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Sensitivity of the absorbed energy into a ROPS during a rollover situation: Comparison to the security level proposed into OECD Code 4

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Abstract

This paper proposes a generic model for agricultural tractor able to study the variation of energy level absorbed by Roll-Over Protective Structure (ROPS) during an impact induced by rollover situation with respect to several parameters (mass, shape, environment, ...). In relationship with the origin of the tractor cabin testing procedure detailed by the Organisation for Economic Co-operation and Development (OECD), such a model (designed using the simulation software Adams) allows the simulations of hazardous situations for impact energy calculation. Based on this material, a sensitivity study of this energy variation is proposed and compared to the standard provided by official testing procedure in order to check its relevance with respect to current tractor design. The results presented in that paper allow to define some theoretical limits to the applicability of ROPS Code 4 and open the way to some update for a better correlation between testing procedure and tractor design evolution.

1. Introduction

The design of tractor (in terms of general shape, mass repartition and configuration) has considerably changed since the definition of Rollover Protective Structure (ROPS) testing procedure. In particular, the energy levels to be absorbed by the test code 4 [1] supplied by the Organisation for Economic Co-operation and Development related to agricultural tractor ROPS resistance has been determined quite a long time ago and result from an empirical deformation study based on the notion of "standard" tractor. As a consequence the calculation of the energy applied for the deformation tests only relies on its reference mass, without taking into account explicitly other influent parameters. From an historical point view, the limitation of the applicability of these testing procedures are defined in terms of agricultural uses of machine, with a minor consideration of limitations due to physical vehicle characteristics (as it can be noticed in [2] and in testing Code 4 definition).

The evolution of OECD testing code since its creation in 60's, has mainly dealt with the improvement of methodology (introduction of static tests and simplification of formulas, additional information related to force direction, ...). Nevertheless, the validity of the linear formulas defining the values of energy to be applied in the procedure has not been updated with respect to the evolution of the tractors design and their actual use in agricultural activities. Moreover, the few literature still existing, concerning the design of these formulas has been only focused on the mass dependence, rejecting the other aspects of tractor definition, considering the tractor design variability as low influent. Such a point of view, chosen for simplicity reasons with respect to applicability, does not allow to define a scope for the validity of theoretical impact energy to be applied. If some works have highlighted the dependence of rollover behaviour with respect to other parameters than mass (see [3] or [4]), such work suffers of some drawbacks:

On one hand, these studies appear to be quite old and the variables range considered does not necessarily match the standards currently used in tractor design. Some experimental tests of rollover situations have nevertheless been achieved more recently for different kind of research. For example, in [5], some experiments have been achieved to propose an extension of ROPS tests on small vehicles, while in [6] or in [7], some rollover situations have been reproduced to test active rollover protection devices, allowing to extract level of energy absorbed during impacts. However, such experimental background has not been related to the definition of limitations related to the relevance of testing procedure.

On the other hand, such results rely on computation of simplified analytical model, based on restrictive hypothesis, which are not necessarily satisfied any longer in an actual use of farm tractor, or not relevant in the frame of a procedure evaluation. If such restricted models are useful to understand rollover phenomena, more complex representations are needed to be closer to actual behavior. Dynamical simulations achieved thanks to improvements of numerical modeling software appear to be useful. However, most of these virtual models are often focused on the representation of a particular vehicle (such as pointed out in [8] or more recently in [9] and [10]), and aim at building an accurate modeling of the vehicle as detailed as possible. As a consequence, such a point of view does not allow to modify easily the tractor parameters in order to study the influence of their design variability.

This paper aims at defining a generic and adaptable numeric model of tractor, able to study the level of energy absorbed during an impact induced by a rollover situation in function of its design parameters (shape, mass repartition, ...) and its environment of work (slope, mounted implement, ...). Simulations results are treated to be compared with the nominal levels supplied by OECD Code for tractor ROPS tests in order to point out a framework for applicability of the official procedures. The advances presented in that project constitute a first step allowing to update the testing procedure in order to ensure the farmers security. The paper is organized as followed. In a first part, assumptions achieved in the impact energy calculation are presented and discussed through the purpose of that paper. In a second part, the numeric model built thanks to multi-body dynamic software Adams is detailed and the variables used for sensitivity study are presented. The methodology used for simulation and impact energy calculation is then reported. Using this material, the results related to the variation of impact energy levels with respect to parameters variation are presented and confronted to those supplied by OECD ROPS Code 4. Using this study, a preliminary frame of applicability of these theoretical formulas is proposed with respect to the evolution of tractor market and farmers applications.

