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Development of a tractor dynamic stability index calculator utilizing some tractor specifications

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Abstract: To examine the effects of different geometries and mass specifications of a tractor operating across irregular sloping grounds on the lateral stability of this machine, a dynamic model was developed. In the proposed model, overturn and skid instabilities were studied and the tractor stability indexes were formulated (i.e. $TSI_{overturn}$ and TSI_{skid}). Using a modified Excel spreadsheet package employing the parameters of the model, the *TSI*s were then determined. Finally, the effects of variation in the parameters of the model on *TSI*s were evaluated. The results of the analyses indicate that changing the tractor mass moment of inertias about the x- and y-axes had no influence on TSI_{skid}, whereas increasing the tractor mass moment of inertias about the x-axis by 71% led to a 2.5% reduction of $TSI_{overturn}$ and increasing the tractor mass moment of inertias about the y-axis by 71% led to a 1.8% reduction of $TSI_{overturn}$. However, increasing the wheel–ground coefficient of friction from 0.34 to 0.84 improved TSI_{skid} by up to 27%. Moreover, the effect of tractor wheel track width and the height of its center of gravity on $TSI_{overturn}$ was greater than the effect of the tractor wheel base on this stability index. Therefore, the best strategy for stabilizing a tractor against overturn is to lower the tractor's center of gravity and increase the tractor's wheel track width simultaneously.

Keywords: Overturn, skid, tractor stability index

1. Introduction

Tractor rollover incidents continue to be a major source of fatal and serious farm work injuries (National Safety Council 2001). Globally, the death toll of tractor rollover accidents is more than 400, and approximately 16,000 people are injured each year (Abubakar et al. 2010). Therefore, tractor stability and the reduction of injuries related to tractor rollovers are areas addressed by many researchers (Purschwitz 1992; Goldenhar and Schulte 1996; Yoder and Murphy 2000). Kise and Zhang (2006) declared, "The use of 'sensor in-the-loop (SIL)' online tractor attitude and motion simulation provides rollover warnings based on estimated look-ahead tractor attitude and motion status. The validation test results indicated that the SIL vehicle attitude simulator could predict the attitude and motion status of the vehicle approximately 8 m ahead of its actual position with favorable and consistent accuracy at all test sites." Another effort to prevent tractor overturns is designing a chassis balancing system. In this regard, Mashadi and Nasrollahi (2009) designed an automatic control system (ACS) for a modified tractor to maintain its stability during work on steep side-slope lands. In this system, tractor stability was achieved by keeping the chassis at a horizontal level using hydraulic jacks, which received commands from ACS. In another study, Silleli et al. (2007) reported, "A chemically deploying anchor mechanism has been designed aimed to be used for narrow track orchard and vineyard tractors. The efficiency of the mechanism was tested with a rigid anchor attached to the tractor ROPS [rollover protection structure]. The test results showed that the anchor mechanism increases the clearance zone, reduces the amount of tractor surface area touching the ground and decreases the overturning time." Spencer (1978) developed a theoretical model for predicting the conditions of overturning and controlling the instability of 2-wheel drive tractors with towed implements. "The minimum safe operating slope of a loaded silage trailer is 27%, at a path angle of 15 degrees from the straight line up the sloping ground," Spencer stated. The mechanics and dynamical behavior of a tractor–trailer system moving up and down on sloping ground under different operating conditions were theoretically simulated by Abu-Hamdeh and Al-Jalil (2004). They developed a computer program for analyzing the system and predicting the effects of both the trailer loading weight and the slope angle on tractor stability, traction ability, and drawbar loading. The

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application of computer analysis in the study by Hamdeh and Al-Jalil (2004) significantly improved the process of predicting the effect of different parameters on stability and control of tractor–trailer combinations on sloping ground. Ahmadi (2011) announced, "Three possibilities exist about a tractor that works on sloping lands while being subjected to position disturbances: 1- Stability 2- Instability due to overturn 3- Instability due to skid." He developed a dynamic overturning model for tractors operating across irregular sloping grounds. In this paper, using the same methodology as that discussed by Ahmadi (2011), tractor instability models were proposed, and then a modified Excel spreadsheet package was developed to derive tractor stability indexes (*TSI*s), utilizing the parameters of the model. Finally, the effects of different variations of the parameters of the model on the *TSI*s were evaluated.

2. Materials and methods

2.1. Dynamics of the lateral overturn of tractor

If the left rear wheel of a tractor operating across a ground with a slope angle of θ, passes through an obstacle that can be described by the function $h=f(x)$ (Figures 1a and 1b), the rolling angular velocity (ω_r) and acceleration (α_r) of the tractor that operates with a constant speed of V_f on the surface with a soil–tire friction coefficient of μ can be obtained as shown in Eqs. (1) and (2). (Figure 1c).

