Safety Level Investigation of Front Mounted Roll-Over Protective Structures on Narrow-Track Wheeled Agricultural and Forestry Tractors

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Abstract

Nowadays many narrow-track wheeled agricultural and forestry tractors are equipped with two posts front mounted Roll-Over Protective Structures (ROPS). These kind of ROPS are of two different types: fixed or completely foldable. In Italy is largely widespread the foldable type of ROPS because, in its folded configuration, it allows to work under trees or in greenhouses. Fatal accidents recently occurred in Italy involving narrow-track wheeled tractors equipped with two posts front mounted ROPS in safety position. Thus, National Institute for Occupational Safety and Prevention (ISPESL) developed an investigation in order to define the safety level of this kind of structures and design a Compact Roll-Over Protective Structure (CROPS) for this kind of tractors. For CROPS design it has been applied an iterative procedure made up of the following steps:

1. **a parametric CAD model of the structure fitted on a virtual model of a narrow-track tractor;**
2. **finite element analyses (FEA) according to OECD code 7;**
3. **optimization in order to reduce CROPS dimensions.**

Finally a prototype of the structure has been realized for performing experimental strength test and handling test in the field.

Keywords:compact roll-over protective structure, finite element analysis

Introduction

In Italy many agricultural and forestry tractors are equipped with two posts front mounted foldable ROPS. The main reason lies on the necessity to work under trees and/or in greenhouses, and a completely folded ROPS fulfils this necessity. However, from safety point of view, the use of this kind of ROPS does not comply with the required safety level with respect to roll-over risk neither in folded configuration nor in safety one. In fact, the two posts front mounted ROPS grants a lower safety level with respect other protective structures, e.g. rear mounted two posts ROPS or four posts frame, even when it is locked in safety configuration or it is not foldable at all. This is more evident considering the last fatal accidents recently occurred in Italy involving tractors equipped with two post front mounted ROPS in safety position. For these reasons, ISPESL developed a specific research activity in order to investigate the safety level of this kind of protective structures. In this paper the main results of this investigation are presented. Moreover an innovative compact roll-over protective structure (CROPS) and its design process developed by the authors are herein described. This structure, installed on the actual narrow-track wheeled tractors, allows to perform under trees or in-greenhouses working activities ensuring adequate protection against roll-over risk.

Safety level investigation

Considering that it is possible to equip narrow-track wheeled tractors both with a rear two posts ROPS, as defined in OECD code 7, or with a front two posts one, as defined in OECD code 6, a comparison between these two kinds of protective structures has been carried out. The main difference concerns the shape and the dimensions of the operator clearance zones protected by each structure. This peculiarity is also reported in the field of application of OECD code 6 which, at point 2.1.4, specifies that it refers to tractors "*being fitted with roll-over protective structures of the dual-pillar type mounted in front of the driver's seat and characterised by a* <u>*reduced clearance zone*</u> *attributable to the tractor silhouette, thus rendering it inadvisable, under any circumstances, to impede access to the driving position but worthwhile retaining these structures (fold-down or not) in view of their undoubted ease of use*". In figure 1 these two clearance zones are shown.

