

Lateral Stability Performance of Narrow-track tractors

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Abstract

A tractor losing lateral stability starts to rollover. It is a matter of fact that tractor lateral rollover accident is one of the most frequent causes of death and injuries for the farmers. Consequently, tractor is fitted with a specific protective structure to minimise the consequences for the driver during the rollover (ROPS). The narrow-track tractor, designed to operate in vineyards and orchards, is a tractor category with a very narrow track width and the risk of rollover is higher.

The aim of the study was to evaluate the compact narrow-track tractor types commercially available, designed to mount a cantilever engine in the forward position with effects on the Center of Gravity (CoG) because more than 50% of the tractor weight is loaded on the front axle, and specifically the articulated narrow-track tractors where the stability is affected by the pivot point connecting the two tractor bodies. As a consequence of the typical tractor design of the articulated tractors, during the steering action the line passing through the front and rear tire contact points on the ground changes influencing the tractor stability. Moreover, the horizontal rotation of the tractor pivot point influences the tractor CoG position and finally the tractor stability. The approach of the research was based on reproducing the lateral stability tractor condition by developing a kinematic model, with the goal to virtual simulate the tractor behaviour and to calculate the lateral stability angle for the steering wheel and the articulated tractors. The model at the tractor design stage will allow adjusting the tractor parameters to improve the lateral stability performance.

Keywords: Articulated tractor, stability angle, mathematical model, safety, rollover.

1. Introduction

Tractor overturning accidents on slopes have serious consequences for the farmer (Hunter & Owen, 1983). Studies indicate that over 80% of tractor accidents are sideways overturns (Rondelli, Martelli, & Casazza, 2018). Determining the lateral stability of agricultural tractor has been a subject to deepen for tractor designers and researchers over the years (Kim & Rehkugler, 1987; Shu, Ahmad, & Akande, 2010). Studies were conducted to determine the factors influencing tractor stability in sloped fields (Franceschetti, Rondelli, & Ciuffoli, 2019; A. Guzzomi & Rondelli, 2013). The tipping event for a tractor in static condition was also analysed (A. L. Guzzomi, 2012). The tractor stability issue on slopes was studied for vehicles designed with fixed-chassis (Grecenko, 1984) and with articulated chassis (Mazzetto, Bietresato, Gasparetto, & Vidoni, 2013); so as for the combination tractor-implement (Yisa, Terao, Noguchi, & Kubota, 1998). Pershing and Yoerger (Pershing R.L. & Yoerger R.R., 1969) investigated the tractor dynamic behaviour on side slopes. Dynamic studies relating inertia properties and energy levels during the tractor rollover were performed (Franceschetti, Lenain, & Rondelli, 2014; A. Guzzomi, Rondelli, Guarnieri, Molari, & Molari, 2009).

Since the last century many research approaches were addressed to develop models for predicting the tractor behaviour in normal operation with the aim to reduce the risk of rollover (Franceschetti, Capacci, & Rondelli, 2016; Li et al., 2016; Spencer, 1978). These attempts were combined to the design of passive protective devices (Roll-Over Protective Structures, ROPS) to be mounted on the tractor to minimize the risk of driver injuries in case of a rollover event. Indeed, over the time it has been recognised that the tractor is really a vehicle prone to rollover because of the high versatility in the use and in the operating conditions (A. L. Guzzomi, Rondelli, & Capacci, 2019; Liu & Ayers, 1999). Nevertheless formulating a tractor lateral stability model is a difficult exercise mainly in properly defining the geometry of the machine and predicting the kinematic effects during its operation in the field, since the forces and moment arms are not coplanar, especially if the case of articulated chassis tractors is considered (Gibson, Elliot, & Persson, 1971). However vector methods provide a powerful analytic tool for the description of 3D motion such as the sideways overturning of a farm tractor (Smith, Perumpral, & Liljedahl, 1974). Basing on this approach, with the aim to calculate the lateral stability angle of a tractor designed with articulated chassis independently on its position on the ground, a kinematic model based on the mass and geometrical tractor data was developed. Often modern compact narrow track tractors are made of two separate bodies centrally joined. These vehicles are frequently in use on sloped areas in orchard, vineyard and forage harvesting operations. Consequently, to analyse the stability performance of articulated chassis tractors is of interest in reason of the specific and wide use currently foreseen in narrow environments and sloped areas.

