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Analysis of Static Lateral Stability Using Mathematical Simulations for 3-Axis Tractor-Baler System

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Abstract

Purpose: This study aims to evaluate the applicability of a tractor-baler system equipped with a newly developed round baler by conducting stability analyses via static-state mathematical simulations and verification experiments for the tractor equipped with a loader. **Methods:** The centers of gravity of the tractor and baler were calculated to analyze the transverse overturning of the system. This overturning of the system was analyzed by applying mathematical equations presented in previous research and comparing the results with those obtained by the newly developed mathematical simulation. For the case of the tractor equipped with a loader, mathematical simulation results and experimental values from verification experiments were compared and verified. **Results:** The center of gravity of the system became lower after the baler was attached to the tractor and the angle of transverse overturning of the system steadily increased or decreased as the deflection angle increased or decreased between 0° and 180° on the same gradient. In the results of the simulations performed by applying mathematical equations from previous research, right transverse overturning occurred when the tilt angle was at least 19.5° and the range of deflection angles was from 82° to 262° in counter clockwise. Additionally, left transverse overturning also occurred at tilt angles of at least 19.5° and the range of deflection angles was from 259° to 79° in counter clockwise. Under the 0° deflection angle condition, in simulations of the tractor equipped with a loader, transverse overturning occurred at 17.9°, which is a 2.3% change from the results of the verification experiment (17.5°). The simulations applied the center of gravity and the correlations between the tilt angles, formed by individual wheel ground contact points excluding wheel radius and hinge point height, which cannot be easily measured, for the convenient use of mathematical equations. The results indicated that both left and right transverse overturning occurred at 19.5°. **Conclusions:** The transverse overturning stability evaluation of the system, conducted via mathematical equation modeling, was stable enough to replace the mathematical equations proposed by previous researchers. The verification experiments and their results indicated that the system is workable at 12°, which is the tolerance limit for agricultural machines on the sloped lands in South Korea, and 15°, which is the tolerance limit for agricultural machines on the sloped grasslands of hay in Japan.

Keywords: Deflection angle, Lateral stability, Mathematical model, Simulation, Tractor-baler system, Transverse overturning

Introduction

Over the last five years (2011-2015), agricultural machine related traffic accidents increased by 32% nationally. In 2015, 500 agricultural machine related traffic accidents occurred, resulting in 65 fatalities and 563 injuries. The fatality rate was 13%, which is 1.0%, 1.7%, and 3.9% higher when compared to taxi, city bus, and express bus related traffic accidents, respectively (KOROAD, 2016). Additionally, among agricultural machine related safety accidents, tiller or tractor related safety accidents accounted for 61% of the accidents. The ratios of overturns/collisions were reported to be 39% in the

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case of tillers and 15.4% in the case of tractors (NAAS, 2016).

Many tractor stability analyses have been conducted and most of them focus on longitudinal or transverse overturning stability. For example, Wang et al. (2011a), and (2011b), Wang (2002), Hussain et al. (2005), Dahlerg and Vagstedt (1997), Chen et al. (2009), Zhao et al. (2012), and Franceschetti et al. (2014) all conducted dynamic analyses on transverse overturning. Mathijs (2010), Vincent (2005), and Liu (2010) conducted transverse overturning analyses via nonlinear modeling. Pacejka (1973), Mathijs (2010), Vincent (2005), Daniel and Adam (2004), Lukowski et al. (2009), Winkler (1998), Yeh and Chen (1990), and Hillegass et al. (2004) conducted studies on handling diagrams, which are useful for steady-state turning behavior. Demsar et al. (2012) conducted a transverse overturning study via mathematical equation modeling and Guzzomi (2012) conducted a transverse overturning study via kineto-static models. Baker and Guzzomi (2013) conducted a mathematical equation study on parametric models of tractors with anterior mass and Redl et al. (2014) conducted mathematical analyses on the active stability control systems of agricultural vehicles. Li et al. (2013) studied dynamic mathematical equation models for loaders on slopes. With regard to longitudinal overturning, Nidal and Hamid (2004) studied the automatic control of tractor-trailers, Gialamas et al. (2006) conducted bench structure tests, Vidoni et al. (2015) conducted agricultural vehicle stability analyses, Popescu and Sutru (2009) studied the weight shift of tractors equipped with a loader and a lift, and Guzzomi et al. (2009) studied energy that can be used in the event of tractor overturning. Ahmadi (2014) studied longitudinal stability in relation to the plow attached to a tractor. Lee et al. (1989, 1990), Jang et al. (1991), and Daniel and Adam (2004) conducted studies on the improvement of agricultural machine adaptability to sloped terrain. Park and Park (1990) conducted a study on Tiller-Trailer System movements and transverse overturning, while Jung and Kim (1990) conducted a study on tractor-trailer system transverse overturning. Park et al. (2005) conducted a study on stability based on Mini-Forwarder loading methods. However, studies on farm machinery attached to tractors as complete systems are rare and necessary.

In this study, for the first time in this research field, we deeply explore the static stability of a 3-axis tractor-baler system connected by a 3-point hitch through analyses on centers of gravity and transverse overturning angles. For the transverse stability analysis in particular, the applicability of the newly proposed method was examined by comparing its results with the simulation results of the mathematical equations proposed in previous research.

Materials and Methods

Experimental Environment

In the stability evaluation, 15° was used as the slope limit for tractor-baler systems based on the laws of South Korea and Japan. In the case of South Korea, for the application of tractor-baler systems to upland crop sloped lands, the limit for plough operation of 12° and the limit for tillage operation of 10° were applied as the worst-case conditions in typical environments, excluding obstacle passing (MAFRA, 2002). In case of Japan, gradients not exceeding 8-10° were applied to forage crops that do not require management work, gradients of 10-15° were applied to grasslands for hay, and gradients exceeding 15° were applied to pastures (MAFF, 2016). In both South Korea and Japan, gradient limits for farm work are mandated to reduce the risk of tractor overturning and increase the efficiency of farm machinery.

Specification of Tractor-Baler System

The system consists of a tractor in the front and an integrated round baler attached by a 3-point hitch in the rear. The tractor is an agricultural four-wheel drive machine with a maximum PTO output of 43 kW and a loader installed on the front. A baler without its own power source was newly developed to use the PTO/hydraulic/electric power of the tractor. It also contains an internal wrapping machine. The specifications from the test results of the tractor were applied to our modeling along with the measured values of the baler. Additionally, in the test on the center of gravity and transverse overturning of the tractor, the fuel tank was completely filled and a load of 75 kg was placed on the driver's seat when no additional weight was included. The loader installed on the tractor was analyzed when was raised to its maximum height (Figure 4-(A)) so that the visual field of the driver was unobstructed during the baler operation situations (Table 1).

