Research on Applying an Anchor Mechanism to Orchard and Vineyard Tractors Produced in Turkey

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Abstract: In recent years, orchard and vineyard tractors have become widespread in Turkey. Owing to their narrow-track width and work environment, these tractors overturn easily. Therefore, tractor manufacturers have to fabricate roll-over protective structures (ROPS) that are high enough to prevent continuous rolling. In this study, an innovative system that increases the safety of the driver and decreases the ROPS height was tested on 20 tractors that are currently available for retail sale in Turkey. In order to determine the effect of an anchor mechanism on the height of the ROPS, the following parameters were investigated: tractor mass, the type of drive capability, the height of the center of gravity, and the moment of inertia. It was observed that an anchor mechanism could decrease the height of the ROPS by between 183 and 455 mm. The use of an anchor mechanism provides the manufacturers with an option that will allow them to produce more effective tractors with lower ROPS heights.

Key Words: Roll-Over Protective Structures, ROPS, orchard and vineyard tractors, narrow-track tractor, safety

Abbreviations: Directorate of Agricultural Equipment and Machinery Test Center (TAMTEST), center of gravity (CG), Roll-Over Protective Structures (ROPS)

Türkiye'de Üretilen Bağ ve Bahçe Traktörlerine Çapa Mekanizmalı Koruyucu Yapı Uygulaması Üzerine Bir Araştırma

Özet: Bağ ve bahçe traktörlerinin son yıllardaki kullanımı Türkiye'de yaygınlaşmaktadır. Bu tür traktörler, çalışma ortamları ve tekerlek iz genişliğinin dar olması nedeniyle kolay devrilirler. Bu etki nedeniyle traktör üreticileri Yuvarlanmaya Karşı Koruyucu Yapıları (YKKY) sürekli yuvarlanmayı engelleyecek şekilde yüksek üretmek durumundadır. Bu çalışmada sürücünün emniyetini artıran ve aynı zamanda YKKY'nın boyunun kısaltılmasına olanak sağlayan yeni bir buluş piyasada bulunan 20 traktör üzerine uygulandı. Çapa mekanizmasının YKKY üzerine olan etkilerini belirlemek amacıyla; traktör kütlesi, muharrik tekerlek sayısı, ağırlık merkezinin yerden yüksekliği ve atalet momenti araştırıldı. Çapa mekanizmalı traktörlerde koruyucu yapı yüksekliğinin 183 ile 455 mm arasında azaltabileceği görüldü. Çapa mekanizmasının kullanımı traktör üreticilerine alçak YKKY yüksekliğine sahip daha etkili traktörler imal etmeleri için bir opsiyon sağlayacaktır.

Anahtar Sözcükler: Yuvarlanmaya Karşı Koruyucu Yapılar, YKKY, bağ-bahçe traktörleri, dar izli traktörler, emniyet

Introduction

In agricultural operations, tractor overturns are the single largest cause of injuries and fatalities (Nichol et al., 2004). Overturn accidents occur so rapidly that the operators may not be able to dismount their tractors and get trapped under the machines (Springfeldt, 1996). The best-known method used to prevent fatalities and injuries in these instances is the installation of Roll-Over Protective Structures (ROPS) (Powers et al., 2000). In addition to protecting the driver, ROPS can help prevent the continuous rolling narrow-track tractors that are most commonly used in orchard and vineyard operations. Tractor manufacturers have to fabricate ROPS that are high enough to prevent continuous rolling but farmers often need to either fold or completely disassemble the ROPS on their tractors because of the difficulties encountered when entering rural buildings or the problems associated with low overhanging tree branches

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or other obstacles. Often farmers either forget or neglect to reposition the structure after the adjustments of the ROPS thereby endangering themselves if a tractor rollover occurs (OECD, 2003).

In recent years, tractor models have increased in Turkey (Sabancı et al., 2003). As a consequence of this increase, orchard and vineyard tractors have become widely available in the market. The narrow-track agricultural tractor has been defined in the standards and codes of multinational organizations such as the International Organisation for Standardisation (ISO), the European Community (EC) and the Organisation for Economic Co-operation and Development (OECD). Several countries apply these standards not only to narrow-track tractors but also to standard tractors used in orchards and vineyards equipped with front ROPS. These standards and codes are not completely applicable to standard tractors. In Turkey, a National Standards Bulletin SGM 2002/7 was issued for standard tractors fitted with front ROPS and having a track width larger than 1150 mm.

According to the standards mentioned above, narrow-track agricultural tractors have to pass a lateral stability and a non-continuous rolling test. Non-continuous rolling tests can be conducted experimentally with a real tractor or by following a theoretical calculation procedure based on a dynamic simulation outlined in OECD Code-6. When investigating the simulation procedure, the height and the width of the ROPS are 2 of the most influential design parameters that can be easily altered so that the continuous rolling of narrow-track tractors can be prevented. The relationship between the height and the width of the ROPS was defined by Schwanghart (1982) and is illustrated in Figure 1. There are limits to the range of height and width adjustment that can be made to the ROPS. The width of the ROPS cannot be too large (Silleli et al., 2007), because it may cause similar problems with functionality as previously mentioned. Thus, an innovative device called an anchor mechanism may be a solution to this problem.