The model was developed considering the tractor as composed by two rigid elements with different mass and geometry. The two body parts were modelled as joined by two links allowing for two different rotations, horizontal (roll angle) and vertical (yaw angle) rotations. The tractor model evaluates the effect of the two mutual rotations of the tractor bodies, estimating the influence of the tractor masses repartition. The goal was to determine the unstable equilibrium of

the tractor by defining the slope angle of the ground in order to calculate the lateral stability angle of the tractor.

2. Materials and Methods

To identify the unstable equilibrium condition of a compact articulated chassis tractor, a kinematic model was developed to evaluate the tractor lateral stability performance. The model can estimate the critical configuration of the tractor overcoming the unstable equilibrium with the consequence that the rollover event starts.

2.1. Kinematic model for lateral stability test

In developing the kinematic model to study the behavior of a compact articulated chassis tractor, the design of the tractor was simplified considering a rear body, composed of the rear axle and the driver seat, joined to a front body, made of the front axle and the engine. The tractor rear body was allowed to assume an angle of inclination and a position different with respect to the front body because of the pivot point jointing the two bodies. This articulation mechanism in the normal operation of the tractor affects its configuration during the steering action, the rear and front parts can mutually rotate to change the tractor path. Assumptions made to derive the mathematical model of the tractor were: tractor composed of two rigid bodies centrally joined to permit their mutual rotation, the full tractor CoG divided into two distinct portions that are the rear and front tractor body CoG, tractor median longitudinal plane, defined with respect to the two bodies in the straight configuration, symmetrical and parallel to the y-z plane, aerodynamic forces ignored, ground surface nondeformable and slip effect of the tractor on the ground ignored. Five characteristics points were identified to describe the virtual tractor. The approach in modelling the compact articulated tractor was to represent the complex geometry of the vehicle (Figure 1-a) through the decomposition of the tractor into two bodies, front and rear ones, connected with a joint allowing their mutual rotation both on the vertical axis of the tractor (yaw angle $-\mu$, Figure 1-b and Figure 2-b), and on the longitudinal one (roll angle $-\vartheta$, Figure 1-b and Figure 2-c), identifying five parameters related to the geometry and the mass repartition of the tractor (Figure 1-b):

$$\vec{P}_1 = x_{P_1}\hat{i} + y_{P_1}\hat{j} + z_{P_1}\hat{k} \quad (1)$$

$$\vec{P}_2 = x_{P_2}\hat{i} + y_{P_2}\hat{j} + z_{P_2}\hat{k} \quad (2)$$

$$\vec{G}_1 = x_{G_1}\hat{i} + y_{G_1}\hat{j} + z_{G_1}\hat{k} \quad (3)$$

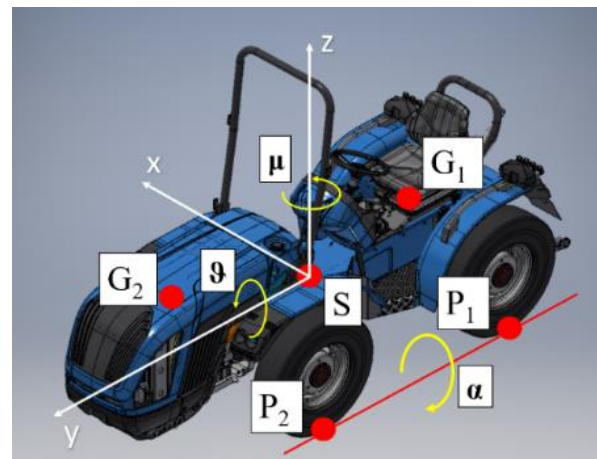
$$\vec{G}_2 = x_{G_2}\hat{i} + y_{G_2}\hat{j} + z_{G_2}\hat{k} \quad (4)$$

$$\vec{S} = x_S\hat{i} + y_S\hat{j} + z_S\hat{k} \quad (5)$$

where \vec{P}_1 and \vec{P}_2 are the contact points of the rear and front tires on the ground, \vec{G}_1 and \vec{G}_2 specify the position of the CoG of the rear and front bodies of the tractor and \vec{S} is the pivot point of the tractor.



