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https://doi.org/10.5109/1564097

出版情報：九州大学大学院農学研究院紀要. 61 (1), pp.153-156, 2016-02-29. 九州大学大学院農学研究院

J. Fac. Agr., Kyushu Univ., **61** (1), 153–156 (2016)

Effect of Geometric Configuration on Tractor Stability Characteristics

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(*Received November 4, 2015 and accepted November 19, 2015*)

In this study, tractor stability was discussed from the aspects of rollover initiation, vertical and lateral vibration characteristics considering tractor dynamics in Phase I overturn. As two of the key geometric parameters of a tractor, track width ratio and wheel base ratio were intro–duced into the mathematical model developed earlier as the independent variables. Results showed that both factors greatly reduced the risk of initializing tractor rollover with their in–creasing values. Higher track width ratios were found to generally enhance the contact condition between the sensitive tire and the ground, while higher wheel base ratios showed an effect of stabilizing the vehicle more rapidly after a disturbance. However, no obvious changes in tractor bounce acceleration were observed with the variation in track width ratio, nor were the changes in lateral acceleration found with different values of wheel base ratio.

Key words: geometric parameter, tractor stability, lateral rollover

INTRODUCTION

The safety of tractor operators highly depends on tractor stability. There are ways to look into various aspects of stability characteristics of agricultural machineries, such as experimental and simulation approaches (Davis and Rehkugler, 1974; Zhu *et al.*, 2014). Mathematical modeling, from another perspective, avoids high cost while providing fundamental mechanisms which can be further applied for research or commercial use. Taking into consideration the dynamic re–sponse of a tractor, previous studies have shown the effects of tractor speed, lateral slope angle, coefficient of friction, and obstacle height on tractor behaviors (Li *et al.*, 2014a, 2014b, 2015; Li *et al.*, 2015a, 2015b). As for tractor geometry, it has been discovered that the track width ratio predominantly influences tractor stability against rollover (Allen *et al.*, 1992).

From a static perspective, such influence can be represented as the ability of tractor resisting rollover on the corresponding maximum lateral incline, as shown in Fig. 1. It can be seen that the allowable lateral gradient steadily grows with increases in track width ratio. Although an infinitely increasing trend is predicted, only the tractor models in static or quasi–static state are suitable to be applied to. In a dynamic case, however, a tractor tends to lose stability on much more gentle slopes. For example, even a small bump can roll a tractor over considering a low speed for tractor physical configurations with certain track width ratios. Another key parameter related to tractor geometry is the wheel base ratio. A change in wheel base ratio affects the locations of the COGs of tractor components and consequently influences tractor response to disturbances.

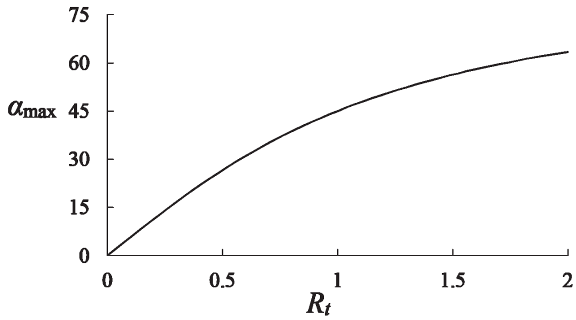

Fig. 1. Limit lateral slope angle for tractor static rollover.

As stated by Li *et al.* (2015), predictions of rollover initiation benefit the operators by providing more reacting time to adjust tractors, tractor stability characteristics during Phase I overturn were further investigated in this study. Parameters of track width ratio and wheel base ratio were considered as the two factors varying tractor behavior under dynamic conditions.

MATERIALS AND METHODS

The mathematical model developed by Li *et al.* (2015) was adopted in this study. This model considers a conventional agricultural wheel tractor as two parts: the rotatable front end and the main body. Both of them have respective centers of gravity (COGs) and the two parts are con–nected at the front axle pivot. As long as the relative roll motion between the two parts stays within the designed swing angle, the front end and the main body roll independently, which de–clares the constraint

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condition under which this model is properly considered.

Tractor stability characteristics were investigated from the perspectives of rollover initiation, tractor vertical (bounce) and lateral accelerations. Tractor potential of falling into Phase I over–turn due to loss of tire–ground contact was evaluated by the overturning indicator (i_o) proposed by Li *et al.* (2015). The zero value of i_o indicates loss of contact between a specific tractor tire and the ground. Therefore a region of interest approaching zero implies a decreasing trend of tractor stability against rollover. Furthermore, tractor vertical and lateral accelerations were de–rived from global observation according to the adopted model.

