin \alpha_{lim}}{\cos \alpha_{lim}} = \frac{\frac{T}{G}}{\frac{N}{G}} = \frac{T}{N} \tag{2.4}$$

Considering that the angle $\widehat{BAC}$ is equal to the angle $\widehat{GFD}$, as corresponding angles, and the angle $\widehat{GFD}$ is equal to the angle $\widehat{FEG}$, because they are complementary to the same angle. The $tan\ \alpha_{lim}$ is:

$$\tan \alpha_{lim} = \frac{\frac{w}{2}}{\mathrm{h}} \tag{2.5}$$

Appropriate simplifications:

$$\alpha_{lim} = \tan^{-1} \frac{w}{2h} \tag{2.6}$$

To summarise, a tractor is stable if:

$$\tan \alpha < \frac{w}{2} h \tag{2.7}$$

For each tractor, there is a maximum angle limit that can be obtained by the track width and the height of the CoG. Any condition that modifies these two factors will change the stability limit angle and thus the stability of the tractor. Recent studies about this issue support the hypothesis that there is a non-linear relationship between tractor mass and available energy; however, the forward velocity affects the available energy (A. L. Guzzomi, Rondelli, Guarnieri, Molari, & Molari, 2009).

2.3 Dynamic stability

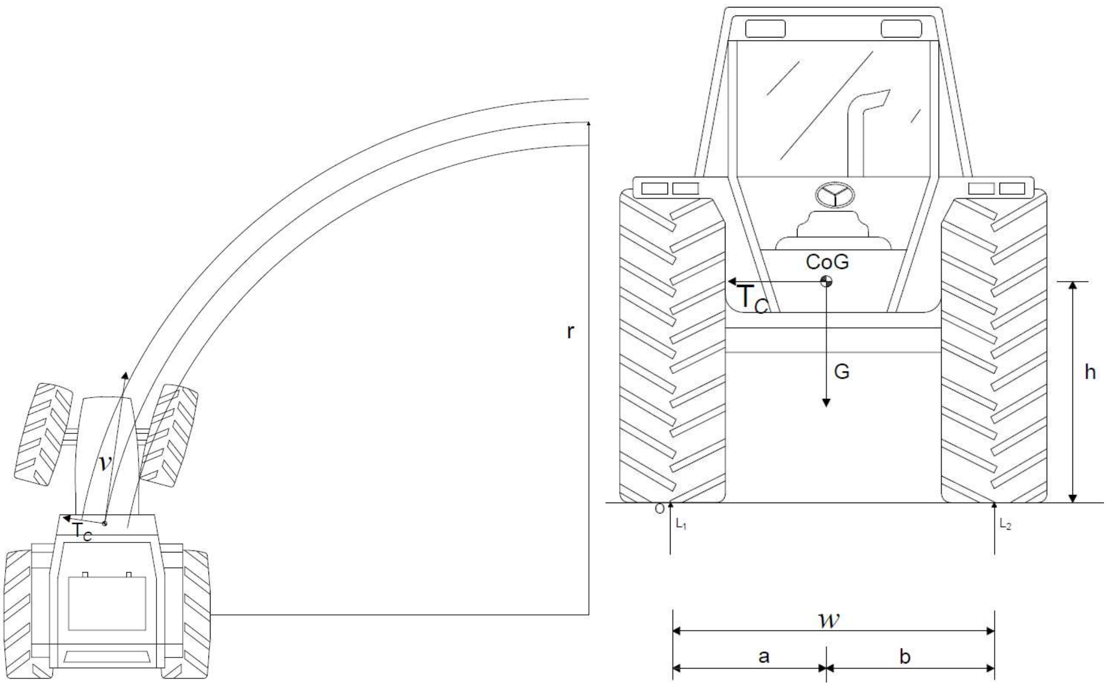

Figure 2.5 Tractor during the steering action

Taking into consideration that the tractor is moving with a constant forward velocity and without consider the friction force between the tyres and the ground surface, if the tractor is turning on a horizontal plane but in a dynamic condition , in Figure 2.5 all the acting forces are represented.

On a horizontal plane and in dynamic conditions the tractor is with mass=*m* and weight force G=*mg*. The two reactions of the ground to the tyres are L_1 and L_2. The height of the centre of gravity is h and the half-track's width is $\frac{w}{2}$. When the tractor is travelling along a path with a constant radius of curvature *r*, it is subject to a centrifugal force T_C:

$$T_C = m\,\omega^2 r \tag{2.8}$$

Where ω corresponds to the angular velocity.

In this case the tractor can be defined stable when the equilibrium of moments around O is:

$$T_C\, h - G\,\frac{w}{2} \leq 0 \tag{2.9}$$

To understand how the velocity of the tractor affects the rollover, the angular velocity can be considered as a function of the linear velocity:

$$\omega = \frac{\frac{\delta w}{r}}{\delta t} \tag{2.10}$$

Where $\frac{\delta w}{r}$ is the angular displacement (rad) in an infinitesimal space and δt is the infinitesimal time. Therefore, the angular velocity can be expressed as:

$$\omega = \frac{1}{r}\frac{\delta w}{\delta t} = \frac{1}{r}\,v \tag{2.11}$$

considering the angular velocity in the formula of the centrifugal force:

$$T_C = m\,r\left(\frac{1}{r}\,v\right)^2 = m\,\frac{v^2}{r} \tag{2.12}$$

By resuming the formula of the equilibrium of moments around O is:

$$m\,\frac{v^2}{r}\,h = G\,\frac{w}{2} \tag{2.13}$$

With the appropriate convenient simplifications, the rollover velocity will be:

$$v^2 = \frac{r\,g\,w}{2h} \tag{2.14}$$

Equations shows that if the forward velocity increases, the centrifugal force and consequently the machine instability will increase. Moreover, the tractor stability is affected by the track width and the CoG height.

2.4 Additional Effect

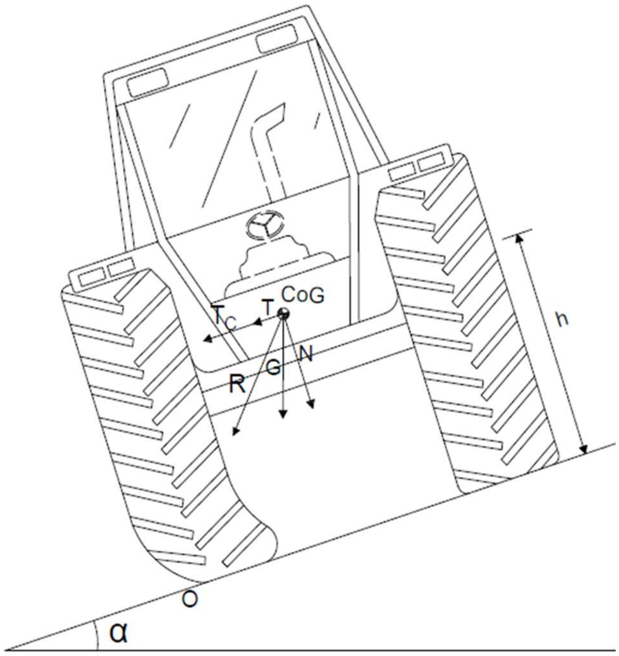

Figure 2.6 Tractor on sloping plane with the additional effect due to the velocity

In the previous paragraphs the forces contributing to the loss of stability of the tractor were analysed. Static and dynamic conditions were examined. Referring to a dynamic situation on a slope the effect of the slope will be added to the effect due to the centrifugal force T_c. The consequence is that the resultant G moves, affecting the stability of the machine. Although the tractor does not reach its stability limit angle, it will overturn due to the centrifugal force generated by the velocity of the tractor.

2.5 Other factors

It is evident that the stability is the result of forces applied to the tractor. In the first step the forces acting in a static condition on a slope were examined. In the second step the forces on a sloping plane but in a dynamic condition were considered: the effect of the velocity is added, and the tractor reaches before the stability limit angle. Many researchers evaluated over the years the contribute of different variables on the stability of the machine (Table 2.1).

FACTOR	VARIABLES	REFERENCES
TRACTOR	*CoG position*	(Ahmadi, 2011)(Spencer & Gilfillan, 1976)(Sun, Chen, Wang, & Wang, 2016)(D. J. Murphy et al., 1985)
	Wheel-track	(Ahmadi, 2011) (Gravalos et al., 2011)(Sun et al., 2016)(D. J. Murphy et al., 1985)
	Wheel-base	(Ahmadi, 2011) (Gravalos et al., 2011)(Sun et al., 2016)(D. J. Murphy et al., 1985)
	Mass	(Ahmadi, 2011) (Gravalos et al., 2011)(Rehkugler, 1980)(D. J. Murphy et al., 1985)
	Moment of Inertia	(Ahmadi, 2011) (Spencer & Gilfillan, 1976)(Sun et al., 2016)
	Tyre size	(Febo & Pessina, 2001)(Rehkugler, 1980)
	Turning Radius	(Liu & Ayers, 1999)(Sun et al., 2016)(D. J. Murphy et al., 1985)
IMPLEMENTS	*Mounted*	M. G. Yisa, Terao, Noguchi, & Kubota, 1998)(Murphy, Beppler, & Sommer, 1985)
	Towed	(Mohammed G. Yisa & Terao, 1995)(Spencer, 1978)(M. G. Yisa et al., 1998)(M. G. Yisa et al., 1998)
ENVIROMENT	*Tractor Forward velocity*	(Ahmadi, 2011) (Spencer & Gilfillan, 1976)(Gravalos et al., 2011)(Liu & Ayers, 1999)(Rehkugler, 1980)(Sun et al., 2016)(D. J. Murphy et al., 1985)(Bietresato & Mazzetto, 2017)
	Wheel–ground coefficient of friction	(Ahmadi, 2011)
	Height of the obstacle	(Ahmadi, 2011)(D. J. Murphy et al., 1985)
	Slope of the obstacle	(Ahmadi, 2011)(D. J. Murphy et al., 1985)
	Ground slope	(Ahmadi, 2011)(Hunter, 1982) (Rehkugler, 1980)(Sun et al., 2016)(Rondelli, Martelli, Casazza, & Guarnieri, 2013)(Spencer, 1978)(Kise & Zhang, 2006)
	Roughness of the Ground/Terrain or nature of the ground	(Spencer & Gilfillan, 1976) (Gravalos et al., 2011) (Hunter, 1982)(Liu & Ayers, 1999)(Rondelli et al., 2013)(D. J. Murphy et al., 1985)
	Side slipping	(Gravalos et al., 2011) (Hunter, 1982)(Mohammed G. Yisa & Terao, 1995)(Febo & Pessina, 2001)

Table 2.1 Working factors involved in tractor stability with reference

Over the years, researchers developed several models to evaluate and predict directly factors modifying the stability. One of the first researchers was Chisolm (Chisholm, 1979) who described the dynamic behaviour of a body in multiple contact with the ground with his two-dimensional mathematical model, i.e. the simultaneous behaviour of the tractor's parts during impact with the ground in a rollover situation.

Murphy, Beppler, and Sommer (1985), carried out research on tractor-human interactions and on man-environment interactions. The main objective was to comprehend if it is possible to quantify the extent of the variables modifying the stability during a normal operation only with the intuition and/or experience of the operator. The result was the development of a mathematical model to measure the relative stability of an agricultural tractor. In addition, they presented an electronic system with a display monitor the stability and help the tractor operator to become aware of a potential risky situation for the tractor.

Recent studies are taking into account devices that allow to predict and warn against dangerous operation fields. A commercial device that allows the continuous monitoring of working conditions of the machines was placed on standard tractors during the normal operation. The device was made by accelerometers, gyroscope, GSM/GPRS, GPS for georeferencing and a transceiver for automatic recognition of the equipment connected to the tractor. All these sensors were coordinated by a microprocessor that processes data and provides information through a dedicated algorithm, giving a real-time risk picture to the operator in terms of potential loss of stability, with suggestions for corrective measures to reduce the instability of the tractor. The result denoted that the device could avoid a dangerous situation and advise the operator but the complexity of the measurements was clear. The consequence is that the operator could ignore the device because alerting him too frequently and an actual risk would be ignored in the normal working condition (V. Rondelli, Martelli, Casazza, & Guarnieri, 2013).

Other researchers have developed models that are able to predict the dynamic behaviour of variables involving the loss of stability (Mohammed G. Yisa & Terao, 1995), (Liu & Ayers, 1999) (Li, Mitsuoka, Inoue, Okayasu, & Hirai, 2015), (Febo & Pessina, 2001) ,(M. G. Yisa, Terao, Noguchi, & Kubota, 1998), Mayrhofer, Quendler, and Boxberger (2014), conducted a research on the analysis of databases and surveys concerning accident victims with the objective of presenting sustainable prevention measures against tractors' rollovers. Interestingly, the implementation of the standards' recommendations for the design of vehicles with modern safety features was not always able to reach satisfactory safety levels. In addition, it is essential to focus on rollover problems and the solutions for a specific target machine type. For all categories of machinery, accident factor very important is the operator. This is a very interesting fact because, all the variables concerning the tractor were analysed without taking into account the fact that in a real situation the human factor has been not extensively examined yet.

The tractor can be used under different circumstances and in various ground condition, consequently these factors make the evaluation of the stability difficult. The effort made by the researchers during the last decade for modelling the behaviour of the tractor in field, is not so complete to allow for a technology able to avoid a potential rollover. For this reason, it seems quite ambiguous nowadays to declare that the ROPS could be subject to evaluation in a defined machine type. Currently the ROPS approach is the most consolidated approach to provide for a passive protection in case of overturning.

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3 *Tractor stability: the ROPS approach for driver protection*

3.1 Overview

Within the European Community (EC), for road use, tractors have to be tested and certified according to the EU Regulation 167/2013. Certification refers to the tractor type that typically encompasses different variants. Variants represent tractors of the same family that can vary in the: number of motorised axles; number of steered axles; number of braked axles and the ROPS type. Within the Community Regulation, 4 wheeled-tractor categories are considered. Each wheeled tractor categories are supplemented by an 'a' or 'b' index according to its design speed: 'a' for wheeled tractors with a maximum design speed below or equal to 40 km/h; 'b' for wheeled tractors with a maximum design speed above 40 km/h.

