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Numerical analysis of rollover risk of a fruit-harvesting truck

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Abstract

Trucks for fruit harvesting are off-road vehicles widely used for speeding up the harvesting process during operations in the field. These trucks move with a low forward speed along the rows of trees while the operators stay on a cargo-bed that can be raised up to 3 meters from the ground. Due to the position of the centre of gravity and to the movement on a sloping, irregular and deformable terrain, risk of rollover may be significant. The work presents a numerical analysis of rollover risk of a truck for fruit harvesting; experimental tests were carried out on a tilting platform to determine the maximum lateral inclination angle allowed before rollover. A 3D multi-body model of the truck was developed and validated against the available experimental data. A sensitivity analysis was then carried out to estimate the rollover limit along a generic direction as function of vehicle's parameters (i.e. centre of gravity position and stiffness of suspensions). Guidelines for setting a safe forward speed of the vehicle are also proposed.

***Keywords*:** 3D Mutli-body model; Full scale test; Rollover condition; Sensitivity analysis; Forward speed limit

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1. Introduction

Fruit-harvesting trucks are widely employed to enhance productivity in agricultural operations. These vehicles can be classified as rough-terrain work platforms for orchard's operations (WPO) which are self-propelled machines designed to work on unimproved natural terrain or disturbed terrain [1]. A possible configuration of FHT is presented in Fig. 1.

Figure 1. Layout of Fruit-harvesting truck (the shown agricultural vehicle is meant just as example).

The vehicle is provided with diesel or electric motors allowing a maximum forward speed of 15 km/h. During harvesting operations the forward speed is usually below 2 km/h. The motion of the vehicle can be controlled by operators directly from the cargo-bed where they move and collect the fruits from the plants. The cargo-bed can be raised up to 3 meters above ground level and it is provided with lateral telescopic platforms; these lasts allow the operators to get closer to the plants to easy the harvesting operations. Fruit-harvesting trucks generally operate on flat ground moving along the inter-rows of the orchard; anyway it is possible to use them also when moderate slopes are present especially when the vehicles are equipped with a self-levelling system allowing compensating for the ground gradient keeping the cargo-bed in horizontal position.

Though these vehicles proved to be reasonably safe, some accidents due to their rollover are reported; rollover stability of these vehicles can be in fact critical due to several reasons:

- height of the centre of gravity: the cargo-bed is raised up to 3 meters above ground level to allow the operators to reach the top of the trees;
- Lateral position of the centre of gravity: the operators usually move on the lateral telescopic platforms that open from the sides of the cargo-bed. Fruit are usually collected in buckets fastened to the lateral balustrades. The weight is thus shifted laterally, especially when only one of the side platforms is open.

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- Characteristics of the terrain: the vehicle moves on an irregular, deformable and also sloping terrain causing sudden variation of roll angle.

Manufacturers of fruit-harvesting trucks specify limits for the maximum allowed roll-angle but uncertainties due to wrong evaluation of total mass or position of centre of gravity and local slopes associated to terrain irregularity or deformability, may increase the rollover risk [2][3].

This research was carried out within the "PROMOSIC" project, within the framework of the "BRIC 2015" call funded by INAIL (Italian National Institute for Insurance against Accidents at Work), aiming at analysing the stability of fruit harvesting trucks with particular focus on rollover risk.

Rollover risk of agricultural vehicles is widely analysed in literature: Franceschetti *et al*. [4] used a mathematical model to analyse the effect of inertial and geometrical parameters of a tractor on the energy absorbed by a rollover protective structure. In Ref. [5] Vidoni *et al.* investigated the stability of robotic platforms in side-slip operations, using a roll stability index to compare different layouts. Wang *et al.* [5] focused their work on a wearable robot for orchard operations, proposing a mathematical model to study its stability and design a control strategy. Jung *et al.* [7] used numerical simulations to evaluate the rollover stability of a vehicle with a lifting utility. In the research by Liu and Ayers [8] the effect of forward speed, ramp height, slope and turning radius on rollover stability of a tractor was analysed. No specific study of trucks for fruit harvesting is present in literature, as far as authors know.

