Some dynamic considerations for agricultural tractor rollover

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Abstract

The potential for tractor rollover exists in some applications within agriculture. To help minimise the danger to the tractor driver Roll-Over Protective Structures (ROPS) were introduced some time ago along with corresponding international testing procedures. Some deaths and serious injuries resulting from failure of ROPS however still occur. This has led to recent renewed interest in tractor rollover research to gain an understanding of the processes involved. The impact that could potentially be experienced by the ROPS is a function of the energy available at the start of rollover. This paper presents some of the initial work on rollover by considering different initial conditions; in particular, the theoretical difference in available energy for lateral rollover on different planes together with the inclusion of forward velocity. Measured data pertaining to 102 narrow type tractors fitted with front ROPS, with mass variation between 700 and 2700 kg, was used to calculate the available energy. Some addition considerations complicate the analysis, for example, the coupling of forward momentum and lateral roll when forward velocity is included.

Keywords: energy, ROPS, velocity, impact.

Introduction

Tractors are particularly prone to rollover due to a number of reasons; unlike road bound vehicles they tend to have a much higher centre of mass (COM) position, they are exposed to large external loads which may arise from implements, they can traverse and work on extreme undulations. Changes in amount of fuel carried, payload and the drying action of the sun on the terrain can change subtly and in combination can lead to a major overall change in stability conditions (Stockton et al., 2002). In addition, many tractor-implement combinations and a large number of operating conditions give rise to infinite potential rollover scenarios with some more likely than others. It comes thus as no surprise that tractor operators of all ages and experience and on a variety of terrains have been victims of rollovers (Hallman, 2004). This paper first looks at some of the work done in this field and then explains some of the preliminary research being conducted by the University of Bologna regarding tractor rollover and Roll-Over Protective Structures (ROPS).

The Introduction of ROPS

Before ROPS could be implemented, an acceptable amount of energy they would have to absorb needed to be quantified. This led to research being conducted in order to understand rollover in an effort to ultimately design systems to protect the operator. This saw studies associated with real rollover of machines on variety of slopes and terrains be performed to determine the relative risk (Schwanghart, 1973; Chisholm, 1979b; Chisholm, 1979d; Chisholm, 1979c; Chisholm, 1979a; Schwanghart, 1982; Langley et al., 1997; Stockton et al., 2002; Nichol et al., 2005). However, as pointed out by Langley et al. some of the statistical information related to real rollover events gives insufficient description as to the true nature of the rollover (Langley et al., 1997).

The intention of ROPS were to prevent or minimise the effects of the majority of typical accidents, as defined in most of the international standards for testing of ROPS (SAE, 1977; EEC, 1987). It is noted that the introduction of ROPS was not expected to prevent all deaths since such a system would almost be impossible to design.

The most important updates of the standards were carried out at the end of the 80s to account for the mechanisation of vineyards and orchards and the operation on hillsides. The main innovations at that time were the evaluation of the lateral stability and the non continuous roll behavior of the tractors (Schwanghart, 1973; Schwanghart, 1982; EEC, 1987; OECD, 2008).

Due to the different operating environments a tendency to develop innovative ROPS solutions is evident in the research field. These proposed solutions, sometimes complex (Etherton et al., 2002; Silleli et al., 2007), aim to achieve the purpose for which ROPS were originally fitted to tractors without restricting the functionality in orchards and vineyards. To further complicate the issue, the evolution of machinery is outpacing the development of ROPS Standards (Stockton et al., 2002). This has led to renewed interest in rollover research and questioning of the formulas presented in the Standards.

Some limitations in the ROPS Standards can become evident if it is made note that several parameters are likely to influence overturning behaviour however only tractor mass is included in the current test formulae (EEC, 1987; OECD, 2008). Part of the reason for this is that Standards' committees, however, have shown an understandable reluctance to base ROPS strength test criteria on complicated formulae involving many parameters (Chisholm, 1979b).

Research on very low mass vehicles, stated that the ROPS performance test criterion may result in an energy overestimate; the criterion appearing to become progressively more appropriate as vehicle mass increases (Scarlett et al., 2006). Following the same reasoning, this would seem to indicate that as vehicle mass continues to increase it will surpass the threshold boundary defined by the equation, eventually becoming inappropriate. In fact, Chisholm (Chisholm, 1979d) noted from personal communication with Schwanghart that "the energy absorbed in the ROPS was found to increase with mass in a relationship that could be approximated by a low order polynomial". This would thus seem to also suggest that a linear relationship may not be appropriate. A more accurate understanding of the relationship would therefore be deemed necessary.