a)



b)

Figure 1. Compact articulated tractor: a) Actual tractor in the straight configuration; b) Graphical representation of the five tractor parameters

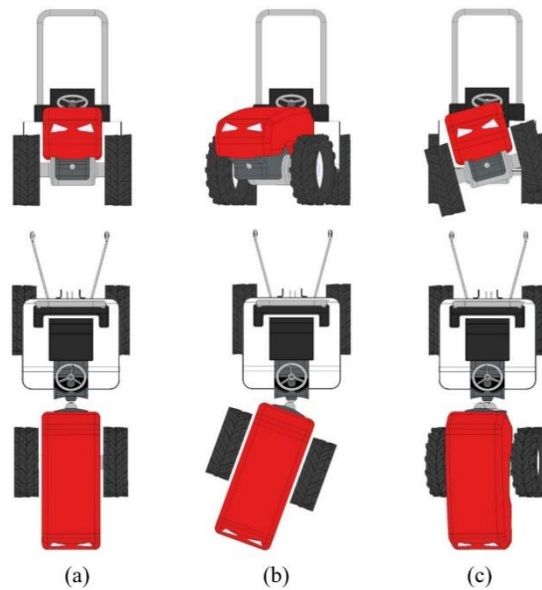


Figure 2. The configurations of the compact articulated chassis tractor:
a) Straight configuration b) Yaw angle limit c) Roll angle limit

When the tractor tip sideways, the first rotation take place about an axis connecting the central pivot point to the contact point of the tire remaining on the ground during the initial tipping motion. Eventually, the tipping body of the tractor strikes a stop on the steady tractor body with further tipping of the whole tractor taking place about an axis connecting the contact points of the front and rear tires on the ground. The lateral stability angle (α) was defined as the angle the full tractor body CoG must assume from the horizontal position on the ground (with the four tractor tires touching the ground) till the inclined position corresponding to the unstable equilibrium of the tractor on the two tires in contact with the ground. The tractor axis of rotation to evaluate the lateral stability angle is varying because affected by the position of the front and rear wheels in contact with the ground plane; these will assume different positions in reason of the mutual rotation of the two tractor bodies, defining the boundary condition the CoG must respect to maintain the stability of the tractor. It is clear, even before analyzing the model results, that the lateral stability angle is linked to the tractor configuration. To represent the complex tractor scenario the first step in modeling was to define a selected configuration based on geometry, masses, and mutual position of the two tractor bodies, to define the roll and yaw angle values. In the second step the corresponding angle of stability was evaluated. Final step will be to identify the worst tractor scenario and to calculate the lateral tractor stability limit angle.

Study development:

- a) Modelling the vertical pivot point (yaw angle)
- b) Modelling the horizontal pivot point (roll angle)
- c) Modelling the lateral tractor stability

2.1.1. Modelling the vertical pivot point (yaw angle)

A fixed chassis tractor typically is designed with front wheels mounted on the steering axle, even if over the years the modern tractors are more and more in the type of four-wheel drive (4WD), where the front axle is at the same time a drive and a steering axle. In the fixed chassis tractor design the yaw angle is equal to zero because the rotation of the front wheels is considered negligible. Taking into consideration the articulated chassis tractor, where the steering action is performed by the rotation of the front body with respect to the rear one, the effect of this rotation needs to be considered. The rotation allowed for the joint defines the yaw angle and affects the two points in Equations (1) and (3). Rotation can be clockwise or anti-clockwise oriented, consistent with a right or a left steering action. Having a maximum value of the yaw angle, a parameter defined at the tractor design stage, tractor bodies can assume positions in between the minimum to the maximum articulation values, with zero value when the two bodies are in the straight configuration, that is a configuration equivalent to a fixed chassis tractor.