Table 1. Specifications of the tractor and baler

				Tractor		Baler
Model				RX601*	RX601**	Multi-pro***
Maximum PTO power/speed (kW/rpm)				43/2,444	43/2,444	-
	Weight of wheel	Front	Left (kg)	1,020	786.0	602
			Right (kg)		761.5	
		Rear	Left (kg)	1,610	911.5	1250.5
			Right (kg)		912.5	1194.5
Dimensions	Length of front axle (mm)			1,465	1,465	-
	Length of rear axle (mm)			1,415	1,415	1,910
	Length of wheelbase (mm)			2,100	2,100	-
	Width of tractor-baler (mm)			1,875	1,875	2,507
	Height of tractor-baler (mm)			2,630	3,809	2,129
	Length of tractor-baler (mm)			3,590	4,695	5,427
	Weight of tractor-baler (kg)			2,630	3,371.5	3,047.0

* Analysis test report: Tractor (FACT. 12-M-3-154. 2012)
** Analysis test report: Tractor with loader (FACT. 17-MT-011. 2017)
*** Specifications of the newly developed baler (Myungsung. 2017)

Modeling of Tractor-Baler System

The modeling of the tractor-baler system for stability analysis was performed in the following manner. First, the centers of gravity of the tractor and baler were calculated. Second, the center of gravity of the system was calculated by integrating the individual centers of gravity. Third, the transverse overturning of the system was predicted based on mathematical equations. Fourth, the predicted value of transverse overturning was tested using experimental equipment to verify its accuracy. For ease of modeling, the system components of the tractor and baler were assumed to be rigid bodies connected via PTO and a 3-point hitch. A schematic of the applied system modeling is presented in Figure 1.

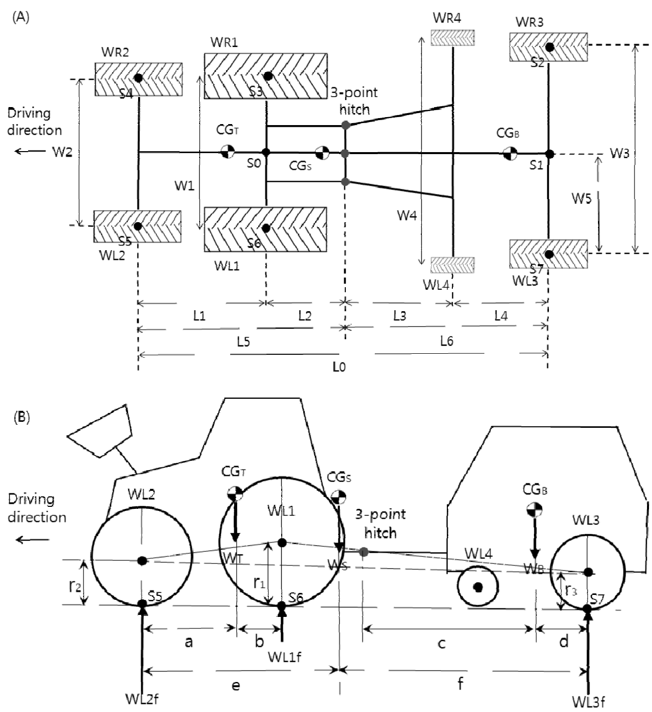

Figure 1. Schematic of model of tractor-baler system - (A): Top view and (B): Side view.

The tractor equipped with a loader is composed of the following components: center of gravity (CG_T), wheel loads (W_{L1}, W_{R1}, W_{L2}, W_{R2}), loads placed on the wheel ground contact points (W_{L1f}, W_{R1f}, W_{L2f}, W_{R2f}), front wheel radius (r_2), rear wheel radius (r_1), horizontal distances from the contact point on the vertical line segment where the center of gravity (CG_T) meets the ground to the front wheel axle (a), and to the rear wheel axle (b), axle lengths (W_1, W_2), and the coordinate reference point for the center of gravity (S0: the center point of the tractor rear wheel axle). The baler is composed of the following components: center of gravity (CG_B) for the vehicle weight (W_B), wheel loads (W_{L3}, W_{R3}), loads placed on the wheel ground contact points (W_{L3}, W_{R3}), rear wheel radius (r_3), the horizontal distances from the contact point of the vertical line segment where the center of gravity (CG_T) meets the ground to the 3-point hitch (c), and to the rear wheel axle (d), axle length (W_3), and the coordinate reference point of the center of gravity (CG_B) (S_1: center point of the baler rear wheel axle). Additionally, the distances from the 3-point hitch ground contact point to the individual ground contact points (L_1, L_2, L_3, L_4, L_5, and L_6) were included, as were the center of gravity (CG_S) for the system's vehicle weight (W_S), the horizontal distances from the contact point of the vertical line segment where the center of gravity (CG_T) meets the ground to the tractor front wheel axle (e), and to the baler rear wheel axle (f), and the coordinate reference point of the center of gravity (S_2: ground contact point of the baler rear right wheel). However, the baler auxiliary wheels (W_{L4}, W_{R4}) that do not place vehicle loads on the ground were not considered. Furthermore, the ground contact points of individual wheels were assumed to be the tractor's front right wheel (S_4), front left wheel (S_5), rear right wheel (S_3), and rear left wheel (S_6), and the baler's rear left wheel (S_7). The tractor's centers of gravity (CG_T: X_T, Y_T, Z_T) and the baler's centers of gravity (CG_B: X_B, Y_B, Z_B) were calculated using equations from previous research, (Lee et al., 1989, Lee et al., 1990, Jang et al., 1991) equations (1)-(4) and (6), combined with our newly modified equation (5). The tractor's centers of gravity (X_T, Y_T, Z_T) were calculated using individual wheel loads in conjunction with the tilt angle (δ) for the height of the front wheel when lifted up (h) and the front wheel load ($W_{(L/R)2f1}$) when lifted up ($W_{(L/R)2f1}$) (Figure 2-(A)). The baler's centers of gravity (X_B, Y_B, Z_B) were calculated using the tilt angle (α) formed by the 3-point hitch installation height and its height when let down (h) in conjunction with the vehicle body loads (W_{Bf}, W_{Bf1}) before and after being let down (Figure 2-(B)). The centers of gravity (CGS: X_S, Y_S, Z_S) of the tractor-baler system, assumed to have been connected as a rigid body, were determined by converting the individual center of gravity coordinates of the tractor and baler into coordinate reference points (S2) and applying equations (7)-(9) (ISO/DIS, 2012).