Simple consideration of velocity and height of fall during accidents shows that the amount of "available" energy far exceeds that absorbed in the ROPS in any standard tests or in the severest accident (Chisholm, 1979d). Obviously not all this energy has to be dissipated by the ROPS in all rollover events. The majority of the energy being dissipated in sliding friction, ground penetration and deformation of other tractor parts, particularly the rear wheels (Chisholm, 1979d). Other mechanisms are also available to dissipate the energy and some of these are depicted in Figure 1.

It may be possible that sequence does not stop at the first time the ROPS contacts the surface: this scenario has not been shown but is possible. Chisholm (Chisholm, 1979b) noted that in some instances it is possible for the tractor to become airborne after its first roll and then impact heavily on the ROPS, without energy being absorbed by rear wheel deformation. It is thus the instant at which rollover commences that changes the initial conditions. Once initiated, the sequence describing the rollover stages can take, in theory, an infinite number of forms. The events in which the ROPS impacts the ground, may or may not render failure. The last distribution in Figure 1 shows a very unlikely but possible situation in which rollover begins at the point with the maximum available energy and all that energy is subjected in the ROPS on first impact.

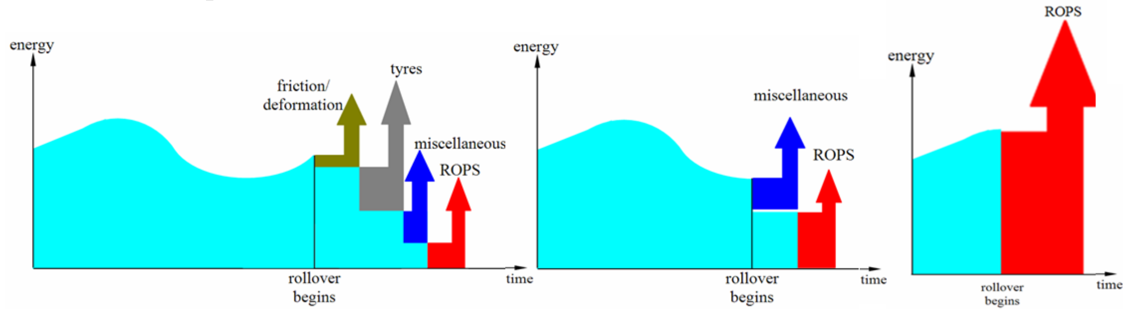

Figure 1. the total available energy for an operating tractor may vary with time. Rollover may occur at any location and be comprised of many steps (left) or just a few (middle), and a very rare and severe event (right).

Materials and Methods

Available Energy

It seems logical that the tractor rolls from an unstable state (for example, when the COM exits the base rectangle) to a stable state (e.g. the plane's surface) via lateral roll. Ignoring any tyre deformation or other dissipation mechanisms and assuming all potential energy is converted to kinetic it is simple to calculate the energy available between the initial, 1, and first impact, 2, positions i.e. $E=mg(h_2-h_1)$. All symbols are defined in Table 1. Considering a tractor with zero velocity at the verge of rollover is not dissimilar to an inverted pendulum released from rest. Thus, the energy available is related to the difference in centre-of-mass (COM) position at the initiation of rollover and when part of the structure first contacts the ground. Thus the potential energy is related to the COM position, the mass and the geometry of the tractor. When considering rollover a horizontal surface is typically utilised, Figure 2a. However, it is also possible for the tractor to roll onto a plane which extends below the rollover point, Figure 2b. Clearly the amount of energy is different for the two cases.

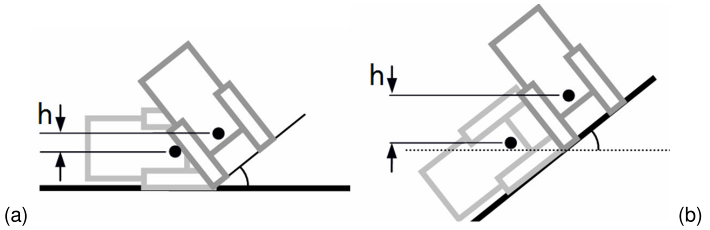

Figure 2. tractor lateral rollover from the slope's surface onto: a horizontal surface (a), and the plane's surface which extends below the rollover point (b).