2. Simulation context and model hypothesis

2.1. Modelling assumptions

The study presented in this paper aims at simulating rollover and overturning situations in order to calculate the impact energy to be absorbed by a tractor protective structure. The dependency of the absorbed energy to the tractor design parameters is particularly targeted. The assumptions made for modelling are chosen in order to maximize the level of absorbed energy in the same framework as actual tests reported in [2]. Consequently, the following hypotheses are applied for model design and simulation tests, on the following different aspects:

- **Nature of impacts:** in the simulations achieved in the following, impacts are supposed to be hard (except for tire interactions, see below). Then, both tractor cabin and soil are supposed to be infinitely rigid for energy calculation. Nevertheless, as pointed out in [3], and in conformity with theoretical aspects of Code definition, 20% of this preliminary derived impact energy is supposed to be dissipated mainly by the soil. Finally, the results presented then consider only 80% of the derived impact energy, obtained by simulation.
- **Ground geometry:** several geometries for ground can be considered for rollover situation (slope, embankment, ...). In this paper, the choice has been made to consider a constant sloppy ground, as it maximizes the level of impact energy.
- **Wheels and tires:** contrary to other bodies, the tires are supposed to be deformable and can then be considered as energy dissipative elements if these parts touch the ground before ROPS. A soft shock is then considered for tyre.
- **Initial conditions for rollover situation:** in accordance with the first experiments behind the definition of impact energy formulas, the initial velocities from which the tractor starts to rollover are expected to be null. In the simulation framework, the inclination of vehicle is slowly brought to the rollover motion limit (as detailed in the methodology section).

2.2. Influence of variables

Thanks to a preliminary theoretical study achieved thanks to a mathematical computation of mechanical dynamics, it is possible to determine the most influent variables acting on the level of impact energy to be absorbed by tractor ROPS. Two kinds of variables can be distinguished. The first considered category gathers the variable pending on tractor design.

- **Vehicle and mounted masses and inertia**, which depend on both tractor design and its use. Theoretical studies as well as preliminary experimentations show that the linearity between the absorbed energy and the sole tractor mass and corresponding inertia is ensured. As a result, in the sensitivity study, variable masses and inertia will be used only to extract the coefficient of the linear expression in order to compare it with formulas supplied in OECD Code 4. Nevertheless, the ballasting masses as well as mounted implements modify the nominal tractor mass influencing directly the absorbed energy.
- **Position of the centre of gravity** (denoted point G in the following), pending on mass repartition in the vehicle and its geometrical design (wheelbase and track width). This position influences the stability limits and consequently the time before the impact.
- **Position of the impact point** (denoted point A in the following), which is linked to the vehicle and ROPS geometry (height, length, ...). In the same way that point G influence, this position modifies directly the motion duration before the impact.

The second category of variables is linked to the environment. If the nature of the soil or the cabin material is not considered (hard shock assumption), the main parameter considered is the **slope value** (denoted α in the following of that paper).

3. Model design and simulation procedure

3.1. Overview of multi body model design

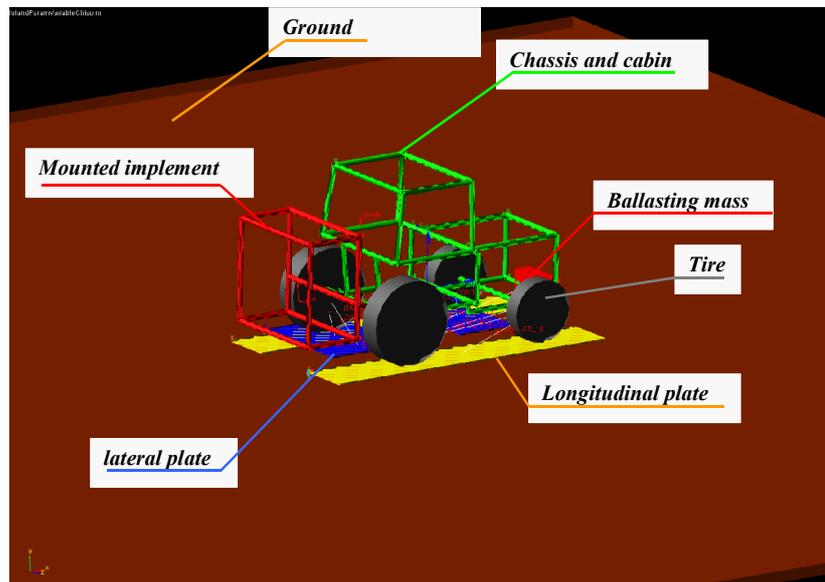


Figure 1: general view of Adams model and main part considered

The computer model of tractor for rollover simulation is defined thanks to several bodies presented on figure 1 and listed here below:

- **Ground part:** this first body models the soil, the inclination of which is variable, in order to be representative of an accidental case.
- **Chassis and cabin part:** this part constitutes the modelling of the main tractor body. It is composed of a tubular structure, the shape of which can be easily modified and is parametrized to be very hard in its contact properties with the soil. Indeed, the 34 cylinders defining the tractor structure are referred to markers, the positions and orientations of which are entered thanks to modifiable values with respect to a master marker. This fundamental marker is located at the middle of the rear tractor axle. The

mechanical and dynamical properties of this body are not restricted by the tubular structure properties. Its mass, inertia and centre of gravity position are indeed entered independently in the modelling. This point of view allows to decouple the mass value and its repartition from tractor shape. The influence of each of the identified design variables can then be studied independently.

- **Tires:** they are fixed to the chassis part thanks to revolutes joints, which are motorized. In the frame of that paper where only roll-over motion is studied, these degrees of freedom are fixed to zero. Tire deformation is taken into account thanks to the contact definition with the ground. In the frame of that paper, the dumping, stiffness and elasticity are chosen to obtain a soft shock.
- **Longitudinal and lateral plates:** these parts are only linked to tires in order to allow the rollover motion. They indeed move to raise some of the wheels (for example the two front wheels) in order to make the tractor incline sufficiently to initiate its rollover motion.
- **Mounted implement and ballasting mass:** these parts are fixed to the vehicle and can be inverted between front and rear. The dimension and shape of implement can be changed modifying the position of their own centre of gravity.

The model used for simulation is then defined by 48 parameters, which allow to modify easily the shape and mechanical properties of the different elements, such as the tractor mass, its inertia, position of the centre of gravity...

3.2. Simulation of rollover situations and extraction of impact energy

For a choice of one configuration for model parameters (dimensions and masses), a rollover simulation can be achieved following the same procedure for lateral and longitudinal rollover, as illustrated on the figure 2. In a first period (step a), the rollover plates lift off slowly in order to bring the tractor in a self-rollover motion with almost null initial conditions (step b). Then the rollover motion starts and goes up to the impact considered on point A (step c). After the impact, simulation is still running for a short time (step d) to evaluate the kinetic energy preserved by the following of the vehicle motion after the impact.

The direct measurement of the impact energy absorbed by the chassis/cabin body by the impact is not possible. Nevertheless, thanks to the achieved hard shock assumption (conservation of kinetic momentum principle), it can be defined as the step of kinetic energy occurring at the impact time (which can be seen on figure 3). As a result, the measure of this difference constitutes the energy to be absorbed during impact by the chassis body, and consequently by the ROPS, under the hard shock assumption. Finally, to take into account the amount of energy absorbed mainly by the soil (in accordance with [3]), only 80% of the measured energy is considered to be dissipated into ROPS structure.