A fruit harvesting truck with a front pivoting axle was considered in this work. Full scale tests were performed on a vehicle by means of a tilting table so that the maximum allowed roll angle for different configurations (positions of centre of gravity) could be identified. A 3D multi-body model of the vehicle was then set-up and validated against the results of the aforementioned tests. The model was then used to determine the rollover limit along a generic direction for different configuration of payload and for different values of stiffness of the pivoting axle.

2. Vehicle analysed in the research

Table 1. Geometrical and inertial data of the vehicle analysed in the research

Parameter	Value
Mass	2490 kg
Centre of gravity height from ground	1540 mm
Centre of gravity distance from rear axle	703 mm
Wheelbase	1700 mm
Front track width	1670 mm
Rear track width	1690 mm
Minimum cargo bed height	1000 mm
Maximum cargo bed height	2920 mm
Side platform max. opening	800 mm

The main geometrical and inertial parameters of the vehicle analysed in this research are reported in Table 1. The gross weight of the vehicle is close to 2.5 tons and the cargo-bed can be moved from 1690 mm up to 2920 mm. A particular feature of this vehicle is the presence of a pivoting front axle which actually reduces the roll stiffness thus increasing the rollover risk in lateral direction: the front axle is in fact free to rotate with respect to the vehicle chassis for a wide angle range until the axle/tires get in touch with the chassis. The vehicle is equipped with 2 side platforms that open at the car-bed sides. Geometric and inertial data of Table 1 are referred to configuration 1 of Table 2 (i.e. cargo-bed at the maximum allowed height, side platforms closed, no additional loads). The position of the centre of gravity was obtained by measuring the force on each wheel by means of load cells while the vehicle was still on a flat ground and measuring the load on the rear wheel when the front of the vehicle was elevated thanks to an overhead crane as specified by standard ISO 789-6 [9].

3. Experimental tests

Full scale tests were carried out on the vehicle by means of a tilting platform (Fig. 1). The experimental setup, in accordance with standard ISO 16231-1 [10] and ISO 16231-2 [11], consists in positioning the fruit-harvesting truck on a tilting platform with different orientations and measuring the inclination angle of the platform at which the rollover occurs. The following prescriptions were adopted when conducting the experimental tilting tests:

Figure 2. Tests on the tilting platform

- tests were performed in quasi-static conditions increasing the tilting angle slowly to avoid the influence of any dynamic effect;
- deformation of the platform was continuously monitored and no deformation was recorded during the test;
- the vehicle were in running order, i.e.: the fluid tanks (fuel and hydraulic oil) were filled properly and the tires were inflated according to the manufacturer's recommended pressure;
- downstream wheels were laterally blocked in order to limit lateral sliding during the test. The height of blocking

devices was less than 10% of tire nominal radius as prescribed by ISO 16231-1;

- chains were used to prevent full rollover after wheel detachment from platform;
- the bin was fixed to be in the centre of the cargo-bed for safety issues;

Based on the typical operating conditions observed in the fields, tilt tests were executed in the four configurations listed in Table 2. All the tests were performed tilting the platform towards the right side of the vehicle. In addition, operators mass and height of center of gravity from cargo-bed were taken in accordance to ISO 3411 [12], UNI 1459 [13] and ISO 22915-1/2 [14]; always referring to typical operating conditions, operators were placed close to the barriers with their mass increased due to the buckets fastened to the balustrade.

Table 2. Configuration considered for the tests with tilting table.

Configuration	Description
1	cargo-bed at the maximum allowed height, side platforms closed, no additional loads
2	cargo-bed at the maximum allowed height, side platforms completely opened, 4 workers (100 kg each), two on each side of the truck, and one fruit bin, fully loaded, at the center of the cargo bed (380 kg)
3	cargo-bed at the maximum allowed height, right-side platform opened, left-side platform closed, 2 workers (100 kg each) on right side of the truck and fruit bin, fully loaded, at the center of the cargo bed (380 kg)
4	cargo-bed at the maximum allowed height, right-side platform opened, left-side platform closed, 2 workers (100 kg each) on right side of the truck and no fruit bin

The configuration 1 can be regarded as a reference condition, though not the most critical with respect to rollover risk. The other configurations were included to consider the effect of different total mass and different positions (both vertical and lateral) of the centre of gravity. In particular, configuration 2 is characterized by higher centre of gravity and mass; configuration 3 and 4 present a lateral displacement of the position of the centre of gravity with two different distribution of weight of operators and bin.