The anchor mechanism has 2 limbs (anchors) designed to deploy and be locked with pins upon reaching the widest position. These anchors are also sized to be able to support the weight of the tractor in the event of a turnover. Widened ROPS prevent the bonnet from touching the ground, thereby protecting the driver from the possibility of injury. The grade sensor attached to the
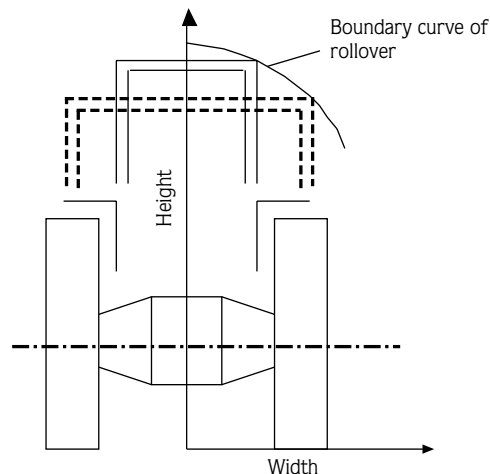

Figure 1. Relationship between ROPS height and width (Schwangart, 1982).

tractor detects an instability event. Once instability has been detected, pyrotechnic and chemical reactions cause the deployment of the anchors. Figure 2 illustrates the components of the system and shows the anchors in the deployed position. The anchors are set out towards each side of the ROPS in the event of an overturn (OECD 2005b, Silleli et al., 2007).

The major objective of this system is to increase the protection efficiency of the ROPS for the tractor operators and at the same time reduce the overhead clearance needed by these machines in order to improve their usage potential in orchard and vineyard conditions. Specific features of the anchor mechanism are as follows: 1) prevent continuous rolling of narrow-track tractors during overturn; 2) increase the clearance zone between the ground and the operator; 3) increase the space between the side of the tractor and the ground in order to minimize the mechanical damage to the tractor bonnet and the engine; 4) reduce the ground impact energy by decreasing the roll angle; 5) provide better tractor driving performance in orchard and vineyard field conditions and; 6) enable tractor ROPS to be manufactured with lower heights (Silleli, 2006; Silleli et al., 2007).

This investigation tests and compares the performance of an anchor mechanism on 20 narrow-track and standard tractors that were manufactured for the purpose of orchard and vineyard operations. The scope of this research is to determine the minimal allowable height for the ROPS required to prevent continuous rollover of these tractors when the anchor
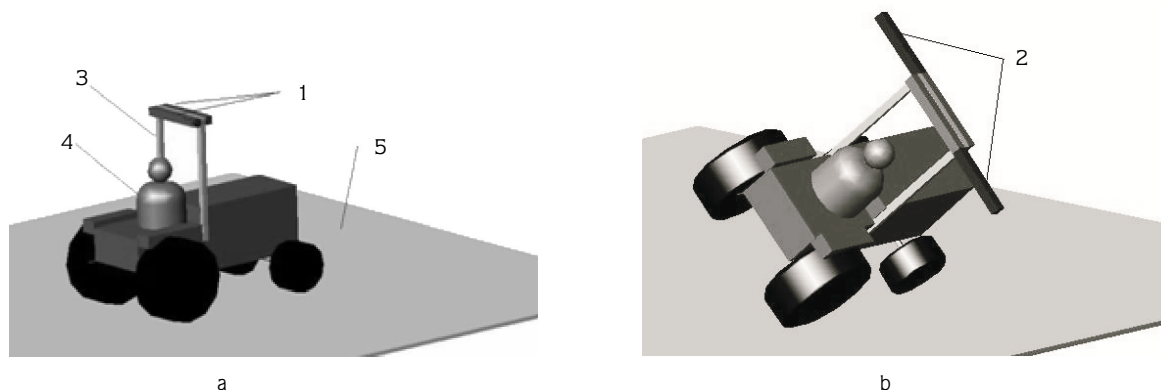
Figure 2. Anchor mechanism mounted on the Roll-Over Protective Structure: Illustration (a) demonstrates the passive position of the anchor system while Illustration (b) depicts the deployed position of the anchor system during a rollover event. Features of the design are as follows: 1) housing of the anchor mechanism; 2) anchors; 3) roll-over protective structure; 4) driver; 5) ground (Silleli, 2006; Silleli et al., 2007).

mechanism is in place. In order to determine the height of the ROPS, a noncontinuous rolling test simulation was applied to each of the tractors tested.