(Note: In the following formulas, the symbol * was used for regular products and the symbol × was used for vector products.)

$$\left.\begin{array}{l} \left.\begin{array}{l} h = f(x) \Rightarrow dh = \dfrac{df(x)}{dx}dx \\ dx = V_f\,dt \end{array}\right\} \Rightarrow dh = \dfrac{df(x)}{dx} * V_f * dt \\ Wd\theta = dh * cos\theta \Rightarrow dh = \dfrac{d\theta * W}{cos\theta} \end{array}\right\} \Rightarrow$$

$$\omega_r = \frac{d\theta}{dt} = \frac{\dfrac{df(x)}{dx} * V_f * cos\theta}{W} \qquad (1)$$

$$\alpha_r = \frac{d}{dt}\left(\frac{d\theta}{dt}\right) = \frac{d}{dt}\left(\frac{\dfrac{df(x)}{dx} * V_f * cos\theta}{W}\right) \Rightarrow$$

$$\alpha_r = \frac{V_f}{W} * \left(\frac{d^2 f(x)}{dx^2} * V_f * cos\theta - \frac{df(x)}{dx} * \omega r * sin\theta\right) \qquad (2)$$

Moreover, displacement of one of the front tires relative to the other leads to the pitching instability of the tractor about the centerline of the rear wheels, because pivoted assembly is utilized to attach the center of the front axle to the tractor chassis. Therefore, if each of the tractor's front tires hits an obstacle, the tractor pitching angular velocity and acceleration (i.e. ω_p and α_p, respectively) can be formulated as shown in Egs. (3) and (4).

$$\omega_p = \frac{d\beta}{dt} = \frac{\dfrac{dg(x)}{dx} * V_f * cos\theta}{2 * WB} \qquad (3)$$

$$\alpha_p = \frac{V_f}{2 * WB} * \left(\frac{d^2 g(x)}{dx^2} * V_f * cos\theta - \frac{dg(x)}{dx} * \omega_r * sin\theta\right) \qquad (4)$$

Here, β is the tractor pitching angle, *WB* is the wheel base of the tractor, and the shape of front wheel obstacle is represented by the function $h = g(x)$. The probability of the tractor overturning still needs to be calculated. To address this, the conservation of energy law should be utilized, which is generally expressed as:

$$U = \Delta T + \Delta V_e + \Delta V_g \qquad (5)$$

where *U* is the work of tractor external forces, and ΔV_g, ΔT and ΔV_e are the variation of potential, kinetic, and elastic energies of the tractor, respectively. The only external force that affects work done by the external forces is the normal force applied to the tire that comes into contact with the obstacle, because this force is the only force that is displaced along its direction (Figure 1d). However, when the tire is separated from the ground because of the tractor rolling and pitching, this force and therefore the term *U* of Eq. (5) become zero. Furthermore, because the majority of tractors are machines without any conventional suspension system (located between the chassis and cab of the tractor), and it is acceptable to consider the tractor tires to act as rigid bodies (nonelastic bodies), ΔV_e can be omitted from Eq. (5). Therefore, Eq. (5) may be simplified to $\Delta T + \Delta V_g = 0$

Moreover, the general form of kinetic energy is shown in Eq. (6).

In Eq. (6), $\overline{V}$ is the absolute velocity of the center of gravity of the tractor, and $\overline{I}_{xx}$ and $\overline{I}_{yy}$ are the mass moment of inertias of the tractor about the roll axis (side overturn axis) and pitch axis (backward overturn axis), respectively. From the mechanical theorem of parallel axes, if the tractor mass (m_t), the tractor mass moment of inertia about the x- and y-axes that pass through the tractor's center of gravity (i.e. I_{xx} and I_{yy}), the distance between the center of gravity of the tractor and its rolling axis (d_r), and the distance between the center of gravity of the tractor and its pitching axis (d_p) are known, then $\overline{I}_{xx}$ and $\overline{I}_{yy}$ can be calculated from $I_{xx} + m_t d_r^2$ and $I_{yy} + m_t d_p^2$, respectively. In order to calculate ΔT, kinetic energy should be measured at 2 moments: the onset of tractor overturn and the time when the center of gravity of the tractor reaches its highest point. When the center of gravity of the tractor reaches

$$T = \frac{1}{2} m_t \overline{V}^2 + \frac{1}{2}\left[\overline{I}_{xx}\omega_x^2 + \overline{I}_{yy}\omega_y^2\right]_{\omega_y=\omega_p}^{\omega_x=\omega_r} \Rightarrow \mathrm{T} = \frac{1}{2}\mathrm{m}_t \overline{\mathrm{V}}^2 + \frac{1}{2}\left[\overline{\mathrm{I}}_{xx}\omega_r^2 + \overline{\mathrm{I}}_{yy}\omega_p^2\right] \quad (6)$$

its highest point, the velocity of the center of gravity of the tractor is equal to the tractor forward speed, i.e. V_f. Furthermore, if the distance between the center of gravity of the tractor and its rolling axis (d_r), and the distance between the center of gravity of the tractor and its pitching axis (d_p) are known, then the velocity of the center of gravity of the tractor at the onset of an overturn phenomenon (V_c) can be calculated. The formula of V_c as a function of d_r and d_p is expressed as shown in Eq. (7). (see Figures 2a and 2b for physical representation of parameters used in Eq. (7), and see Table 1 for parameter nomenclature).