$$X_T = ((W_{R2}+W_{L2})\times L_1)/W_T \quad (1)$$

$$Y_T = X_T\times\cot\delta-(W_{L2f1}\times(L_1\times\cos\delta+(r_1-r_2)\times\sin\delta))/W_T\times\sin\delta \quad (2)$$

$$Z_T = (W_{R1}\times W_{L1}+W_{L2}\times(W_1+W_2)/2+W_{R2}\times(W_1+W_2)/2)/W_T \quad (3)$$

$$X_B = (W_{Bf}\times L_6)/W_B \quad (4)$$

$$Y_B = ((W_{R3}-W_{L3})\times(W_3/2))/W_B \quad (5)$$

$$Z_B = (W_{Bf1}\times L_{6\text{-}1}/W_B\times\sin\alpha)-X_B\times\cot\alpha \quad (6)$$

$$X_S = (W_T\times X_T+W_B\times X_B)/(W_T+W_B) \quad (7)$$

$$Y_S = (W_T\times Y_T+W_B\times Y_B)/(W_T+W_B) \quad (8)$$

$$Z_S = (W_T\times Z_T+W_B\times Z_B)/(W_T+W_B) \quad (9)$$

where: W_{L1}, W_{L2}, W_{L3}, W_{R1}, W_{R2}, and W_{R3} are the loads

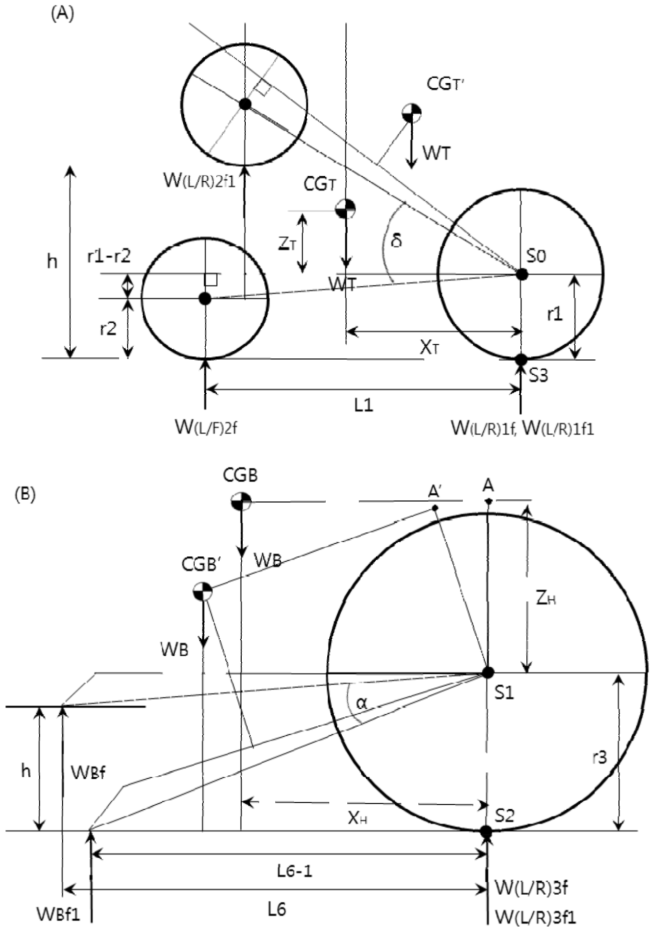

Figure 2. Schematic of center of gravity measurement - (A): tractor and (B): baler.

places on individual wheels,

W_1, W_2, and W_3 are the lengths of individual axles,

W_T, W_B, and W_S are the loads of the tractor, baler, and system,

$W_{(L/F)1f}$, $W_{(L/F)2f}$, $W_{(L/F)3f}$, and W_{Bf} are the loads placed on individual wheel ground contact points,

$W_{(L/F)1f1}$ and $W_{(L/F)2f1}$ are the loads placed on individual wheel ground contact points when lifted up,

$W_{(L/F)3f1}$ and W_{Bf1} are the loads placed on the wheel and 3-point hitch when let down,

L_1 is the horizontal distance between the tractor front wheel and the center of the rear wheel,

L_6 and $L_{6\text{-}1}$ are horizontal distance and tilted horizontal distance from the baler's rear wheel ground contact point to the hitch vertical line

segment's ground contact point,
δ is the angle increase when the tractor was lifted up to a certain height (h),
and α is the angle decrease when the baler was let down to a certain height(h).

The transverse overturning angle (ζ) of the tractor-baler system was defined as the angle formed by the line segment connecting the center of gravity of the system to the line segment connecting the front axle hinge point of the tractor to the ground contact point of the baler rear wheel below the contour line, and the upward line segment from the center of gravity (Lee et al., 1990). The transverse overturning simulation is based on the lateral direction of the tractor using the coordinates (X_S, Y_S, Z_S) of the center of gravity from previous research, the horizontal distance (L_0) between the wheels, the hinge point height (TH), and the deflection angle (γ). The deflection angle was changed in 1° increments over a 360° range at a tilt angle of 90° or less. The deflection angle was incremented in a counterclockwise direction.

The transverse overturning simulation was applied using equation (10), which is a mathematical equation obtained from previous research for the transverse overturning of tractors using the coordinates of the center of gravity (X_S, Y_S, Z_S), horizontal distance between wheels (L_0), hinge point height (TH), and deflection angle (γ). In this case, under the condition where tilt angles do not exceed 90°, the deflection angle was changed in 1° increments over a range of 360° in a counterclockwise direction.

$$\zeta = \tan^{-1}(((L_0-X_S)\times W_2+2Y_S\times L_0)/((Z_S+r_3)\times(2L_0\times\cos\gamma-2\times\sin\gamma)+TH\times(W_2\times\sin\gamma-3X_S\times\cos\gamma+2Y_S\times\sin\gamma))) \quad (10)$$

where W_2 is the tractor front wheel axle length,
L_0 is the horizontal length between the tractor front wheel ground contact point and the baler rear wheel ground contact point,
TH is the tractor front wheel axle hinge point height,
r_3 is the baler rear wheel radius,
and γ is the deflection angle.

In this study, based on the assumption of bilateral symmetry for left and right transverse overturning of the 3-axis tractor-baler system, we considered that the least transverse overturning would occur at certain deflection angles (0°, 180°). We used equations (1)-(9), which are equations for obtaining a new transverse overturning center of gravity. A new mathematical equation was presented that enables easy calculation of transverse overturning angles using only the center of gravity coordinate values obtained by the previous equations and the tilt angles (α_1, α_2, α_3, α_4, α_5, α_6) formed by the center of gravity and the individual wheel ground contact points. A schematic of the system configuration is presented in Figure 3. The tilt angles were obtained using equations (11)-(18). In this case, the right transverse overturning angles were determined using the tilt angles (α_1, α_2, α_3) formed by coordinate reference point (S2) and the center of gravity at a deflection angle of 0°. The left transverse overturning angles were determined using the tilt angles (α_5, α_6, α_7) formed by coordinate reference point (S_7) and the center of gravity at a deflection angle of 180°.