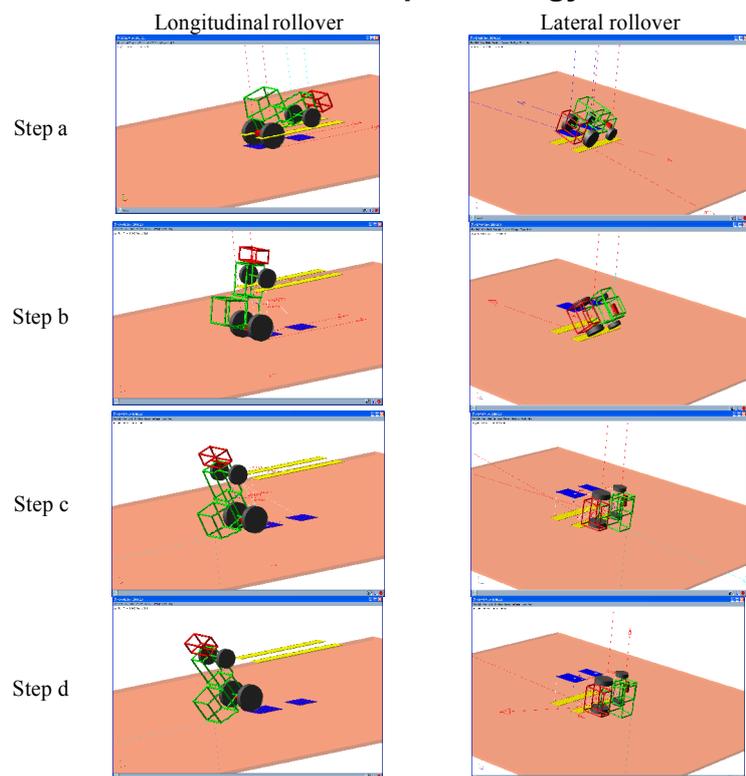


Figure 2: Simulation steps and procedure

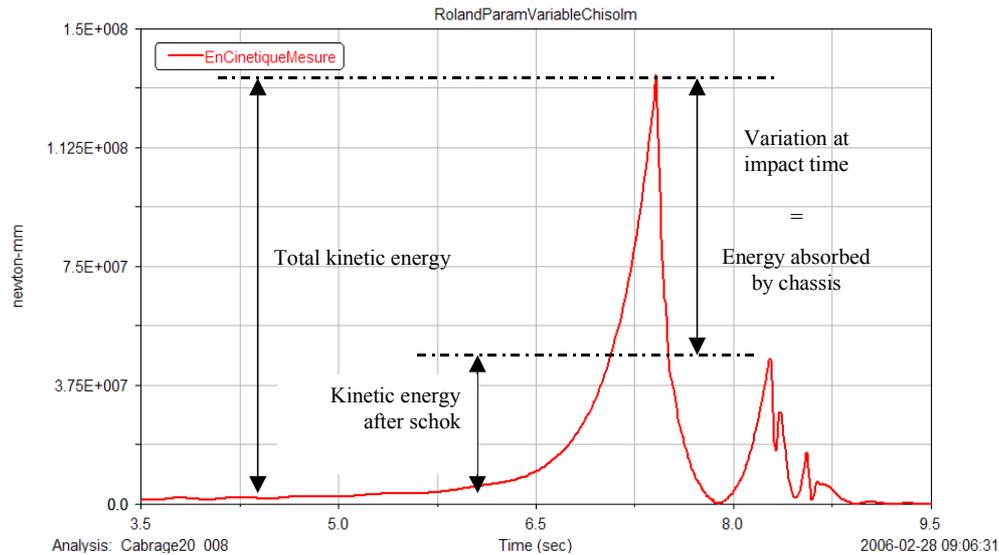


Figure 3: Extraction of impact energy

3.3. Methodology used to sensitivity studies

Variable	Nominal value	Range of variation
Tractor mass	5000kg	1000 to 15000kg
Front ballasting mass/implement	0kg	0 to 600kg
Rear ballasting mass/implement	0kg	0 to 2000kg
Centre of gravity along X	1300mm	800 to 1300mm
Centre of gravity along Y	0mm	0 to 400mm
Centre of gravity along Z	Situatd on half of variable track	
Wheel track	2500mm	2200 to 2800mm
Impact point along X	50mm	-450 to 550mm
Impact point along Y	2200mm	2000 to 2800mm
Impact point along Z	-150mm	-150 to 150mm
Slope value for lateral rollover	8.5°	5 to 20°
Slope value for longitudinal rollover	8.5°	5 to 20°

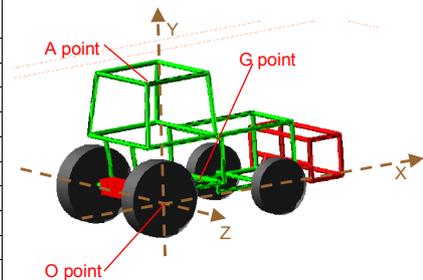


Figure 4: Definition of principal points

Table 1: nominal values and variation range of design variables

As it has been said previously, if the other parameters remain unchanged, the linearity between tractor mass (with associated computed inertia) and energy to be dissipated into protective structure is ensured. As a result, in order to allow a comparison with formulas supplied in the frame of OECD testing procedure, the sensitivity study concerning the dependence to parameters, which do not modify the nominal tractor mass, aims at extracting the value of such a coefficient. In these cases, five simulations are run successively, with varying mass between 1000kg up to 15000kg, and energy to be absorbed is measured. The coefficient is then calculated thanks to least square method (verifying a correlation coefficient above 0.998, ensuring a linear behaviour). For the sensitivity studies, which concern variables modifying the reference mass (dependence to ballasting masses and mounted implements), an unballasted mass is chosen and several simulations are achieved with modification of additional masses. As a general rule, the standard values of variables described previously have been chosen with respect to measures achieved on a recent marketed tractor with a middle power, dedicated to a common agricultural use. The table 1 lists these chosen nominal values as well as their considered range of variation.