In Eq. (7), γ is the initial angle of side overturn and λ is the initial angle of backward overturn. Knowing the parameters listed in Eq. (7), the final height of the tractor's CG, i.e. h_f, can be calculated as shown in Eq. (8).

Here, $\phi = \mathrm{arctg}\left(\frac{2H}{W}\right)$.If the obtained h_f is lower than, $h_{critical} = \sqrt{\frac{W^2}{4} + H^2}$, the tractor will be stable; otherwise, the tractor will overturn

2.2. Dynamics of the tractor skidding model

ω_r and ω_p cause centrifugal linear accelerations. Therefore, centrifugal linear accelerations caused by ω_r and ω_p, i.e. $\overrightarrow{a_{\omega r}}$ and $\overrightarrow{a_{\omega p}}$, must be added to the α_r and α_p-induced linear accelerations, i.e. $\overrightarrow{a_r}$ and $\overrightarrow{a_p}$. Hence, different terms of tractor acceleration can be calculated utilizing Eq. (9).

$$\begin{cases} \overrightarrow{a_{\omega r}} = d_r \times \omega_r^2(\cos\gamma\vec{k} + \sin\gamma\vec{j}), \overrightarrow{a_{\omega p}} = d_p \times \omega_p^2(\sin\lambda\vec{k} + \cos\lambda\vec{j}), \\ \overrightarrow{a_r} = d_r \times \alpha_r(\sin\gamma\vec{k} - \cos\gamma\vec{j}), \overrightarrow{a_p} = d_p \times \alpha_p(\cos\lambda\vec{k} - \sin\lambda\vec{j}), \\ \vec{g} = g(-\cos\theta\vec{k} - \sin\theta\vec{j}) \end{cases} \quad (9)$$

Thus, the overall acceleration of the center of gravity of the tractor can be obtained using Eq. (10).

$$\overrightarrow{a_{CG}} = \overrightarrow{a_{\omega r}} + \overrightarrow{a_{\omega p}} + \overrightarrow{a_r} + \overrightarrow{a_p} + \vec{g} \quad (10)$$

To decide between the skid and overturn of the tractor, the ratio of the linear acceleration of the center of gravity of the tractor in the Y direction to the Z direction should be compared with the soil–tire friction coefficient of μ.

$$\begin{cases} if \frac{\overrightarrow{a_{CG}}.\vec{j}}{\overrightarrow{a_{CG}}.\vec{k}} < \mu \Rightarrow tractor\ will\ face\ an\ overturn \\ if \frac{\overrightarrow{a_{CG}}.\vec{j}}{\overrightarrow{a_{CG}}.\vec{k}} > \mu \Rightarrow tractor\ will\ skid \end{cases} \quad (11)$$

2.3. TSI calculator

As discussed earlier, the instability of the tractor due to overturn should be examined from the difference between h_f and $h_{critical}$. Therefore, $TSI_{overturn}$ may be formulated as:

$$TSI_{overturn} = \frac{h_{critical} - h_f}{h_{critical} - H} \quad (12)$$

Moreover, the instability of the tractor due to skid should be examined from the difference between the ratio of the linear acceleration of the center of gravity of the tractor in the Y direction to the Z direction with μ. Thus, TSI_{skid} may be formulated as:

$$TSI_{skid} = \frac{\mu - \frac{a_y}{a_z}}{\mu} \quad (13)$$

In sum, the overall stability index of the tractor may be obtained as:

$$TSI_{overall} = TSI_{overturn} * TSI_{skid} \quad (14)$$

Considering this formula, $TSI_{overall}$ is an index that varies in [0, 1]. The tractor will be more stable if $TSI_{overall}$ is nearer to 1. The derived equations were entered into Excel spreadsheet software to simplify the calculations. Inputs to the spreadsheet are the tractor input parameters (tractor mass (m_t), tractor mass moment of inertia about the x-axis that passes through the tractor's center of gravity

$$\begin{aligned} &\overrightarrow{V}_c = \overrightarrow{V}_f + \vec{\omega} \times \vec{d}_r + \vec{\omega}_p \times \vec{d}_p, \overrightarrow{V}_f = V_f\,\vec{i}, \\ &\vec{\omega}_r \times \vec{d}_r = d_r \times \omega_r(\cos\gamma\vec{k} - \sin\gamma\vec{j}), \vec{\omega}_p \times \vec{d}_p = d_p \times \omega_p(\cos\lambda\vec{k} - \sin\lambda i \text{ where} \\ &d_r\sqrt{\frac{W^2}{4} + H^2}, \gamma = \arcsin\left(\frac{D}{W}\right) + \mathrm{arctg}\left(\frac{2H}{W}\right), d_p = cte \text{ and } \lambda = \arcsin\left(\frac{D}{2WB}\right) \end{aligned} \quad (7)$$

$$\begin{aligned} &\Delta T + \Delta V_g = 0 \Rightarrow \frac{1}{2}m_t(V_f^2 - V_c^2) - \frac{1}{2}\left[\overline{I}_{xx}\omega_r^2 + \overline{I}_{yy}\omega_p^2\right] + m_t g\left[h_f - \left(\sqrt{\frac{W^2}{4} + H^2}\sin(\theta + \phi)\right)\right] = 0 \\ &\Rightarrow h_f = \frac{\frac{1}{2}m_t(V_c^2 - V_f^2) + \frac{1}{2}\left[\overline{I}_{xx}\omega_r^2 + \overline{I}_{yy}\omega_p^2\right]}{m_t g} + \sqrt{\frac{W^2}{4} + H^2}\sin(\theta + \phi)) \end{aligned} \quad (8)$$