$$\alpha_1 = \tan^{-1}(Z_S/SQRT((L_2+L_6-X_S)^2+(W_1/2+W_3/2+YS)^2) \quad (11)$$

$$\alpha_2 = \tan^{-1}(Z_S/SQRT((L_0-X_S)^2+(W_2/2+Y_S+W_3/2)^2) \quad (12)$$

$$\alpha_3 = \tan^{-1}(Z_S/SQRT((W_3+Y_S)^2+X_S^2) \quad (13)$$

$$\alpha_4 = (\alpha_1+\alpha_3)/2 \quad (14)$$

$$\alpha_5 = \tan^{-1}(Z_S/SQRT((L_0-L_1-X_S)^2+(W_1/2+W_3/2-Y_S)^2) \quad (15)$$

$$\alpha_6 = \tan^{-1}(Z_S/SQRT((L_0-X_S)^2+(W_2/2-Y_S+W_3/2)^2) \quad (16)$$

$$\alpha_7 = \tan^{-1}(Z_S/SQRT((W_3-Y_S)^2+X_S^2) \quad (17)$$

$$\alpha_8 = (\alpha_5+\alpha_7)/2 \quad (18)$$

where S_2, S_3, S_4, S_5, S_6, and S_7 are the individual wheel ground contact points,
X_S, Y_S, and Z_S are the values of the center of

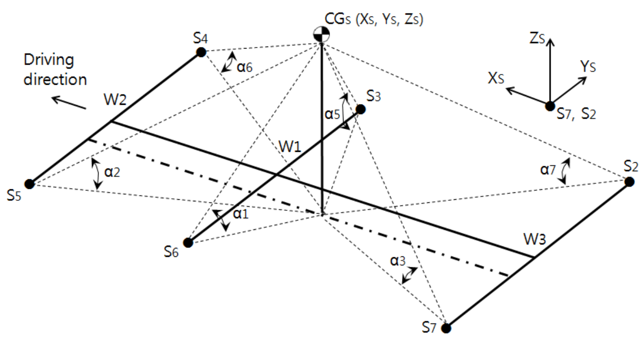

Figure 3. Schematic of tilt angles obtained using the center of gravity and individual. wheel ground contact points.

gravity coordinates of the system,
α_1, α_2, α_3, α_5, α_6, and α_7 are the tilt angles formed by the center of gravity and the individual wheel ground contact points,
α_4 is the average value of α_1 and α_3,
and α_8 is the average value of α_5 and α_7.

Verification experiments using equipment from authorized agencies were conducted based on the structural standards and performance standards of stabilizers from the agricultural machine test standards (MAFRA, 2017). The acceptance criterion of the national institution is that the machine is not left or right transverse-overturned at tilt angles less than or equal to 30°. Left and right transverse overturning experiments for the tractor equipped with a loader were performed by increasing the tilt angle of the experimental equipment in 1° increments across a range of 0-45°.

Results and Discussion

For the static stability analysis of the tractor-baler system, the center of gravity of the tractor and the baler, which are components of the system, were analyzed separately. The system center of gravity was then obtained to calculate transverse overturning angles. We applied the wheel loads for the tractor, baler, and system, measured in a horizontal state and a tilted state. However, due to the limitations of the measuring device, the wheel loads of the system in the tilted state could not be accurately measured (Table 2, Figure 4).

Analysis of the center of gravity of the 3-axis Tractor-Baler System

The centers of gravity of the tractor, baler, and tractor-baler system were calculated separately using equations (1)-(9) based on their respective coordinate reference points. The center of gravity coordinate (X_T, Y_T, Z_T) of the

Table 2. Wheel loads of the tractor, baler, and tractor-baler system in horizontal state and tilted state

State Load weight	Tractor		Baler		System
	Horizontal state	Tilt state	Horizontal state	Tilt state	Horizontal state
W_{L2} (kg)	786	760.4	-	-	815.9
W_{R2} (kg)	761.5	745.4	-	-	791.8
W_{L1} (kg)	911.5	938.7	-	-	1195.7
W_{L1} (kg)	912.5	927.1	-	-	1109.3
3-point hitch (kg)	-	-	602	654.5	-
W_{L3} (kg)	-	-	1250.5	1218.7	1235.9
W_{R3} (kg)	-	-	1194.5	1173.8	1270
Total weight (kg)	3,371.5	3,371.5	3,047	3,047	6,418.5
Tilt: Angle (degree)	-	(δ): +16.7	-	(α): -6.7	-
Tilt: Height (h) (mm)	-	650	-	400	-

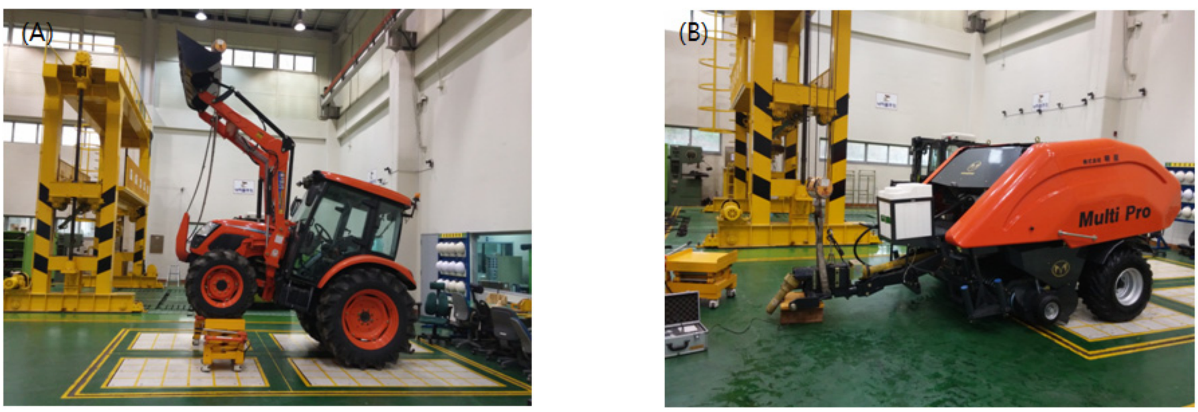

Figure 4. Measurement of the center of gravity in horizontal state and tilted state - (A): Tractor and (B): Baler.

tractor equipped with a loader was calculated to be (963.89, -27.08, 566.11) mm based on coordinate reference point (S_0). Compared to the center of gravity coordinate (814.45, -5.48, 183.04) mm in the state where the loader was not installed (FACT, 2012), X_T moved by 149.44 mm, Y_T moved by 21.6 mm, and Z_T moved by 383.07 mm. The center of gravity coordinate (X_B, Y_B, Z_B) of the baler was (673.82, -17.55, 542) mm based on coordinate reference point (S_1). The center of gravity coordinate (X_S, Y_S, Z_S) of the system using the mathematical equation was (3112.46, -977.56, 1160) mm based on coordinate reference point (S_2), and was (3112.5, 932.5, 1160) mm based on coordinate reference point (S_7).