Materials and Methods

Preliminary Tests

Twenty orchard and vineyard tractors, both 2- and 4-wheel drive models, which are commercially available in the retail market in Turkey, were selected for testing. The initial preliminary tests were conducted in the Turkish Ministry of Agriculture's Directorate of Agricultural Equipment and Machinery Test Center (TAMTEST) laboratories according to Code 6 of the OECD specifications. According to EC Directive 87/402 and Code 6 of the OECD specifications, narrow-track agricultural tractors have to pass a lateral stability and a noncontinuous rolling test. For lateral stability, the angle of inclination of the tractor must be at least 38° at the moment when it is resting in a state of stable equilibrium with its 2 wheels touching the ground (Figure 3). The test was performed once with the steering wheel turned to full right lock and once with it turned to full left lock for the right and left wheels, respectively. The noncontinuous rolling test was completed using a computer simulation program called Vuelco.xls. The Agrarian Mechanization Group at Navarra State University developed this program. It is presented in the form of calculation software and complies with the OECD standard code for the official testing of front mounted ROPS on narrow-track wheeled agricultural and forestry


Figure 3. Determining the lateral stability of a tractor on the reclining platform.

tractors (OECD, 2004a). The simulation utilizes the parameters given in Table 1 including the height of the center of gravity (CG) and the moment of inertia at the longitudinal axis through the CG and dimensional parameters. Moment of inertia and the height of the CG can be determined by means of an oscillating platform and are based on the techniques developed by Casini-Ropa (1976; see Figure 4).

Dynamic simulation procedure

The calculation used in the dynamic simulation, as shown in Figure 5, is explained as follows. When the tractor, with a front swing axle positioned on a platform with a gradient of 1:1.5, loses its stable equilibrium and begins to tilt the CG will immediately becomes a point vertically above the axis of rotation (Figure 5a). The axis

Table 1. The characteristic tractor data for verifying non-continuous rolling behavior using the Vuelco.xls simulation (OECD,2005a).
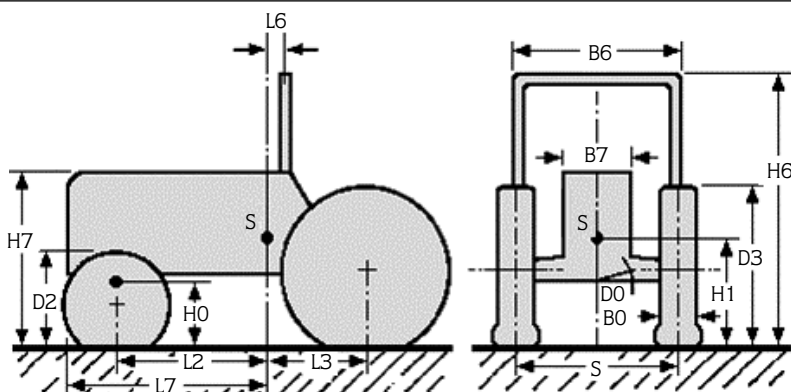
B_0	m	Rear tire width
B_6	m	Width of protective structure between the right and left points of impact
B_7	m	Width of engine bonnet
D_0	rad	Front-axle swing angle from zero position to end of travel
D_2	m	Height of front tires under full axle load
D_3	m	Height of rear tires under full axle load
H_0	m	Height of the front-axle pivot point
H_1	m	Height of CG (s: the location of the center of gravity)
H_6	m	Height of protective structure at the point of impact
H_7	m	Height of engine bonnet
L_2	m	Horizontal distance between the CG and front axle
L_3	m	Horizontal distance between the CG and rear axle
L_6	m	Horizontal distance between the CG and the leading point of intersection of the protective structure
L_7	m	Horizontal distance between the CG and the front corner of the engine bonnet
M_c	kg	Tractor mass used for calculation
Q	kg.m^2	Moment of inertia about the longitudinal axis through the center of gravity
S	m	Rear track width

Figure 4. Determining the center of gravity and moment of inertia using the oscillation platform.

of rotation (Axis 1) is parallel to the longitudinal axis of the tractor and passes through the contact surface of the downhill rear and front wheels. Since the tractor tires deform in this position, the axis of rotation is displaced towards the center of the tires (Figure 5b). When this happens, the tractor overturns and, in a short time, the speed of rotation increases from zero to the value O0 (ω_{A1}) just before the tractor falls on its side on the test platform (Figure 5c).

When the upper edges of the front and rear wheels hit the ground, it is assumed that the front axle is in an intermediate position once more, parallel with the rear axle. The outer edges of both tires are subjected to a semielastic shock (1 shock per tire) in the direction of the hill and perpendicular to the surface of the slope. These 2 shocks are combined in the calculation as a single shock registered in the plane of the CG.