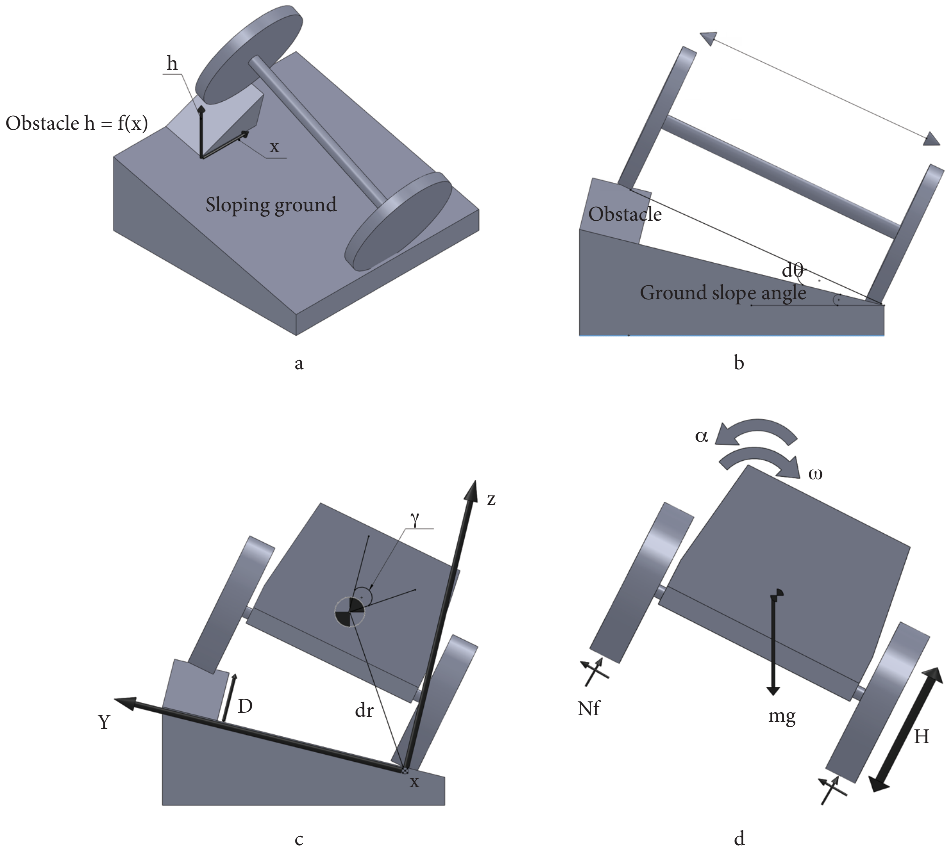

Figure 1. Geometry of the rear wheel axle and obstacle (a: 3D and b: 2D view) and tractor whose left rear wheel has hit an obstacle (c: geometric relations and d: free body diagram of tractor).

(I_{xx}), tractor mass moment of inertia about the y-axis that passes through the tractor's center of gravity (I_{yy}), wheel base of tractor (*WB*), tractor wheel track width (*W*), tractor forward velocity) and obstacle and ground input parameters (wheel–ground coefficient of friction (μ), height of obstacle (*D*), slope of obstacle (*k*), ground slope (θ)). Final outputs are the stability indexes of the tractor, i.e. $TSI_{overturn}$, TSI_{skid}, and $TSI_{overall}$. This spreadsheet may be used in 2 ways: first, for tractor stability index determination, using tractor, obstacle, and ground input parameters; and second, for specifying the effect of variation of input parameters on stability indexes. The latter case should be applied to redesign the parameters of the tractor in order to stabilize it.

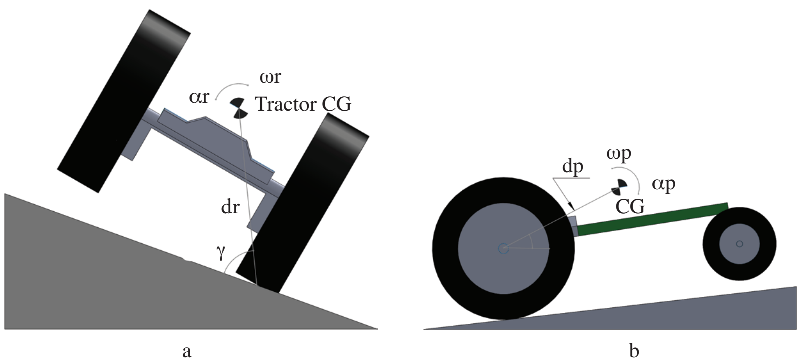

Figure 2. Physical representation of parameters utilized in Eq. (7) for tractor rolling (a) and pitching (b) situations.