The angular orientation of the tractor is related to the rotations about the axes. To model the vertical pivot point, the angular rotation is about the z axis and the following rotation matrix is introducing μ as yaw angle:

$$R_z = \begin{bmatrix} \cos \mu & -\sin \mu & 0 \\ \sin \mu & \cos \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (6)$$

The new contact point of the rear tire on the ground and the new CoG of the rear body of the tractor are represented by the vector equations, respectively \vec{P}_1' and \vec{G}_1' :

$$\vec{P}_1' = \begin{bmatrix} x_{P_1}' \\ y_{P_1}' \\ z_{P_1}' \end{bmatrix} = R_z \begin{bmatrix} x_{P_1} \\ y_{P_1} \\ z_{P_1} \end{bmatrix} \quad (7)$$

$$\vec{G}_1' = \begin{bmatrix} x_{G_1}' \\ y_{G_1}' \\ z_{G_1}' \end{bmatrix} = R_z \begin{bmatrix} x_{G_1} \\ y_{G_1} \\ z_{G_1} \end{bmatrix} \quad (8)$$

2.1.2. Modelling the horizontal pivot point (roll angle)

The joint connection between the front and the rear body of the tractor allows overcoming the ground unevenness conditions. In the fixed chassis tractor, the joint is designed in the central position of the front axle and its effect on the stability is reduced. In compact articulated chassis tractors, the joint is located in the central part of the tractor chassis causing the mutual rotation of the two tractor bodies when tractor needs to overcome obstacles or ditches. The range of rotation of the two tractor bodies is defined at the design stage but this parameter greatly affects the tractor behavior in terms of stability performance. In critical stability conditions, when the tractor reaches the unstable equilibrium, being the CoGs of the front and rear tractor bodies different, there will be one of the two parts that will represent the worst configuration for the stability effect. A loss of adhesion of a wheel on the ground will be observed and the linked body will rotate of an angle equal to the joint angle, defining a new condition for the tractor. The CoG of the rotated body will be affected. CoG will rotate about the axis defined by the straight line passing through the points, the contact point of the tire on the ground and the pivot point, for an angle equal to the maximum roll angle. In the model, in reason of the geometry and mass repartition of the compact tractor this behavior was ascribed to the front or to the rear tractor body. Nevertheless, to improve the understanding only the event related to the front body of the tractor is considered. Since the initial tipping motion does not take place around either the x, y, or z axes, it is convenient to define the skew coordinate axis about which the tractor is assumed to tip. Introducing ϑ as pivot point angle, following the method of Smith et al. (1974), and let \vec{v} be a unit vector in the direction of the first tipping axis, a rotation matrix can be defined:

$$\vec{v} = (x_v, y_v, z_v) = \frac{x_{P_2} \hat{i} + y_{P_2} \hat{j} + z_{P_2} \hat{k}}{\sqrt{x_{P_2}^2 + y_{P_2}^2 + z_{P_2}^2}} \quad (9)$$

$$R_{y'} = \begin{bmatrix} x_v^2 + (1 - x_v^2) \cdot \cos(\vartheta) & [1 - \cos(\vartheta)] \cdot x_v \cdot y_v - \sin(\vartheta) \cdot z_v & [1 - \cos(\vartheta)] \cdot x_v \cdot z_v + \sin(\vartheta) \cdot y_v \\ [1 - \cos(\vartheta)] \cdot x_v \cdot y_v + \sin(\vartheta) \cdot z_v & y_v^2 + (1 - y_v^2) \cdot \cos(\vartheta) & [1 - \cos(\vartheta)] \cdot y_v \cdot z_v - \sin(\vartheta) \cdot x_v \\ [1 - \cos(\vartheta)] \cdot x_v \cdot z_v - \sin(\vartheta) \cdot y_v & [1 - \cos(\vartheta)] \cdot y_v \cdot z_v + \sin(\vartheta) \cdot x_v & z_v^2 + (1 - z_v^2) \cdot \cos(\vartheta) \end{bmatrix} \quad (10)$$

Consequently, the new CoG of the front body of the tractor is:

$$\vec{G}_2' = \begin{bmatrix} x_{G_2}' \\ y_{G_2}' \\ z_{G_2}' \end{bmatrix} = R_{y'}^T \begin{bmatrix} x_{G_2} \\ y_{G_2} \\ z_{G_2} \end{bmatrix} \quad (11)$$