Narrow-track tractor data has been measured at the test facility of the Laboratorio di Meccanica Agraria, Department of Agricultural Economics and Engineering (DEIAgra), University of Bologna, according to the testing code of the Organisation for Economic Cooperation and Development (OECD Code 6, 2008) for a number of years. The testing procedures require preliminary tests to be carried out before the strength tests of the ROPS:

these are the lateral stability test and the non continuous rolling test. Prior evaluation of the total mass and the COM position have to be done in order to use the information together with the simulation program available in Code 6 to determine the critical ROPS height to prevent continuous roll on a 1/1.5 slope. Measurements were performed on 102 narrow track tractors. The COM was determined using an oscillating platform which can carry the tractors, according to the methods studied by Casini Ropa (Casini-Ropa, 1976). The lateral stability tests were carried out positioning the tractors on a horizontal plane and tilting the part of the tractor rigidly connected to the axle bearing more than fifty per cent of the tractor mass. This was in order to verify that at an inclination angle of at least 38° the tractors were in a state of equilibrium on the wheels touching the ground in accordance with Code 6 (OECD, 2008). The data pertaining to the 102 tractors tested according to OECD Code 6 was used to theoretically calculate the angle required to cause 'longitudinal' and 'lateral' rollover purely from geometry. This required the mass and COM location for each tractor. As longitudinal roll is unlikely only lateral roll results are presented. It was assumed that there was no deformation (tyres/surface etc) nor front axle pivot. Hence rollover occurs at the angle when the COM exits the base defined by the tyres.

Table 1. Notation

symbol	definition	unit	symbol	definition	unit
g	gravity acceleration	$m.s^{-2}$	m	mass	kg
h	height	m	v	velocity	$m.s^{-1}$
I	inertia	$kg.m^2$	ω	angular velocity	$rad.s^{-1}$

Initial Velocity

A tractor typically arrives in a rollover event with some initial forward velocity, and this can increase the available energy. Equation (1)[1] may then be used to estimate this additional energy at initiation of rollover. It shows that a small speed increase has the potential to add significant energy to the system since the value is raised to the power of 2.

$$\text{Available energy} = mg\left(h_{xy2} - h_{xy1}\right) + \frac{1}{2}m\left(v_{z2}^{2} - v_{z1}^{2}\right) \tag{1}$$

Considering the more general case in which there also exists initial angular velocity, Equation (1) is modified and Equation (2) is obtained. This assumes that the tractor undertakes fixed axis rotation about a pivot point, for example the lower wheel edges on the slope. Thus the angular kinetic energy and the potential energy in this case occur in the same plane.

$$\text{Available energy} = mg\left(h_{xy2} - h_{xy1}\right) + \frac{1}{2}m\left(v_{z2}^{2} - v_{z1}^{2}\right) + \frac{1}{2}I_{pivot}\left(\omega_{z2}^{2} - \omega_{z1}^{2}\right) \tag{2}$$

Equations (1) and (2) show that, in the presence of velocity components, much greater energy is available. However, it must be noted that the presence of velocity complicates the analysis considerably. The longitudinal momentum would generally render the 2D roll plane analysis inappropriate since it is likely that the tractor during roll continues to travel forward. Thus a 3D analysis would be needed. This may also be true in the subsequent rollover events should the tractor not stop on first impact. It may also be possible for the tractor to not remain in contact with the surface during the roll event. In such cases it is no longer appropriate to use a rearranged version of Equation (2) to determine the conversion of potential to kinetic energy. This is due to the fact that the roll is not about a fixed point. This requires that the more general form of the energy equations be used. Such an equation for rotation, in the *roll plane*

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[1] *x,y* and *z* denote Cartesian axes; z is along the tractor's longitudinal axis, positive in the forward tractor direction.

only, would take the form of Equation (3). This accounts for both the translation and rotation of the tractor body. The inertia is that about the COM and it is denoted by $\bar{I}$.

$$\text{Available energy} = mg\left(h_2 - h_1\right) + \frac{1}{2}m\left({v_{r2}}^2 - {v_{r1}}^2\right) + \frac{1}{2}\bar{I}\left({\omega_{r2}}^2 - {\omega_{r1}}^2\right) \qquad (3)$$

Results and Discussion

The measured COM location, mass for each tractor and the theoretical angle at which rollover occurs when the COM exits the base defined by the tyres are shown in Figure 3. All graphs in this section present data ordered by increasing tractor mass as shown in Figure 3a.