After the shock at the upper edges of the tires, the tractor continues to turn at the speed of rotation O1 (ω_{B0}). It is assumed that the tractor continues to turn and will do so about a new axis (Axis 2) through the upper edges of the rear and front wheel, and the speed of
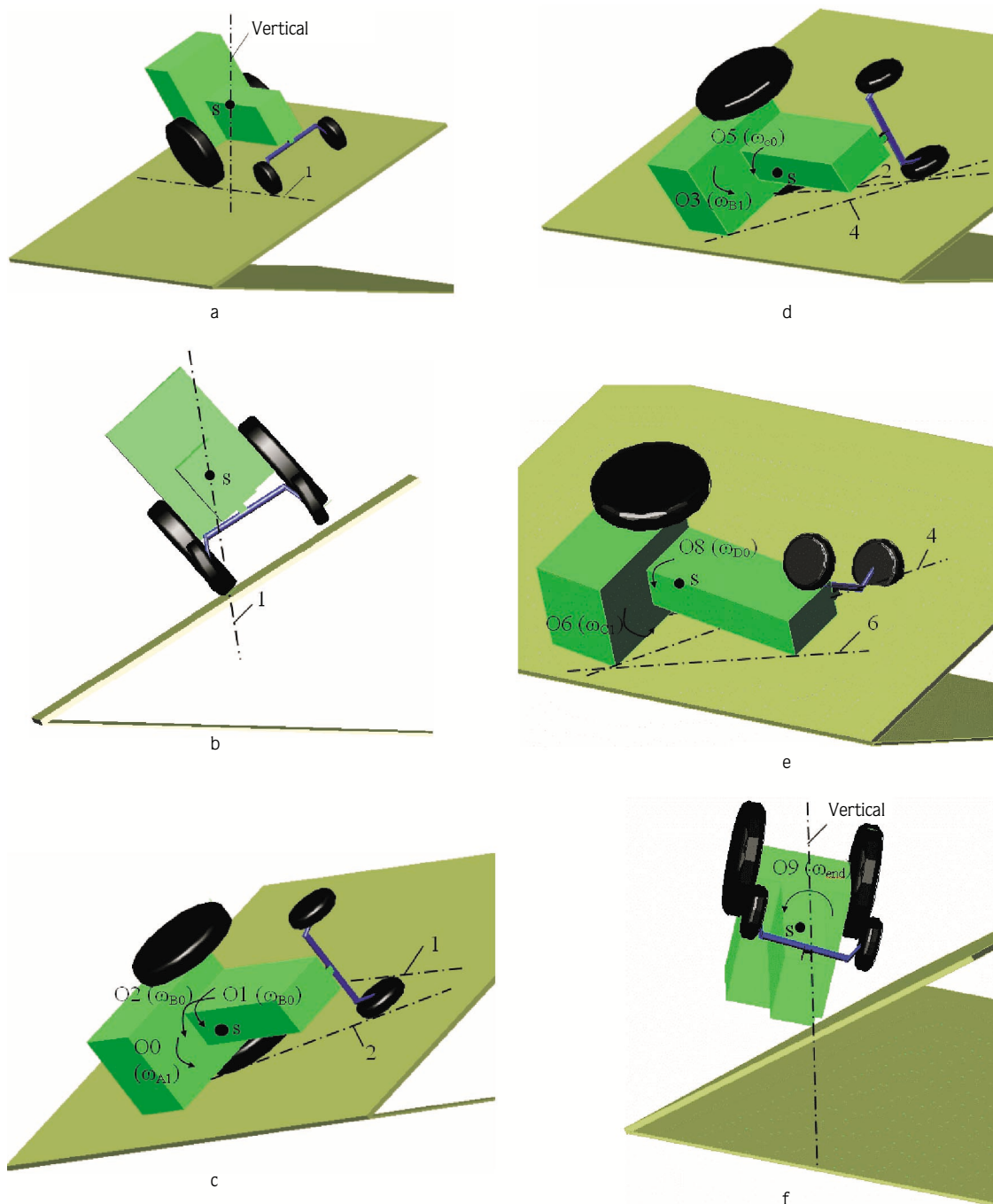
Figure 5. The stages of overturn used to conduct a non-continuous rolling simulation procedure; axes of rotation and speeds of rotation of a tractor that is rolling over on 3 separate axes (Schwanghart, 1982; EC, 1985).

rotation O1 must be converted to speed O2 (ω_{B0}) perpendicular to this new axis of rotation (Axis 2). The gradient angle is slightly transformed by the direction of this new axis of rotation. Similarly, the moment of inertia Q is converted in respect to Axis 2.