2.1.3. Modelling of lateral tractor stability

Basing on the CoG of the two tractor bodies, affected by the rotation angles and the masses of the two bodies, the CoG of the whole tractor in the defined scenario is computable. The stability angle of the tractor is calculated by considering the unstable equilibrium when the tractor CoG position falls outside the basis connecting the contact points of the tires on the ground. A determination of the CoG acting on the whole tractor is essential in any prediction of vehicle behavior; it is through the CoG position that the gravity force, if outside the axis connecting the contact points of the front and rear tires on the ground, causes the instability of the tractor. Taking into consideration the distribution of the masses of the tractor, the roll and yaw angles affected the CoG position and the lateral stability angle consequently. Letting W_1 be the weight of the rear tractor body, W_2 the weight of the front tractor body, and W the weight of the full tractor ($W = W_1 + W_2$), the new CoG of the tractor at the instant the tractor begins to tip is located at the point with coordinates:

$$\vec{G} = \begin{bmatrix} x_G \\ y_G \\ z_G \end{bmatrix} = \left(\frac{\sum_{i=1}^2 W_i x_{G_i}'}{\sum_{i=1}^2 W_i} \right) \hat{i} + \left(\frac{\sum_{i=1}^2 W_i y_{G_i}'}{\sum_{i=1}^2 W_i} \right) \hat{j} + \left(\frac{\sum_{i=1}^2 W_i z_{G_i}'}{\sum_{i=1}^2 W_i} \right) \hat{k} \quad (12)$$

The lateral stability angle is a function of the CoG of the full tractor, and the second tipping axis connecting the contact points of the front and rear tires on the ground:

$$\alpha = f(\vec{G}, \vec{P}_1, \vec{P}_2) \quad (13)$$

2.2. Compact narrow-track tractor evaluated

Narrow track tractors are nowadays designed in different configurations affecting the stability performance of the machine (A. L. Guzzomi et al., 2019). In order to better understand the added value of the model developed it is advisable to explain the main behaviour of the articulated chasis tractor and to introduce the tractor configuration data assumed in the simulation. A pivot point is a mechanical tool for the tractor to overcome the ground unevenness. The standard tractor with a fixed chasis is a steering wheel tractor where the pivot point is located in the mid-point of the front axle. Frequently, the compact narrow-track tractor is designed made of two separate bodies joined and the pivot point is close to the geometric center of the tractor. If the tractor is a steering wheel tractor only one degree of freedom is permitted, the longitudinal rotation (roll angle – ϑ). Otherwise, if the tractor is an articulated tractor, two degrees of freedom are permitted, longitudinal and vertical ones (roll angle – ϑ and yaw angle – μ). The values of the input parameters, for a tractor of 55 kW in the unballasted mass configuration, were obtained from Franceschetti et al. (2019). Table 1 lists the geometrical input parameters of the tractor configuration considered.

Table 1. Input tractor parameters.

Identification	Geometric parameter	Unit	Description
\vec{P}_1	(-555; -915; -540)	mm	Rear tire contact point
\vec{P}_2	(-555; 425; -540)	mm	Front tire contact point
\vec{G}_1	(0; -915; 44)	mm	CoG Rear tractor body
\vec{G}_2	(0; 425; 104)	mm	CoG Front tractor body
\vec{S}	(0; 0; 0)	mm	Pivot point
W_1	450	kg	Rear tractor body weight
W_2	1090	kg	Front tractor body weight
ϑ	[0 ÷ 7.5]	degrees	Roll angle
μ	[-35 ÷ 35]	degrees	Yaw angle



Figure 3. Tractor configuration: a) Roll angle behaviour b) Yaw angle behaviour

3. Results

The mathematical model was used to examine the behavior of the tractor to variable inputs of the rotation angle to produce a steering effect. By combining the effect of the roll and yaw angles, the critical value of the stability angle was determined and the critical condition for the stability of the tractor was established. The results were split into two tractor configurations: straight configuration and articulated configuration.