T1 Refers to wheeled vehicles with the closest axle to the driver having a minimum track width of not less than 1 150 mm, with an unladen mass, in running order, of more than 600 kg and with a ground clearance of not more than 1 000 mm.

T2 Refers to wheeled tractors with a minimum track width of less than 1 150 mm, with an unladen mass, in running order, of more than 600 kg, with a ground clearance of not more than 600 mm; if the height of the centre of gravity of the tractor (measured in relation to the ground) divided by the average minimum track for each axle exceeds 0,90, the maximum design speed shall be restricted to 30 km/h;

Amongst the other categories:

1) T3 is a tractor with an unladen mass, in running order, of not more than 600 kg;
2) T4 refers to special purpose wheeled tractors:
    a) T4.1 (high-clearance tractors) comprises tractors designed for working on high-growing crops, such as vines and maize. They are designed with a raised chassis or section of chassis, enabling them to advance in parallel with the crop. They are intended for carrying or operating tools which may be fitted at the front, between the axles, at the rear or on a platform. When the tractor is in working position the ground clearance perpendicular to the crop rows exceeds 1 000 mm. Where the height of the centre of gravity of the tractor, measured in relation to the ground, using the tyres normally fitted, divided by the average minimum

track of all of the axles exceeds 0,90, the maximum design speed shall not exceed 30 km/h;

b) T4.2 (extra-wide tractors) comprises tractors characterised by their large dimensions, primarily intended for working large areas of farmland;

c) T4.3 (low-clearance tractors) comprises fourwheel drive tractors whose interchangeable equipment is intended for agricultural or forestry use and which are characterised by a supporting frame, equipped with one or more power take-offs, having a technically permissible mass no greater than 10 tonnes, for which the ratio of this mass to the maximum unladen mass in running order is less than 2,5 and having the centre of gravity, measured in relation to the ground using the tyres normally fitted, of less than 850 mm.

Similarity to the T tractors, the EU Regulation 167/2013 considers the C tractors, subdivided in equivalent categories, for crawler or track tractors. Mettere tutto in una pagina oppure dividi T1 e T2 enrico poreferisce

T1 *Tractor* *with a four post ROPS*

T1 *Tractor* *with a ROPS cab*

T1 *Tractor* *with a rear two post ROPS*

Figure 3.1 ROPS types fitted on T1 tractors

T2 ***Tractor*** *with a ROPS cab*

T2 ***Tractor*** *with a rear two post ROPS*

T2 ***Tractor*** *with a front foldable two post ROPS*

T2 ***Tractor*** *with a high visibility cab ROPS*

T2 ***Tractor*** *with a rounded cab ROPS*

Figure 3.2 ROPS types fitted on T2 tractors

3.2 ROPS

Upon completion of homologation the tractor is required to be fitted with a roll-over protective structure (ROPS). This structure, whose purpose is to provide a survival volume in the event of a rollover, is statically tested according to international standard procedures for the particular tractor type. These tests comprise a series of energy (force–displacement) and force requirements whilst ensuring that the survival volume has not been encroached. Official ROPS tests are performed within Europe according to the Codes of the Organisation for Economic and Co-operation Development (OECD) or the equivalent European Regulation. These tests are typically based on the tractor's reference mass (*Mr*), with the only requisite being that it must be greater than or equal to the unladen mass in running order without the driver onboard (A. L. Guzzomi et al., 2009).

The roll-over protective structure is characterized by the provision of space for a clearance zone large enough to protect the driver when seated either inside the envelope of the structure or within a space bounded by a series of straight lines from the outer edges of the structure to any part of the tractor that might come into contact with flat ground and that is capable of supporting the tractor in that position if the tractor overturns (OECD Codes, 2018).

Therefore, the OECD define the ROPS (roll-over protective structure), as a structure that provides a safe environment for the operator in the event of a roll-over. In detail the ROPS structures are designed to minimize injuries due to tractor rollover. The first ROPS device was not marketed on new tractors until 1965. Many of the old tractors currently do not have ROPS. There are specific standards governing the retrofitting of ROPS on old tractors. The ROPS, which is new from the factory, has to pass a series of loading tests with the aim of testing its ability to withstand different loads while maintaining the protection zone around the operator's workstation.

With the definition of different tractor categories different testing Codes were developed. T1 wheeled tractors are required to have their ROPS tested according Code 4 while T2 tractors refer to Code 6 and Code 7; track-laying tractors are regulated by Code 8 (OECD Codes, 2018) while modern tractor fitted with rubber tracks are mounted with ROPS tested according to Codes 4,6 or 7.

When considering wheeled tractors, the choice of ROPS testing procedure is today performed based on which category the tractor falls under .These categories are based on the minimum track width as this is considered a most influential parameter for the stability of the machine: Code 4 applies to T1 tractors; Code 6 to T2 tractors fitted with a two post ROPS mounted in front of the driver; whilst Code 7 applies to T2 tractors fitted with cab or frame type ROPS or a two post rear mounted ROPS. Narrow track wheeled tractors are typically used in vineyards and orchards. The ROPS testing procedure requires that M_r must be defined by the manufacturer. This mass is the basis of most testing formulae within all Codes (A. L. Guzzomi et al., 2009).

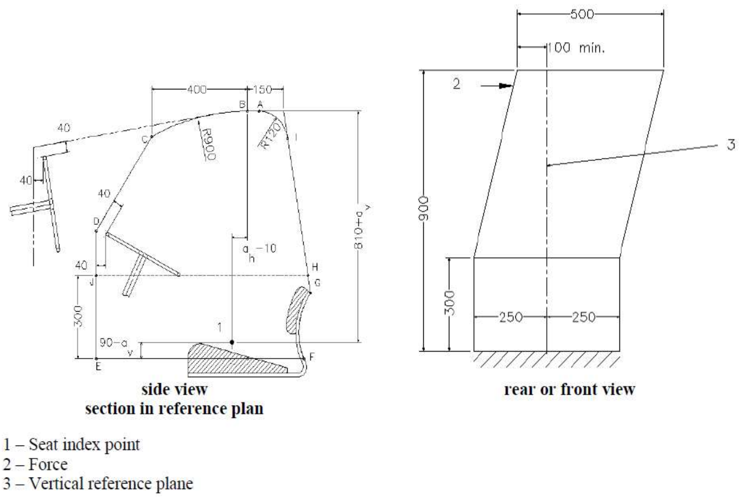
3.2.1 Clearance zone

Roll-over protective structure (safety cab or frame), means the structure on a tractor with the essential purpose of which is to avoid or limit risks to the driver resulting from roll-over of the tractor during normal use. The roll-over protective structure is characterized by the provision of space for a clearance zone large enough to protect the driver when seated either inside the envelope of the structure or within a space bounded by a series of straight lines from the outer edges of the structure to any part of the tractor that might come into contact with flat ground and that is capable of supporting the tractor in that position if the tractor overturns (OECD, 2018).The clearance zone is defined by the position of the Seat Index Point (SIP). The SIP is a reference point for the driver seat according to the ISO 5353:1995.

3.2.1.1 Code 4, Code 7

Code 4 is referred to the T1 tractor while code 7 is applied to T2 tractor and the clearance zones (Figure 3.3) are defined in relation to the reference plane and the seat index point (SIP). The reference plane is a vertical plane, generally longitudinal to the tractor and passing through the seat index point and the centre of the steering wheel. Normally the reference plane coincides with the longitudinal median plane of the tractor. This reference plane shall be assumed to move horizontally with the seat and steering wheel during loading but to remain perpendicular to the tractor or the floor of the rollover protective structure.

a)



b)

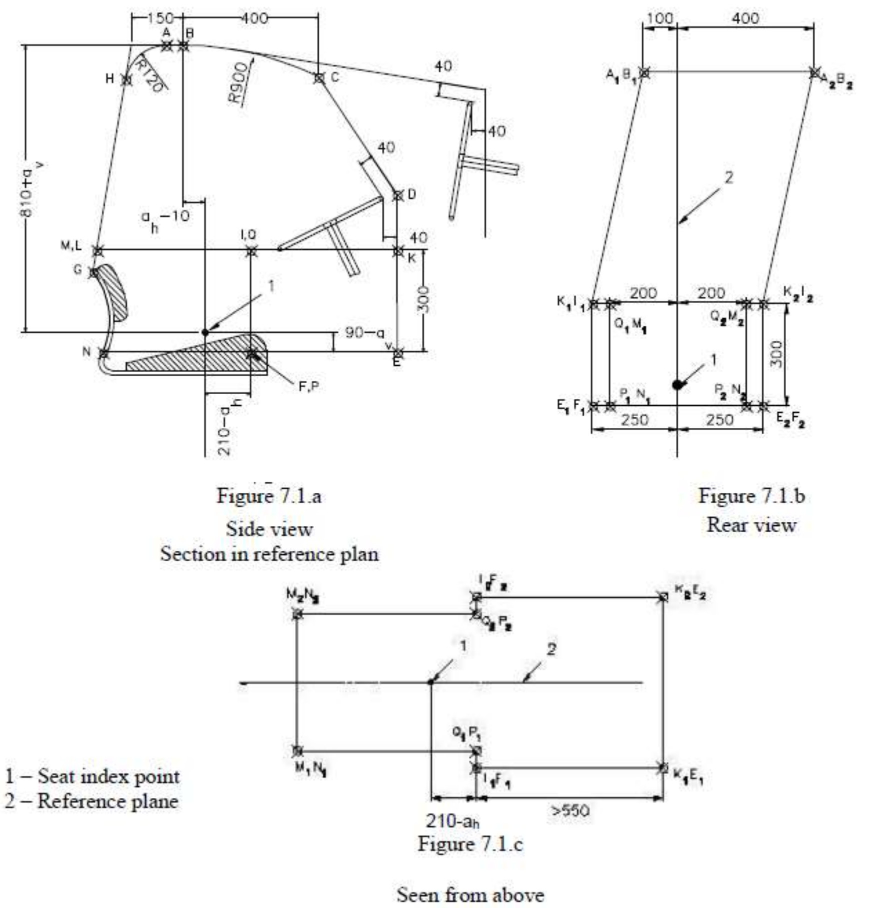


Figure 3.3 Clearance zone : a) code 4; b) code 7

3.2.1.2 Code 6

This code is referred to the T2 tractor fitted with dual pillar type ROPS mounted in front of the Seat Index Point and characterised by a reduced clearance zone (Figure 3.4) due to the tractor silhouette. The clearance zone is defined on the basis of a vertical reference plane and a reference line.

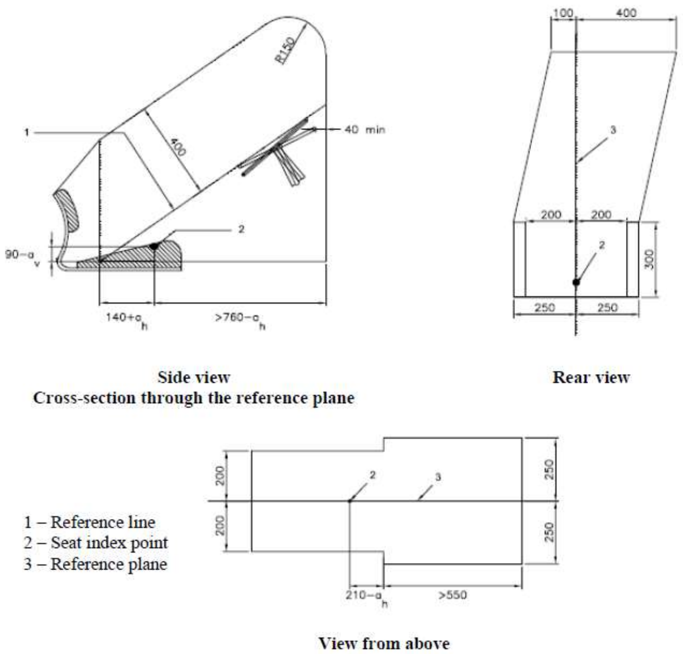


Figure 3.4 Clearance zone (Code 6)

3.3 ROPS history

It is well known that since the middle of the last century the tractor became the most important machine in the farm. The manual force to pull the implements working the ground, first provided by the animals, was quickly replaced by the mechanical force provided by the tractor. Over the time, this machine hanged features to meet the needs of farmers. The tractor therefore evolved into a completely versatile machine. This versatility is well recognized taking into account the working conditions in which this machine operates. The tractor spends most of its off-road working time changing conditions (e.g. slopes, slippery surfaces, rivers and drainage channels) and the high flexibility in meeting the need of different operations will affect the stability of the machine.