Table 1. Tractor stability index calculator.

Tractor stability index calculator					
Tractor input parameters			Obstacle and ground input parameters		
Tractor mass (m)	1084	kg	Wheel–ground coefficient of friction (μ)	0.9	dimensionless
Mass moment of inertia about x-axis (I_{xx})	127.4	kgm^2	Height of the obstacle (D)	0.3	m
Mass moment of inertia about y-axis (I_{yy})	766.5	kgm^2	Slope of the obstacle (k)	0.5	dimensionless
Wheel base of tractor (WB)	1.58	m	Ground slope (θ)	10	degree
Tractor wheel track width (W)	1.14	m		0.174532925	radian
Height of tractor center of gravity (H)	0.6	m			
Radius of backward overturn from rear axle (d_p)	0.765	m			
Tractor forward velocity (v_f)	2.1	$m\ s^{-1}$			
Spreadsheet outputs					
Tractor angular velocity about x-axis (ω_x)	0.907059773	$radian\ s^{-1}$	Kinetic energy 2 (T_2)	2390.22	N.m
Tractor angular velocity about y-axis (ω_y)	0.327230424	$radian\ s^{-1}$	Kinetic energy 1 (T_1)	2744.761137	N.m
Tractor initial absolute speed (V_c)	2.2117237	$m\ s^{-1}$	Potential energy 2 (Vg_1)	7832.668123	N.m
Initial angle of backward overturn (λ)	0.095079901	radian	Potential energy 1 (Vg_2)	7478.126986	N.m
Radius of side overturn from axis of rotation (d_r)	0.827586853	m	Tractor final height (h_f)	0.72257086	m
Initial angle of side overturn (γ)	1.077327589	radian	Tractor overturn critical height	0.827586853	m
Tractor angular acceleration about x-axis (α_x)	-0.145074334	$radian\ s^{-2}$	Linear acceleration in z direction (a_z)	-9.393234538	$m\ s^{-2}$
Tractor angular acceleration about y-axis (α_y)	-0.018881049	$radian\ s^{-2}$	Linear acceleration in y direction (a_y)	-1.193684872	$m\ s^{-2}$
TSI (overturn)	0.461432599	dimensionless			
TSI (skid)	0.858800872	dimensionless			
TSI (overall)	0.396278719	dimensionless			

3. Results

Some of the specifications of the examined tractor (model of tractor: Mitsubishi MT-2501D, which is an 18-kW, 4-wheel-drive tractor) are presented in Table 2 (Vitas et al. 1988).

In order to obtain the static instability angle of the examined tractor, the effects of gradually increased slope angle on the *TSI*s were considered to see which angle causes each *TSI* to become zero. However, in this part of process, V_f is set to zero, the ground is thought to be without any obstacle, and the wheel–ground friction coefficient is set to its maximum value, i.e. 1. The results are summarized in Table 3. As can be seen, the static instability angle of the examined tractor is 45°.

In order to determine the effects of variations in tractor specifications on stability indexes, suppose that this tractor, with a wheel–ground friction coefficient of 0.9, moves perpendicularly to a ground slope of 10° with a speed of 2.1 $m\ s^{-1}$. In these conditions, if the upper wheels of the tractor hit obstacles with a slope angle of $\theta = arctan\ 0.5$ and a height of 0.3 m, then the overturn, skid, and overall tractor

Table 2. Some of the specifications of the examined tractor.

Tractor specification	Quantity	Measurement unit
I_{xx}	127.4	kgm^2
I_{yy}	766.5	kgm^2
d_r	0.765	m
d_p	0.827	m
m_t	1084	kg
WB	1.58	m
W	1.14	m

Table 3. Effect of slope angle variations in static mode on *TSI*s.

	Slope angle of the ground (°)										
	0	5	10	15	20	25	30	35	40	45	50
$TSI_{overturn}$	1	0.79	0.6	0.44	0.3	0.18	0.1	0.04	0.006	0.001	0
TSI_{skid}	1	0.91	0.82	0.73	0.63	0.53	0.42	0.29	0.16	0.01	0

stability indexes will be 0.46, 0.85, and 0.39, respectively. Thus, the stability of this tractor under these conditions is less against overturn than skid. If these data are considered as the calculation base point, the effect of variation in the tractor geometrical and mass specifications on the tractor stability indexes can be quantified. To do this, each of the tractor geometrical and mass parameters were altered in the range of [0.75 X_i , 1.25 X_i] with the step of 0.05 X_i (where X_i is the value of each parameter base point), and the corresponding stability indexes were calculated. To compute each set of stability indexes, only one parameter was changed, and fixed values were considered for the other parameters. With the purpose of comparing the effect of change in different tractor specifications on tractor stability indexes, the variation percentage of each *TSI* relative to the base point stability index was calculated. This process was performed using Eq. (15).

$$\frac{TSI - TSI_{base\ point}}{TSI_{base\ point}} \times 100 \qquad (15)$$

The derived results from the analysis of the effects of change in m_t, I_{xx}, and I_{yy} on the *TSI*s are demonstrated in Figures 3a, 3b, and 3c, respectively.