4. Results

4.1. Sensitivity to centre of gravity position

The main design variables influencing the coefficient linking the impact energy to be absorbed by tractor structure to its own mass is the position of its centre of gravity. This variable, and in particular its height, indeed influences two phenomena impacting the kinetic energy in rollover motion. On one hand, the position of this point influences the intrinsic stability of the vehicle, that is to say the limit tractor inclination, above which rollover motion

starts. On the other hand, the position of centre of gravity is directly linked to the lever arm and finally the roll velocity at the impact time.

From the longitudinal rollover point of view, only the position of point G (depicted on the figure 4) along the axis X and Y can modify the impact energy level, while for a lateral rollover situation, the position along axis Y and Z (induced by a track modification along axis Z) are considered. As a consequence, the results depicted on the figure 6 show the evolution of the coefficient relying the nominal tractor mass and impact energy with respect to the height of centre of gravity and its position along X axis for longitudinal rollover. Figure 5 shows the same coefficient in lateral rollover situation pending on the height of centre of gravity and its position along Z axis. On both of these figures, as an element of comparison, the coefficients supplied by OCDE testing procedure of Code 4 are reported by a red plane (coefficient of 1.4 J/kg for longitudinal situations and 1.75 J/kg for lateral cases).

From a longitudinal point of view (see figure 6), one can see that the influence of centre of gravity height is preponderant with respect to its longitudinal position in the range considered. An elevation of the point G indeed increases considerably the value of the studied coefficient (an elevation of 10cm increases this coefficient of 50%). In comparison with values supplied by testing procedure, a short elevation of the standard value height chosen (Y=100mm), makes the actual coefficient be on the limit of 1.4 coefficient given for security validation.

This centre of gravity elevation has also an important influence on the coefficient concerning lateral rollover situations (see figure 7) in the

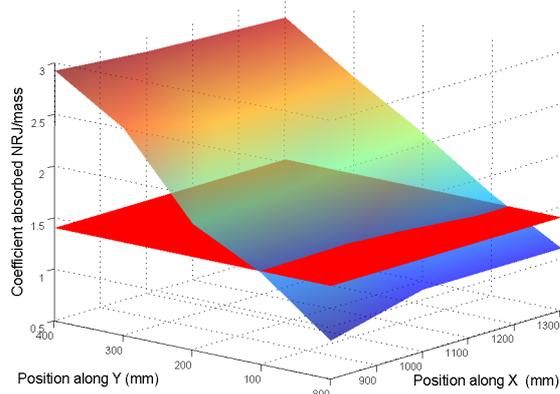


Figure 6: Longitudinal rollover, variation of coefficient between mass and energy w.r. to position of G point

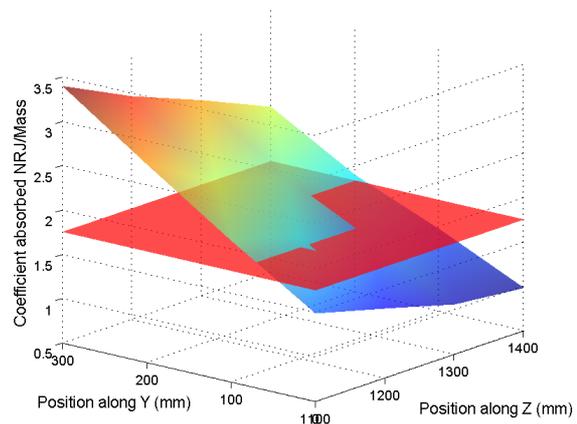


Figure 5: Lateral rollover, variation of coefficient between mass and energy w.r. to position of G point

same proportion. Moreover, the lateral position of the point G (pending on half track dimension) has also a non-negligible influence as a displacement of 100mm can change the coefficient of 15%. From a comparison with standards supplied by OECD Code 4, it can be checked that, like for longitudinal case, a short displacement of the centre of gravity position can lead to cross over the 1.75 coefficient.