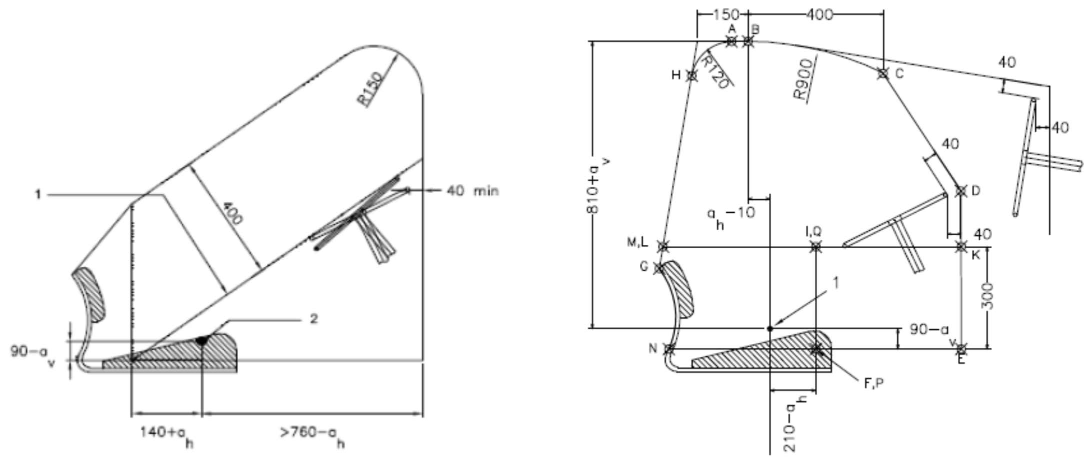

Figure 1. Comparison between operator clearance zones as defined in OECD code 6 (on the left) and in OECD code 7 (on the right)

From the comparison one can see that the clearance zone preserved by a two posts front mounted structure has a completely different shape, conformed in such a way that the operator is in safe position only if he flexes him-self forward, till touching the steering wheel during tractor rolling over. In fact, the simulated ground plane, which is represented by a straight line from the top of the front ROPS to the top of the rear hard fixture, does not intersect the operator clearance zone only if it is shaped in this manner (see figure 2, left hand side). Otherwise, considering the clearance zone defined in OECD code 7, the same front ROPS does not ensure protection in case of roll-over (see figure 2, right hand side), unless significantly increasing the height of the front roll-bar or of the rear hard fixture. Thus, it seems that the safety level guaranteed by this kind of protective structure is quite poor. This is also confirmed by recent fatal accidents occurred in Italy, concerning the roll-over of tractors fitted with foldable front mounted ROPS in safety configuration. Moreover another issue related to this kind of protective structures concerns the possibility of folding them down.

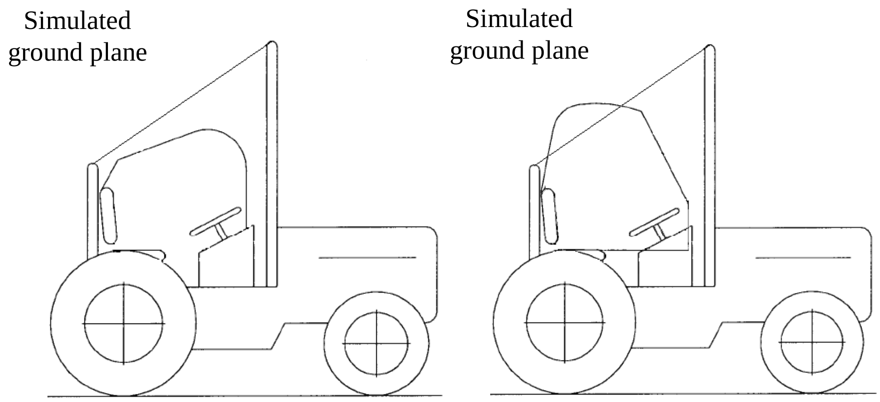

Figure 2. Simulated ground plane protection ensured by a two posts front mounted ROPS with reference to OECD code 6 operator clearance zone (on the left) and OECD code 7 one (on the right)

In many cases the folding operation is achieved by simply removing a pin by hand without the use of any specific tool. The easiness of this operation leads to fold the ROPS even during field operation, completely by-passing a fundamental safety device. Finally, the last concern with respect to front mounted ROPS refers to its application on articulated wheeled tractors. The possibility to rotate about a central pivoting axis of tractor main frame sensibly reduces the already poor safety level of this protective structures. In fact, in case of rolling over or tilting of tractor, the independent rotation of the rear part of tractor main frame, where is seated the operator, with respect to the front one, where is fitted the ROPS, could laterally expose the operator to impact with ground.