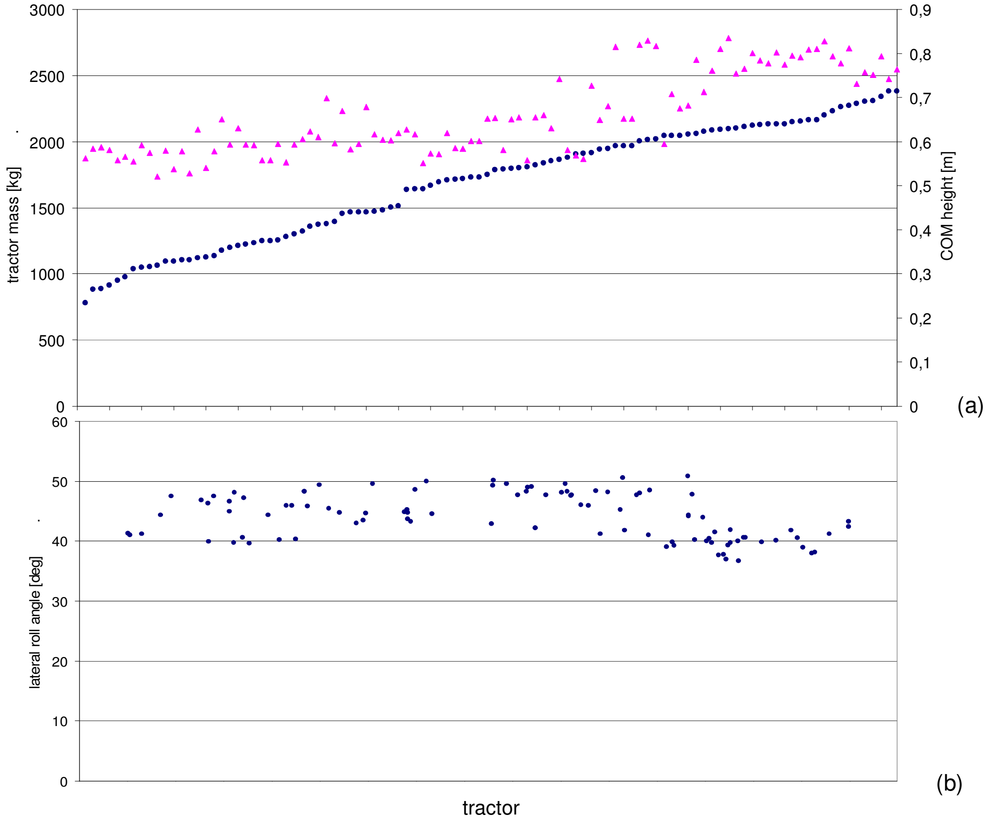

Figure 3. 102 measured tractor distributions for: (a) mass, ●, and COM, ▲, and (b) the theoretical lateral rollover angle assuming rollover occurs when the COM exits the base defined by the outer boundaries of the tyres. Assuming the COM is located along the tractors longitudinal axis and its measured height.

Figure 4 shows the calculated available energy at first impact for the two planes represented in Figure 2. Considering the horizontal resting plane, $g\Delta h$ could reach as much as 3.9 m^2s^{-2} (average 2.77 m^2s^{-2}). It is more likely that the inclined plane extends below the tractors initial starting position, Figure 4 (upper data set). In this case, $g\Delta h$ could amount to as much as 10.7 m^2s^{-2} (average 9.03 m^2s^{-2}). If all this energy had to be dissipated on the first impact, then it is clear that there is a lot of energy available. However, the most interesting point to note in both instances, when the data is arranged in the same order as Figure 3, is that, the $g\Delta h$ value appeared to change with mass. This would seem logical since Δh, defined in Figure 3, is a function of the measured COM height and the wheel base geometry etc. In fact, consistent with Schwanghart's communication to Chisholm (Chisholm, 1979d) it would appear that based on these tractors a low order polynomial would indeed be a better fit.