As can be seen, I_{xx} and I_{yy} did not affect the TSI_{skid}. Because $TSI_{skid} = \frac{\frac{\mu - a_y}{a_z}}{\mu}$ and according to the developed formulas, tractor mass does not affect the acceleration of the center of gravity of the tractor and thus TSI_{skid}. On the other hand, by increasing the tractor mass from 830 to 1430 kg, an improvement of 4.5% was achieved for $TSI_{overturn}$, whereas increasing the tractor mass moment of inertias about the x-axis by 71% led to a 2.5% reduction of $TSI_{overturn}$ and increasing the tractor mass moment of

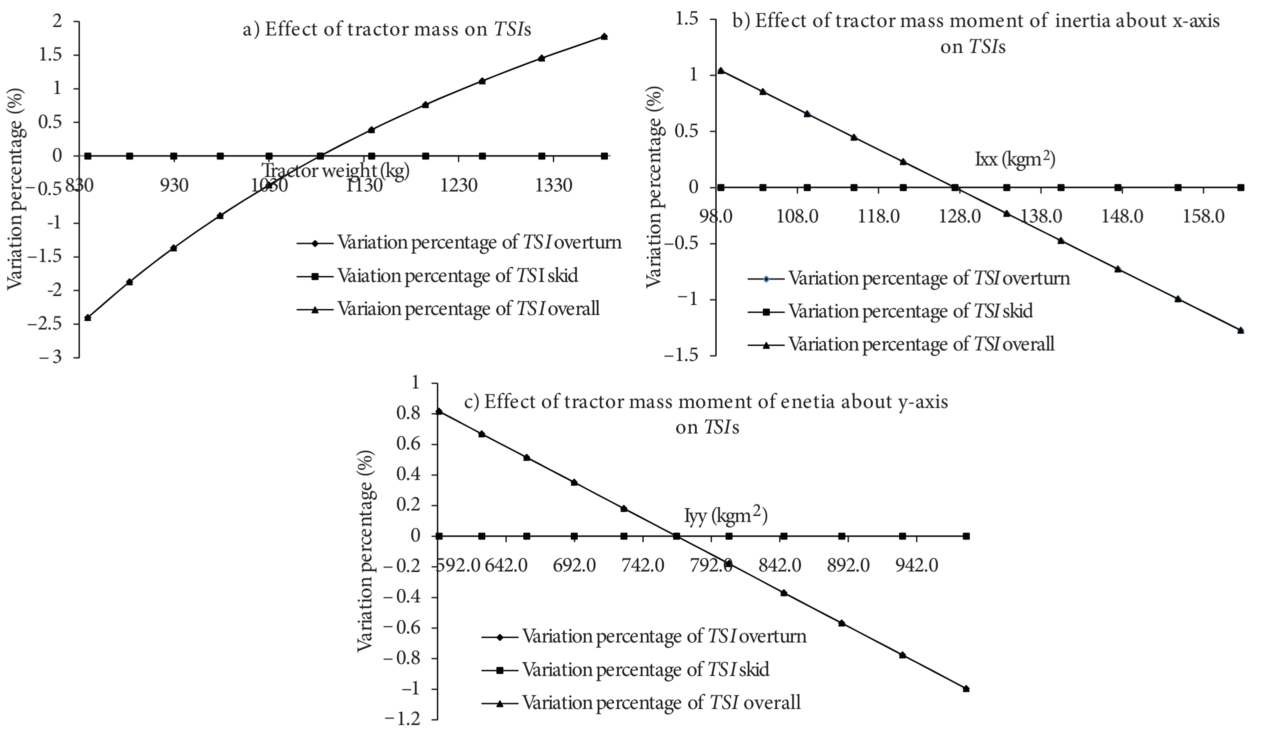

Figure 3. Effect of variations in tractor mass specifications (a: m_t, b: I_{xx}, and c: I_{yy}) on *TSI*s.

inertias about the y-axis by 71% led to a 1.8% reduction of $TSI_{overturn}$. Thus, in tractor designation, to increase the stability of a tractor against overturn, tractor mass should be increased and at the same time tractor mass dispersion should be decreased, because mass moment of inertia is calculated from $\int r^2\, dm$, where *r* is the distance between *dm* (which is a tiny mass element of the tractor body) and the axis about which moment of inertia is calculated, and mass dispersion leads to increasing *r* and therefore increasing mass moment of inertia, which adversely affects $TSI_{overturn}$. However, as shown in Figure 4a, the effect derived by the tractor wheel base on $TSI_{overturn}$ is less than the effects of the tractor wheel track width and the height of the center of gravity of the tractor on this stability index (see Figures 4b and 4c). (Increasing the tractor wheel track width from 0.88 to 1.48 m increased $TSI_{overturn}$ by almost 80%, and decreasing the height of the tractor's center of gravity from 0.76 to 0.48 m improved this index by 50%.) Furthermore, tractor geometrical specifications affect both $TSI_{overturn}$ and TSI_{skid} and thus $TSI_{overall}$. However, the effects of these parameters on TSI_{skid} are minor.