Compact roll-over protective structure design

Considering the concerns previously exposed, the National Institute for Occupational Safety and Prevention (ISPESL) designed an innovative Compact Roll-Over Protective Structure (CROPS) to be fitted on narrow-track wheeled tractors. This structure is a four posts rigid frame made of steel circular tubes with a smooth longitudinal profile, shaped in such a way to make easier the use of tractor beneath trees and preserve the OECD code 7 operator clearance zone, at the same time. The main objectives to be fulfilled with the use of CROPS are to reduce the overall height of the tractor fitted with a non-foldable protective structure and, consequently, to allow to work under trees or in greenhouses in a safer way, avoiding the misuse of foldable ROPS. The CROPS design could be summarized into the following steps:

1. reverse engineering of tractor and virtual prototyping of the CROPS;
2. finite element analysis (FEA) of CROPS according to OECD code 7;
3. shape and dimensions optimization.

Reverse engineering and virtual prototyping

First of all it has been necessary to make a reverse engineering of tractor in order to virtually reproduce the position and the relative disposition of the anchorage points suitable for the CROPS. This also allowed to faithfully reproduce the OECD code 7 operator clearance zone on tractor and to avoid interferences between protective structure and tractor itself. With reference to figure 3, the virtual model of tractor, actually fitted with a foldable front mounted protective structure, has been reproduced. In particular on the right hand side of figure 3, the OECD code 6 operator clearance zone and the simulated ground plane related to the actually fitted two posts ROPS have been represented. One can note that the actual overall height of tractor is 2370 mm from the ground.

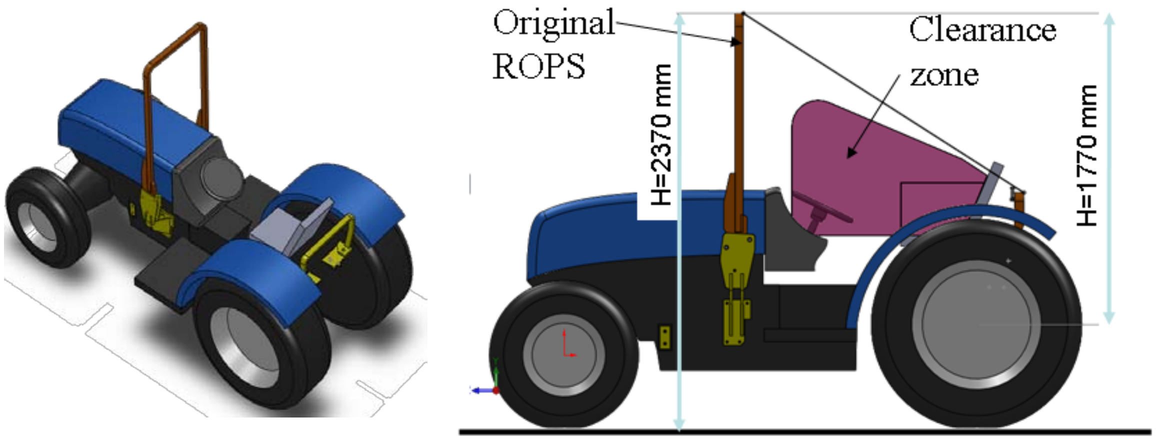

Figure 3. Tractor reverse engineering

In figure 4 left hand side, the front attachment points for CROPS are shown. In particular, they correspond to the bolts and pin joint of the foldable portion of the actual two posts protective structure. The CROPS rear mounting uses the same attachment points of the actual rear hard fixture (figure 4 right hand side).