3.1. Straight configuration (roll angle)

The tractor in the straight configuration, is comparable to a fixed chasis tractor. The model performs the analysis without considering the yaw angle ($\mu = 0^\circ$) while the roll angle is calculated (Figure 4, $\vartheta \neq 0^\circ$). The model simulates the overturning event by increasing progressively the slope of the ground until a part of the tractor loses stability. In this study, the front body was considered to turn out first ($\alpha = 40.8^\circ$) with respect to the whole tractor ($\alpha = 41.5^\circ$) therefore the overturning starts with the rotation of the front body (Figure 5, $\vartheta = 0^\circ$). The front body rotates till the design angle (from 0 to 7.5 degrees, Table 1), basically, until the rotating body rests on the stationary body. In Figure 5, the behavior of the front tractor body (black line) and the whole tractor (red line), at different roll angle values, are shown. The loss of stability of the front body with respect to the stability of the complete tractor leads to the change of the CoG tractor and this affects the angle of stability. In addition, not necessarily the loss of stability of the front body will cause the loss of the stability of the complete tractor. In the first step, there is only a reciprocal rotation between the two bodies which can

eventually cause the beginning of the tractor overturning. The effect of the velocity of the body due to the loss of stability could cause a different behavior with respect to the simulated one, because of the dynamic effect is not considered here. In Figure 5 it has to be underlined that as the roll angle increases, the stability angle decreases, and the tractor reaches earlier the condition of instability. Calculating the limit of the angle at the tractor design stage, engineers can manage the roll angle with respect to the needs of the end user.

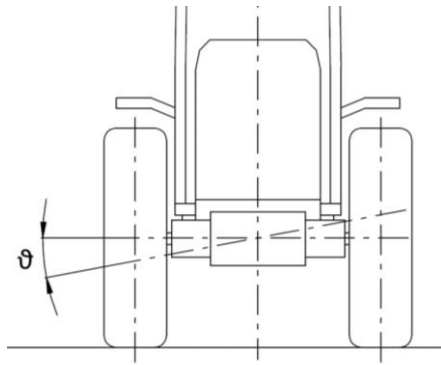


Figure 4. Roll angle graphical representation.

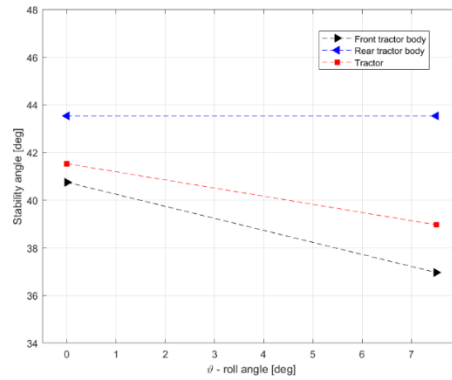


Figure 5. Stability angle vs. roll angle.

3.2. Articulated configuration (yaw angle)

If the tractor steers with the articulation joint the front and the rear tractor bodies, it is necessary to analyze the lateral stability depending on the degree of tractor articulation (Figure 6 - $\mu \neq 0^\circ$). The lateral stability of the tractor is assessed by tilting the tractor till to induce a tip over. The scenario will vary according to the configuration of the tractor, and it will depend on the rotation of the articulation between the front and the rear tractor body. Considering the lower value of yaw angle, equal to -35 degrees (Table 1), the tractor will be fully steered or articulated to the left (Figure 6-a), while for the yaw angle equal to +35 degrees the tractor will be fully articulated to the right (Figure 6-c). The roll angle ($\vartheta \neq 0^\circ$) acts through the rotation of one body on the other.

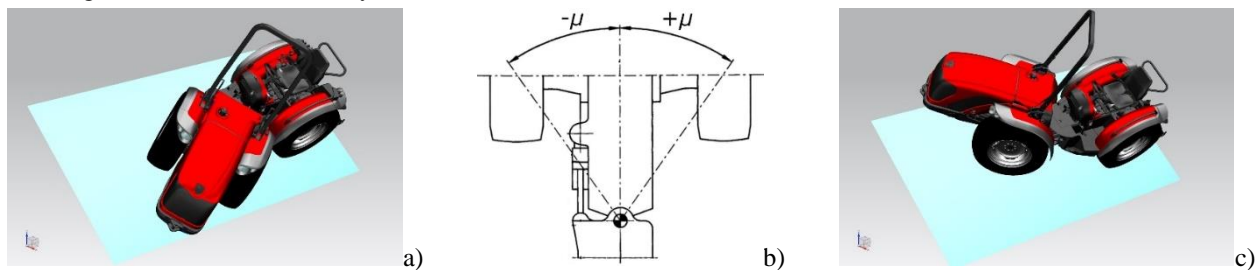


Figure 6. Articulated tractor and yaw angle graphical representations.