Due to the variables that affect the working environment and the strong expansion of the use of the tractor from the outset, there were considerable problems regarding safety. In fact, the roll-over of the tractor soon became the cause of numerous deaths every year (Figure 3.5). The perception of the scientific world and the operators in the sector recognised that ROPS could be an effective means of significantly reducing the

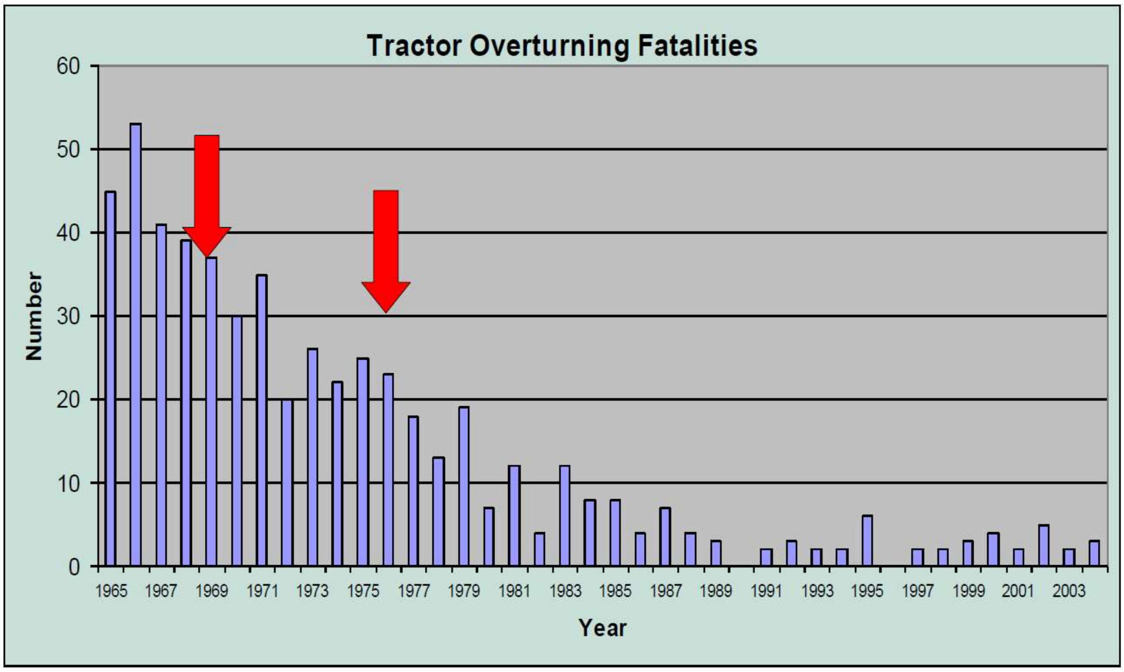


Figure 3.5 Tractor Overturning Fatalities (UK Health & Safety Executive)

probability of fatal injuries to the operator during tractor overturning accidents during the years. However, remember that the presence of ROPS cannot guarantee that the operator will survive against every type of roll-over accident; unfortunately, some cases are simply too serious, but the practical benefits of the ROPS are clearly demonstrated by numerous studies. (OECD History available at www.oecd.org)

Research into tractor rollover began as early as in the 1930s (Arndt, 1971). Numerous cases of documented tractor rollovers led to many international studies being undertaken (Myers, 2000)(Arndt, 1971)(Mayrhofer et al., 2014). These initial works were more concerned with preventing tractor rollover than mitigating its effects. However, with time and the appreciating that the tractor working environments can always result in some rollovers, it was realised that protective structures may be an appropriate means of addressing the problem. This latter approach began in the 1950s in Sweden with the Swedish Institute for Agricultural Machinery Testing (H A Moberg, 1973). The first protective structures for agricultural workers in the US were built in the middle of the last century. In the summer of 1956, because of research by Lloyd H. Lamouria, Ralph R. Parks and Coby Lorensen at the Department of Agricultural Engineering of the University of California in Davis was designed and successfully tested the first ROPS (**Errore. L'origine riferimento non è stata trovata.**). It was later exhibited at the annual meeting of the Pacific Coast section of the American Society of Agricultural Engineers (ASAE, 1986) in December of the same year.

Figure 3.6 John Deere Product Engineering Center, Waterloo, IA; Bonanzaville USA Historic Museum, West Fargo, ND; and Agricultural Engineering Building, University of California, Davis, CA (1986)

In Sweden in 1957, when no tractors were fitted with ROPS, the number of fatalities in Sweden from rollover accidents was 15. In 1990, when all tractors were required to have ROPS, there was only 1 fatality (Thelin, 1998b). As a result of Moberg's work, which showed the importance of driver safety, in 1966 the first ROPS Code was discussed within the OECD and approved in 1967 (OECD, 2018). The Code adopted a dynamic testing method. The tractors were secured to the ground and then subjected to a 2000 kg pendulum impact; the average mass of Moberg's test tractors (Gasparetto, E., Febo, P., & Pessina, 1987). The tractor ROPS was also subjected to a vertical force resistance test. There were however, several limitations with this dynamic method, such as: poor repeatability; possible dangers to testing staff, and the complete destruction of the tractor chassis in poorly designed cases. Subsequently, this dynamic method was replaced with a static procedure as given in Code 4 (OECD Codes, 2018). This latter testing technique, which is still in use today, adopts an instrumented hydraulic cylinder and a series of tests. The recovered force–displacement information is used to determine the ROPS energy/force capabilities. These tests require that the tractor be rigidly secured to 'earth' via anchorage of the axles and/or the chassis.

As already mentioned over the years ROPS types and normalised testing procedures evolved according to the evaluation in types and normal uses of agricultural tractors.

Following years, ROPS started to be implemented in all the world. At the same time the improved work condition for operator led to the massive adoption of cab ROPS for rollover and environmental protection. The ROPS design and construction techniques followed this approach at the aim to protect the operator not only against overturning but also guaranteeing protection from noise, vibrations, weather conditions and contamination of pesticides.

Figure 3.7, (Rondelli et al., 2012) shows the evolution over the years of four different ROPS. The four pillar frames represented in Figure 3.7 has not substantially changed over the years while substantial differences can be appreciated in the cabins of standard

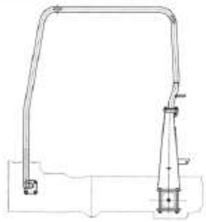
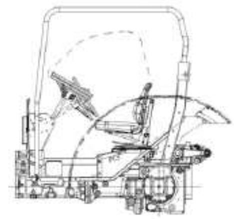
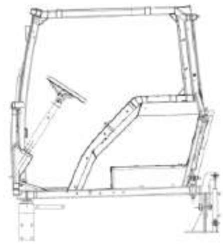
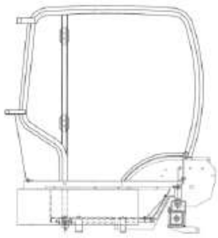
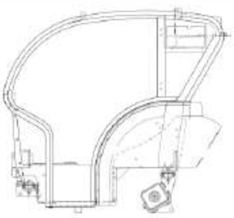
Case	ROPS	Code	ROPS design 1987-1995 years	ROPS design 2008-2012 years
A	Four pillar frame	4		
B	Cab	4		
C	Four pillar frame	7		
D	Cab	7		

Figure 3.7 ROPS design evolution over twenty-five years (Rondelli et al., 2012)

tractors as an interposition of the silent-blocks between the cab and the platform and a cab designed with the platform and the mudguards completely integrated. Indeed the platform was progressively integrated into the cab and hydraulic dampers were added at the rear for additional operator comfort. The same trend was observed in the cab ROPS of narrow tractors. In fact, the operation in intensive very narrow orchards lead the manufacturers to integrate the platform into the cab with the final result that the cab is a compact low clearance and really rounded zone. (case D) (Rondelli et al., 2012).

3.4 ROPS for other agricultural machine

Since the entry into force of Directive 74/150, implemented in Italy by Legislative Decree 572/1977, the mandatory nature of the ROPS for the tractor became immediately compulsory. The European Directive 74/150 and subsequent amendments were directives for the homologation of tractors and all of them contributed to achieve the objective of the "global homologation" of agricultural and forestry tractors. This allowed to reach the free market exchange around the EU community.

For all other machines the issue of safety has been addressed firstly in the EU community at the EU Machine Directive 89/392/EEC (June 14, 1989), modified and integrated over the years. The most recent version is the Machinery Directive 2006/42/EC introduced in the Italian regulation with the Legislative Decree of 27 January 2010. It established the essential health and safety requirements relating to the design and construction of machinery because specifically treated by the EU Regulation 167/2013. Agricultural and forestry tractors and other special equipment are excluded from the scope of the standard. The main principle, of the EC Directive 42/2006 is: "the machines must be able to guarantee the function for which they are intended and to be regulated and maintained without put in danger in any case the safety of exposed employees, provided that these operations are carried out in accordance with the rules and recommendations for use provided by the manufacturer".

The machinery manufacturer must self-certify the machine safety and must ensure that the machinery has been designed according to reduce or eliminate the risks or when risks remain take the necessary measures to avoid them have to be suggested.

Although the Machinery Directive (2006/42) introduces roll-over risk assessment for all machines, there are no testing standards to verify the strength of ROPS protection structures for machines different from the tractors. Despite the fact that other types of machines are also manufactured to perform field operations which are sometimes very specific (e.g. self-propelled sprayers), there are no specific standards that make ROPS always mandatory and there are no testing procedures dedicated to test these ROPS.

However, a specific standard, the ISO 16231:2015, has recently been introduced to assess the stability of self-propelled agricultural machineries. The standard is arranged in order to assess the stability of certain self-propelled agricultural machineries, in view to defines the need to install ROPS protection structures using specific indices.

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4 *Agricultural self-propelled machines stability: the ISO 16231 for the stability assessment of self-propelled sprayers*

4.1 Introduction

More than 40 years ago, the OECD (OECD Codes, 2018) has started to development a series of ROPS test procedure codes to be applied to agricultural and forestry tractors. During the years these tests became valid also for telescopic handlers when used as tractors. OECD codes are mandatory in EU and the new tractors that are built must be equipped with certified ROPS. Despite this, in Italy every year more than 130 fatal accidents happen, caused by the tractors overturning (Domenico Pessina & Facchinetti, 2017). The statistics related to agriculture show that not only tractors are subject to rollover. Indeed, other categories of machines, such as self-propelled machines, have stability problems but for these machines the ROPS is not a compulsory fitment. They have a high overall mass, including the content of large tanks mounted on board, and a high centre of gravity. The reference procedure (ISO, 2015) has been developed to understand through a risk assessment whether the ROPS could be the protection approach.

The ISO is divided in 2 parts. In the part 1 the main principles are described while in the part 2 the determination of static stability and test procedures are explained

4.2 ISO 16231:2013 Self-propelled agricultural machinery — Assessment of stability —Part 1: Principles

In this part it is described that the self-propelled machines can expose the driver to the risk of rolling (>90°) or tipping (<90°) over. The risk assessment should then determine the rollover risk applied to specific machines and the appropriate cases when protective structures have to be used in order to avoid or minimise this risk. This assessment should consider the operating conditions under which the machine is intended to be used, the physical properties of the machine and the required skills to operate as well as any other parameters that may have an impact on the risk of rollover.

The scope of this ISO standard is to specify the principles for assessing the stability of self-propelled machinery and assessing the risk of roll and tipping over. It is applicable on all the self-propelled machine except some cases:

- machines with an unladen mass lower than 400 kg;
- machines covered by other machine specific standards dealing with the protection against rollover and tip-over (e.g. agricultural tractors, forestry tractors)
- Free Fall events
- hazards associated with road transport operations;
- rollover because of impact collisions.

To better understand the whole standard is useful to introduce some definitions:

- **APS**: automatic protective system: passive control systems when the working limits are exceeded (excessive slope)
- **SPS**: self-protective structure: structural components with particular strength which, in the event of rollover, reduce deformation (i.e. additional tank)
- **SPD**: mounted attachment(s) or other device(s) fitted to the base machine which prevent the machine from rollover or tip-over, or both (for example its mass, shape, position)
- **SOA**: static overturning angle: for each direction, angle of inclination in which the vertical projection of the centre of gravity falls beyond the area of stability
- **RSSA**: Required static stability angle: slope required to guarantee the stability of the machine
- **ROLL OVER**: loss of machine stability characterized by a clockwise or counter clockwise rotation of more than 90 degrees around either both the longitudinal of lateral axis of the machine
- **TIP OVER**: loss of machine stability characterized by a clockwise or counter clockwise rotation of no more than 90 degrees around either both the longitudinal of lateral axis of the machine
- **SF**: safety factor: factor taking into account dynamic effects and soil conditions (holes or natural bumps)

During the risk assessment it shall be considered:

- Intended use of the machine (according to operator's manual):
- The operations to be carried out;
- Typical working conditions and characteristics of the terrain (slope);

- Physical properties of the machine (e.g. mass, dimensions) under operating conditions;
- Limits of the machine;
- Operator (e.g. education, training, experience, skills).

It is clear that all of these features are important because they will affect the machine's stability.

After this assessment the ISO says that if the risk assessment indicates that is a need to reduce the risk of rollover or tipping, or both, the machine has to fulfil one of the following conditions:

- designed so that its Static Overturning Angle (SOA) is equal or greater than the Required Static Stability Angle (RSSA), which shall include a suitable safety factor
- equipped with Self-Protective Device (SPD);
- equipped with an Automatic Protective System (APS);
- provided with means to provide for an appropriate deflection limiting volume in case of rollover and/or tip-over, or both. Examples for such means are:
    - self-protective structures (SPS), i.e. resistant machine parts
    - additional structures, i.e. ROPS with corresponding seat belts.

4.3 ISO 16231:2015 Self-propelled agricultural machinery — Assessment of stability — Part 2: Determination of static stability and test procedures

In this part of ISO 16231 a method to determine the centre of gravity of un-laden self-propelled machines is specified together with a method to determine the centre of gravity of laden machines and combinations with attachments. The centre of gravity values will allow to figure out the machine's Static Overturning Angle.

4.3.1 Determination of the centre of gravity (COG) of a self-propelled machine

The procedure as outlined in ISO 789-6 is considered. This method required to weight the machine and it is based on the increasing load on the supporting axle when the other axle is lifted and supported on a certain height; the lifting angle ω and the increased load on the scale allow determination of the height of the COG.