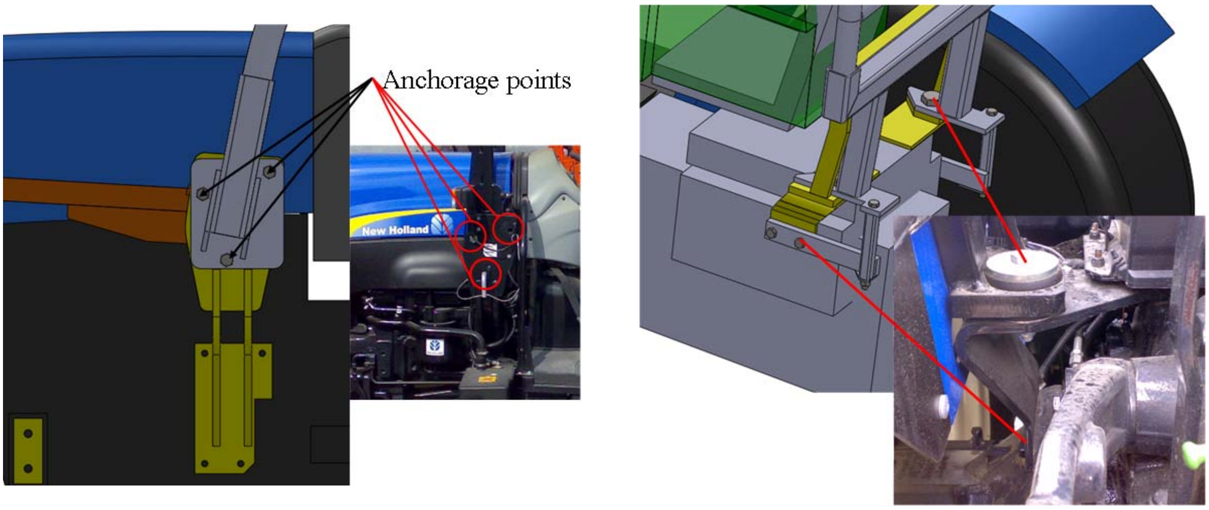

Figure 4. Front (on the left) and rear (on the right) mountings

According to ergonomic principles and safety requirements, a convex volume for CROPS has been designed. This volume has been obtained as an extrusion of a smooth profile in the middle longitudinal geometrical plain of tractor (see figure 5). Moreover it has been compared to the OECD code 7 operator clearance zone in order to verify that this one is completely included into it, as one can see from the side and back views depicted in figure 5. Starting from the convex volume, the tentative shape of the CROPS has been defined. It is represented fitted onto tractor on the left of figure 6, and in its main components in the exploded view (figure 6 right hand side). Thanks to its longitudinal smoothness, the CROPS appears more compact and suitable to work under trees or in greenhouses than the original straight two posts front mounted ROPS.

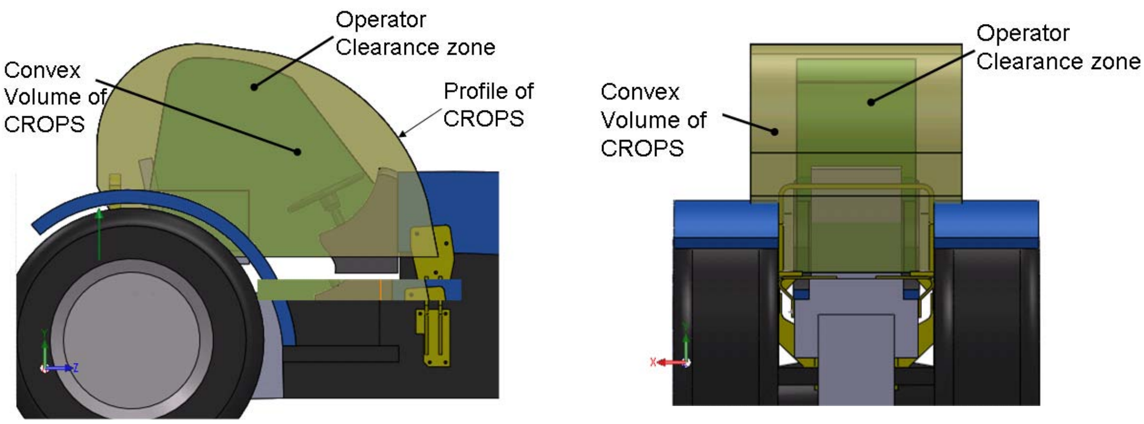

Figure 5. The CROPS convex volume side (on the left) and back (on the right) views

In any case the main function of CROPS is to protect the operator clearance zone. Thus, its size, with respect to this first prototype, has been varied according to the results of structural simulations which leads to the optimization process.