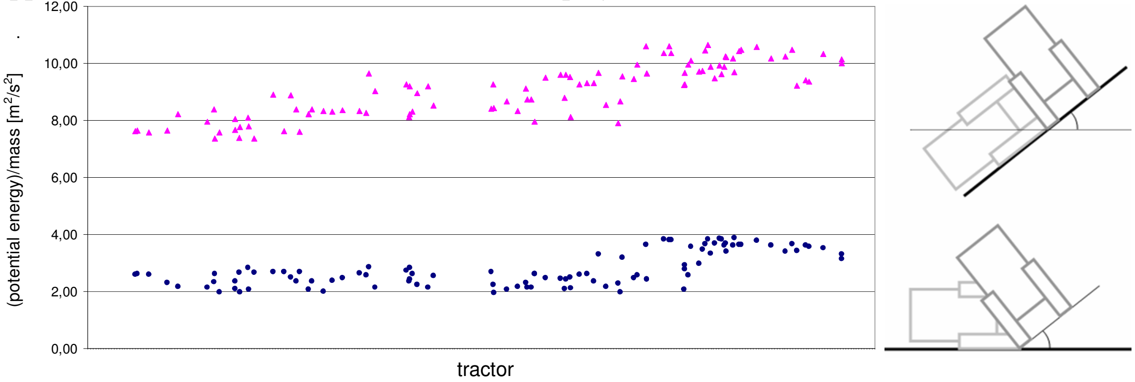

Figure 4: lateral rollover of a tractor on a slope to a horizontal plane, •, and the corresponding magnitude of g□h for lateral rollover on a slope which extends below the rollover point, ▲.

It is possible to combine the information of Figure 4 and Figure 1 into a single figure, Figure 5. This figure shows the average amount of energy available for each case represented in Figure 4 divided by the corresponding tractor's mass and also shows what Code 6 (OECD, 2008) specifies should be absorbed (dissipated) *laterally*. Clearly the total available energy is greater in both cases. However, it is realised that the Code does require that more energy is absorbed via a series of tests which are additionally performed in the longitudinal and vertical directions and that tyre impacts help dissipate some of this available energy. Nonetheless, this simple consideration shows that there is much more energy available at first impact.

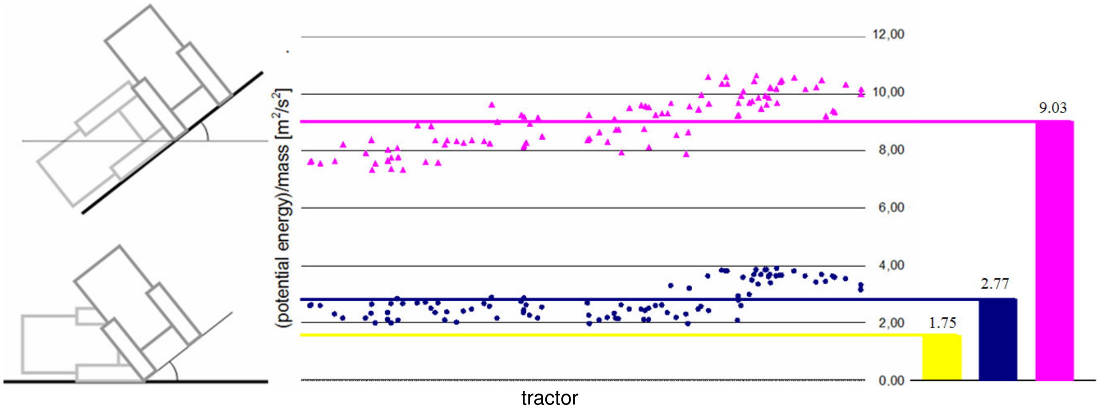

Figure 5: available energy dissipation split based on the two rollover scenarios of Figure 4. That specified in the Code to be absorbed laterally by the ROPS is shown in yellow.

<u>*Influence of forward speed*</u>

Using Equation (1) it is possible estimate how much additional energy is present at the initiation of rollover if forward velocity is included. For simplicity, only the total energy is included here. That is, that arising from velocity in the forward direction and the difference in height assuming that roll occurs on the same planes, as depicted in Figure 4. Although this a very simple case it suffices for demonstration purposes.

Figure 6 shows available energy at first impact calculated from theory from the measured tractor data and assuming a forward speed of 2m/s. It is based on assuming that the kinetic and potential energy are simply added together. No attempt is made here to see how this energy could be dissipated, this is an intended area of future work. Figure 6 shows energy resulting from just potential and with the addition of the kinetic, for the case of rolling onto the horizontal plane. It is possible to see that the inclusion of velocity increases the available energy. Again it is noted that in effect it has been assumed here that all forward velocity and potential energy give rise to a total energy which could be available at first impact: it is only in rare instances that all this energy is subject to the ROPS.