4.3.2 Methods to determine the centre of gravity of a laden machine or a machine with attachments

4.3.2.1 Graphical method

Because weighing a laden machine with attachments under an angle is not practical and can be unsafe, it is advisable to determine the COG of the laden machine by means of a graphical method. It is assumed that the weight and the COG of the load (e.g. grain) and the attachment(s) are known. The following example shows a combine harvester with

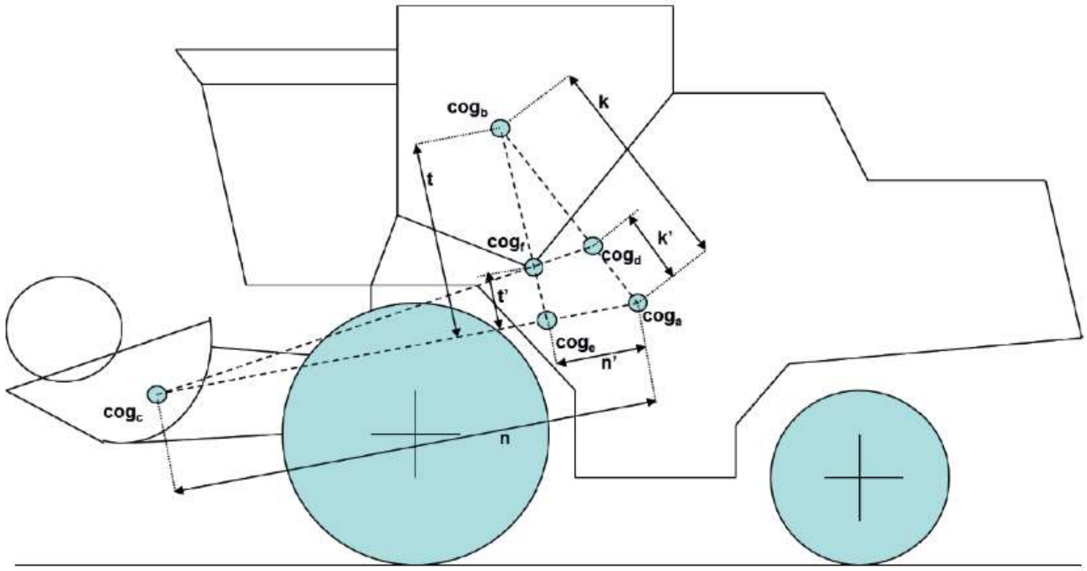

Figure 4.1 Machine with attachment - Side view

full grain tank and a header in the raised position (worst case field condition). The COG of the empty machine is known and marked on the scaled drawing of the machine as cog_a (see Figure 4). The COG of the grain in the tank can be defined graphically as cog_b. The mass of the grain represents, for instance 50% of the empty weight of the machine. The COG of the combination empty machine and grain load is marked as cog_d and falls on the line between cog_a and cog_b at 1/3 from cog_a. The mass of the header is, for instance, 20% of the empty mass of the machine. The COG of the attachment marked as cog_c is known (e.g. by weighing on a hoist under two angles). The COG of the combination empty machine and attachment falls on the line between cog_a and cog_c at 1/6 from cog_a. The COG of the combination loaded machine and attachment can be determined in a similar way. The height and the longitudinal position of the new COG can now be measured on the drawing. The same principles apply to determine the new lateral position (y) of the COG.

4.3.2.2 Mathematical method

In the ISO there is a calculation sheet for determination of the centre of gravity (COG) by calculation. Then it will possible to calculate the static overturning angle (SOA) and the required static stability angle (RSSA). A calculation sheet format is available at http://standards.iso. org/iso/16231-2/ed-1/.

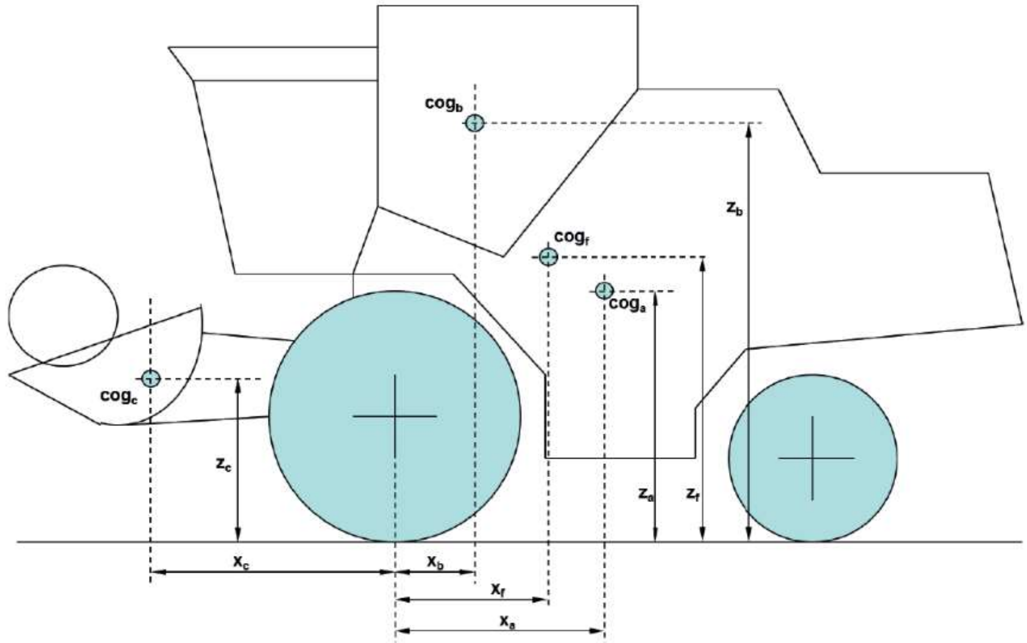

Figure 4.2 Combined CoG - by calculation

4.3.3 Static overturning angle (SOA)

After the determination of Centre of Gravity coordinates it is possible to calculate the SOA. There are different approaches depending of the machine's features as the swivelling axle. Indeed, there are machines with one fixed axle and the other one swivelling without limiting device, there are machines with one fixed axle and the other one swivelling with limiting device. This difference is very important because during the rollover event if there is the limiting device, it restricts further the swivelling of the axle prior to the complete overturn of the machine.

Furthermore, machines which don't have a swivelling axle exist. For example, machine on tracks or machine with devices to lock the swivelling axle or to modify the stability triangle.

In case of tracks the static overturning angle SOA (%) is the ratio between the lateral position of the centre of gravity $COG\ (o/2 - y)$ and the height of the centre of gravity

z. The machine reaches, then exceeds the static overturning angle SOA when the vertical projection of centre of gravity COG falls outside the pivot line.

$$SOA\ (\%) = \ (o/2 - y)/z(\%) \tag{4.1}$$

where “o” for steel tracks is the outer edge of the track shoes and “o” for rubber track belts is the outer edge of the rollers.

In case of machines that have devices to modify the stability triangle as a function of the slope, itaffect the static overturning angle SOA in a positive way. The determination of the static overturning angle SOA shall consider the positive impact of these solutions, according to the system applied, and the value σ can potentially be used as SOA.

4.3.4 Tip forward and tip rearward

Tip forward and Tip rearward are important, and they can be evaluated as follow. 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 (%)* is the ratio between the horizontal position of the *COG (x)* and the height of the centre of gravity (z).

$$SOA\ (\%) = x/z(\%) \tag{4.2}$$

The machine tips rearward when the vertical projection of the COG crosses the axle line of the rear wheels. In this case, the *SOA (%)* is the ratio between the horizontal position of the COG (W – x) and the height of the centre of gravity (z).

$$SOA\ (\%) = (W - x)/z(\%) \tag{4.3}$$

4.3.5 Alternative methods

When there are not enough reliable data available or when there are appropriate facilities available, other methods are allowed to determine the SOA. Examples of other methods are the following:

- the machine is lifted respectively in the four directions by means of a hoist to angles equal to the rolling over angle;
- the machine is placed on a tilting platform respectively in the four directions to angles equal to the rolling over angle;
- virtual simulation models.

The test shall be stopped when the SOA is reached (when tip over is about to start) or when the SOA reaches a slope equal to 100 %.

4.3.6 Comparison of SOA and RSSA

The RSSA provides the calculated slope on which the machine is required to be stable. The RSSA is determined by using the maximum operating slope (MOS) and safety factor (SF) values in Figure 4.3 . The Safety factor (SF) takes account for an appropriate safety margin. It is difficult to assess the individual impact of all the dynamic effects. For this reason, a safety Factor of 1,5 has been established for calculation of the RSSA.

$$RSSA = MOS * SF \tag{4.4}$$

In case SOA is higher than the RSSA, the risk for roll-over or tip-over is low and no further roll-over protection is needed.

Machine type	**Lateral roll/tip-over**			**Front/rear tip-over**		
	MOS (%)	SF	**RSSA** (%)	**MOS** (%)	SF	**RSSA** (%)
Combine harvester without slope compensation system	12	1,5	18	18	1,5	27
Combine harvester with slope compensation system	20	1,5	30	20	1,5	30
Combine harvester with body levelling system	30	1,5	45	30	1,5	45
Forage harvester (maize and grass)	25	1,5	37,5	25	1,5	37,5
Field crop sprayer	15	1,5	22,5	25	1,5	37,5
Root crop harvester (beet, potato, carrot, onions)	10	1,5	15	15	1,5	22,5
Green vegetable harvester (pea, bean, spinach)						
Grape harvester without body levelling system	20	1,5	30	30	1,5	45
Grape harvester with body levelling system	30	1,5	45	30	1,5	45
Cotton harvester	16	1,5	24	16	1,5	24
Sugar cane harvester	10	1,5	15	30	1,5	45
Mower conditioner (same as for forage harvester)	25	1,5	37,5	25	1,5	37,5
Self-propelled mixer-feeders	30	1,5	45	n.r.	n.r.	n.r.
Slurry tanker						
Bale collecting vehicle						
Self-propelled hay pick-up wagon						
Machine xxx						
n.r.: not relevant						

Figure 4.3 MOS, SF, and RSSA for self-propelled agricultural machines

In addition, when there is a machine with a body levelling system it shall be equipped with the following requirements: in the operator station an acoustic or visual warning device which indicates to the operator when the machine is moving on a lateral or up-and-down slope greater than the 80 % of MOS has to be mounted. The warning shall activate when the slope reference value has been reached or exceeded for 3 s; a device continuously indicating the value of the slope.

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5 *A tractor safety assessment to stress the influence of ROPS type on lateral stability*

5.1 Abstract

Tractor overturns are a major cause of death in agriculture. Many variables are involved. The Roll-Over Protective Structure (ROPS) has been invented to minimise the risks of driver injuries in a tractor overturn. Narrow-track tractors for orchard and vineyard operations are mainly available with two different ROPS types: an enclosed cab frequently fitted with filters and air-conditioning system or a simple two post ROPS designed to be folded down to allow the tractor to operate in a reduced surrounding space. Concerning stability, the tractor lateral stability angle is the result of the tractor configuration and its position with respect to the ground slope. The aim of the paper was to study the effect of ROPS type on tractor stability performance. The tractor stability parameters were evaluated on 22 modern narrow-track tractors measuring mass, track-width, wheelbase, Centre of Gravity (CoG) and Moments of Inertia (MoI). The evaluation considered pairs of tractors equipped with two post ROPS and cab ROPS. In the design of compact narrow-track tractors the cab fitment keeps the wheelbase and track-width of the tractor unchanged with respect to the front foldable ROPS but affects the mass, position of the CoG and longitudinal and transversal MoI. Data show an increase in tractor mass and higher CoG and MoI for the cab fitment with respect to the two post ROPS. A recent international debate on the safety performance of two post ROPS was consequent to the incorrect use of the foldable ROPS in field operations. Cab ROPS is thus often claimed to provide higher protection to the driver. This investigation denotes that on sloping fields narrow-track tractors fitted with a cab ROPS reach the lateral unstable state at a lower angle than two post ROPS tractors; consequently, the stability performance of the tractor worsens.

Keywords: *Front foldable ROPS, Enclosed cab, Rollover, Moment of inertia, Lateral stability angle*

Nomenclature		
Variables		
g	Gravity acceleration	(9.81 ms^{-2})
Θ	Oscillation angle	(rad)
M	Generic mass	(kg)
R	Generic distance from suspension axis to CoG	(m)
I_o	Generic moment of inertia about the suspension axis	(kg m^2)
m_p	Oscillating platform mass	(kg)
r_p	Distance from suspension axis to oscillating platform CoG	(m)
I_p	Moment of inertia about the suspension axis of the oscillating platform	(kg m^2)
m_t	Tractor mass	(kg)
r_t	Distance from suspension axis to tractor CoG	(m)
I_t	Tractor moment of inertia about the suspension axis	(kg m^2)
M	Mass of the oscillating platform-tractor system	(kg)
R	Distance from suspension axis to the oscillating platform-tractor system CoG	(m)
I	Moment of inertia about the suspension axis of the oscillating platform-tractor system	(kg m^2)
D	Distance from suspension axis to platform base	(m)
Measured parameter		
m_t	Tractor mass	(kg)
α	Lateral stability angle	(deg)
H_{CoG}	CoG height	(m)
w	Track-width	(m)
b	Wheelbase	(m)
MoI_l	Longitudinal moment of inertia	(kg m^2)
MoI_t	Transversal moment of inertia	(kg m^2)
Statistical parameter		
$\overline{\Delta x}\%$	Stability parameter index	(%)
X	Generic stability parameter	
Δx_i	Difference between parameter data of the two ROPS treatments for each i-th pair of tractors	

N	Number of tested paired tractors	(11)
I	Number of treatments (ROPS type)	(1=two post ROPS; 2=cab ROPS)
J	Number of randomized blocks (tractor configuration)	(11)
X_{ij}	Measured parameter	
μ	Overall mean	
γi	Effect of the treatment	
β_j	Effect of the block	
ε_{ij}	Residual error	
Abbreviations		
CoG	Centre of Gravity	
MoI	Moment of Inertia	
OECD	Organisation for Economic Co-operation and Development	
ROPS	Roll-Over Protective structures	
RBD	Randomized Blocks Design	

5.2 Introduction

Roll-Over Protective Structures (ROPS) were conceived in Europe in the 1950s as a passive approach for driver protection in case of tractor overturning (Harald A. Moberg, 1964). Data on fatal accidents for tractor rollover in Sweden showed a sharp decrease in twenty years and confirmed the efficacy of the device (Springfeldt, 1996; Thelin, 1998a). The high performance of ROPS in driver protection was the result of an accurate design by the tractor manufacturer combined with standardized tests for evaluating the strength behaviour of the structure in a load sequence where the ROPS had to sustain and absorb normalised forces and energies (OECD Standard Codes, 2017). Over the years ROPS have continued to be used for tractor rollover protection and research on tractor stability performance has also continued (Casazza, Martelli, & Rondelli, 2016; B. Franceschetti, Capacci, & Rondelli, 2016; Liu & Ayers, 1998; D. J. Murphy, Beppler, & Sommer, 1985). ROPS mounted on agricultural tractors are currently designed as two post protective structures, fixed to the rear or in front of the driver, and enclosed cabs with windows and doors. The ROPS structures mounted on narrow-track tractors, specifically designed for operating in orchards and vineyards, are commonly front foldable two post ROPS and enclosed cabs (Figure 5.1), recently designed also in a configuration type with a very rounded shape and a reduced height to better match with the lower overhead clearance in vine and fruit tree inter-rows (Rondelli et al., 2012).