The tractor continues to turn about Axis 2 until the corner of the bar hits and penetrates the ground (Figure 5d). The speed of rotation prior to impact on the bar and front wheel is designated as O3 (ω_{B1}). After the impact,

the speed of continuous rotation is designated as O4 (ω_{CO}). Since the tractor would rebound after the impact on the protection structure, Axis 2 is parallel to Axis 3, and the tractor will continue to turn at the speed of rotation O5 (ω_{CO}) about a new axis (Axis 4) through the upper edge of the front wheel and a point on the surface of the slope above the impacted bar. When the engine bonnet touches the ground (Axis 5 is parallel to Axis 4), the speed of rotation will be O6 (ω_{C1}) (Figure 5e). After the impact of the bar and bonnet (Figure 5f), the tractor will have a speed of rotation designated as O7 (ω_{DO}) or O8 (ω_{DO}), which will be perpendicular to the new axis of rotation (Axis 6). If the tractor still has a great enough speed of rotation, designated as O9 (ω_{end}), at this moment of unstable equilibrium, it will continue to roll. If the energy of rotation was previously so slight that unstable equilibrium is not attained, and the tractor will come to rest on the slope (Schwanghart, 1982; EC, 1985).

Statistical analysis

MINITAB 15 was used to perform the paired t-tests and to calculate the correlation coefficients between the 2 variables.

Results and Discussion

Table 2 shows the geometric dimensions, masses (M), the height of center of gravities (H1), and moments of inertia (Q) that affect the continuous rolling behavior of 20 tractors manufactured in Turkey, which were tested in TAMTEST with respect to the OECD Code 6 procedure. In this table, 16 of the machines tested are standard tractors that are equipped with front ROPS so that they can be used in vineyards and orchards. The remaining 4 are narrow-track tractors (T1, T12, T16, T20) with a track width less than 1150 mm. Among these 20 tractors, 13 are 2-wheel drive (2WD) (T1, T2, T3, T5, T9, T10, T12, T13, T14, T16, T17, T18, and T20) and the remaining are 4-wheel drive (4WD) models. The dimensions and other properties of the tractors, such as the effect of the anchor mechanism on the ROPS height, can be seen in column H6a. Column H6 shows the current height of the ROPS of these tractors. CG height of the tractors (H1) and moments of inertia about the longitudinal axis (Q) were determined on the oscillation platform.

After determining the input variables in Table 2, 2 preliminary tests, 1 for lateral stability and 1 for non-continuous behavior, were performed for all tractors.

Table 2. The dimensions and some properties of tested orchard and vineyard tractors.

	H1	L3	L2	D3	D2	H6	H6a	L6	B6	H7	B7	L7	H0	S	B0	D0	M	Q
T1	0.666	0.772	1.178	1.172	0.670	2.355	1.900	-0.298	1.500	1.190	0.604	1.503	0.486	1.088	0.358	0.209	2,060	327.04
T2	0.666	0.772	1.178	1.172	0.670	2.355	2.020	-0.298	1.500	1.190	0.604	1.503	0.486	1.321	0.358	0.209	2,140	339.74
T3	0.523	0.668	1.282	1.172	0.670	2.37	1.920	-0.402	1.500	1.213	0.608	1.607	0.486	1.332	0.358	0.209	2,160	342.92
T4	0.743	0.868	1.082	1.145	0.815	2.371	2.000	-0.202	1.500	1.213	0.608	1.407	0.494	1.332	0.360	0.409	2,360	419.18
T5	0.570	0.745	1.355	1.172	0.670	2.371	2.020	-0.475	1.500	1.213	0.608	1.680	0.486	1.332	0.358	0.209	2,200	349.27
T6	0.647	0.861	1.239	1.145	0.815	2.371	2.060	-0.325	1.500	1.213	0.608	1.549	0.494	1.332	0.360	0.409	2,390	424.51
T7	0.655	0.847	1.239	1.143	0.857	2.346	2.100	-0.349	1.700	1.236	0.536	1.502	0.425	1.352	0.388	0.127	2,590	635.75
T8	0.698	0.846	1.235	1.252	0.933	2.385	2.180	-0.352	1.700	1.278	0.555	1.494	0.485	1.408	0.389	0.196	2,604	599.98
T9	0.631	0.728	1.169	1.238	0.705	2.173	1.990	-0.294	1.600	1.140	0.556	1.463	0.400	1.322	0.323	0.185	2,120	537.83
T10	0.751	0.731	1.197	1.362	0.742	2.304	2.080	-0.333	1.600	1.170	0.687	1.567	0.489	1.329	0.377	0.177	2,094	431.00
T11	0.713	0.845	1.093	1.253	0.933	2.320	2.130	-0.217	1.600	1.282	0.535	1.380	0.457	1.331	0.381	0.174	2,382	529.73
T12	0.700	0.759	1.181	1.140	0.677	2.107	1.870	-0.027	1.400	1.198	0.546	1.443	0.456	1.098	0.304	0.479	1,826	282.72
T13	0.662	0.687	1.207	1.289	0.725	2.186	1.990	-0.342	1.600	1.160	0.523	1.514	0.354	1.323	0.354	0.152	2,046	479.97
T14	0.753	0.728	1.200	1.367	0.734	2.302	2.080	-0.340	1.600	1.172	0.684	1.568	0.481	1.330	0.375	0.182	2,088	427.63
T15	0.693	0.848	1.086	1.257	0.929	2.324	2.130	-0.211	1.600	1.269	0.559	1.368	0.451	1.331	0.387	0.169	2,364	581.71
T16	0.722	0.733	1.207	1.168	0.676	2.109	1.860	-0.327	1.400	1.205	0.546	1.482	0.389	1.096	0.340	0.227	1,880	271.85
T17	0.667	0.695	1.207	1.290	0.726	2.191	2.000	-0.339	1.600	1.164	0.529	1.510	0.405	1.326	0.357	0.190	2,010	479.01
T18	0.766	0.737	1.198	1.367	0.745	2.306	2.090	-0.325	1.600	1.183	0.683	1.565	0.493	1.328	0.375	0.201	2,078	402.63
T19	0.713	0.855	1.081	1.261	0.939	2.323	2.130	-0.211	1.600	1.275	0.544	1.431	0.461	1.328	0.382	0.169	2,390	527.36
T20	0.732	0.734	1.206	1.255	0.697	2.134	1.920	-0.050	1.400	1.212	0.538	1.489	0.465	1.068	0.360	0.469	1,904	294.89