Furthermore, as shown in Figure 5a, increasing the wheel–ground coefficient of friction from 0.34 to 0.84 improves the TSI_{skid} by 27%. Therefore, the effect of the wheel–ground friction coefficient on TSI_{skid} has more weight than the effects of the tractor geometrical specifications on this stability index. On the other hand, when the ground slope is increased from 7.5° to 12.5°,the *TSI*s of overturn, skid, and overall are decreased by approximately 37%, 13%, and 50%, respectively (see Figure 5b).

A similar trend was observed concerning the effect of variation of ground slope (examined range of 7.5° to 42.5°) on *TSI*s, as shown in Figure 6.

Therefore, to stabilize the tractor against overturn, the best strategy is to decrease the height of the center of gravity of the tractor and increase the tractor wheel track width simultaneously.

4. Discussion

In this study, a static instability angle of 45° was obtained for the examined tractor. This result is comparable to a preliminary test conducted according to OECD Code 6 on the examined tractor used by Silleli et al. (2007). However, Abubakar et al. (2010) reported, "When tractor stability is the main concern, then a slope of 15° must be classified as steep and a slope of 30° is extremely steep." In this regard, a radical idea was proposed by Myers et al. (2006). They announced, "Rollovers are more frequently reported to have occurred on sloping terrains, often during a sharp turn at high speed, although data show that rollovers do occur on flat land after hitting obstacles or through inappropriate use and hitching of implements." In addition, Myers (2008) stated, "The general ground slope may be small but its roughness can cause local slopes to become steep, and these local slopes may cause tractor overturn." Therefore, the determination of a dynamic instability angle for a

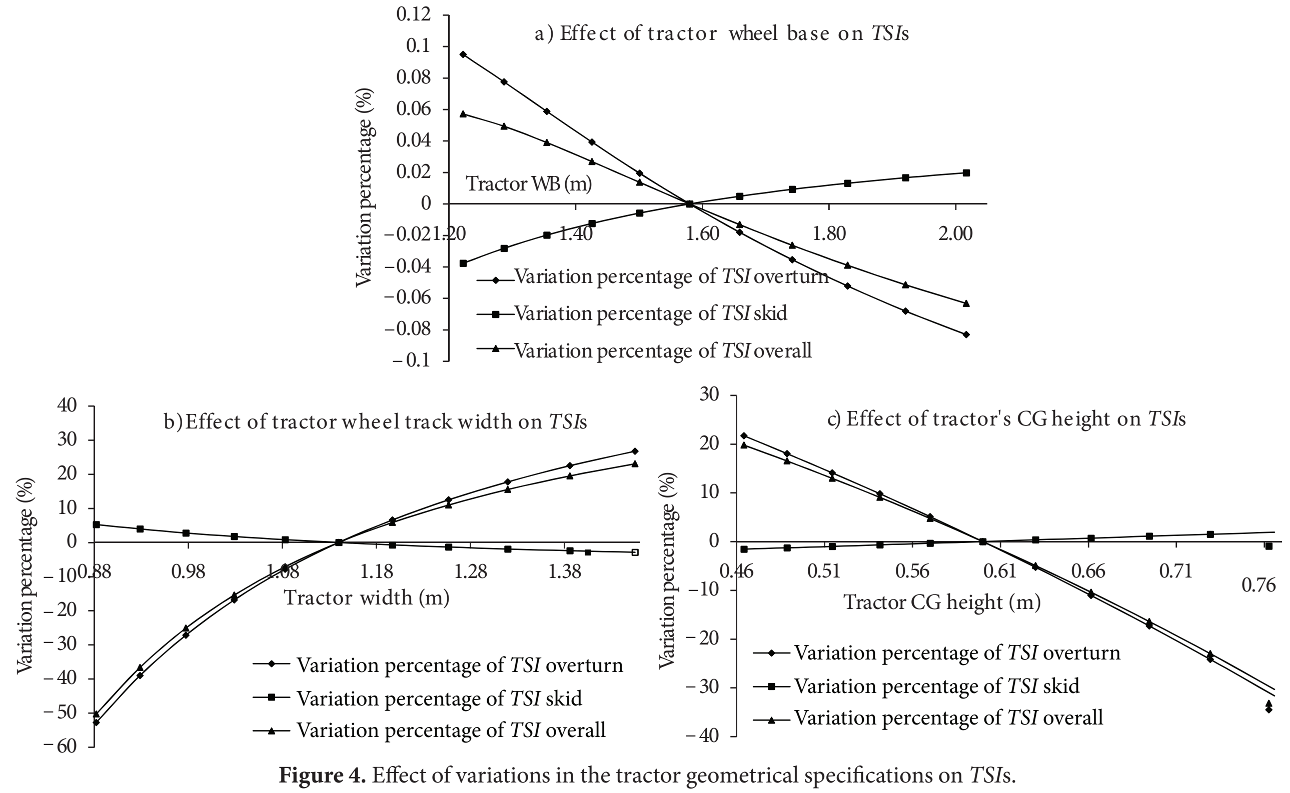

Figure 4. Effect of variations in the tractor geometrical specifications on *TSI*s.