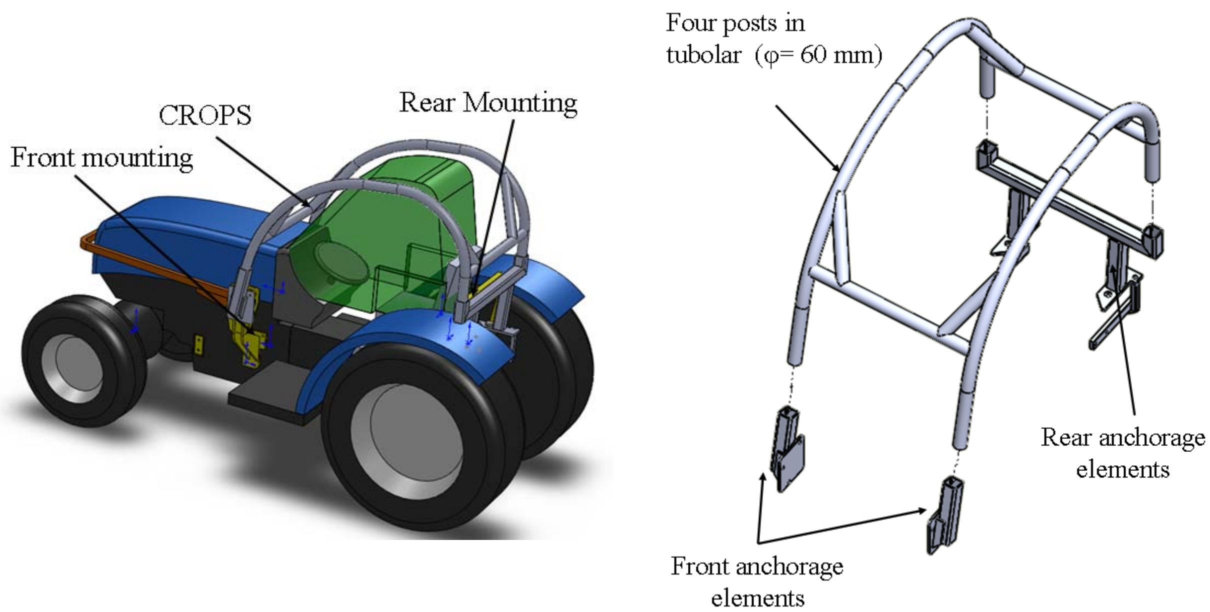

Figure 6. The first virtual prototype of the CROPS.

Finite element analysis

The first virtual CAD prototype of CROPS has been meshed in order to perform the finite element analysis on it. The geometrical properties have been modelled by means of plate elements of variable thickness. Since the OECD code 7 test procedure requires to evaluate the plastic energy absorbed by the protective structure, it is necessary to mimic the plastic behaviour of the material and to represent the large deformations which the structure undergoes. For these reasons the *Ramberg–Osgood* equation has been used for reproducing the elasto-plastic features of steel. In figure 7 the FEA model has been reproduced. In particular mountings of the actual two posts ROPS, on which CROPS attaches (see figure 4), have been not included in the model. In fact, they could be considered as significantly more rigid than the remainder of the structure. This allowed to reduce the number of elements in the model and consequently to speed up the analysis process.