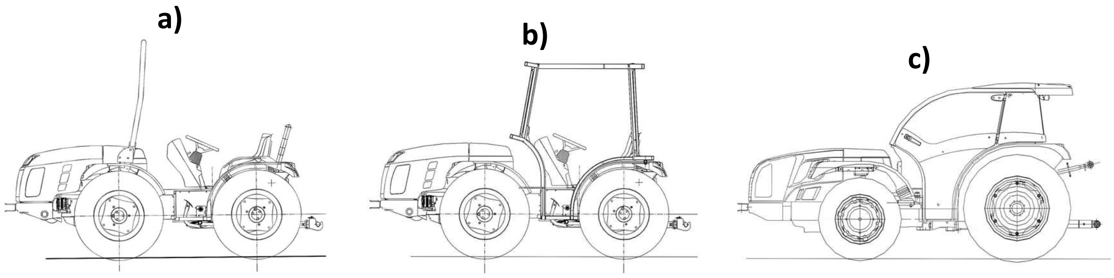


Figure 5.1 ROPS types currently mounted on compact narrow-track tractors for orchards and vineyards: a) front foldable two post ROPS, b) square cab ROPS, c) round cab ROPS.

Enclosed cab ROPS have added advantages for the driver with respect to the front ROPS because, when pressurized and fitted with filters, they also provide protection from high or low temperatures, rain, dust and chemicals, and offer greater comfort when tractors are in normal field operation. Front ROPS have advantages when the tractor needs to operate in reduced overhead clearance conditions, such as intensive cropped orchards and vineyards, because if strictly necessary the ROPS can be folded by turning the upper part down on the supports fixed to the tractor chassis. A recent international debate was related to the incorrect use of front foldable ROPS, potentially because of the difficulty in raising the structure due to its heavy mass and the uncomfortable position of the operator during the manual handling. Increased rollover fatalities and serious injuries were recently reported as deriving from front ROPS in the folded-down position (Hoy, 2009; Pessina et al., 2015). An approach selected at the standardization level was to complement the sequence of ROPS loadings with a limit in the force to be manually sustained in the ROPS actuation combined with a clear identification of the points from which to carry out the handling operation. At present, due to a predictable incorrect use of front ROPS, enclosed cabs are considered to be the safer option because the clearance zone always remains steady and surrounds the driver. Given the high tractor rollover risk as a consequence of its configuration and position with respect to the ground slope, the aim of this paper was to study the effect of ROPS types on tractor stability performance. Front two post ROPS and enclosed cabs fitted on narrow-track tractors were compared.

5.3 Methodology

The influence of the ROPS type mounted on the tractor on its lateral stability was studied in stationary conditions. A rollover event may occur if the tractor reaches an unstable condition. The static stability of the tractor is mainly based on its dimensions and the centre of gravity (CoG). The mass of the tractor and its dimensions are correlated to the inertia and therefore to its propensity to maintain the position on the ground. To evaluate the stability of the following tractor parameters were measured: mass, wheelbase, track-width, centre of gravity height and moments of inertia. Twenty-two tractors specifically designed for use in orchards and vineyards were analysed. The safety assessment of the effect of ROPS type on tractor stability performance was carried out at the official OECD Test Station, Laboratorio di Meccanica Agraria of the University of Bologna.

5.3.1 Tractor configurations

Eleven pairs of compact narrow-track tractor configurations were considered for a total of twenty-two tractors, each tractor pair being mounted with two different ROPS types: two post ROPS and cab ROPS. The comparison between tractor type configurations is depicted in Figure 5.2.Seven types were equipped with equal-sized wheels, and of these, five had the steering wheel acting on the front wheels while two were articulated tractor types with the steering wheel acting on the central articulation joint. Seven types were fitted with square-shaped cabs allowing a wide field of vision because they were designed for normal and reversible driving positions. Four types were provided with standard wheels, one was equipped with a dual steering system acting on the front wheels and central articulation joint and the other three had the steering wheel acting just on the front wheels. In this group of tractors the cab ROPS fitted had a highly rounded shape and a reduced height because it was designed for normal driving standard wheeled narrow-track tractors operating in low overhead clearance conditions, such as modern orchards and vineyards. The main characteristics of the tractor types are summarized in Figure 5.3.

Figure 5.2 Tractor configurations mounted with two different ROPS: two post ROPS and cab ROPS are shown as examples of the tractor pairs evaluated: a) Tractor equal-sized wheels type, b) Tractor standard wheels type.

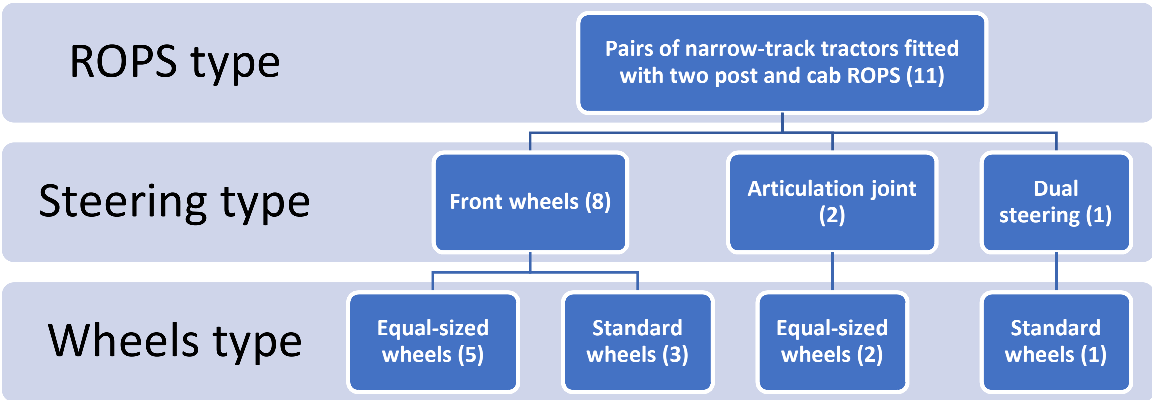


Figure 5.3 Tractor configurations considered in the tests. The number of tractor tested is specified in the bracket.

5.3.2 Tractor stability parameters

Mass, track-width and wheelbase were directly measured on the tested tractors while the tractor inertia and centre of gravity height (H_{CoG}) were indirectly obtained by calculation from the period of oscillation measured when the tractor was secured on an oscillating platform for two different pivot heights (Figure 5.4), according to the parallel axis theorem (Casini-Ropa, 1976).

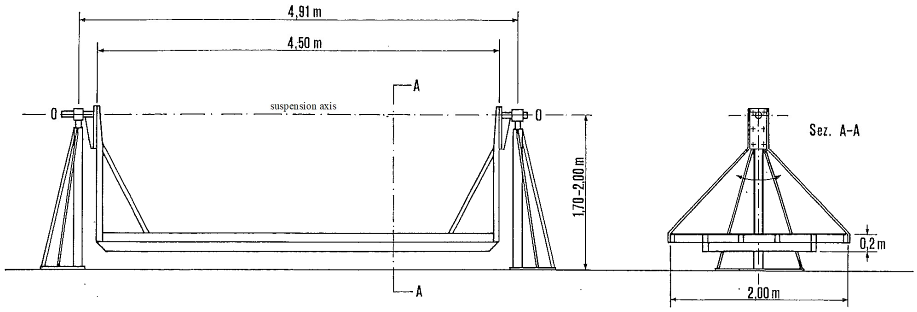


Figure 5.4 Schematic side view and cross section of the oscillating platform for calculation of tractor inertia and CoG height, according to Casini-Ropa, 1976.

From the rigid body theory, it is possible to assimilate the oscillating platform to a physical pendulum. Adding a restriction to the size of the oscillation's amplitude the differential equation to represent the motion is:

$$\frac{d^2\vartheta}{dt^2} + \frac{m\,g\,r}{I_0}\vartheta = 0 \qquad \vartheta \ll 1\,rad \tag{5.1}$$

The equation of harmonic oscillator has solution:

$$\vartheta = \vartheta_0 \sin(\omega t + \varphi_0) \tag{5.2}$$

and period of oscillation

$$T = 2\pi\sqrt{\frac{I_0}{m\,g\,r}} \tag{5.3}$$

Where m is the mass of the oscillating platform-tractor system, g is the gravity acceleration, r is the distance from suspension axis to CoG height and I_0 is the moment of inertia about the suspension axis. In eq. (5.3) the moment of inertia and r are unknown values. The two different swinging heights allow data calculation. According to the period of oscillation at the two different heights r and I_0 are obtained. Because of the oscillating platform, it is necessary to swing the tractor and the platform mass is not negligible, so the periods of oscillation for the empty platform have to be measured, since the platform oscillation periods referred to the tractor supported on it combine the results of the tractor and the platform itself.

5.3.2.1 Centre of gravity height and moments of inertia determination

The distance between the tractor CoG and the suspension axis is obtained, according to Casini-Ropa (1976), by the static equilibrium of the moments of the masses relative to the suspension axis:

$$r_t = \frac{M\,R - m_p\,r_p}{m_t} \tag{5.4}$$

where M is the sum of the tractor mass and platform mass, R is the distance from suspension axis to CoG height of the system, m is the platform mass, r is the distance from suspension axis to CoG height of the platform, m_t is the tractor mass. Measuring the distance from the suspension axis to the contact surface of the tractor wheels on the platform, the CoG height of the tested tractor is obtained:

$$H_{CoG} = D - r_t \tag{5.5}$$

From Eq. (5.3) the tractor inertia with respect to the suspension axis for the oscillating platform-tractor system and for the empty oscillating platform is defined:

$$I_0 = \left(\frac{T}{2\pi}\right)^2 m\, g\, r \tag{5.6}$$

According to the theorem of Huygens-Steiner the moment of inertia of the tractor with respect to the CoG height of the tractor is:

$$I_{\mathrm{t}} = \left(I - I_{\mathrm{p}}\right) - m_t\, (r_t)^2 \tag{5.7}$$

Two tractor positions on the oscillating platform were tested allowing the longitudinal (MoI_l) and transversal (MoI_t) moments of inertia to be calculated (Figure 5.5).

a)

b)

Figure 5.5 Tractor positions on the oscillating platform for longitudinal and transversal moments of inertia calculation: a) tractor with two post ROPS, b) tractor with Cab ROPS.

5.3.2.2 Lateral stability angle determination

The lateral stability angle (α) was calculated assuming that the front and rear track-widths of the tractors were exactly the same. Tractor rotation was considered with respect to the midpoint of the wheels in contact with the ground, taking into account tyre deformation:

$$\alpha(m_t) = \tan^{-1}\left(\frac{w}{2 \cdot H_{CoG}(m_t)}\right) \quad (5.8)$$

Where *w* is the track-width, equivalent for each pair of tractor configurations, while H_{CoG} is the CoG height affected by ROPS type. H_{CoG}, MoI_l, MoI_t and α were then evaluated in the range of masses referred to compact narrow-track tractors to analyse the relationship with the tractor mass and two ROPS types.

5.3.2.3 Effect of ROPS type on tractor stability parameters

The effect of the two post ROPS with respect to the cab ROPS was defined as the difference between their measured stability parameters:

$$\Delta x = \frac{x_2 - x_1}{x_1} \quad (5.9)$$

The overall effect of ROPS type on tractor stability parameters was then evaluated:

$$\overline{\Delta x}\% = \frac{\sum_{j=1}^{n} \Delta x_j}{n} \cdot 100 \quad (5.10)$$

5.3.3 Tractor stability analysis

Measured data of the 11 pairs of narrow-track tractors were analysed (R®, 2016; Statgraphics Centurion XVI, 2016). The data sample was small, being composed of less than 30 observations (Spiegel & Stephens, 2007) and the statistical distribution was unknown a priori. With the aim of assessing the effect of ROPS type, two post ROPS and cab ROPS (in the following statistical analysis defined as treatments), on the tractor stability parameters, an explorative survey based on a non-parametric test fitting to paired samples was initially run: the Wilcoxon signed-rank test based on analysis of the rank, which is the position of the data when placed in an ordered series. Based on the result of the non-parametric test the data were then analysed by the ANOVA Randomized Blocks Design (RBD) parametric test, a more powerful statistical method. In assessing the effect of the two ROPS treatments the 11 pairs of tractors were managed as randomized blocks to verify if they pertained to different samples. Because of the small number of observations, data distribution was assessed with the Shapiro-Wilk test (Shapiro & Wilk, 1964), while the homogeneity of the variance was checked with the Levene test (Cochran, 1987). Equation (5.11) refers to each measured parameter with respect to the overall mean (μ), the effect of treatment (γ_i, i.e. two post

ROPS and cab ROPS), the effect of block (β_j, 11 pairs of tractor configurations) and residual error (ε_{ij}).

$$X_{ij} = \mu + \gamma i + \beta_j + \varepsilon_{ij} \qquad (5.11)$$

In the parametric test of the parameters considered as affecting the tractor stability behaviour, track-width and wheelbase were ignored because they did not differ in the paired tractors. Proving the effect of the two ROPS treatments and the difference among the randomized blocks, a linear regression analysis was performed to evaluate the relationship between tractor mass (*mt*) and the other measured stability parameters (*HCoG, MoIl, MoIt, w, b* and α). The mass was selected as independent variable because it was the basic and direct measurement differing in each pair of tractors. A linear regression was performed for each ROPS treatment and stability parameter as a function of the tractor mass. The comparison between the two ROPS treatments was considered, as were R^2, the intercept and slope of the linear regressions.