A longitudinal rollover test was also performed: the vehicle was placed with rear axle downstream and the tilt table was rotated until detachment of front axle from the ground. Only configuration 1 was considered in the longitudinal rollover test.

Results of tests are reported in Table 3; as expected configuration 1 is the less critical setting a limit of 24.8° for the longitudinal rollover test and of 20.0° for the lateral rollover test. The most critical configuration is number 3 characterized by a high centre of gravity and asymmetrical load: in this case the limit is 11.9°.

Table 3. Experimental rollover limit for the configurations tested

Configuration	Roll over limit
1	24.8° (longitudinal)
	20.0°
2	14.8°
3	11.9°
4	13.3°

4. Numerical model

A 3D multi-body model of the fruit-harvesting truck was developed using the commercial software SimMechanics included in Matalb/Simulink. Once tuned to reproduce results of the experimental tests described in the previous chapter, the model allows investigating the behaviour of the vehicle in conditions not considered during the experimental phase. Moreover, sensitivity analysis with respect to vehicle's parameters can be carried out.

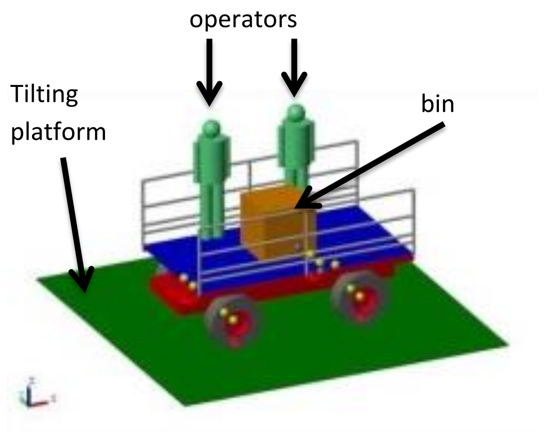

Figure 3. Multibody model of the truck

The model is represented in Fig. 3 and takes into account the main specific features of this kind of vehicles in particular:

- 1 rigid body is used to model the vehicle chassis;
- 1 rigid body, representing the rear axle, is rigidly connected to chassis;
- 1 rigid body representing the swivelling front axle is connected to chassis through an hinge;
- 1 rigid body is used to reproduce the lifting cargo-bed; this last is connected to the chassis by two bodies representing the bellow mechanism. Rigid bodies rigidly connected to the cargo-bed representing the fruit bin and the workers are added;
- 2 rigid bodies are used to model the side platforms which can slide laterally with respect to the cargo-bed.

As far as the connection between the front axle and the chassis is concerned, a nonlinear spring-damper element is introduced which avoids interpenetration between front axle and chassis for relative rotations larger than 10°. Moreover, the model includes the presence of front suspensions whose stiffness is set to zero in nominal operating condition. Suspensions can be “activated” to investigate their effect on the rollover limit.

The vehicle chassis is interfaced through tires with a tilting platform (modelled as a rigid body); the orientation of the tilting axis can be changed arbitrarily so that the rollover limit of the vehicle along a generic axis (i.e. not just lateral or longitudinal) can be identified.

The tire is modelled as a visco-elastic component that can exchange vertical, longitudinal and lateral forces with the tilting table. Tire deformation allows different orientation between the chassis and the tilting table. Tires are modelled with bushings characterized with different stiffness and damping along the three directions (vertical, lateral and longitudinal). The force normal to the tilting platform F_z is computed as follows:

$$F_z = \begin{cases} k_z z + r_z \dot{z}, & z < 0 \\ 0, & z \geq 0 \end{cases} \tag{1}$$

where z is the vertical deflection of the tire computed as difference between the nominal radius R_0 and the actual one (R); k_z and r_z are the vertical stiffness and damping coefficients of the tire. The vertical stiffness plays an important role in determining rollover limit as it allows the centre of gravity to move along the rollover direction, thus increasing the tilting moment due to the vehicle’s weight.