First, the tractor lateral stability test was performed on the platform at an inclination of 38° at the moment when the tractor is resting in a state of stable equilibrium with the wheels touching the ground. There was no distortion of the tractors' lateral stability; all tractors passed the test successfully.

The noncontinuous rolling behavior of the tractor was checked using the Vuelco.xls simulation program with and without the anchor mechanism for all tractors in the event of a lateral overturn on a 34° slope. The results that influence the ROPS height are given in Figure 6.

Figure 6 shows the effect of the anchor mechanism on the height of the ROPS; an obvious change in the ROPS height can be seen. The ROPS heights changed between 183 and 455 mm, with the average reduction being 261 mm. Dependent and paired samples t-test was used to determine the affect of the anchor mechanism and the outputs of these tests can be seen in Table 3. Results were found to be statistically significant if the P value was less than 0.001.

Table 3. The output of the paired t-test used to compare the ROPS height with and without anchor mechanism.

ROPS height (m)		Statistical analysis	
Without anchor	With anchor	Mean difference (m)	P
2.285 ± 0.02	2.023 ± 0.02	0.261	0.001

In the research carried out by Silleli (2006) the ROPS shortened method was applied for verification of the anchor system on a model tractor by using the ADAMS simulation program. According to the simulation results, the height of the ROPS (H_6) could be reduced from 2355 to 1860 mm. In this research, an anchor mechanism was applied to 20 tractors and the results obtained from these

2 studies were consistent. It was found that the anchor mechanism reduces the heights of the ROPS. These decreases in height are important because this mechanism provides a means for manufacturers to decrease the height of the ROPS in order to meet the demands of their consumers. Based on current regulations, manufacturers have little flexibility in the height of the ROPS that are needed to be in place on their product in order to pass the preliminary assessments before static loading tests. The use of the anchor mechanism provides manufacturers with an option that will allow them to produce more effective tractors with lower ROPS heights.

Tractors were also investigated based on the type of drive capability [i.e. whether they were 2- or 4-wheel drive (2WD or 4WD)]. The 4WD version tractors are always heavier than the 2WD tractors of the same model. It is reported that if the total mass increases the lateral moment of inertia is higher, and consequently the tractor is more susceptible to rolling (OECD, 2004b). A t-test was performed to compare the 2WD tractors with the 4WD ones with and without anchor mechanisms. The t-test showed that there was an obvious difference in the required height for the ROPS between the 2 configurations (Table 4). It was found that the ROPS of the 4WD tractors needed to be higher than those installed on the 2WD tractors due to the higher mass. In addition,

Table 4. Comparison of ROPS height reduction between 2- and 4-wheel drive tractors with and without the anchor mechanism (t-test, P < 0.001).

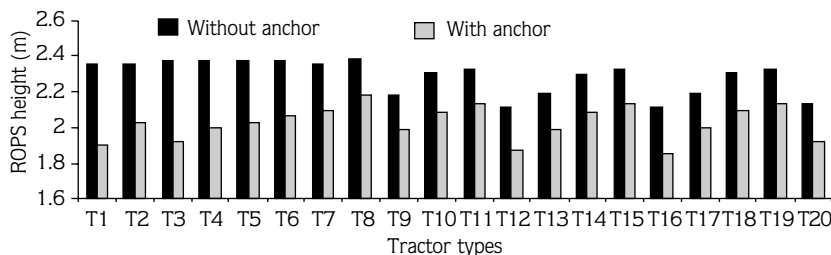|	ROPS height (m)		Statistical analysis	
	Without anchor	With anchor	Mean difference (m)	P
(2WD)	2.251 ± 0.02	1.980 ± 0.02	0.271	0.001
(4WD)	2.348 ± 0.01	2.104 ± 0.02	0.244	0.001
P		0.001	0.001	

Figure 6. Effects of the anchor mechanism on the roll-over protective structures heights.

when the anchor mechanism was installed on the 2WD and 4WD drive tractors, a significant difference between the heights of the ROPS was found (P < 0.001). The anchor mechanism enabled the ROPS of the 2WD tractors to be reduced to a greater extent compared to the 4WD tractors. The mean reduction was found to be 271 mm for the 2WD tractors and 244 mm for the 4WD tractors.