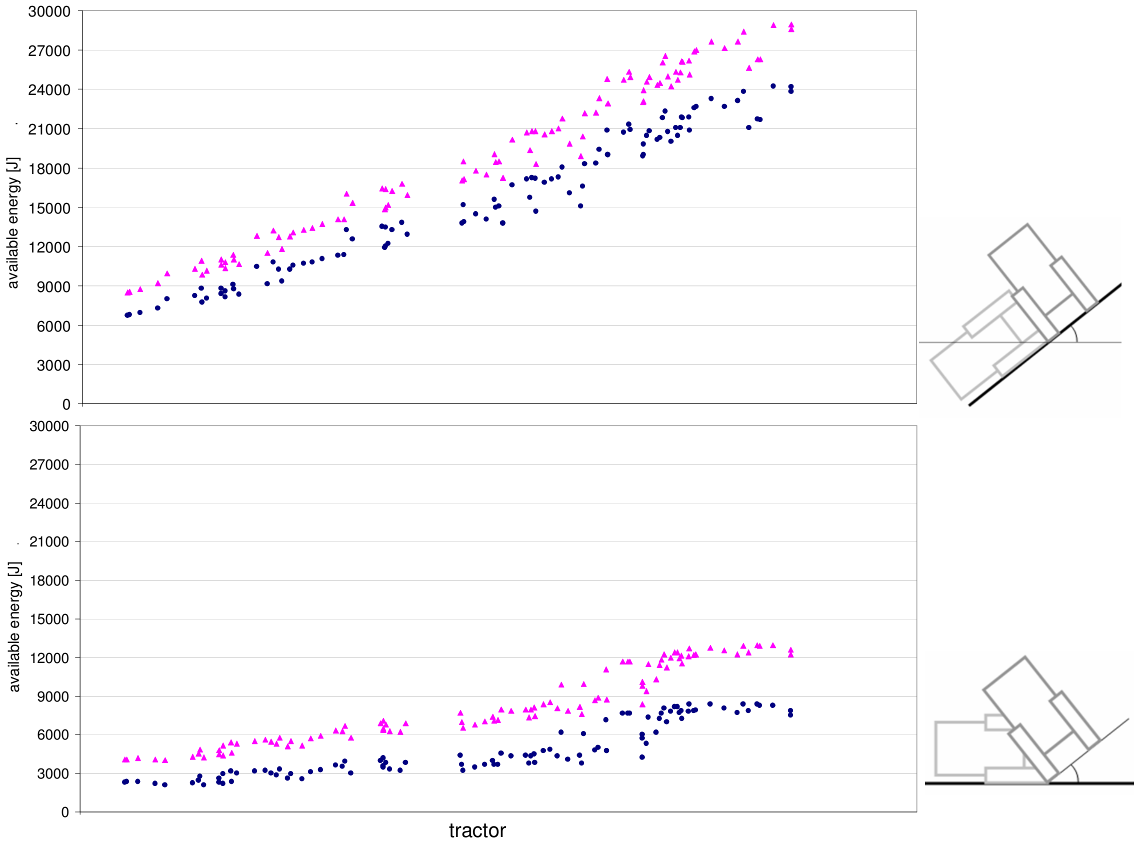

Figure 6. How the total available energy may vary for each tractor: just considering potential, •, and with the inclusion of kinetic for a 2m/s forward velocity, ▲. The cases are those of Figure 4 for the planes as shown.

Conclusions

This paper was mostly concerned with the theoretical energy that may be available at the start of rollover. To that end, using data pertaining to 102 narrow track tractors tested according to the provisions of the OECD Code 6, the energy was calculated for two types of lateral roll. These were the standard roll onto horizontal plane and the rollover onto a plane which extends below the rollover point. The available energy at first impact in the second scenario was understandably shown to be greater than the first. It was also shown, based on the assumptions given, that when the tractors are ordered by their mass, the $g\Delta h$ parameter appears to be nonlinear. This would seem logical since h is a function of COM height and wheelbase. Further calculations and measurements are needed to fully confirm this, and this is intended future work. In addition, it was shown via simple energy calculation that the addition of forward velocity can increase the energy available at first impact. It was noted that the inclusion of velocity however, considerably complicates the analysis and is likely to couple roll into more than the lateral plane. A most appropriate way to determine the nature and extent of this coupling is to perform real tests using modern tractors on a typical slope.

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