Longitudinal and lateral forces (respectively F_x and F_y) are modelled according to the following equations:

$$F_x = \begin{cases} k_x x + r_x \dot{x}, & |k_x x + r_x \dot{x}| < \mu F_z \\ \mu F_z, & |k_x x + r_x \dot{x}| \geq \mu F_z \end{cases} \tag{2}$$

$$F_y = \begin{cases} k_y y + r_y \dot{y}, & |k_y y + r_y \dot{y}| < \mu F_z \\ \mu F_z, & |k_y y + r_y \dot{y}| \geq \mu F_z \end{cases} \tag{3}$$

being x and y the lateral displacements of tire contact point in longitudinal and lateral direction, k_x and k_y the longitudinal and lateral stiffness of the tire carcass and r_x and r_y the corresponding damping coefficients. μ represents the coefficient of friction at the contact interface.

5. Numerical simulations

Numerical simulations were performed to determine the rollover limit (in terms of maximum inclination angle allowed before rollover) along a generic direction. For this purpose, the simulations were carried out by gradually increasing the tilt angle of the platform so to produce a quasi-static rollover. In particular the tilt angle was increased at a rate of 8° per minute. The rollover was assumed to take place when both wheels upstream detached from the platform. A 4th order explicit Runge-Kutta solver with variable integration step was used.

6. Tuning of numerical model

Parameters of multi-body model were in part measured (inertial and geometrical parameters) and in part identified though comparison with the available experimental data (tires stiffness). In particular, the model was used to simulate the rollover dynamics in quasi-static conditions considering the configurations of Table 3.

Table 4. Comparison between experimental and numerical limits in terms of maximum angle before rollover

Configuration	Rollover limit (numerical)	Rollover limit (experimental)
1	27.3°	24.8° (longitudinal)
	21.6°	20.0°
2	15.5°	14.8°
3	11.9°	11.9°
4	13.0°	13.3°

Table 4 reports a comparison between the maximum allowed angles before rollover obtained with experimental tests and numerical model. Differences between numerical and experimental results are below 5% with the exception of the rollover in longitudinal direction, where the error is around 10%.

Results of Table 4 were obtained using the values of tire stiffness collected in Table 5. Being the simulation quasi-static, tire damping coefficients r_x, r_y and r_z were set as small as possible (5e3 Ns/m) to avoid numerical instability.

Table 5. Values of identified contact stiffness

Configuration	Stiffness
Kx	400 kN/m
Ky	300 kN/m
Kz	300 kN/m

7. Numerical analysis

The numerical model was then used to simulate other rollover scenarios not tested with the tilting table. In particular, the base platform of the multi-body model was tilted along axes in generic directions; in this way it was possible to identify the maximum inclination angle allowed to avoid rollover along a generic axis.

Numerical simulations were focused on the identification of roll over limit for four operating conditions, listed in Table 6. The operating conditions consider the truck with the cargo-bed at two different heights and with 2 different load configurations; operating conditions A and C are referred to a misaligned load, where 2 operators stay on the same side. Conditions B and D refer to the cargo-bed with the maximum load and 4 operators distributed symmetrically. Conditions C and D considers the cargo-bed at its maximum height (2920 mm), while conditions A and B are referred to the cargo-bed at 2420 mm.

Table 6. Operating conditions analysed during simulations

Operating condition	Cargo-bed height	Operators	BIN
A	2420 mm	2 per side (4x100 kg)	1 in centre: 380 kg
B	2420 mm	2 on right side (2x100 kg)	1 in centre: 380 kg
C	2920 mm	2 per side (4x100 kg)	1 in centre: 380 kg
D	2920 mm	2 on right side (2x100 kg)	1 in centre: 380 kg

The effect of additional roll stiffness on the swivelling axle was included in the numerical analysis, to show the possible benefits in terms of rollover stability.