For the determination of the CG projection on the ground plane, it is sufficient to apply equilibrium considerations to the reaction of the ground under every wheel (Fabri and Molari, 2004). The height of CG is one of the most influential parameters that affects the likelihood of an overturned tractor to roll continuously (Liu and Ayers, 1998) and risks are increased in the case of wheeled tractors with high CG, especially narrow tractors, which have even less stability than wide ones (Springfeldt, 1996). In this study, the significance of the correlation coefficient between CG and the difference in the height of the ROPS obtained by an anchor mechanism was determined using Pearson's correlation coefficients and found to be 50.9% (P < 0.05; Figure 7). It was also discovered that there was a negative linear relationship between the height of CG and the height of the ROPS. A decrease in the height of CG value results in an increase in the change in the height of the ROPS.

Based on the relation between tractor mass and moment of inertia reported by OECD (2004b), the effect of the tractor mass and moment of inertia on the height of the ROPS was also investigated. There was a linear relationship between tractor mass (M) and the height of the ROPS in tractors without an anchor mechanism (H6a; Pearson correlation coefficient: 0.745, P < 0.01). Increasing the tractor mass results in an increase in the height of the ROPS. A linear relationship was found between the mass (M) and the height of the ROPS in

tractors with an anchor mechanism (H6a; Pearson correlation coefficient: 0.796, P < 0.01). Similarly, increasing the tractor mass resulted in higher ROPS. Moment of inertia also affected the height of the ROPS in tractors with an anchor mechanism; there was a significant relationship between these 2 parameters (0.799; P < 0.01). It was found that the height of the ROPS with an anchor mechanism was high in instances of high moment of inertia (see Table 2).

The results of the effect of the anchor mechanism on the angular velocity of the overturning tractor calculated using the Vuelco.xls simulation for all tractors at each point during a rollover event (Figure 5) are outlined in Table 5. The rotation speed of all tractors is reduced to zero (i.e. tractor comes to rest in a stable position at the end of the overturn event) in machines with and without an anchor mechanism resulting in the machine coming to rest at the rotation speed O5 (ω_{CO}) of the roll. As previously mentioned, the anchor mechanism can reduce the ground impact energy by decreasing the roll angle. Ground impact can be explained by investigating the rotation speed O3 (ω_{B1}) of an overturn. It is at this point in the roll that the protective structure and the front wheel hit the ground and the rotation speed of the tractors with an anchor mechanism was found to be less than that in tractors without an anchor mechanism. These results were investigated in the research carried out by Silleli et al. (2007). In their real field upset test, the time between the front tires lifting off from the ground to the anchor hitting the ground was 640 ms for the anchored system and 800 ms for the system without an anchor. Dependent and paired sample t-tests were used to determine the affect of the anchor mechanism (Table 6) on rotation speed of a tractor during a roll event. The result was found to be significant (P < 0.001). The anchor mechanism widens the ROPS so that, during an
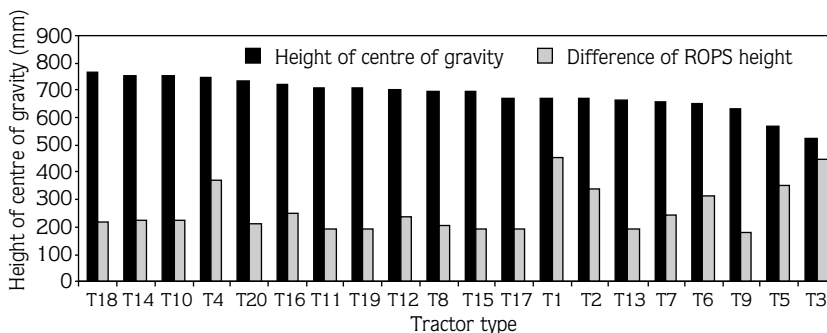

Figure 7. Evaluation of the anchor mechanism with respect to center of gravity of tractors.

Table 5. The effect of the anchor mechanism on the rotation speed during each step of a rollover event for all 20 tractors examined.