The stability angles of the separate bodies and that of the whole tractor are shown in Figure 7. The curves represent the trend of the stability angle as a function of the yaw angle μ and the roll angle ϑ .

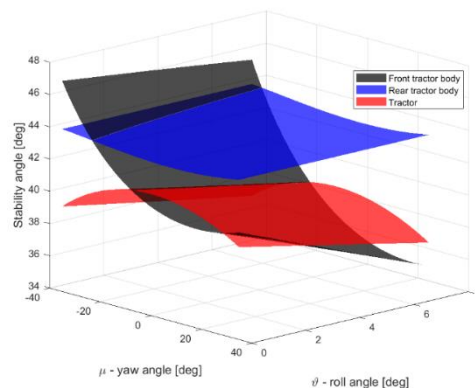


Figure 7. Stability angle vs. yaw and roll angles.

To better figure the part of the tractor losing stability first, the results have been simplified by defining the roll angle equal to zero (Figure 8). The rear tractor body (blue line) will never start the overturning, while the black line representing the front tractor body and the red line representing the whole tractor, are intersecting and this suggests a turnover between the trigger of the overturning cause. Depending on the tractor configuration there are situations where the whole tractor will lose stability first and other cases where the front body will firstly rollover.

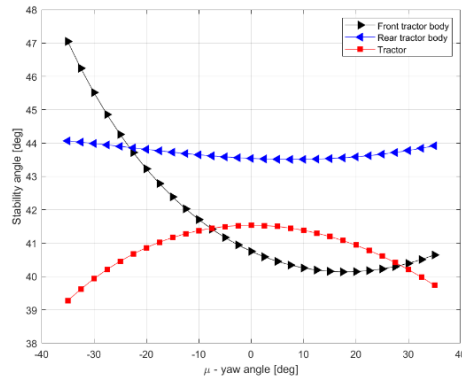


Figure 8. Stability angle vs. yaw angle

4. Discussion

The lateral stability angle of a compact narrow track tractor was calculated using a kinematic model. The results were split into two categories: steering wheel tractor and articulated tractor. The lateral stability angle for the tractor with steering wheel, in the straight configuration, was $\alpha = 41.5^\circ$, when the roll angle $\vartheta = 0^\circ$ (configuration equivalent to a fixed chassis tractor), and $\alpha = 39.0^\circ$ with $\vartheta = 7.5^\circ$. In the case of an articulated tractor, the angle of stability is not unique, and depends on the yaw angle. The lower value of the stability angle is $\alpha = 39.3^\circ$, measured with an angle $\mu = -35^\circ$. These values fulfill the required angle value of the tractors equipped with a front ROPS (the angle must be at least 38 degrees at the moment when the tractor is resting in a state of unstable equilibrium) according to the official OECD procedure (OECD Code 6, 2021). However, difficulties were related to the definition of the lateral stability limit angle of the articulated tractor due to the roll and yaw angle combined effects. The lateral stability angles are theoretically calculated considering the rotation of the tractor with respect to a line passing through the contact points of the tires on the ground. In detail the contact point was considered located in the mid of the tire width. Nevertheless, the tire deformation behavior during an actual rollover can significantly affect the contact points of the tire on the ground. The results presented do not consider all the phenomena of friction, air resistance, internal moving liquids and dynamic behavior that could occur during a real overturn. The dynamic effect of the central pivot point during the rotation of one body of the tractor with respect to the second one, if not properly damped by suitable viscoelastic components, might negatively affect the stability angle leading to an early rollover. Future step will be addressed to compare theoretical and experimental data.

5. Conclusions

This study combines known facts and engineering principles related to compact narrow-track tractor design to predict with a mathematical model the tractor behaviour on sloped ground. The model was set up for the steady-state behaviour, and it predicted the orientation as well as the stability of the vehicle on idealized slopes. Various parameter values were used in a computer analysis to study the effects of tractor geometry, including drive and steer design possibilities. The results highlight critical situations for improvements in design as well as horizons for future study.

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