Results of Fig. 5 shows the maximum inclination angle allowed before rollover for the operating conditions A and B. The polar plot should be read considering the vehicle seen from the top with the front axle towards the top of the page. The axis 0°-180° thus represents a lateral direction while the axis 90°-270° refers to the longitudinal direction. The lines are the maximum allowed angle before rollover on the corresponding direction. Focusing con operating condition A, the reference condition is the red line (i.e. k0): in this case the vehicle is provided with a swivelling axle on the front without suspensions. It can be noticed how the rollover in lateral direction is about 25°, while a rollover in longitudinal direction (towards the front part of the vehicle) is more unlikely, requiring a longitudinal slope of 35°. Roll over towards the rear is instead easier, due to the longitudinal position of the centre of gravity, with a limit of 23°. It is interesting to notice how the configuration of the front axle gives a sort of triangular shape to the limit surface In fact, due to the absence of a roll stiffness on the front there is a high probability of roll over in directions around 45° and 135°.

When roll stiffness is added (conditions k1, k2 and k3), the safety margin towards rollover along these directions significantly improves. Roll stiffness k1 correspond to 52kNm/rad; k2 and k3 are respectively two and three times this value. Therefore, front swivelling axle may pose safety issues for these kinds of vehicles.

Considering now operating condition B, the lateral shift of the load on the cargo-bed makes the limit surface strongly asymmetrical: roll over toward the right side (which is the most loaded) is much more likely. If no suspension is introduced on the front axle, the maximum allowed inclination along 0° direction is 12.5° while along 180° direction is 30°. Using suspensions on the front axle allows enlarging the limit surface, especially in the high part of the chart.

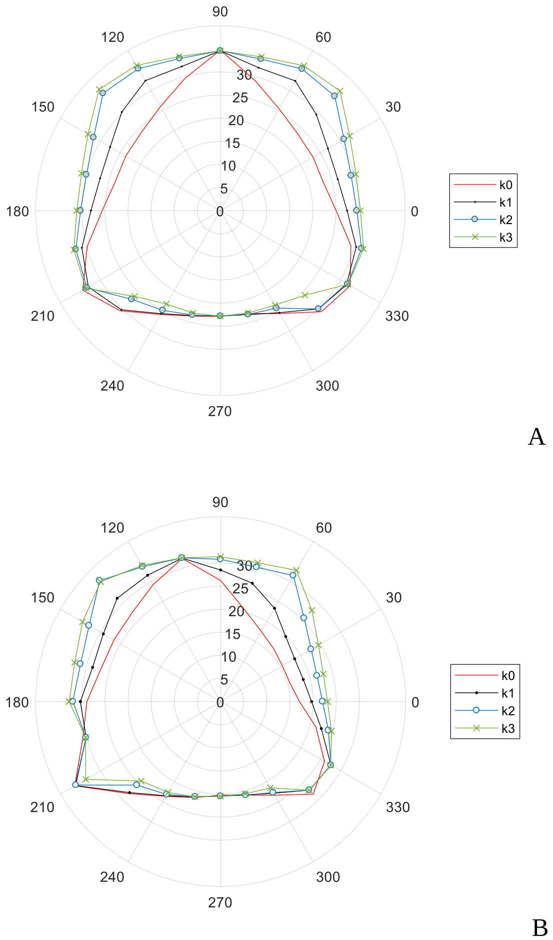

Figure 4. maximum allowed inclination angle [°] before rollover for operating condition A and B

When the cargo bed is raised to its maximum height, the rollover risk increases (Fig. 5). Considering operating conditions C, the limit in 0° direction is around 20°, in 90° direction is 30° and in 270° direction is 21°. Again, if no suspension is used on the front axle, rollover along 45° and 135° happens for inclinations higher than 18°. Introducing suspensions improves the safety margin towards rollover for almost all the direction.