	Rotation speed (rads^{-1})																			
	00(ω_{A1})		01(ω_{B0})		02(ω_{B0})		03(ω_{B1})		04(ω_{C0})		05(ω_{C0})		06(ω_{C1})		07(ω_{D0})		08(ω_{D0})		09(ω_{end})	
Tractor type	without anchor	with anchor	without anchor	with anchor	without anchor	with anchor	without anchor	with anchor	without anchor	with anchor	without	with	without	with	without	with	without	with	without	with
T1	3.481	3.481	1.779	1.779	1.721	1.721	2.292	2.050	0.410	0.870	0	0	0	0	0	0	0	0	0	0
T2	3.180	3.180	1.918	1.918	1.855	1.855	2.577	2.250	0.508	0.829	0	0	0	0	0	0	0	0	0	0
T3	2.898	2.898	1.334	1.334	1.291	1.291	1.894	1.640	0.466	0.723	0	0	0	0	0	0	0	0	0	0
T4	3.211	3.211	2.155	2.155	2.124	2.124	2.878	2.517	0.541	0.825	0	0	0	0	0	0	0	0	0	0
T5	3.000	3.000	1.506	1.506	1.464	1.464	2.098	1.797	0.467	0.684	0	0	0	0	0	0	0	0	0	0
T6	3.080	3.080	1.734	1.734	1.713	1.713	2.417	2.093	0.530	0.789	0	0	0	0	0	0	0	0	0	0
T7	2.975	2.975	1.762	1.762	1.746	1.746	2.497	1.980	0.613	0.778	0	0	0	0	0	0	0	0	0	0
T8	2.994	2.994	1.566	1.566	1.547	1.547	2.367	1.813	0.662	0.749	0	0	0	0	0	0	0	0	0	0
T9	3.035	3.035	1.547	1.547	1.487	1.487	2.278	1.717	0.739	0.762	0	0	0	0	0	0	0	0	0	0
T10	3.198	3.198	1.557	1.557	1.479	1.479	2.335	1.807	0.704	0.797	0	0	0	0	0	0	0	0	0	0
T11	3.119	3.119	1.592	1.592	1.570	1.570	2.396	1.878	0.706	0.788	0	0	0	0	0	0	0	0	0	0
T12	3.574	3.574	1.995	1.995	1.939	1.939	2.749	2.283	0.677	0.903	0	0	0	0	0	0	0	0	0	0
T13	3.079	3.079	1.469	1.469	1.405	1.405	2.264	1.681	0.762	0.781	0	0	0	0	0	0	0	0	0	0
T14	3.202	3.202	1.552	1.552	1.471	1.471	2.329	1.798	0.704	0.793	0	0	0	0	0	0	0	0	0	0
T15	3.053	3.053	1.546	1.546	1.524	1.524	2.320	1.817	0.708	0.779	0	0	0	0	0	0	0	0	0	0
T16	3.586	3.586	1.975	1.975	1.913	1.913	2.724	2.280	0.623	0.869	0	0	0	0	0	0	0	0	0	0
T17	3.072	3.072	1.492	1.492	1.428	1.428	2.29	1.708	0.766	0.788	0	0	0	0	0	0	0	0	0	0
T18	3.231	3.231	1.581	1.581	1.501	1.501	2.379	1.837	0.704	0.798	0	0	0	0	0	0	0	0	0	0
T19	3.123	3.123	1.568	1.568	1.546	1.546	2.373	1.852	0.704	0.783	0	0	0	0	0	0	0	0	0	0
T20	3.560	3.56	1.601	1.601	1.536	1.536	2.462	1.916	0.728	0.835	0	0	0	0	0	0	0	0	0	0

Table 6. Statistical analysis of anchor mechanism on the rotation speed of rolling.

Rotation speed		Statistical analysis	
Without anchor	With anchor	F	P
2.36 ± 0.05	1.94 ± 0.05	40.37	0.001

overturn, the rotation speed decreases. Decreasing the rotation speed resulted in decreasing the impact velocity of the ROPS. In this way, the anchor mechanism protects the drivers from the possibility of injury and also protects the tractor from excessive damage.

Conclusions

The use of the anchor mechanism reduces the height of the ROPS considerably while preventing the continuous rolling of the tractor in the event of a rollover. This reduction in the height of the ROPS still allows for an adequate zone of safety around the operator. Lower ROPS reduce or eliminate the need for operators to either fold or completely disassemble the ROPS in instances where there may be difficulty entering rural buildings or to avoid low overhanging tree branches. For the 20 tractors tested, the current height of the ROPS could be decreased by between 183 and 455 mm if the anchor mechanism were installed on these machines. The effect of the tractor mass, the height of the CG, and moment of inertia on the height of the ROPS was also investigated. A linear relationship was found between the tractor mass and the height of the ROPS as well as moment of inertia and the height of the ROPS in tractors with an anchor mechanism. It was also found that there was a negative linear relationship between the height of CG and the height of the ROPS. Furthermore, the use of an anchor mechanism decreased the rotation velocity. Decreasing the rotation velocity may protect the drivers from the possibility of injury and protect the tractor from excessive damage.

Acknowledgments

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