5.4 Results

5.4.1 Tractor stability parameters

The results obtained from the measurements performed on the 11 pairs of tractors evidenced the effect of the replacement of a two post ROPS with a cab ROPS on the repartition of total mass and the consequence on the stability performance of the machine. Tractor mass (m_t) ranged from 1126 kg to 2470 kg, which is broadly representative of compact narrow-track tractors. Cab ROPS mounted tractors had a higher total mass with respect to the two post ROPS tractors. In terms of median values, the tractor with the two post ROPS (1478 kg) had a lower mass than the tractor with the cab ROPS (1618 kg). This result clearly highlights that the cab ROPS is heavier than the two post ROPS but this did not affect the track-width and wheelbase. It should also be noted that mounting a cab ROPS instead of a two post ROPS caused an increment in the tractor inertia and CoG height due to the location of the cab. This trend was common for all tractors. On the contrary, the cab ROPS caused a decrement of the lateral stability angle. H_{CoG} ranged from 0.52 m to 0.73 m. In terms of median values, the two post ROPS tractor had a lower CoG height than the cab ROPS tractor, 0.60 m and 0.66 m respectively. MoI_l ranged from 140.00 kgm^2 to 612.00 kgm^2. In terms of median values, the two post ROPS tractor had a lower longitudinal inertia than the cab ROPS tractor, 214.00 kgm^2 and 353.00 kgm^2 respectively. MoI_t ranged from 595.00 kgm^2 to 2286.00 kgm^2. In terms of median values, the two post ROPS tractor had a lower transversal inertia than the cab ROPS tractor, 1049.00 kgm^2 and 1454.00 kgm^2 respectively. α ranged from 30.36 deg to 42.26 deg. In terms of median values, the two post ROPS tractor had a higher lateral stability angle than the tractor with cab ROPS, 39.04 deg and 36.37 deg respectively. The stability parameter indexes are depicted in Figure 5.6 in terms of percentage variation of the cab ROPS configuration with respect to the two post ROPS configuration. Results in Figure 5.6 show a 10.81% increment in the cab ROPS tractor mass and consequently a CoG height 10.98% higher, a MoI_l 63.57% higher, a MoI_t 36.77% higher and a lateral stability angle 7.73% lower.

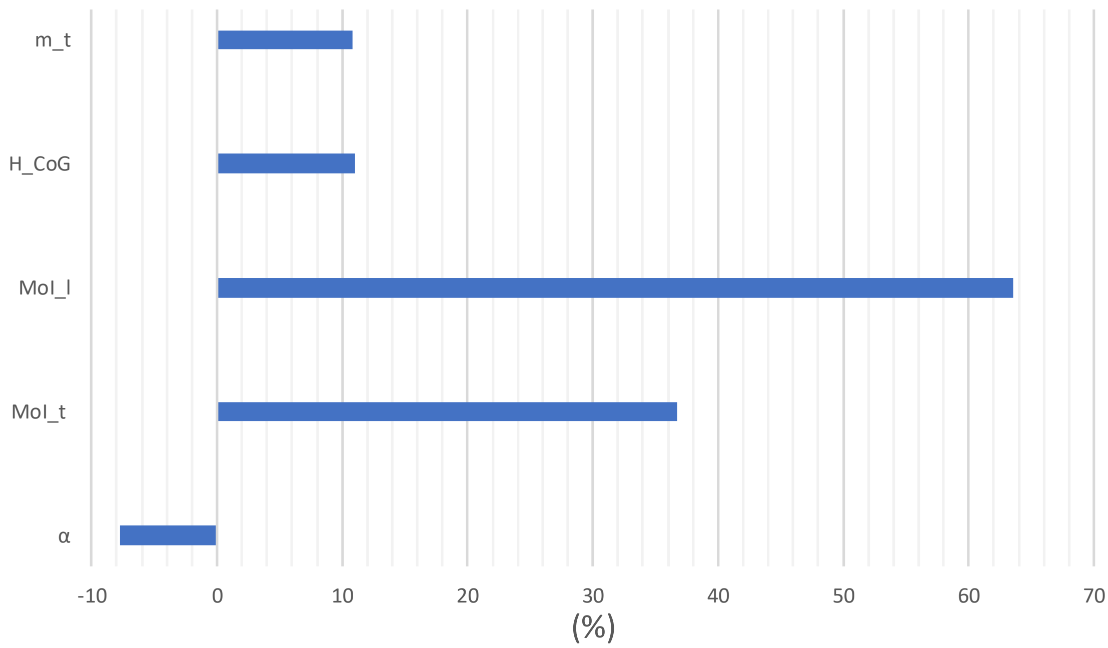


Figure 5.6 Overall effect of ROPS type on tractor stability parameter: % variation of the cab ROPS configuration with respect to the two post ROPS configuration.

5.4.2 Tractor stability analysis

Results of the statistical analysis are summarized in Table 5.1 for both the non-parametric and parametric tests. Wilcoxon signed-rank test in evaluating the difference between the two ROPS types showed a p-value lower than 0.01 meaning that the effect of ROPS type on the median values of tractor stability parameters was highly significant, with a 99% level of confidence. Concerning the parametric analysis, the result of the

Shapiro-Wilk test allowed a normal data distribution to be assumed and the Leven test verified the homogeneity of variance. The randomized block design of the data provided an equivalent result for the two compared treatments with respect to the non-parametric test, with a level of confidence higher than 99%. Focussing on the tractor mass parameter (Table 5.2), the randomized block design, as expected due to the various makes and features of the tractors, demonstrated that the 11 pairs of tractors differed highly, with a 99% confidence level. Tractor mass was selected as independent variable for the regression analysis to evaluate H_{CoG}, MoI_l, MoI_t, α, w and b trend for the two post and cab ROPS configurations. Table 5.3 gives the p-value of the model, intercept and slope and the R^2 of the linear regressions. Because the p-value of fitting a linear regression model was less than 0.05, there is a statistically significant relationship between the variables at a 95% confidence level. The statistical significance of the intercepts demonstrated the different effect of the ROPS type on the stability parameters, while the statistical significance of the slopes indicated that the difference between the two ROPS types remained constant in relation to the tractor mass variation.

	Non-parametric test	**Parametric test**		
	Wilcoxon test	**Levene test**	**Shapiro-Wilk test**	**ANOVA RBD test**
Parameters	**p-value**	**p-value**	**p-value**	**p-value**
M_t	0.0038	0.8773	0.8056	<0.001
H_{CoG}	0.0039	0.4977	0.3413	<0.001
MoI_l	0.0039	0.0497	0.0737	<0.001
MoI_t	0.0039	0.2672	0.2500	<0.001
α	0.0039	0.9014	0.5891	<0.001

Table 5.1 Statistical Analysis: Comparison between the two ROPS treatments.

	DF	**Sum of Square**	**Mean square**	**F**	**p-value**
Treatments	1	158610.18	158610.18	346.32	<0.001
Blocks	10	3772591.09	377259.11	823.74	<0.001
Residual	10	4579.81	457.98	--	--
Total	21	3935781.08	187418.15	--	--

Table 5.2 Analysis of variance test for the tractor mass in the RBD test.

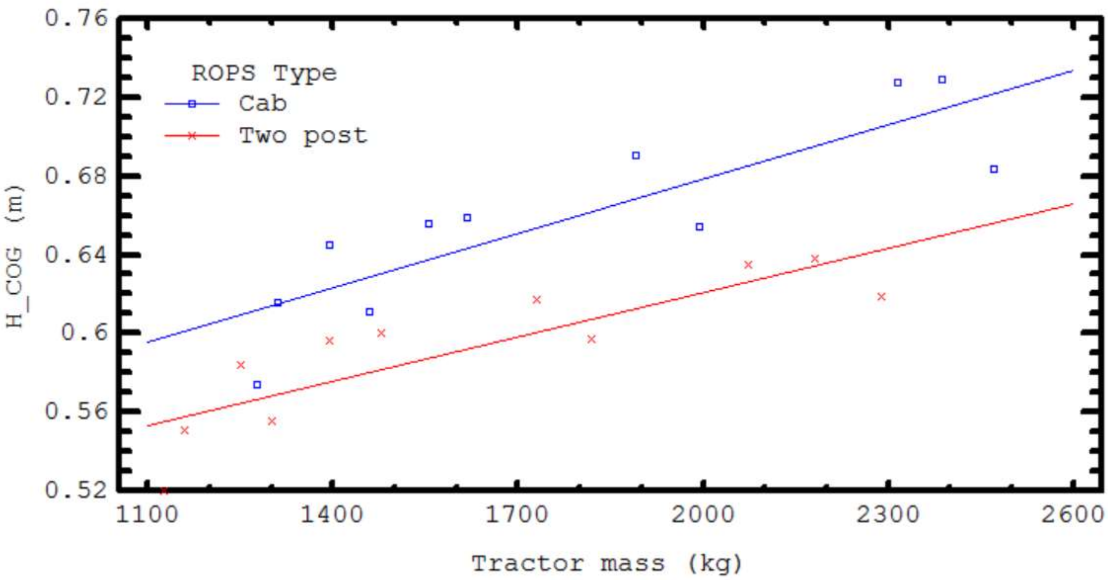
Parameter	Model p-value	Intercepts p-value	Slopes p-value	R^2
H_{CoG}	0.0000	0.0003	0.4865	0.82
MoI_l	0.0000	0.0000	0.0054	0.94
MoI_t	0.0000	0.0000	0.0075	0.98
α	0.2403	0.0846	0.8871	0.20
w	0.1053	0.7308	0.9295	0.15
b	0.0000	0.1059	0.7805	0.80

Table 5.3 Linear regression model for describing the relationship between tractor stability parameters, tractor mass and ROPS type.

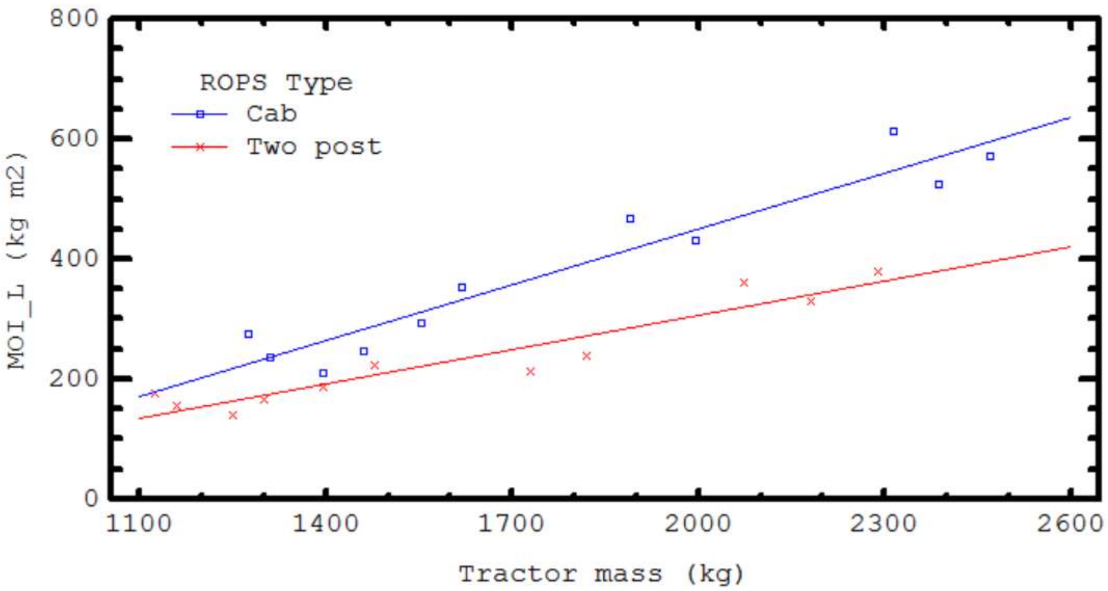
5.4.2.1.1 Relationship between tractor CoG height and MoI, tractor mass and ROPS type

Figure 5.7 shows that the H_{CoG}, MoI_l and MoI_t trends versus m_t increase. H_{CoG}, MoI_l and MoI_t linear regressions calculated were significant (model p-value=0.0, R^2>0.90). The regression analysis confirmed the influence of ROPS type on CoG heights and moments of inertia (intercept p-value=0.00). Increasing the mass the difference in the *MoI* calculated for the two ROPS types also increased (slopes p-value=0.00), while the difference was almost constant (slopes p-value>0.05) in the case of the H_{CoG}, deeming the slope variation not statistically significant.

a)



b)



c)

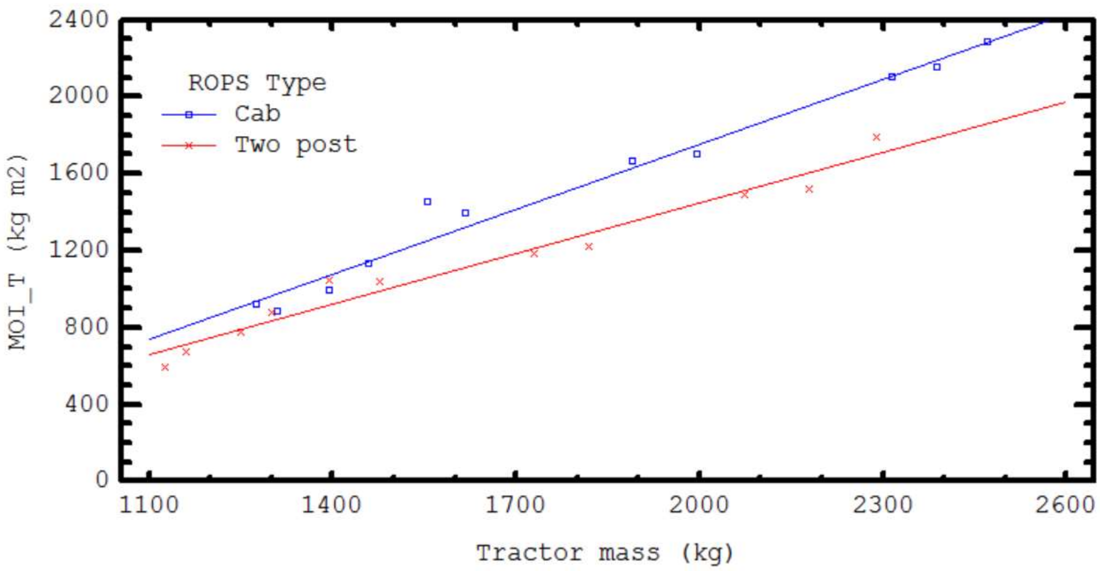
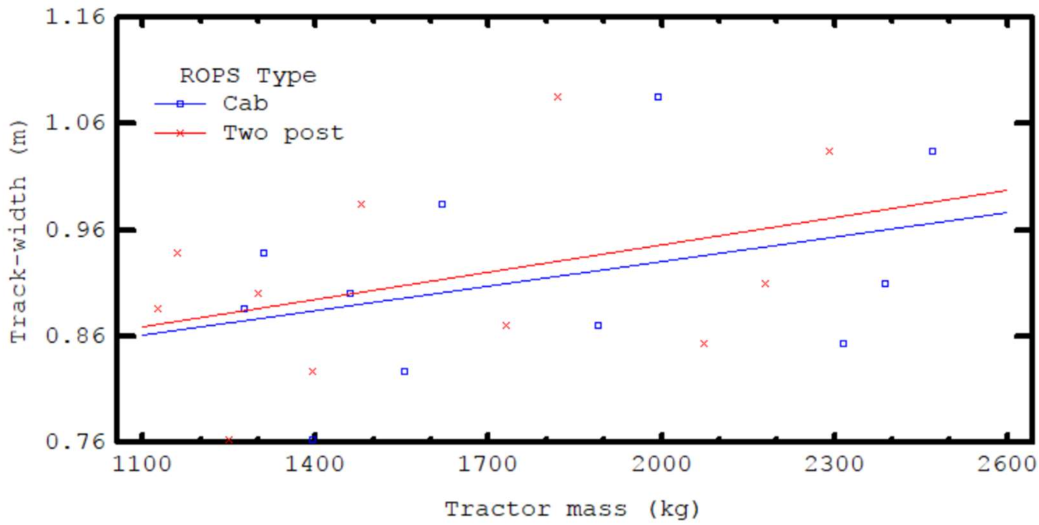