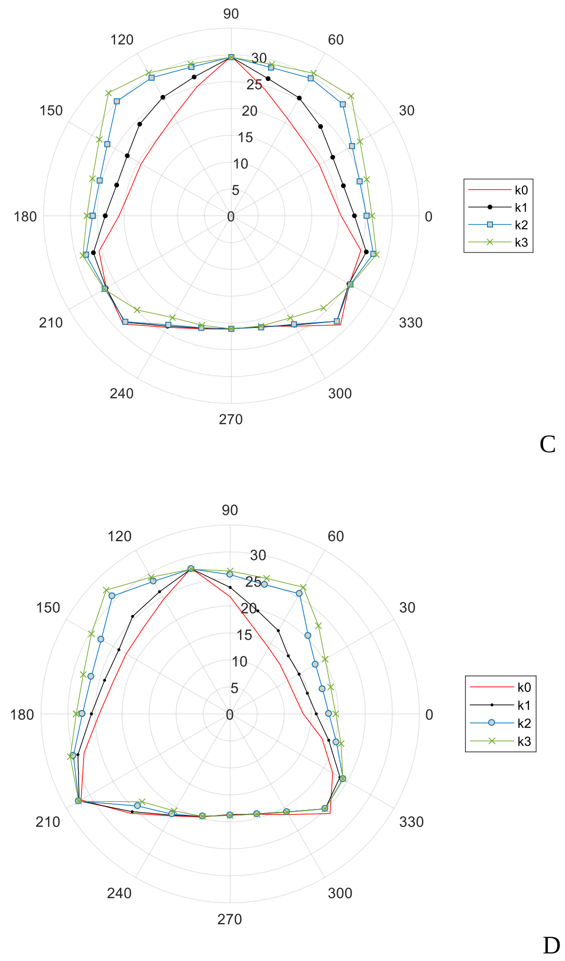

Figure 5. Maximum allowed inclination angle [°] before rollover

for operating conditions C and D.

Operating condition D appears as the most critical in terms of roll overs safety: moving the load on the right side and setting the platform at the maximum height lead to poor margins for rollover toward right direction. The reference configuration of the truck, without suspension on the front axle, lead to limits along 0° and 30° directions of 13° and 12° respectively. Also in this case, numerical simulations point out the benefits associated with the introduction of front suspensions.

8. Estimation of maximum operating speed

The following analysis will be focused on the conditions with the cargo-bed at maximum height and swivelling axle with no suspensions. The target of the following analysis is to provide the operators with some indications about the maximum operating speed to keep the operations within reasonable safety margins.

As first, the limits determined on maximum inclination of the platform are representative for maximum inclination of the soil. Actually, what causes the roll over is the moment generated by weight force due to the projection of gravity acceleration on a plane tangent to the ground. The same effect can be generated by a system of inertia forces, i.e. acceleration of the centre of gravity. Being φ the limit on soil inclination, the same effect of the projection of g can be obtained by the acceleration a of the truck's centre of gravity:

$$g \cdot \sin\varphi = a \tag{4}$$

The rollover limits in terms of acceleration of the centre of gravity can thus be derived and values are reported in Fig. 6 for configurations C and D. Data of Fig. 6 means that rollover may be caused also by crossing certain limits of centre of gravity acceleration. Some combinations of longitudinal and lateral acceleration may be more critical. However, under normal operating conditions, forward speed is rather low and almost constant; therefore, longitudinal acceleration has usually a minimal impact on stability. Lateral acceleration is instead present when the vehicle reaches the end of a row and has to turn and begin harvesting in the new row. In this situation the cargo-bed would have to be lowered by the driver, so we will analyse the risk in case operators do not lower the platform. During this phase, lateral acceleration sums up with the effect of local slope.

