Design, manufacturing, and strength test of a 4-post ROPS fitted on a very low-profile tractor (TRACLAS project)

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Abstract. To improve the safety level when agricultural tractors work on slope under canopy, INAIL (the Italian National Institute for Insurance against Accidents at Work) funded a research project, named TRACLAS, devoted to set-up a prototype of low-profile compact tractor, not exceeding 1.60 m overall height, equipped with a 4-post ROPS (RollOver Protective Structure).
After the complete set-up of the prototype, some field and lab tests were carried out to compare its performance with those of some comparable tractor models already on the market, used in vineyards, orchards and greenhouses.
A basic step of the TRACLAS project was the execution of the strength test of the customized 4-post frame (the ROPS) carried out in compliance with the OECD Code 4. The main features concerning the design, the manufacturing and the validation test of the ROPS are reported in this paper. The low-profile compact tractor prototype was obtained starting from a Goldoni E100 commercial tractor. The 4-post ROPS was tested successfully, being able to fully satisfy the desired requirement, i.e., the protection of the clearance zone, located with reference to the tractor driving place (operator's seat and steering-wheel) during all the loads provided by the official procedure.

Keywords: agricultural work safety; tractor overturning; Roll-Over Protective Structure (ROPS); vineyard, orchard and greenhouse

1 Introduction

The main cause of accidents in agriculture concerns the tractor loss of control and the consequent its overturning [Facchinetti et al., 2021; Cecchini et al., 2013]. Considering the working conditions and the typical shape of agricultural tractors, the most frequent rollovers occur on the lateral axis (about 75% of cases) [Inail, 2017, Inail, 2016]. Furthermore, the highest number of fatal accidents, resulting in death or permanent disability involving the operators of agricultural tractors, demonstrates that the current safety devices mounted on tractors, especially on narrow-track tractors, used particularly in specialized crops (orchards) need to be improved [Bambach et al., 2013]. The mainly adopted solution to reduce the consequences of the overturning of tractors is made up of passive protection devices [Rondelli et al., 2018]. The combination of a RollOver Protective Structure (ROPS) with a restraint system (seat belt) creates and guarantees, around the operator, a "safety volume", named also "clearance zone" (Pascuzzi, 2015; Kim et al., 2011). Mainly on narrow-track tractors, ROPS are folding type, to make easy the execution of the garaging and some working routines under canopy. Nevertheless, the folding of the ROPS could lead to an improper use [Mattetti et al., 2017]. So, several fatal accidents are caused by the tractor overturning, resulting in hitting and crushing the driver, due to the missing of the re-positioning in safety condition of the ROPS [Facchinetti et al., 2021; Melvin et al., 2009; Molari and Rondelli, 2007]. This is a quite important question, on which much work has to be still carried out, to improve the overall tractor safety, by setting-up more efficient solutions able to protect suitably the operator (Myers, 2010).

To improve the safety level when tractors work on slope under canopy, and solve the described problem, with the collaboration of some research units belonging to university and research bodies, INAIL (the Italian National Institute for Insurance against Accidents at Work) funded a research project, named TRACLAS (messa a punto di un TRattore Agricolo Compatto per le LAvorazioni Sottochioma). The project was devoted to set-up a compact tractor (called like the project, i.e. “TRACLAS”), complementary and competitive in terms of performance to the models at present available on the market, but equipped with a not-folding ROPS.

In addition to compactness, another important feature was the very high lateral and longitudinal stability, as well as an excellent manoeuvrability. A further added value has been the fitting of a 4-post ROPS (or, alternatively, a cab), obviously coupled with a safety belt of the driving seat, to assure an effective driver protection in case of overturning.