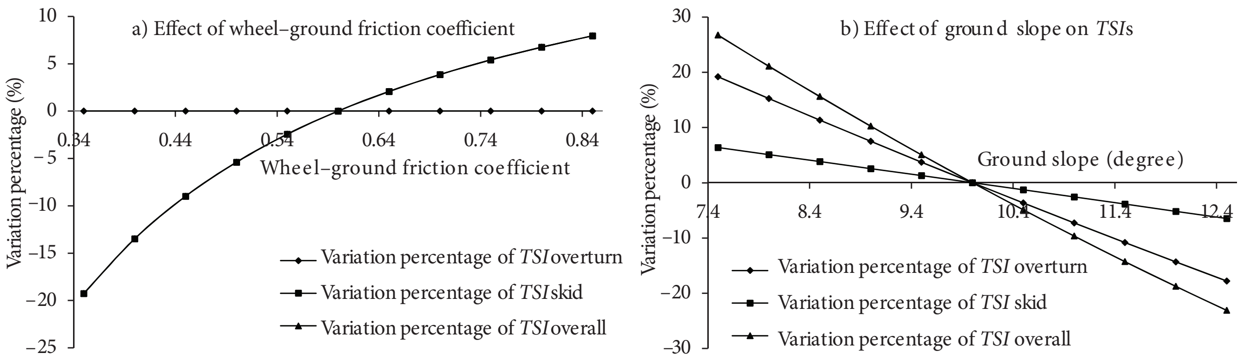

Figure 5. Effect of variations in the wheel–ground friction coefficient and ground slope (examined range of 7.5° to 12.5°) on *TSI*s.

tractor is a multifaceted problem and cannot be achieved only by its static instability angle. Furthermore, according to the obtained results, tractor geometrical specifications had more effect on tractor stability against overturning than did tractor mass specifications, and tractor stability against skidding was severely influenced by the wheel–ground coefficient of friction. In this regard, Mashadi and Nasrollahi (2009) declared, "Skidding downhill occurs if the ground is too slippery for the tractor to remain under control, and this is also common on grass fields as well as loose surfaces. Skidding or overturning usually occurs at a high speed. Sideways overturning often occurs on steep slopes and on rough ground." These findings are in agreement with the results obtained in this study.

The stability model developed in this study receives the parameters of tractor (tractor geometrical and mass specifications) and obstacle and ground (wheel–ground friction coefficient and ground slope) as inputs and numerically calculates indexes with regard to the stability of the tractor. Thus, this model can be used for investigating the different effects of the model parameters on tractor stability. Moreover, according to the results of

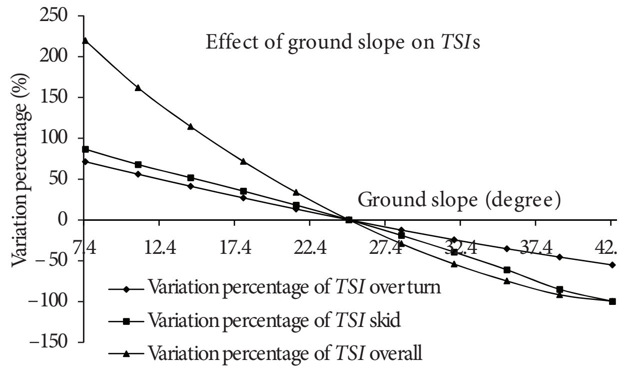

Figure 6. Effect of variation of ground slope (examined range of 7.5° to 42.5°) on *TSI*s.

this study, there are some practical precautions that can be taken in order to reduce the probability of overturning a tractor that moves perpendicularly to the ground slope, as follows:

1) Increase the distance between the right and left wheels of the tractor as much as possible.

2) Try to lower the height of the tractor's center of gravity by adding ballast to the lowermost parts of the tractor or by filling 75% of the tractor wheels' space by water.

3) Inspect the tractor driving wheels for the presence of V-shape lugs.

4) Design an alarm system in order to warn the tractor operator of possible overturning or skidding at times of working on steep side slopes.

5) The breaks of right and left rear wheels of the tractor may be operated independently in order to reduce the tractor radius of turning. This situation lowers the stability of the tractor at the instant of breaking in straight paths. Therefore, make sure that the rear wheel brakes are locked together when the tractor moves straight ahead.

6) Make sure that a ROPS and seat belts are available on the tractor, because they are highly effective with regard to the reduction of casualties in tractor overturning accidents.

7) Reduce the tractor velocity during tractor turning, because turning at high speed is one of the main factors that increase the probability of tractor overturning.

8) Avoid operating the tractor across steep slopes, especially when the ground is slippery.

9) When a tractor operates across moderate slopes, the tractor velocity must be as low as possible. Moreover, notice the ground obstacles that the wheels may hit.

10) Because the 4-wheel-drive tractor has better front-wheel grip, this type of tractor is safer on slopes than the 2-wheel-drive tractor.

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