It is possible to compute a new limit on ground slope, taking into account the simultaneous presence of a lateral acceleration. In particular, referring Fig. 7, it is possible to identify the new limit curve considering that the vector sum of lateral acceleration $\mathbf{a}_y$ plus the new limit $\mathbf{a}_{\mathrm{lim,new}}$ should be equal to the old limit ($\mathbf{a}_{\mathrm{lim,old}}$) shown in Fig. 5.

$$\mathbf{a}_{\mathrm{lim,\,old}} = \mathbf{a}_y + \mathbf{a}_{\mathrm{lim,\,new}} \tag{5}$$

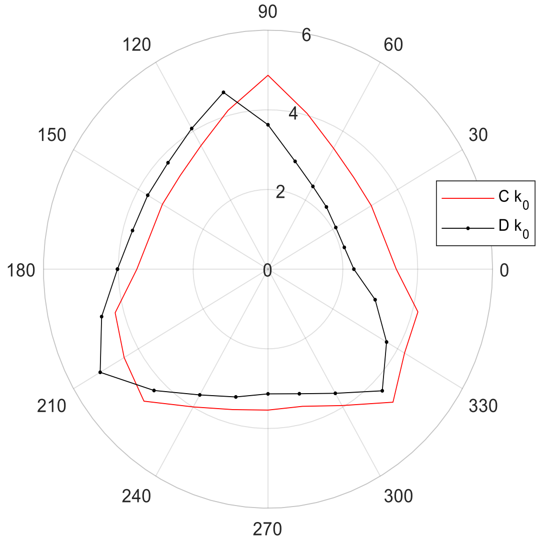

Figure 6. Maximum allowed acceleration [m/s^2] before rollover

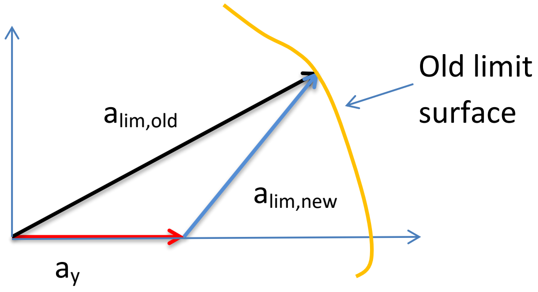

Figure 7. Determination of new limit for center of gravity acceleration

Following this procedure the new limit surface for the local slope of the ground that takes into account the presence of a lateral acceleration, can be derived combining Eq. 4 and Eq. 5:

$$\varphi = \arcsin\left(\frac{\left|\mathbf{a}_{\text{lim, new}}\right|}{g}\right) \tag{6}$$

The results for operating conditions C and D are shown in Fig. 8, where a lateral acceleration of 1 m/s2 is assumed. Comparing results of Fig. 8 with those of Fig. 5 it is possible to notice how the charts moved laterally reducing the safety margin on one side.

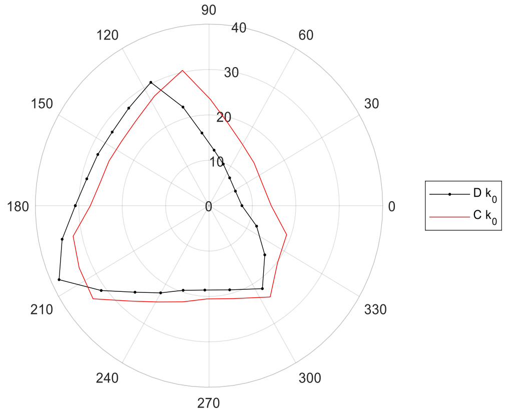

Figure 8. Maximum allowed inclination angle [°] before rollover considering the simultaneous lateral acceleration of 1m/s^2.

Trying to identify a safe speed limit for harvesting operations, one may take into account that the rows of plants are usually directed as the local slope of the terrain to easy the irrigation procedure. As a consequence, when a vehicle reaches the end of a row and reverts direction, the slope of the terrain is projected along all the axes between 90°-270° or between 270°-90° according to the turn direction. Assuming the most critical situation, for safety reason, this means that the maximum allowed slope is the point on the limit curve closer to the origin. For example, assuming a lateral acceleration of 1 m/s^2, the limit slope for configuration C is 13.2° and for configuration D is 6.9°. The same computation can be repeated for several values of lateral acceleration, thus relating lateral acceleration to a corresponding maximum slope.

This chart is reported in for operating condition D in Fig. 9.