Figure 5.7 Comparison of linear regression models: a) $\boldsymbol{H_{CoG}}$ *(m) vs. Tractor mass (kg), b)* $\boldsymbol{MoI_l}$ *(kg m2) vs. Tractor mass (kg), and c)* $\boldsymbol{MoI_t}$ *(kg m2) vs. Tractor mass (kg).*

5.4.2.1.2 Relationship between track-width and wheelbase, tractor mass and ROPS type

Track-width and wheelbase did not differ among the tractors fitted with the two ROPS types. In Figure 8 the trend of the two parameters as a function of tractor mass seems different and highest for the two post ROPS treatment. Track-width is an important parameter in tractor design as it is closely linked to its field operation; in the case of narrow-track tractors the widths between the orchard and vineyard rows and the clearance space surrounding the tractor in the inter-rows greatly affect the track-width adjustment. Therefore, it is difficult to precisely define the track-width parameter a priori and each tractor is allowed to have a large variation in widths. In the evaluation, the minimum track-width for each tractor configuration was assessed because, being recognized as the worst condition in terms of rollover behaviour, this width was associated to the smallest lateral stability angle. The statistical result confirms that this parameter is not affected by the mass (model p-value>0.05, R^2<0.70). The wheelbase is instead directly correlated to the tractor mass because the track-width is constrained within 1.15 m defined by the OECD for narrow-track tractors (OECD Code 6, 1990), therefore, increasing tractor mass the tractor length and consequently its wheelbase necessarily increase (model p-value=0.00, R^2>0.80). However, both for the wheelbase and track-width the ROPS type installed on the tractor showed no statistical significance (intercept and slope p-values>0.05).

a)



b)

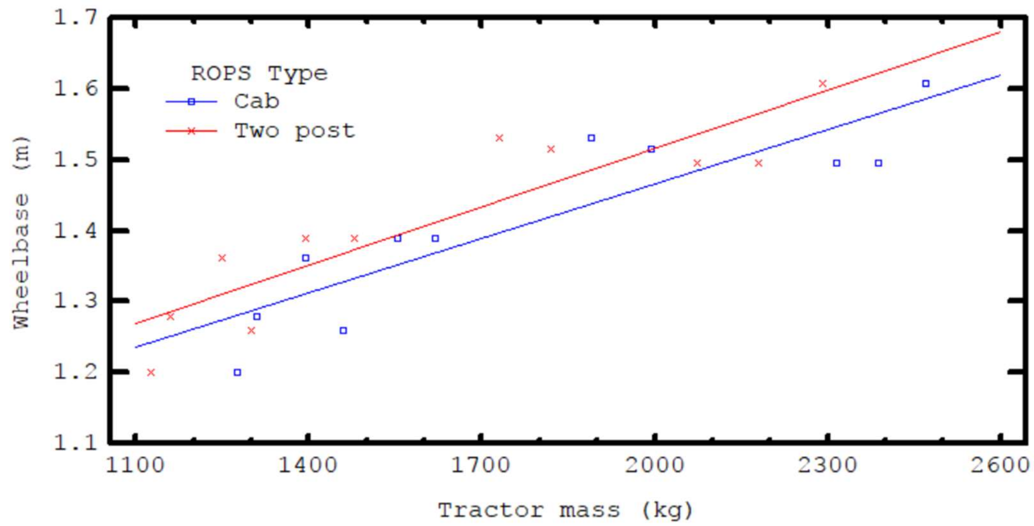


Figure 5.8 Comparison of linear regression models: a) Track-width (m) vs. Tractor mass (kg) and b) Wheelbase (m) vs. Tractor mass (kg).

5.4.2.1.3 Relationship between lateral stability angle, tractor mass and ROPS type

H_{CoG} and w allowed α for the narrow-track tractors to be calculated (Eq. 5.8). Analysing its variation vs. the tractor mass, in relation to the ROPS fitted on the tractor, the intercept, slope and related models are not statistically significant (p-value>0.05, R2<0.25). The linear regression increasing tractor mass showed a decreasing trend for α (Figure 5.9), but the statistical result denoted the absence of a relationship between the lateral stability angle and tractor mass (Table 5.3); consequently α values were treated as belonging to two separate groups of tractors, one fitted with the cab ROPS and the other with the two post ROPS (Table 5.4). The box and whisker plot related to the lateral stability angle (α) is depicted in Figure 5.10: the mean α calculated for the two post ROPS tractor group (37.62 degrees) was higher than the mean value of the tractor group fitted with the cab ROPS (34.74 degrees).

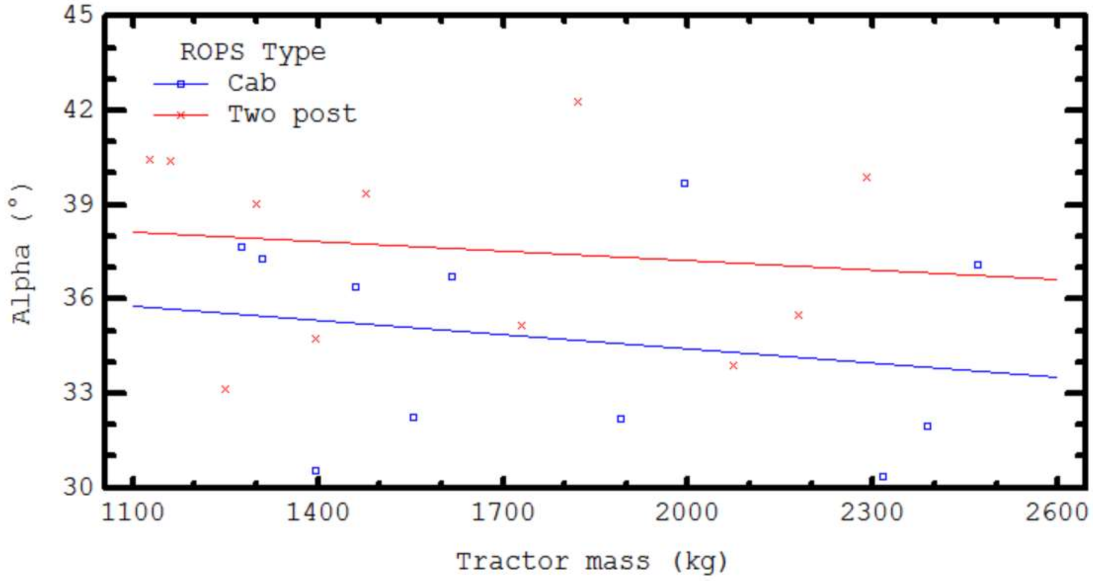


Figure 5.9 Comparison of linear regression models:

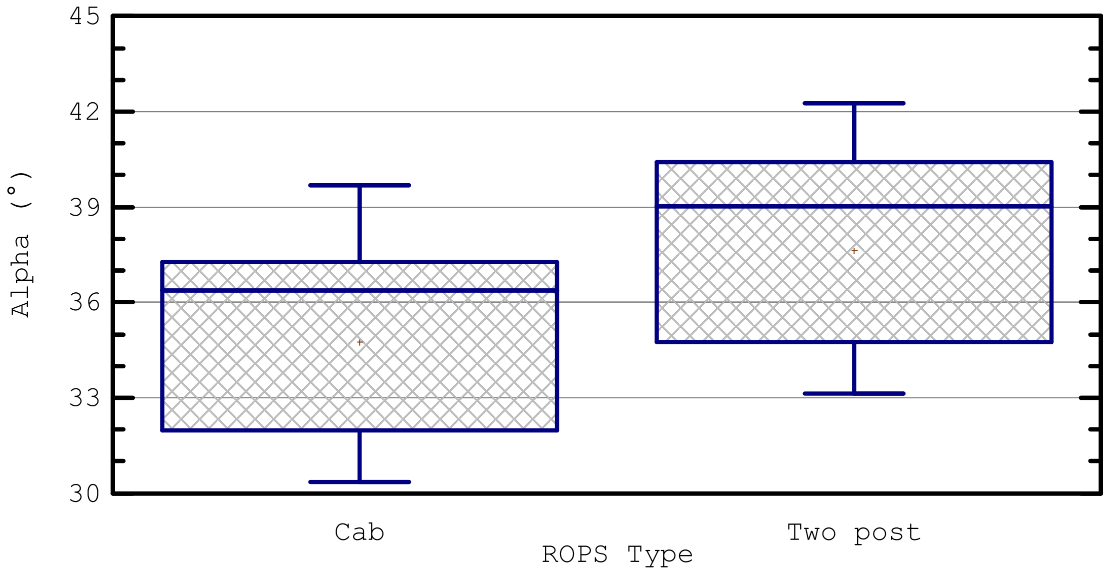


Figure 5.10 Box and whisker plot: lateral stability angle of the Two post ROPS configuration compared to Cab ROPS configuration.

ROPS Type	*Count*	*Mean (degrees)*	*Median (degrees)*	*Standard deviation (degrees)*	*Coeff. of variation*	*Standard error (degrees)*	*Minimum (degrees)*	*Maximum (degrees)*
Cab	11	34.74	36.37	3.295	9.49%	0.99	30.36	39.68
Two post	11	37.62	39.04	3.164	8.41%	0.95	33.12	42.26
Total	22	36.18	36.56	3.479	9.62%	0.74	30.36	42.26

Table 5.4 Summary statistics for α: Cab, Two post and Total tractor data

5.5 Discussion

Analysing the results obtained from the seven stability parameters evaluated, five, i.e. m_t, H_{CoG}, MoI_l, MoI_t and α, were affected by the ROPS type mounted on the tractor, and four, i.e. H_{CoG}, MoI_l, MoI_t and b, were related to the tractor mass m_t. The relationship with tractor mass is in line with the results obtained by Guzzomi and Rondelli (2013) in a study on the variation of some parameters, among others H_{CoG}, MoI_l, b and w, of narrow-track wheeled agricultural tractors mounted with a two post ROPS.

The main findings can be condensed in the following points:

- Centre of gravity height increased when the tractor mass increased; in each tractor pair the machine mounted with the cab ROPS showed a higher centre of gravity height than the tractor with the two post ROPS. The result also denotes that the difference between the two centre of gravity height remained constant increasing the tractor mass (Figure 5.7a).
- The effect of ROPS type on the moments of inertia varied between the paired tractors. The cab ROPS increased tractor inertia with respect to the two post ROPS in the pair characterised by the same tractor mass. At the same time tractor inertia increased increasing tractor mass but the inertia difference between the two ROPS type also increased (Figure 5.7b and Figure 5.7c).
- Tractor wheelbase was not affected by the ROPS type mounted on the tractor but the parameter increased increasing the tractor mass (Figure 5.8b).
- The lateral stability angle was not related to tractor mass and was lower for the tractor configurations fitted with the cab ROPS. The additional mass due to the cab fitment, causing an increase in the centre of gravity height, decreased the angle. Moreover, by increasing the mass and moments of inertia, greater tractor energy is involved in the rollover event, as previously evidenced in studies analysing tractor rollover behaviour (Bruno Franceschetti et al., 2014; A. L. Guzzomi et al., 2009).

5.6 Conclusions

The contribution of the ROPS type to the stability performance of narrow-track tractors specialized for operating in orchards and vineyards was analysed. Two post and cab ROPS effect on the tractor were evaluated by measuring the tractor mass, centre of gravity height, track-width, wheelbase, longitudinal and transversal moments of inertia and lateral stability angle, as the parameters affecting tractor behaviour in a rollover event. The cab ROPS mounted on the same narrow-track tractor decreased the machine stability with respect to the two post ROPS. The results of the lateral stability angle seemed to show that this was not related to the tractor mass; nonetheless by fitting a cab ROPS, due to the tractor shape and position of the driver's seat, the centre of gravity position negatively influenced the lateral stability angle. Moreover, the tractor with the cab ROPS was also associated to a higher tractor mass and inertia causing greater energy involved in the rollover event.

A recent debate at international level on the safety performance of the two post ROPS, consequent to an increase in the number of fatal accidents involving tractors with foldable ROPS in the folded-down position, led to claims that the cab ROPS provide better driver protection in a rollover event because the clearance zone always remains surrounding the driver. However, the investigation denoted that on sloping areas, typical of many orchards and vineyards, narrow-track tractors fitted with a cab ROPS reach an unstable state on a lower slope than that of the two post ROPS tractors. This finding should be carefully considered when designing the modern highly rounded cab ROPS for compact narrow-track tractors, because these cabs are of reduced height, close to the height of the safety clearance zone, and consequently in a case of tractor rollover on the impact with the ground cab deflection has to be prevented by designing it with a high level of stiffness.