2 Materials and methods

2.1 Farms survey

Taking into account 20 farms located all over Italy, found concerning the most popular crops in the reference areas, the first step of the project involved a series of detailed static (planting layout) and dynamic (cultivation methods) surveys of the main specialized italian open field crops (grape, olive, hazel, almond, kiwi, etc.). The selection of these crops was connected in particular to the difficulty of working with tractors under canopy. In each farm, the main characteristics of the tractors and implements used were carefully analysed. In detail, the data investigated concerned:

methods and frequency of execution, assessment of the boundary conditions (e.g. state of the soil in different cultivation periods, vegetation, stage of growth of the main crop, etc.); size and particularity of the equipment used; power and dimensions of coupled tractors; plant layout; working speeds, theoretical and real work capacity, including the accessory transfer routines.
In the investigated farms, the operators were interviewed about the critical issues encountered in their activity with tractor, the desired stability of the machine and its most suitable overall dimensions taking into account the non damage of the canopy and the production. Furthermore, they were asked about the desirable design and performance features of a new compact tractor for specialized crops.
The further step concerned an ad-hoc study of the canopy volumes of the investigated crops, in the period of their maximum growing, to assess the possible interferences during the travelling of specific tractor models currently operating in the farms. Also the overall dimensions of a theoretical tractor, passing in the inter-rows with no interference were properly defined [Pascuzzi et al., 2020].

2.2 Tractor prototype

The results of this study led to the definition of the main technical requirements for the TRACLAS. The prototype was set-up by modifying a Goldoni E100 (Goldoni, Migliarina di Carpi, Modena - Italy) narrow-track, isodiametric wheels tractor, equipped as standard with a 2-post front foldable ROPS, homologated according to OECD Code 6.
As part of the modifications introduced on the Goldoni E100, the 2-post front rollbar rollbar was replaced with a 4-post frame. Moreover, to reduce the overall height of the machine, the tyres 320/70R20 were replaced with tyres 31.5-15, thus satisfying this limit provided by the project, i.e. overall height not exceeding 1600 mm. Due to the modified set-up (in particular for the fitting of very wide tyres), the minimum track width of the front and rear axles exceeded the conventional limit of 1150 mm; as a consequence, the tractor was included in the “conventional” category instead of the "narrow-track" category.
One of the most important goals of the project was to ascertain the safety requirements of the new ROPS fitted on the prototype. Thus, the main goal of this paper is to report the study carried out to design and manufacture the 4-post frame mounted on the TRACLAS, as well as the tests carried out according to the OECD Code 4.

2.3 The 4-post frame

The new customized 4-post frame is fixed rigidly on the tractor body, with no silent blocks. Usually, silent-blocks reduce the transmission of high frequency vibrations, that are producing negative effects, such as a noise resonance in case of fitting of a closed cab as well as fatigue phenomena on the main structure.
The four posts of the frame are made with steel square tubes 50x50x5 mm, welded to an upper ring also made by square tubes 50x50x5 mm, reinforced with some crossbars (always made by square tubes 50x50x5 mm) and plates, to increase the structure stiffness. Steps were then taken to optimize the ROPS stiffness, concerning the optimization of the overall dimensions, by reducing the so called “margin”, i.e. the free space remaining between the safety zone volume and the ROPS structural members.

Therefore, this is the reason why several reinforcements were added (in terms of crossbars and corner plates), to reduce at a minimum the elastic and plastic deflections resulting from the loads application, thus ensuring the respect of the clearance zone, avoiding the intrusion of structural elements (Figs. 1 and 2).

Fig 1. The 4-post frame installed on the compact agricultural tractor (TRACLAS). In red, the crossbars and corner plates added as stiffening elements.