4.2. Sensitivity to impact point position

The relative position of impact point (denoted by A on the figure 4) directly influences the impact time (rollover motion duration). The more the time to impact is important, the higher the angular velocity of tractor at the impact moment is. As a result, the kinetic energy when the cabin touches the ground, and finally, the energy level to be absorbed by the tractor structure is deeply modified. The position of this point is defined by the tractor cabin design (position, shape...) and can have important range of variation from one tractor model to another.

In the same way as the influence of the centre of gravity, only positions along X and Y axis modify the energy level to be absorbed in a longitudinal rollover framework, while only the position with respect to Y and Z are considered in lateral rollover motion. The results

concerning the variation of the coefficient linking the absorbed energy and the reference tractor mass with respect to the impact point position in longitudinal rollover situations is depicted on figure 7, while the figure 8 depicts the same results related to lateral rollover situations. As in the previous study, the standard coefficient values, supplied in Code 4 procedure (1.4 for longitudinal and 1.75 for lateral) are reported in a red plane.

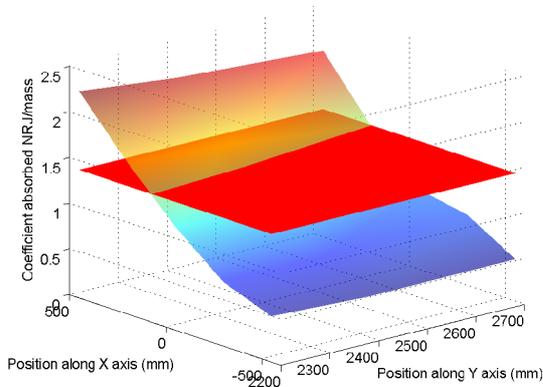


Figure 7: Longitudinal rollover, variation of coefficient between mass and energy w.r. to position of point A

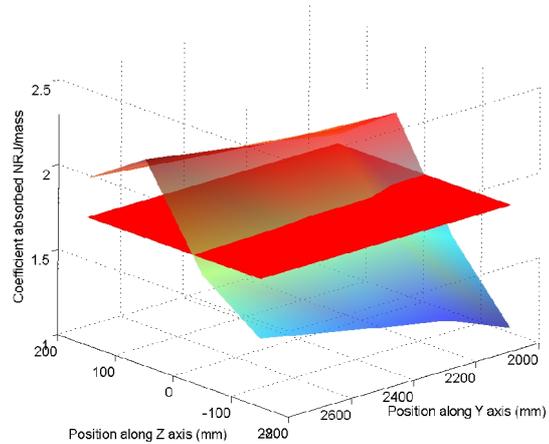


Figure 8: Lateral rollover, variation of coefficient between mass and energy w.r. to position of point A

On both of figures, it can be noticed that the influence of the height of the impact point is not significant for the value of the coefficient, within the variation range considered. Nevertheless, the position of point A in a horizontal plane with respect to tractor frame is quite important. For longitudinal rollover situations, one can see that position with respect to X axis has a great influence as an increase of the longitudinal distance between the middle of rear axle and the impact point makes the coefficient increases with a second order curvature shape (see figure 7). As a result, the measured coefficient crosses the limit of 1.4 after a variation of 150mm.

The interpretation of the results related to lateral rollover (reported on figure 8) is more complex. Indeed, in lateral motion, the sides of tires can touch the ground before the structure. Then, for negative values of lateral impact point position, tire faces instead of the structure absorb a major part of impact energy. Around zero, the tractor cabin touches the ground first, which explains the step noticed around zero related to the position of point A along the Z axis. After this discontinuity, the coefficient decreases since the point A becomes closer to the soil and reduces the rollover motion duration. In the lateral rollover case, the position of point A with respect to tire side position appears to be preponderant in the level of absorbed energy. It can be seen, that if structure touches the ground before (around zero) the coefficient relating absorbed energy and nominal mass is bigger than the one supplied in OECD ROPS testing procedure of Code 4.

4.3. Sensitivity to slope value

The slope values considered for tractor rollover cases naturally influence deeply the energy to be absorbed. This parameter comes from the environment and is not managed by the tractor design. Nevertheless, manufactured tractors are designed to move on a limited value of slope, which has to be considered in farm applications. The influence of the slope is then to be considered in order to check that the use limitation is not above a hazardous limit. The nominal value of 8.5° chosen for both longitudinal and lateral rollover case has been taken with respect to the preliminary experimental tests considered in the OECD Code 6 (ROPS Code for narrow-track tractors).