As the ROPS types are currently tested according to standardized procedures, none of them could be defined as providing a higher safety level for the driver in terms of strength behaviour. Furthermore, for the narrow-track tractors when mounted with a two post ROPS, OECD Code 6 includes preliminary tests to ascertain non-continuous rolling behaviour in a rollover event because the two post ROPS has to be designed to stop the rollover at ROPS-ground impact time.

Given that the results obtained demonstrate that driver safety is greater if the two post ROPS is correctly mounted and used in the upright position during normal operations, as tractor stability is higher and continuous rolling is prevented, an effective training campaign should be promoted to teach tractor drivers the correct use of foldable ROPS combined with improving the ease of ROPS manual handling to positively affect the number of fatal accidents.

5.7 Acknowledgements

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

6.1 Abstract

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.

6.2 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.

6.3 Materials and Methods

6.3.1 Machines and equipment

Two self-propelled sprayers for field crops, manufactured by Grim Ltd (Jesi, AN, Italy) (Figure 6.1) 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 6.1 .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.

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

Table 6.1 Technical features of the sprayers

Type 1

Type 2

Figure 6.1 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 6.1; 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.

6.3.2 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 (6.1), where F_2 is the ground reaction at the front axle due to the machine mass (Figure 6.2(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 6.2(2)). The offset (b) of the CoG was obtained using the wheel track (d_t) as the moment arm (Eq 6.2); the lateral coordinate y was given by Eq (6.3). 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 6.2 (3)). The horizontal distance (c) from the CoG to the line of suspension was calculated (Eq 6.4-6.5). 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 (6.6) 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 6.1) in contact with the ground (Eq 6.7). 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 6.5 and 6.6.

$$x = \frac{w\,F_2}{m} \tag{6.1}$$

$$b = \frac{d_t\, F_5}{m} \tag{6.2}$$

$$y = \frac{d_t}{2} - b \tag{6.3}$$

$$c = \frac{d\, F_3}{m} \tag{6.4}$$

$$c = (d - x)\cos\alpha \pm e\ \sin\alpha + h\ \sin\alpha \tag{6.5}$$

$$h = d\, cot\, \alpha \left[\frac{(F_3 - F_2)}{m}\right] \pm e\ \left[\frac{F_3 - m}{m}\right] \tag{6.6}$$

$$z = h + r \tag{6.7}$$

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 6.8-6.9-6.10 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.

$$x = \frac{\sum_{i=1}^{2} m_i x_i}{M} \tag{6.8}$$

$$y = \frac{\sum_{i=1}^{2} m_i y_i}{M} \tag{6.9}$$

$$z = \frac{\sum_{i=1}^{2} m_i z_i}{M} \tag{6.10}$$

6.3.3 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 6.3a).

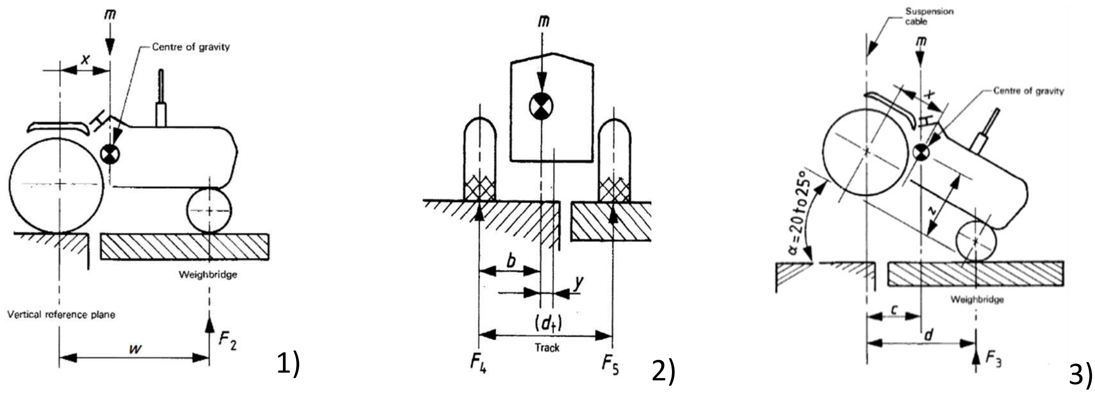
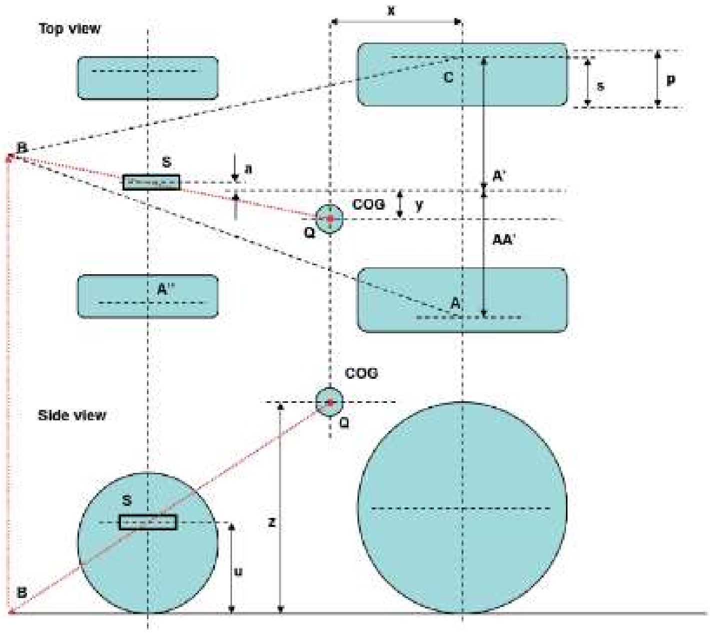


Figure 6.2 Reference for the determination of the coordinates of CoG: 1) horizontal fore-and-aft (x), 2) lateral (y) and 3) vertical (z).

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 6.3a), 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 (6.11). 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 6.12). Angles α, σ, and δ are illustrated in Figure 6.3b. The SOA_{σ} (Eq 6.13), with respect to the line formed by the front and rear wheels, according to Eq (6.11) denotes AA' as the base line of the stability triangle (Figure 6.3a) and Δo is the difference in track width between front and rear tyre.

$$SOA_{\sigma} = tan^{-1}\left(\left(AA' - y - \left(\Delta o \ \frac{x}{w}\right)\right)\frac{100}{z}\right) \tag{6.11}$$

a)



b)

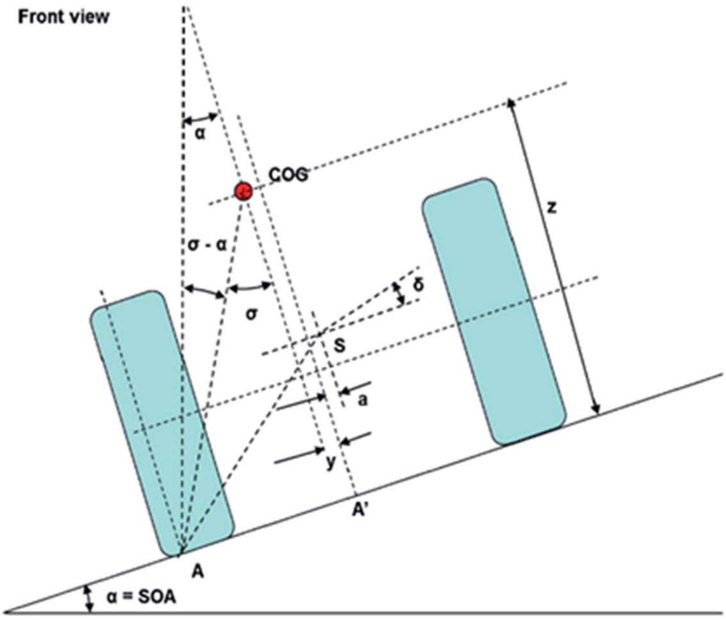


Figure 6.3 Determination of the stability: a) Graphical determination of the stability triangle, b) COG during roll-over around line AS and angles in the same transversal plane.

$$\sigma - \alpha < 1.25 \cdot \delta \;\; \Rightarrow \;\; SOA = \alpha \tag{6.12}$$

$$\sigma - \alpha \geq 1.25 \cdot \delta \;\; \Rightarrow \;\; SOA = \sigma \tag{6.13}$$

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 6.14). 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 6.15).

$$SOA_F = tan^{-1}(x/z) \tag{6.14}$$

$$SOA_R = tan^{-1}((W - x)/z) \tag{6.15}$$

6.4 Results

6.4.1 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 6.2 gives the coordinates of the CoG with respect to the coordinate system represented in Figure 6.3.

		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

Table 6.2: x, y, z coordinates of the CoG of the sprayers

6.4.2 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 6.3 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 6.4. Table 6.4 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°).

		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°

Table 6.3 Static Overturning Angle of the sprayers

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

Table 6.4 Tip-Over angles of the sprayers

6.5 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.

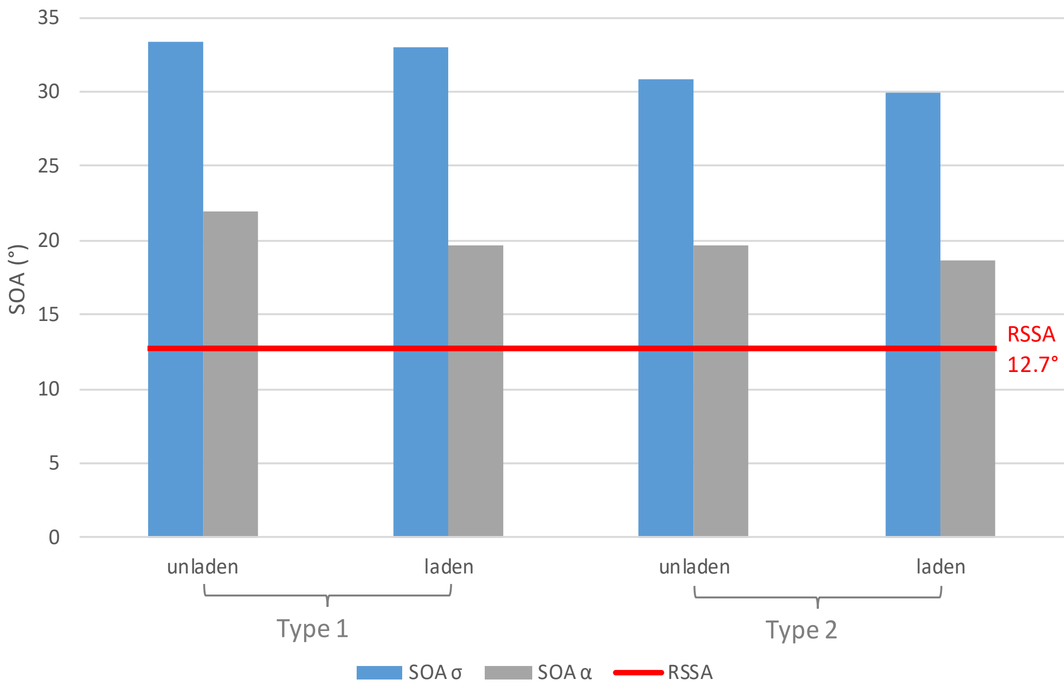


Figure 6.4 SOAσ and SOAα for the unladen and laden sprayers. Red line represents the RSSA

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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7 Conclusion

The research studies on tractors related to the stability have been recognized valid at scientific level from several studies. For several years, the researchers studied the stability topic related to tractor design and operation to minimize the dangerous for the operator and at the same time to maximize the tractor working features.

Related to the aim of the first evaluation the cab ROPS mounted on the same narrow-track tractor decreased the machine stability with respect to the two post ROPS. Furthermore, the results of the lateral stability angle seemed to show that this was not related to the tractor mass. Nonetheless by fitting a cab ROPS, due to the tractor shape and position of the driver’s seat, the CoG position negatively influenced the lateral stability angle. Moreover, the tractor with the cab ROPS was also associated to a higher tractor mass and inertia causing greater energy involved in the rollover event.

As confirmed in a recent debate at international level on the safety performance of the two post ROPS, consequent to an increase in the number of fatal accidents involving tractors with foldable ROPS in the folded-down position, the cab ROPS seem to provide better driver protection in a rollover event because the clearance zone always remains surrounding the driver. However, the investigation denoted that on sloping areas, typical of many orchards and vineyards, narrow-track tractors fitted with a cab ROPS reach an unstable state on a lower slope than that of the two post ROPS tractors. This should be taken into account when designing the ROPS for modern narrow-track tractors. In fact, the peculiarity of these tractors is not only the reduced track width but also the small size of the rounded cab. The clearance zone will therefore be very close to the overall dimensions of the cab and, consequently, in the event of the tractor rollover, in the impact of the cab on the ground, any deflection must be avoided by designing it with a high level of stiffness.

It should be stressed also that none of the ROPS types, currently tested according to standardized procedures, provides a higher safety level for the driver in terms of strength behaviour with respect the others. Furthermore, for the narrow-track tractors when mounted with a two post ROPS, OECD Code 6 includes preliminary tests to ascertain non-continuous rolling behaviour in a rollover event because the two post

ROPS has to be designed to stop the rollover at ROPS-ground impact time. Given that an acceptable driver safety level is guaranteed only if the foldable ROPS is correctly mounted and used in the upright position during normal operations, as tractor stability is higher and continuous rolling is prevented. An effective training campaign should be promoted to teach tractor drivers the correct use of foldable ROPS combined with improving the ease of ROPS manual handling to positively affect the number of fatal accidents.

Considering the second part of the research the rollover and tip-over risk, according to the ISO 16231-1/2, is low and a ROPS fitment is not needed in the case of the two field self-propelled tested. By the way 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.

Nevertheless, it has to be considered that the ROPS approach for the tractors is mandatory and allowed fatal accidents due to tractor rollover to be sharply decreased over the years. In reason of this experience the compulsory installation of a ROPS on the self-propelled sprayers could produce the same result over the time. Therefore, before to consider the ROPS approach as a not compulsory procedure for self-propelled machines, a deep evaluation and experience on the provisions of the recent ISO 16231 appear necessary. The point is that excluding the potential risk of machine rollover is a difficult exercise and if the decision taken is not correct the injuries for the driver will be certainly serious or fatal.