Analysis of system transverse overturning when applying previous mathematical equations

The transverse overturning angle analysis in the system simulation was performed using equation (10) while changing the tilt angle by rotating the deflection angle counterclockwise. In this case, the tilt angle was increased by 1° at a time over a range of 90°. In Figure 5, the radiating circle represents the tilt of the system, which is the deflection angle direction. The sizes of the concentric circles (0°-90°) are the ground gradients and the points are the tilt angles for the system to be left/right overturned, meaning the transverse overturning angles. In this case, the transverse overturning angle curve leaned toward the left from the center vertical line segment due to the differences in axle lengths between the system and the tractor. In the system, the W_{L2} ground contact point and W_{L3} ground contact point were separated from the center line by 1.7°, while the WL2 ground contact point and WL1 ground contact point for the tractor were separated from the center line by 7°.

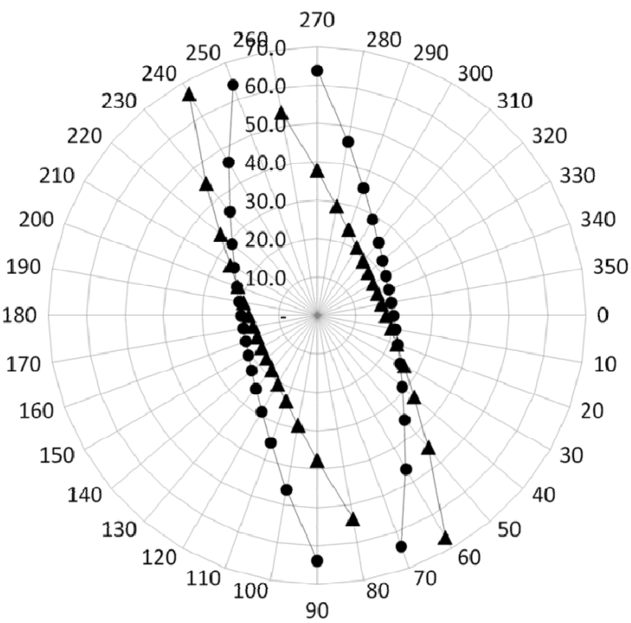

Figure 5. Analysis of transverse overturning angles based on changes in deflection angles and tilt angles.
(●: Tractor-baler system, ▲: tractor equipped with a loader)

In the simulation of the tractor equipped with a loader, which is a system component, right transverse overturning occurred at tilt angles between 16.6° and 88.8° at deflection angles in the range from 67° to 252° in counter clockwise, while left transverse overturning occurred at tilt angles between 16.6° and 88.8° at deflection angles in the range from 247° to72° in counter clockwise. Additionally, in the verification experiments on the tractor equipped with a loader, the transverse overturning angle was 17.5° based on a deflection angle of 0°, which is a difference of 2.3% from the simulation result of 17.9°. In the simulation of the system, right transverse overturning occurred at tilt angles between 19.5° and 87.3° at deflection angles in the range from 82° to 262° in counter clockwise, while left transverse overturning occurred at tilt angles between 19.5° and 87.3° at deflection angles in the range from 259° to 79° in counter clockwise.

In the verification experiments on the system, the transverse overturning angle was 19.8° based on a deflection angle of 0°. Thus, the system showed higher overturning angles compared to the tractor equipped with a loader by 13.1% and 10.6% in the results of the simulations and verification experiments, respectively.

Analysis of system transverse overturning using the new mathematical equation

The tilt angles (α_1, α_2, α_3, α_5, α_6, α_7) formed by the individual wheel ground contact points and the center of gravity gradually increase and decrease based on changes in the tilt angles. Transverse overturning occurs at a peak. In the simulations, with regard to right transverse overturning, the tractor tilt angle (α_2) formed by the ground contact point (S_5) of the front left wheel and the center of gravity reached its peak at 22.36° (Figure 6-(A)(a)), and the tilt angle (α_1) formed by the ground contact point (S_6) of the rear left wheel and the center of gravity reached its peak at 40.61° (Figure 6-(B)(b)). Additionally, the tilt angle (α_3) formed by the ground contact point (S_7) of the baler rear left wheel and the center of gravity reached its peak