The results obtained for slope values modification are reported on figure 9 for longitudinal motion and on figure 10 for lateral rollover situation. For both of figures, coefficient linking the nominal mass and absorbed energy by tractor cabin are reported and compared with the

coefficient supplied by OECD depicted in red line. For the range of variations considered in that paper for slope values, both of the coefficients evolves almost linearly. As expected, this relation is far from being negligible compared to the standard coefficients. It can indeed be noticed that 8.5° supplies coefficients which are very close to the limit given in code 4 definition. Then, farm operations achieved above this angle can lead to hazard with respect to the energy level a rollover protection structure is supposed to absorb with a preservation of safety zone for driver.

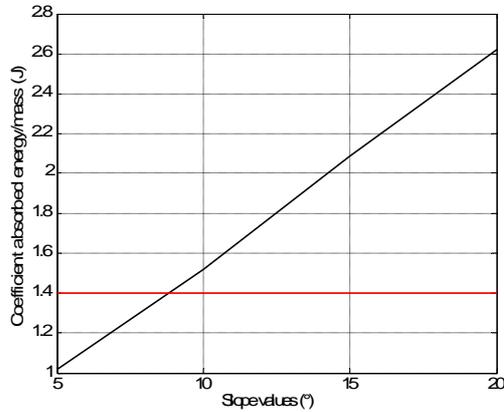


Figure 9: Longitudinal rollover, variation of coefficient between mass and energy w.r. to slope

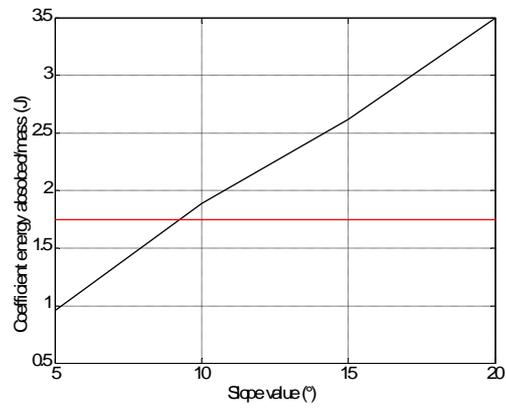


Figure 10: Lateral rollover, variation of coefficient between mass and energy w.r. to slope

4.4. Sensitivity to ballasting masses and mounted implements

In that case of sensitivity study, it is not possible to extract a coefficient linking the absorbed energy and the reference mass. As a result, all the design variables are set to their nominal values listed on the table 1, and variable masses for implement and ballast (as depicted on figure 1) are mounted on tractor. The influence can be non negligible since on one hand, the global mass is different from the reference mass used to calculate energy and, on the other hand, the addition of heavy element can influence the position of the global centre of gravity of the set {tractor, implement(s), ballasting masses}.

The results of additional masses mounted on a 5000 kg tractor on the level of energy absorbed are depicted on figure 11, for longitudinal rollover situations and on figure 12 for lateral case. All the other variables are set to the nominal values reported on table 1 for both cases. In longitudinal rollover situations, a front mounted implement is considered, with a mass range of variation within 0 and 2000kg while ballasting masses are considered in the back of the tractor with a variation range within 0 and 600kg. Concerning the lateral rollover situation, the positions of mass and implement are inverted (mounted implement on the back and ballasting mass on the tractor front). On these figures the levels of energy used in ROPS testing procedure supplied by OECD, are reported by a red plane, representative of the coefficient used in this framework and a nominal mass of 5000kg.

Both of the figures show a comparable sensitivity to the addition of ballasting masses on the variation of energy absorbed during a shock due to a rollover situation. The absorbed energy modifications are indeed more important, when the mounted implement mass is increased. In both lateral and longitudinal rollover situations, an increase of around 60% can be recorded on the energy level for a 2000kg-mounted implement. As a result, it can be noticed that for both of cases, the energy rises across the standard level supplied by the coefficients 1.4 (longitudinal case) and 1.75 (lateral rollover) for a mass implement corresponding to around 33% of nominal tractor mass (around 1500kg). On the other hand, the addition of ballast seems to have a limited impact on the absorbed energy with respect to mounted implement. The addition of ballasting masses indeed let almost unchanged the position of the global centre of gravity, on the contrary of a large mounted implement.