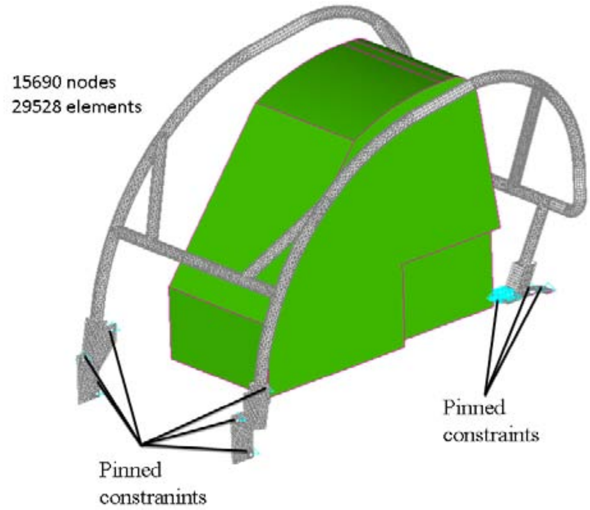

Figure 7. The finite element model of the CROPS

As the CROPS is connected to the front and rear mountings by means of threaded connections (see figure 4) the constraints in the model are of pinned type. They have been applied at the centre of each hole representing bolt by means of rigid elements (see figure 7).

Table 1. Test procedure and acceptance criteria according to OECD code 7

	TEST DESCRIPTION	ACCEPTANCE CRITERIA	ACCEPTANCE VALUE
1st test	Loading at the rear of the structure	Energy	≥ 3.055 J
2nd test	Rear crushing	Load	≥ 60.000 N
3rd test	Loading at the front of the structure	Energy	≥ 2.000 J
4th test	Loading at the side of the structure	Energy	≥5.250 J
5th test	Crushing at the front	Load	≥ 60.000 N

For what concerns the sequence of loads and the acceptance criteria, table 1 summarizes the compulsory requirements established by the testing procedure according to OECD code 7 with respect to a tractor mass of 3000 kg.

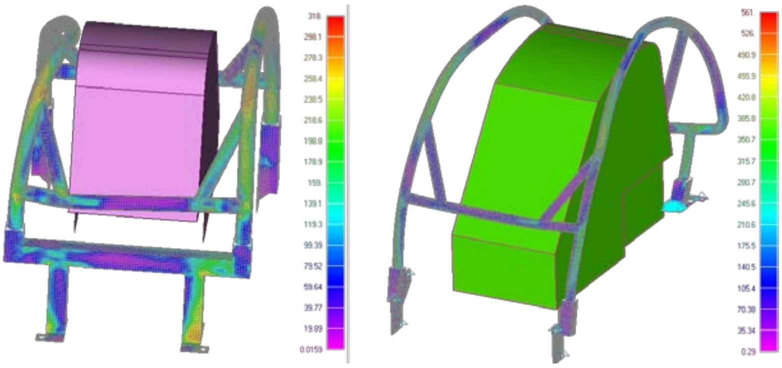

Figure 8. Contour diagram of Von Mises stress and deformations for the side load: first CROPS version (on the left) and last CROPS version (on the right)

In figure 8 an example of analysis result referring to the side load test is shown for two different versions of CROPS. On the left hand side of figure 8 the first version is depicted, while on the right hand side the last version is shown. The first version was realized by means of tubular having a circular cross section of 60 mm diameter realizaed in S235 steel, while the last version, obtained from the optimization process (see next paragraph), is made up of tubular having a reduced cross section, 40 mm diameter, but realized in S355 steel.
It is important to notice that each load of the sequence in table 1 is to be applied on the residual deformations and stresses due to the application of the previous load in the sequence. Once reached the required energy/load, one has to verify that no elements of the structures approach to the material breaking strength value and that no part of the CROPS, while deformed, leads to the infringement of the operator clearance zone or to its invasion by the simulated ground plane. For both the side load depicted in figure 8, the maximum stress recovered was sensible lower than the material breaking strength value, and the operator clearance zone was always protected.

<u>Optimization</u>

Different aspects are involved in the optimization process of the CROPS:

- enhancement of mechanical strength for the critical points of the structure;
- reduction of tractor overall height;
- reduction of CROPS width;
- simplify and retrench the production phase;
- use of structural members with reduced cross section to streamline the structure.

Each of the cited aspects leaded to new version of CROPS for which it is necessary a new design and finite element analysis, as previously described. So, the CROPS final version is the best compromise between structural and practical requirements, even if it probably could be still enhanced. The left hand side of figure 9 compares the first, on the bottom, and the last, on the top, versions of CROPS, where a steel tubular with a reduced cross section has been used. The right hand side of figure 9 shows that one of the effects of the optimization was the reduction of other 100 mm to the overall height of the tractor, continuing to ensure operator protection.