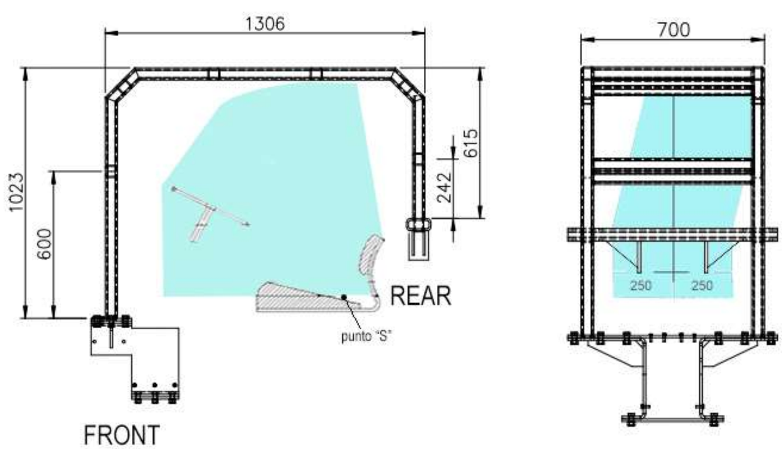

Fig. 2. Main dimensions of the 4-post ROPS fitted on TRACLAS, and location of the clearance zone (according OECD Code 4).

2.4 The ROPS tests

The test of the 4-post frame installed on the compact profile agricultural tractor prototype was carried out according to OECD Code 4, that provides a given sequence of horizontal and vertical loads. More in detail, in the horizontal (longitudinal and side) loads, a given energy is to be absorbed, derived from the integral of the load-deflection curve, having the so-called "reference mass" of the tractor as a reference (Mrif.). Conversely, for the vertical loads a given crushing force has to be attained, always connected to the reference mass. Each test is passed if during its execution and at the end no part of the frame shall enter the clearance zone and furthermore the clearance zone shall not be outside the protection of the protective structure [OECD, 2021].
Considering the fitting of the 4-post frame and all the tanks full, the compact tractor reached an overall mass of 1950 kg, burdening for the 65.4% (1275 kg) on the front axle and the 34.6% (680 kg) on the rear axle. The "reference mass" (i.e. the value used for the calculation of the values of energy to be absorbed and the force to be attained) [OECD, 2021] was therefore set at 2000 kg, a little bit more than the measured mass, to take into account some accessories that could be fitted at a later extent.
The longitudinal load (energy to be absorbed, to be calculated with the formula (*not an equation*): E (J) = 1.4 * Mrif = 2800 J) was carried out from the front (because this is the part of the tractor bearing the major part of the mass) by means of a hydraulic cylinder, operated in a quasi-static mode (max speed: 5 mm/s). During the test, the incremental values of force and deflection were recorded (Fig. 3a). The energy absorbed E_{tot} (J) by the ROPS was calculated in accordance of the following formula:

$$E_{tot} = \sum (F_i \cdot \Delta d_i)$$

where :
F_i = measured loading force (N);
Δd_i = incremental deformation in the loading direction (single step 0.1 mm)

The front vertical load (max force to be attained, to be calculated with the formula: F (N) = 20 * Mrif = 40 kN) was carried out by means of a steel beam, connected at the ends to two hydraulic cylinders, in turn fixed to the plant base (Fig. 3b).

Fig. 3. The tractor ROPS at the end of the front loads: longitudinal (a) and vertical (b).

The side load provided an energy absorption of 3500 J (E = 1.75 * Mrif), and was executed placing the TRACLAS laterally in respect to the loading hydraulic cylinder (Fig. 4a). Finally, the rear vertical test (again the max force to be attained was 40 kN) was carried out in a similar way to the aforesaid front compression test, but with the horizontal beam placed on the rear area of the safety frame (Fig. 4b).

Fig. 4. The tractor ROPS at the end of the side (a) and rear vertical (b) loads.

3 Results and discussion

3.1 The manufactured compact tractor fitted with the 4-post ROPS

As results of previous specific tests, carried out in accordance with ISO 789, ISO 22915 and OECD Code 6 standards, the TRACLAS highlighted a remarkable lateral static stability, combined with excellent manoeuvrability (Figs. 5 and 6).
The fitting of the non-foldable 4-post ROPS assured a constant and effective protection to the driver in the event of overturning, provided he/she is properly fastened to the seat with a safety belt.
Table 1 reports the main features of the compact tractor.