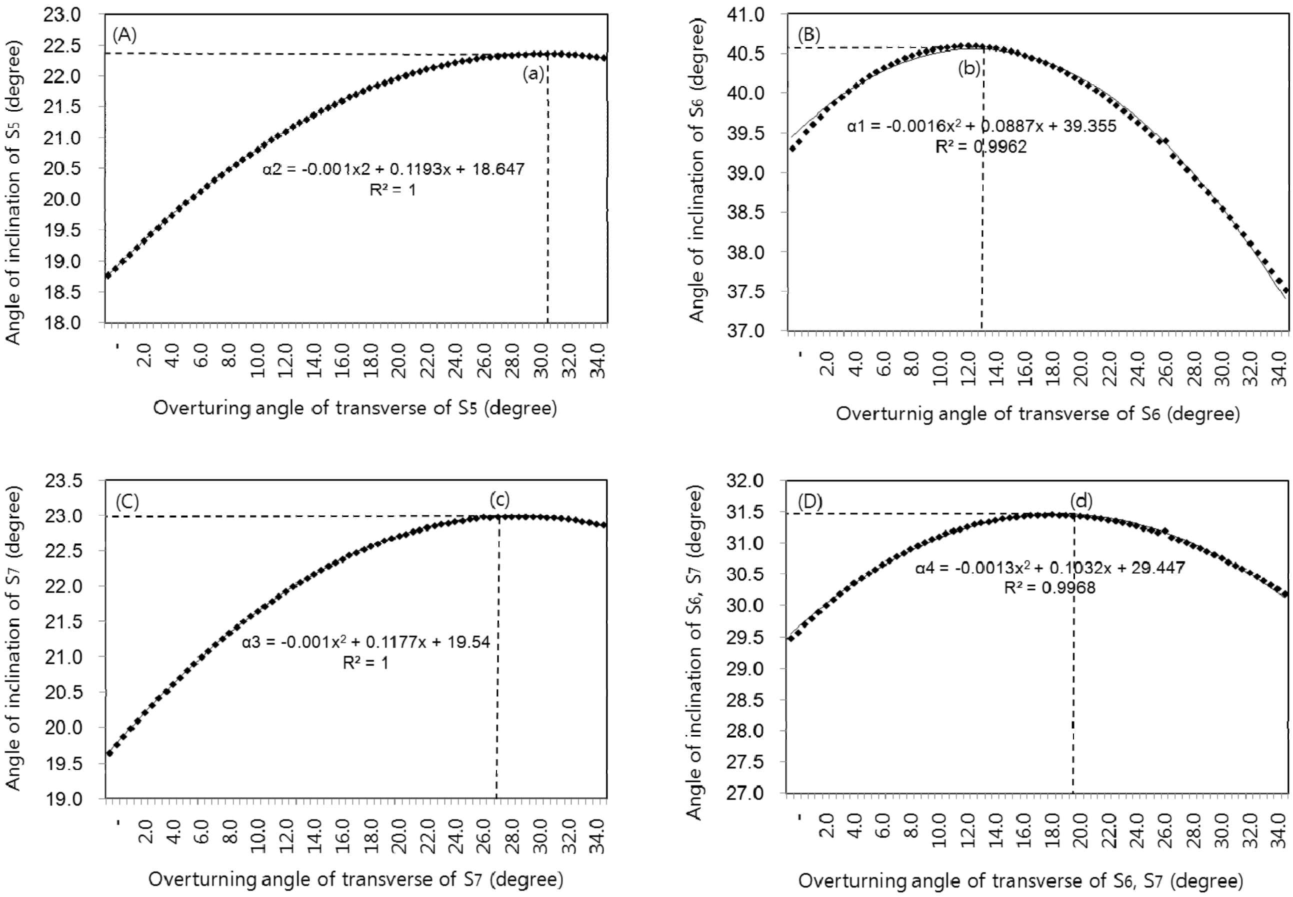

Figure 6. Right transverse overturning analysis of tractor-baler system.

at 31.45° (Figure 6-(C)(c)). System transverse overturning occurred at 31.45° (Figure 6-(D)(d)), which is the average tilt angle (α_4) of the tractor's rear left wheel tilt angle (α_1) and the baler's rear left wheel tilt angle (α_3). The right transverse overturning angle in this case was calculated to be 19.5°. When the deflection angle was 0°, the system's right transverse overturning occurred at tilt angles greater than or equal to 19.5° (Figure 6-(D)(d)), and the absolute coordinate (X_{S1}, Y_{S1}, Z_{S1}) of the center of gravity in this case was found to be (3112.5, -534.3, 1419.5) mm. As shown in Figure 6-(D), the average tilt angle (α_4) of the tilt angle (α_1), formed by the center of gravity and the tractor's rear left wheel ground contact point (S_6), and the tilt angle (α_3), formed by the center of gravity and the baler's rear left wheel ground contact point (S_7), is 31.45° (y-axis). In this case, 19.5° on the x-axis is the transverse overturning angle.

The following equations (19)-(21) show the tilt angles (α_2, α_1, α_3) at which tractor transverse overturning occurs at the ground contact points (S_5, S_6, S_7) of the individual wheels and the tilt angle (α_4) at which system transverse overturning occurs using MATLAB (R2010b). In this case, the maximum angle substituted into the average (α_4) of tilt angles (α_1, α_3) as a variable was determined to be the right transverse overturning angle.

$$\alpha_1 = -0.0016x^2 + 0.0887x + 39.355,\ R^2 = 0.9962 \quad (19)$$

$$\alpha_2 = -0.001x^2 + 0.1193x + 18.647,\ R^2 = 1 \quad (20)$$

$$\alpha_3 = -0.001x^2 + 0.1177x + 19.54,\ R^2 = 1 \quad (21)$$

$$\alpha_4 = -0.0013x^2 + 0.1032x + 29.447,\ R^2 = 0.9968 \quad (22)$$

Furthermore, using the same methods with regard to left transverse overturning, when the deflection angle was 180°, the tilt angle (α_6) formed by the center of gravity and the ground contact point (S_4) of the tractor's front right wheel reached its peak at 21.98° (Figure 7-(A)(a)), and the tilt angle (α_5) formed by the center of gravity and the ground contact point (S_3) of the tractor's rear right wheel reached its peak at 39.93° (Figure 7-(B)(b)). Additionally, the tilt angle (α_7) formed by the center of gravity and the ground contact point (S_2) of the baler rear right wheel reached its peak at 22.6° (Figure 7-(C)(c)).

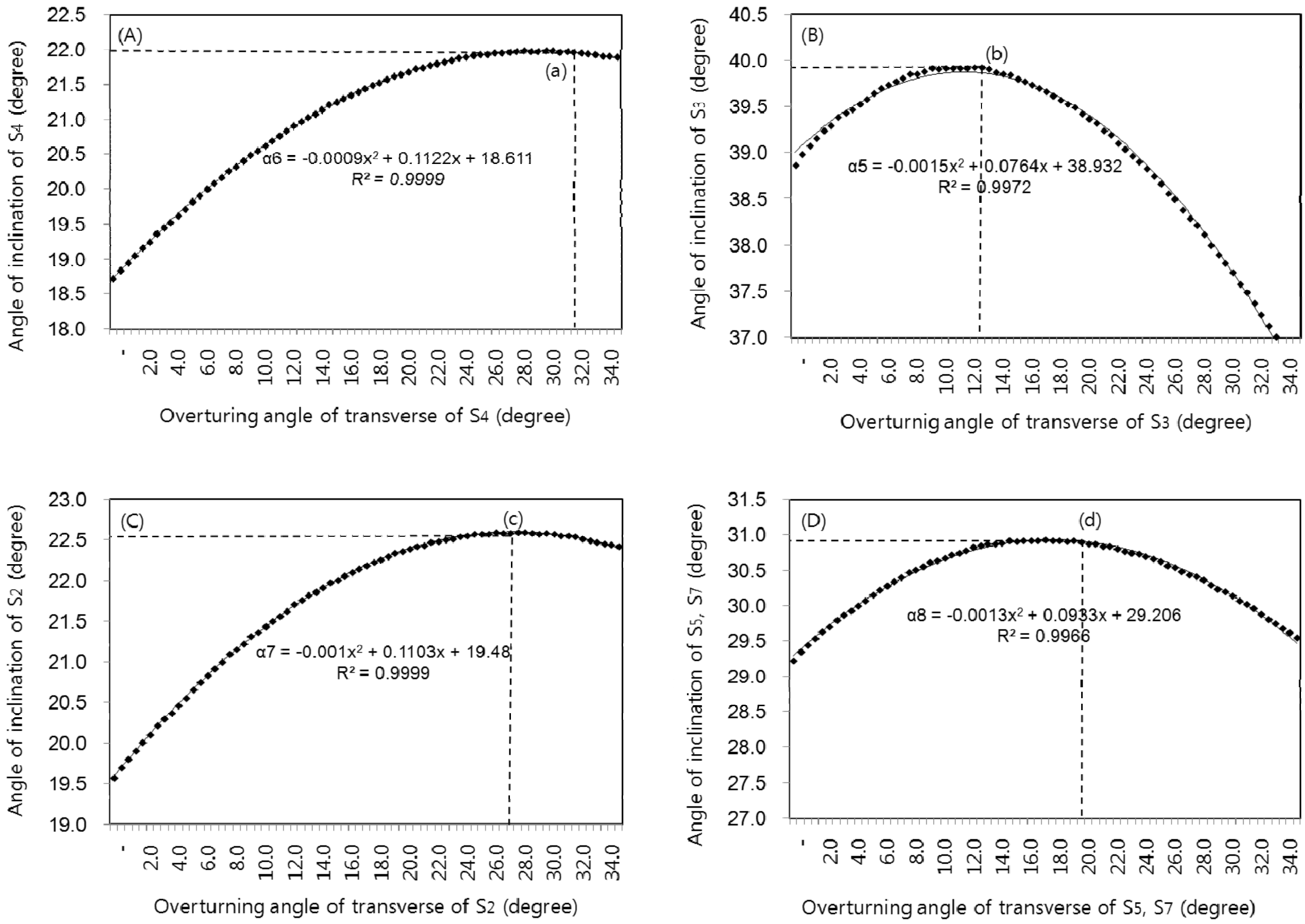

Figure 7. Tractor-baler system left transverse overturning analysis.