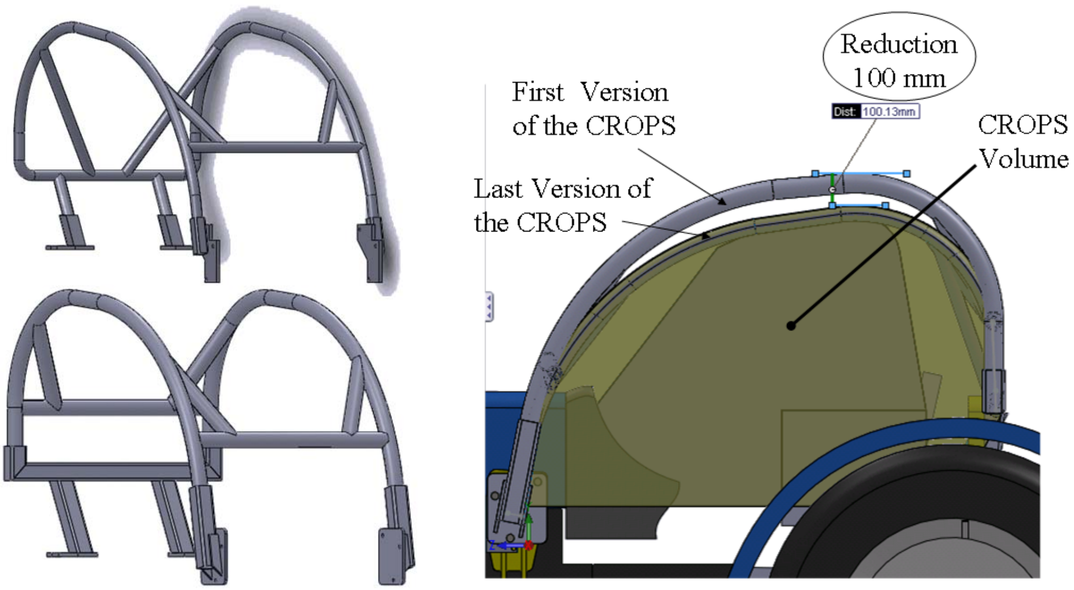

Figure 9. Comparison between first and last CROPS versions

Results and conclusions

The main result achieved in the CROPS designing process was the reduction of tractor overall height, fitted with a protective structure, of about 480 mm (see figure 10). Moreover the particular shape of the structure makes easier working under trees without damaging their branches. Finally this last prototype has been realized and structural tested at the ISPESL experimental test rig in Monte Porzio Catone research centre. The last step is to perform handling tests in the field in order to verify or at least optimize the CROPS shape for improving its performance under trees.

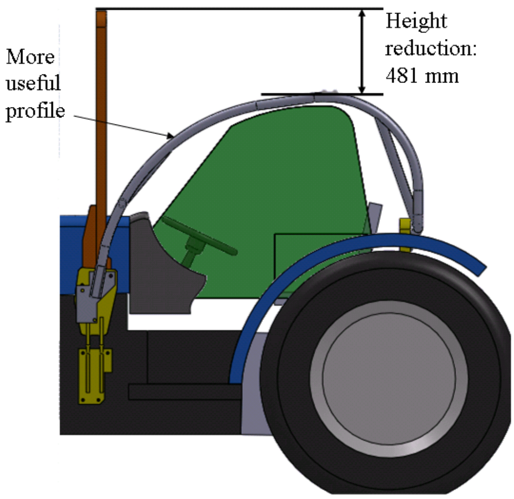

Figure 10. Overall height reduction

Reference

OECD Standard Codes for the Official Testing of Agricultural and Forestry Tractors. 2010. www.oecd.org/document/10/0,3343,en_2649_33905_34735882_1_1_1_1,00.html