Fig. 5. Front (left) and side (right) views of the TRACLAS, a very low-profile tractor equipped with a 4-post frame.

Fig. 6. Lateral static stability test: hoist (left) and platform (right) method, carried out in accordance with OECD Code 6.

Table 1. Main features of the TRACLAS

	front	rear
Track, mm	1350	1290
Tyres	31.5-15	31.5-15
Mass, kg	1275	680
Overall width, mm	1710	

3.2 Results of strength test

In fig. 7 are shown the load-deflection curves of the front and side strength tests, as well as the elastic, plastic and total deflection values recorded at the end of each test.
Table 2 shows the final deflection values measured at the end of the sequence of tests. The remarkable robustness of the ROPS in fully confirmed, because the overall deflections have been very limited, especially in the longitudinal and vertical direction.

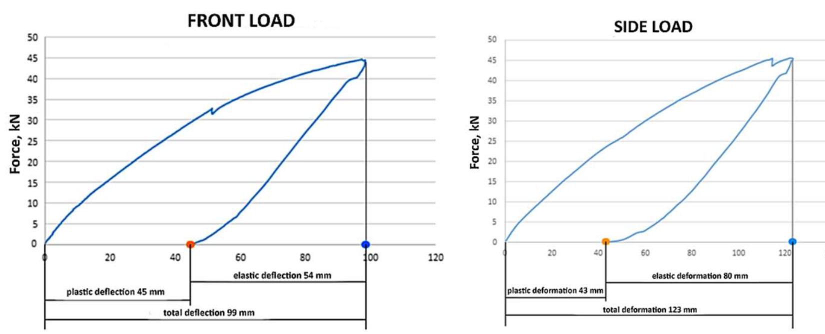

Fig. 7. Load-deflection curves of the front and side strength tests.

Table 2. ROPS deflection values measured at the end of the test sequence.

		Deflection, mm
Longitudinal (to the rear)	right	4
	left	4
Side	front	100
	rear	100
Vertical (front)	right	5
	left	3
Vertical (rear)	right	2
	left	23

The side deflection recorded has been higher than those measured in the other directions, but this is justified by the severity of the correspondent load, for the highest energy amount to be absorbed by the ROPS. In general, the deflection values have been much lower than those commonly recorded in the safety frames installed on other tractors comparable to the TRACLAS.
Moreover, to validate the suitability in carrying out the typical tasks of specialized crops, the TRACLAS was tested at work either inside a hazelnut orchard and an olive grove. Also considering the cultivation season, a shredder make Facma model TR 200 BVE has been coupled to the compact tractor to execute an inter-row grass cutting at a travelling speed of 5 km/h, obtaining a quite good working capacity, of about 1 ha/h.

4 Conclusions

All the tests required by the OECD Code 4, to which the 4-post frame fitted on the TRACLAS was subjected, were successfully passed. The safety zone, representing the volume occupied by the driver normally placed at the seat with the torso erect and his hands on the steering wheel and suitably fastened with a seat belt, has been always protected throughout and at the end of each loading test.
Indeed, this is the only requirement provided by the applied standard but, in this specific case, it was revealed particularly critical, considering the severe constraint of the ROPS design, i.e. the compact dimensions especially in height (max 1600 mm above the ground).
The design and manufacturing of a very rigid ROPS (significantly oversized compared to commercial ROPS) was very challenging, because it was mandatory the absorption of the energy especially in terms of resistance (i.e. high strength) rather than deformation (i.e. high elasticity). This goal was fully achieved, thus confirming the design forewords, being those the protection of a certain safety volume on a compact vehicle.
The TRACLAS was easy to be used, highlighting good reliability and trim stability. Above all, due to its extremely low overall height, the compact tractor evidenced no interference at all with the canopy when passing in the inter-rows, between the plants.

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All the authors contributed equally to this paper.

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