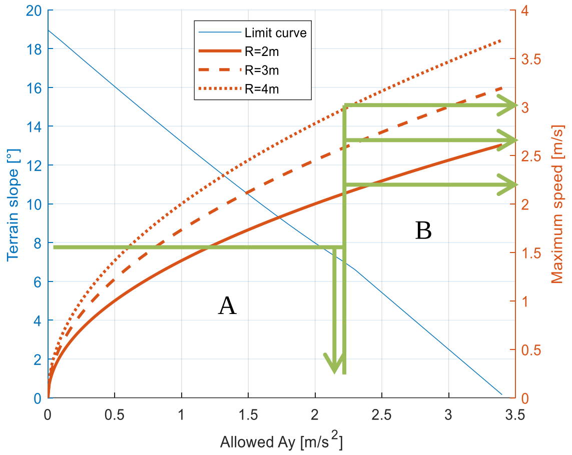

Figure 9. Determining limit of forward speed for operating condition C.

As forward motion is slow and occurs at almost constant speed, lateral acceleration can be considered related to forward speed V and turn radius R by the equation:

$$a_y = \frac{V^2}{R} \tag{7}$$

resulting in:

$$V = \sqrt{a_y R} \tag{8}$$

Looking now at Fig. 9: the field sets the values in terms of maximum slope and in terms of distance between rows; following path A, in Fig. 9, the terrain slope sets an upper limit for lateral acceleration that cannot be exceeded without causing rollover. Lateral acceleration is in turn related to the travelling speed according to the turn radius; following path B, the operators can thus have an indication of maximum forward speed. Fig. 10 reports similar data for operating condition D where limits are clearly more stringent.

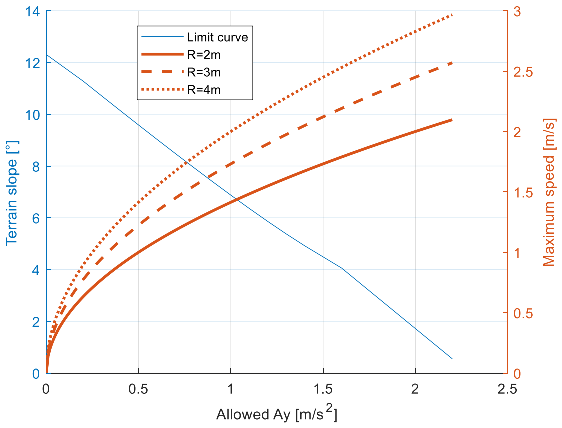

Figure 10. Determining limit of forward speed for operating condition C.

9. Conclusions

This paper analysed the rollover dynamics of a truck for fruit harvesting. These kinds of vehicle allow to easy and speed-up the harvesting procedure due to their particular layout characterized by a cargo-bed that can be raised up to 3 meters from ground level. Due to high centre of gravity and asymmetrical load conditions, running on irregular, deformable and sloping terrains may jeopardize the vehicle stability, in particular as far as rollover risk is concerned.

Analysis of rollover risk was carried out at first from an experimental point of view: full scale tests on a tilting platform were performed to determine the maximum inclination angle allowed before rollover.

A 3D multi-body model of the truck was then developed and tuned on the basis of the experimental data. Once comparisons between numerical and experimental results were satisfying, a sensitivity analysis was then carried out to estimate the rollover limit along a generic direction as function of vehicle's parameters (i.e. centre of gravity position and stiffness of suspensions).

The numerical model allowed predicting the maximum inclination before rollover along a generic axle. The analysis pointed out that the risk of rollover is not just related to lateral rollover. Due to the presence of a front swivelling axle without suspensions, rollover risk in directions between lateral and longitudinal ones is still significant. Adding roll stiffness on the front axle allows reduction of rollover risk.

In addition, numerical results showed that the most critical condition is the one with asymmetrical load, where two operators stay on the same side of the cargo-bed; though this is not the condition with the maximum load, the lateral shift of centre of gravity threatens stability in one direction.

As last, an attempt to provide guidelines for operators was proposed: in particular a strategy for determining a limit for the forward speed compliant with the characteristic of the field was suggested.

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