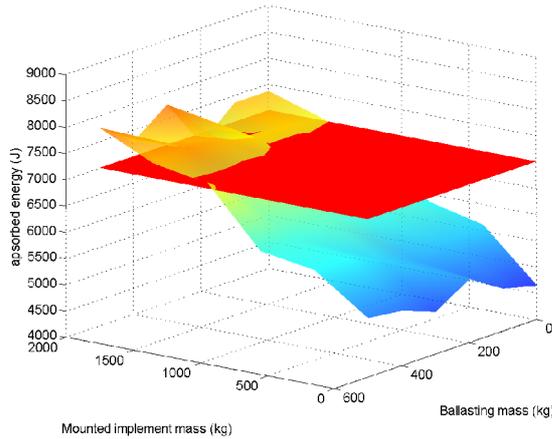


Figure 11: Longitudinal rollover, variation of coefficient between mass and energy w.r. to additional masses

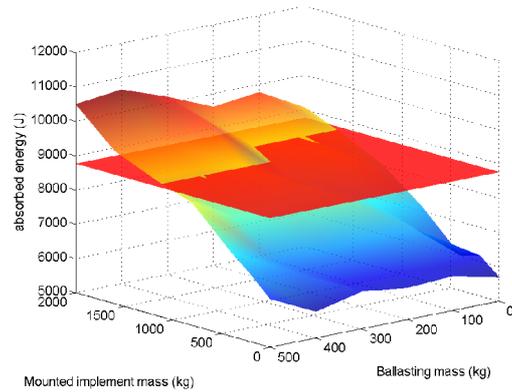


Figure 12: Lateral rollover, variation of coefficient between mass and energy w.r. to additional masses

4.5. Summary and estimation of OECD Code 4 relevance

<i>Design variables</i>	<i>Limit values for longitudinal rollover case</i>	<i>Limit values for lateral rollover case</i>
Centre of gravity along X	-	-
Centre of gravity along Y	<150mm	<150mm
Centre of gravity along Z (half wheel track)	-	>800mm
Impact point along X	<50mm	-
Impact point along Y	-	-
Impact point along Z		<-50mm (wheel side absorption) >+300mm
Lateral slope value	-	<10°
Longitudinal slope value	<10	-
Ballasting mass	-	-
Mounted implement mass	<40% of Nominal mass	<40% of nominal mass

Table 2: Design variable limit values extracted to preserve OECD Code 4 validity. Using the different results on absorbed energy obtained thanks to the sensitivity study achieved previously, it is possible to define a kind of validity limit of the linear equations supplied in OECD Code 4 procedure, linking nominal tractor mass and level of energy to be absorbed by tractor structure. By considering each of the design variable variation, without any change in others, previous results allow to derive the table 2, which proposes an acceptable modification for each of the design variables (i.e. for which the standard coefficient are not trespassed). As it has been seen on figures 5 to 12, the variations of the absorbed level of energy is highly correlated to all of the variables. As an example, a decrease of centre of gravity height allows to increase the maximal values of impact point position. The representation reported on table 2 is then supplied indicatively since it does not account for this important correlation. Nevertheless, it can be exploited in order to give a global field of application for the OECD testing procedure of agricultural tractor ROPS. In particular, the interest of table 2 lies in the comparison of the limit pointed out with respect to the evolution of future marketed tractor.

5. Conclusions and future works

This paper proposes a numerical model of tractor dedicated to simulate rollover motion in order to estimate the level of energy to be absorbed during impact by Rollover Protective Structure (ROPS) in function of design parameters and environmental context. Such a study first permit to extract the main variables, which modify the level of energy to be absorbed by

ROPS, and then to investigate their influence. Based on the results presented, a scope for the application of OECD Code 4 testing procedure for tractor can be proposed. This allows evaluating the relevance and the potential adaptation of the testing methodology to the agricultural machinery evolution. Works presented in this paper (simulations method and results) then constitute a first step in order to explain some 'small signals' given by unexplained accidents and then improve the OECD testing procedure with respect to the evolution of the farm tractor market.

Finally, the relevance of simulated results obtained with the presented numerical model have to be confronted to actual results. The range of values obtained fits correctly both experimental results presented in literature and mathematical model integration, but can require a rescale from dedicated experiments. First experiments achieved in that sense (together with [11]) nevertheless show a good correlation with actual tests.

6. Acknowledgements

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