System transverse overturning occurred at 30.92° (Figure 7-(D)(d)), which is the average tilt angle (α_8) of the tilt angle (α_5), formed by the center of gravity and the ground contact point of the tractor's rear right wheel, and the tilt angle (α_7), formed by the center of gravity and the ground contact point of the baler rear right wheel. The transverse overturning angle in this case was calculated to be 19.5°. In this case, the absolute coordinate (X_{S1}, Y_{S1}, Z_{S1}) of the center of gravity was found to be (3112.5, 491.7, 1405.7) mm based on the baler's rear left wheel ground contact point (S_7). Therefore, the average tilt angle (α_8) of the tilt angle (α_5), formed by the center of gravity and the tractor's rear right wheel ground contact point (S_3), and the tilt angle (α_7), formed by the center of gravity and the baler's rear right wheel ground contact point (S_7), is 30.92° (y-axis). In this case, 19.5° on the x-axis is the transverse overturning angle.

Using the following equations (23)-(25), the tilt angles (α_7, α_5, α_6) at which tractor transverse overturning occurs at the ground contact points (S_2, S_3, S_4) of the individual wheels and the tilt angle (α_8) at which system transverse overturning occurs were calculated. In this case, the maximum angle substituted into the average (α_8) of tilt angles (α_5, α_7) as a variable was determined to be the left transverse overturning angle. The nearly symmetric left/right transverse overturning angles obtained using the mathematical equations are attributed to the fact that the y-axis coordinate value (Y_S) of the center of gravity leans toward the left from the center line by only 22.6 mm.

$$\alpha_5 = -0.0015x^2 + 0.0764x + 38.932,\ R^2 = 0.9972 \quad (23)$$

$$\alpha_6 = -0.0009x^2 + 0.1122x + 18.611,\ R^2 = 0.9999 \quad (24)$$

$$\alpha_7 = -0.001x^2 + 0.1103x + 19.48,\ R^2 = 0.9999 \quad (25)$$

$$\alpha_8 = -0.0013x^2 + 0.0933x + 29.206,\ R^2 = 0.9966 \quad (26)$$

Conclusions

This study focused on evaluation of the stability of a tractor-baler system with a tractor equipped with a newly developed baler and aimed to compare and analyze transverse overturning cases through mathematical simulations and verification experiments to review the possibility of commercialization of the system.

Based on the results of this analysis, the center of gravity of the system was lowered when a baler was attached to the tractor and the transverse overturning angle of the system steadily increased as the deflection angle increased or decreased between 0° and 180° when the gradient remained constant. Based on the results of simulations performed by applying the mathematical equations from previous research, right transverse overturning occurred at tilt angles greater than or equal to 19.5° with a range of deflection angles of from 82° to 262° in counter clockwise. Left transverse overturning also occurred at 19.5° with a range of deflection angles of from 259° to 79° in counter clockwise. In simulations of the tractor equipped with a loader performed at a deflection angle of 0°, transverse overturning occurred at a tilt angle of 17.9°, which is a difference of 2.3% from the result of the verification experiment, which was 17.5°. The simulations of the system used the center of gravity, as well as the correlations between the tilt angles formed by the center of gravity and individual wheel ground contact points, excluding the wheel radius and hinge point height, which cannot be easily measured, for the convenient use of mathematical equations. The results revealed that both left and right transverse overturning occurred at 19.5°.

The transverse overturning stability evaluation conducted through mathematical equation modeling of the system was stable enough to replace the mathematical equations from previous research, and the verification experiments and their results indicated that the system is workable on a 12° slope, which is the limit of use for agricultural machines on sloped farmland in South Korea, and on a 15° slope, which is the limit of use for agricultural machines on sloped farmland in Japan.

Conflict of Interest

The authors have no conflicting financial or other interests.

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References

Ahmadi, I. 2014. Effect of Transition of Mounted Chisel Plow from Operation to Transport on Longitudinal Stability of Tractor (Part 1-Modeling). Agriculturae Conspectus Scientificus 78(4):343-351.

Baker, V. and A. L. Guzzomi. 2013. A model and comparison of 4-wheel-drive fixed-chassis tractor rollover during Phase I. Biosystems Engineering 116(2):179-189.

Chen, W., Z. Zhang, and C. Zhou. 2009. Simulation for the handling and stability of four-wheel steering vehicle based on Matlab/simulink. Proceedings of the 2nd International Conference on Transportation Engineering pp.1908–1913.

Dahlberg, E. and N. G. Vagstedt. 1997. Advantages of a simple approach modeling heavy vehicle handling. SAE Special Publications 1308:113-120.

Daniel, A. F. and S. Adam. 2004. Passenger vehicle steady-state directional stability analysis utilizing EDVSM and SIMON. Proceedings of the WP HVE Forum, San Francisco, Calif, USA. WP#2004-3.

Demšar, I., R. Bernik and J. Duhovnik. 2012. A Math ematical Model and Numerical Simulation of the Static Stability of a Tractor. Agriculturae Conspectus Scientificus 77(3):143-150.

FACT (The Foundation of AG. Tech. Commercialization and Transfer). 2014. Test standards of agricultural machinery-agricultural Tractor. (In Korean).

FACT (The Foundation of AG. Tech. Commercialization and Transfer). 2012. Inspection report-agricultural Tractor RX601:12-M-3-154. (In Korean).

FACT (The Foundation of AG. Tech. Commercialization and Transfer). 2017. Inspection report-agricultural Tractor RX620:17-M-011. (In Korean).

Franceschetti, B., R. Lenain and V. Rondelli. 2014. Comparison between a rollover tractor dynamic model and actual lateral tests. Biosystems Engineering 127:79-91.

Gialamas, T. A., D. Bochtis, Y. Ampatzidis, D. Kateris, T. A. Gemtos and C. A. Tsatsarelis. 2006. Tractor stability estimation using adjusting testing-bench. In The International Conference HAICTA pp. 179-186.

Guzzomi, A. L. 2012. A revised kineto-static model for Phase I tractor rollover. Biosystems engineering 113(1):65-75.

Guzzomi, A. L., V. Rondelli, A. Guarnieri, G. Molari and P. G. Molari. 2009. Available energy during the rollover of narrow-track wheeled agricultural tractors. Biosystems Engineering 104(3):318-323.

Hussain, K., W. Stein and A. J. Day. 2005. Modelling commercial vehicle handling and rolling stability. Journal of Multi-Body Dynamics 219(4):357-369.

Hillegass, M. J., J. G. Faller, M. S. Bounds, M. El-Gindy and A. S. Joshi. 2004. Validating the directional performance of multi-wheeled combat vehicle computer simulation models. Proceedings of the ASME International Mechanical Engineering Congress and Exposition pp.781-789.

ISO/DIS. 2012. Draft International Standard: Self-propelled agricultural machinery- Assessment of stability 16231-2.

Jang, Y. S., J. H. Yun and W. R. Lee. 1991. A Study on Improvement of Adaptability of Slopes in Agricultural Machinery pp.128-135. Code No.:230301-2. (In Korean).

Jung, S. Y. and K. U. Kim. 1990. Simulation of transverse overturning of Agricultural Tractor-Trailer Systems 15(4):298-309. (In Korean, with English abstract).

Jung, C. J., K. H. Ru, S. R. Kim, Y. W. Kim, K. M. Lee, H. G. Song, K. D. Cha, J. H. Lee, Y. G. Lee and H. K. Go. 1974. Agricultural mechanics pp.283-299.

KOROAD. 2016. The summary of traffic accident statistics pp. 35-41. (In Korean).

Lee, Y. R., J. H. Yun, Y. S. Jang and H. S. Park. 1989. A Study on Improvement of Adaptability of Slopes in Agricultural Machinery pp.170-177. Code No.:2303-03. (In Korean).

Lee, Y. R., J. H. Yun, H. S. Park and Y. S. Jang. 1990. A Study on Improvement of Adaptability of Slopes in Agricultural Machinery pp.156-185. Code No.:2303-01. (In Korean).

Li, X., G. Wang, Z. Yao and J. Qu. 2013. Dynamic model and validation of an articulated steering wheel loader on slopes and over obstacles. Vehicle System Dynamics 51(9):1305-1323.

Liu, L. 2010. Nonlinear analysis and control strategy evaluation on the stability of vehicle 3-DOF planar motion [Ph. D. thesis], College of Traffic, Jilin University.

Lukowski, S., M. Momot, D. Kraemer and D. Kunz. 2009. Basic linear theory of handling and stability of automobiles. Journal of Automobile Engineering 223(1): 1-10.

MAFF (Ministry of Agriculture, Fisheries, and Food). 2017. Specific farming village law-Direct support system for middle-moun tainous area. (In Japanese).

MAFRA (Ministry of Agriculture, Food and Rural Affairs). Agricultural Mechanization Promotion Act. Article 9. 2017. (In Korean).

MAFRA (Ministry of Agriculture, Food and Rural Affairs). 2002. A study on GIS gradient-based coverage area map building for a direct farmland payment program in less favored areas pp.66-76. (In Korean).

Mathijs, K. 2010. Longitudinal force distribution and road vehicle handling [Ph. D. thesis], Department of Applied Mechanics, Chialmers University of Technology.

NAAS (National Institute of Agricultural Sciences). 2016. The damage situation of Farmers related to agricultural machinery pp.39-48. Publication registration No.: 11-1390802-001087-01. (In Korean).

Nidal. H. H. and A. J. Hamidf. 2004. Computer simulation of stability and control of tractortrailed implement combinations under different operating conditions Bragantia Campinas 63(1):149-162.

Pacejka, H. B. 1973. Simplified analysis of steady-state turning behaviour of motor vehicles part 1. Handling diagrams of simple systems. Vehicle System Dynamics 2(3):161-172.

Pacejka, H. B. 1973. Simplified analysis of steady-state turning behaviour of motor vehicles part 2: stability of the steady-state turn. Vehicle System Dynamics 2(4):173-183.

Pacejka, H. B. 1973. Simplified analysis of steady-state turning behaviour of motor vehicles part 3: more elaborate systems. Vehicle System Dynamics 2(4): 185-204.

Park, K. J. and U. L. Park. 1992. Simulation of Motion and Overturns for Power Tiller-Trailer System. Journal of Biosystems Engineering 17(1):27-36. . (In Korean, with English abstract).

Pereira, D. P., N. C. Fiedler, M. D. O. Bauer, A. V. Rezende, A. A. Missiaggia and J. B. P. Simão. 2011. Lateral stability limits of farm tractors for forest plantations in steep areas. Sci. For Piracicaba 39(92): 433-439.

Popescu, S. and N. Sutru. 2009. Contributions to the study of the dynamics of agricultural tractors equipped with front-end loader and rear forklift loader. Engineering for Rural Development-International Scientific Con. 165-170.

Rédl, J., V. Váliková and J. Antl. 2014. Design of active stability control system of agricultural off-road vehicles. Research in Agricultural Engineering 60:77-84.

Shim, S. B., Y. J. Park, K. U. Kim, J. W. Kim, M. S. Park and T. Y. Song. 2005. Computer Simulation of transverse overturning of Side-Loaded Mini-Forwarder. Journal of Biosystems Engineering 30(6):366-372. (In Korean, with English abstract).

Vincent, N. 2005. Vehicle handling, stability, and bifurcation analysis for nonlinear vehicle models [M. S. thesis]. Department of Mechanical Engineering, University of Maryland.

Vidoni, R., M. Bietresato, A. Gasparetto and F. Mazzetto. 2015. Evaluation and stability comparison of different vehicle configurations for robotic agricultural operations on side-slopes. Biosystems Engineering 129:197-211.

Wang, W. H. 2002. A digital-driving system for smart vehicles, IEEE Intelligent Systems 17(5):81–83.

Wang, W. H., W. Zhang, H. W. Guo, H. Bubb and K. Ikeuchi. 2011a, A safety-based approaching behavioural model with various driving characteristics. Transportation Research (Part C) 19(6):1202-1214.

Wang, W. H., M. Yan, J. Jin, X. Wang, H. Guo, X. Ren and K. Ikeuchi. 2011b. Driver's various information process and multi-ruled decisionmaking mechanism: a fundamental of intelligent driving shaping model. International Journal of Computational Intelligence Systems 4(3):297-305.

Winkler, C. B. 1998. Simplified analysis of the steady-state turning of complex vehicles. Vehicle System Dynamics 29(3):141-180.

Yeh, E. C. and Y. L. Chen. 1990. Handling analysis of a motorcycle with added cambering of the front frame. Vehicle System Dynamics 19(2):49-70.

Zhao, Q. F., T. He and W. J. Xu. 2012. The research of vehicle handling stability based on ADAMS. Applied Mechanics and Materials 127:248-251.