Among the key geometric parameters of a tractor, we assigned track width ratio (R_t) and wheel base ratio (R_w) as the main factors influencing tractor stability. Track width ratio is commonly defined as the ratio of half the track width to the COG height. As illustrated in Fig. 2, it follows the form:

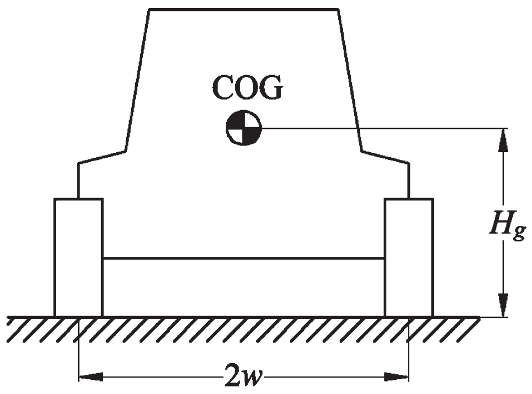

Fig. 2. Tractor geometry, back view.

$$R_t = \frac{w}{H_g} \tag{1}$$

Wheel base ratio is the ratio of the wheel base to the COG height:

$$R_w = \frac{L}{H_g} \tag{2}$$

Note that for the adopted mathematical model, each part of the tractor is separately analyzed basing on the corresponding COG. It is therefore necessary to determine the positions of the anterior, posterior and entire COGs while the wheel base changes. Consider that the proportion of the longitudinal distance between the front or rear wheels and the entire COG (L_f or L_r) is fixed. Measurements carried out by Takeda *et al.* (2010) indicate that $L_f = 0.562L$ and $L_r = 0.438L$. Using the parameter values of the example tractor given by Takeda *et al.* (2010), one can consequently notice the relation between the ground supporting forces applied to the front and rear tires as $F_f = 0.78F_r$. As illustrated in Fig. 3, the following equations can be obtained considering the static state of tractor:

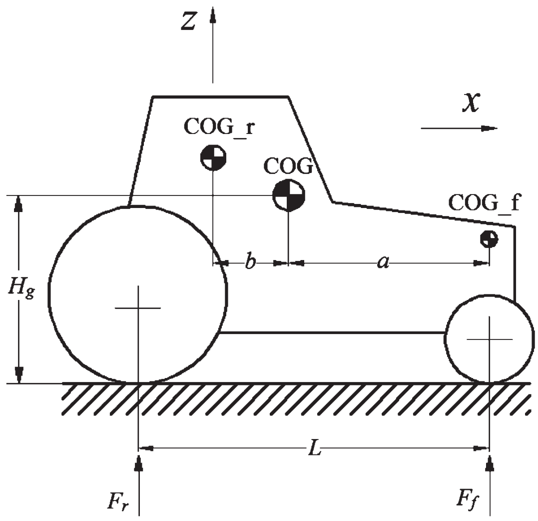

Fig. 3. Schematic of tractor geometric configuration, considering the tractor as the combination of the front end and the main body, right side view.

$$F_f + F_r - (m_f + m_r)\,g = 0 \tag{3}$$

$$m_r g(a + b) - F_r L = 0 \tag{4}$$

where m_f is the mass of the front end, kg; m_r is the mass of the main body, kg; a is the longitu–dinal distance between the anterior COG and the entire COG, m; b is the longitudinal distance between the posterior COG and the entire COG, m; g is the acceleration due to gravity, m s^{-2}.

Assuming the anterior COG to be located in the tractor mid–plane above the pivot point at the geometric center of the front axle gives a = L_f. It then determines the horizontal location of the posterior COG as:

$$b = \left(\frac{m_f + m_r}{1.78 m_r} - 0.562\right)L \tag{5}$$

In this way, the longitudinal locations of the COGs are determined with the wheel base varies. Predictions of tractor behavior were carried out through programming with Microsoft Excel Worksheet. The example tractor was set to travel over a half–sine bump on a 5° lateral slope at the speed of 0.5 m s^{-1}. For the dimensions of the obstacle, we referred to the same values given by Takeda *et al.* (2010) for the bump dimensions. The bump was set under the tires on the right side of the tractor. Furthermore, the coefficient of friction between the tires and the ground was considered 0.9. Other parameters required for simulation but unavailable from the work of Takeda *et al.* (2010) were cited from Li *et al.* (2015). Note that although Li *et al.* (2015) stated another stability index (i_s) denoting the tractor sliding potential, the predominant factors influ–encing i_s were found to be tractor speed, lateral slope angle, and coefficient of friction. There–fore, these parameters were set as fixed values in our case. Consequently, the stability of the example tractor against sideslip was not concerned in this study. As declared by Li *et al.* (2015), the example tractor we used tended to lose stability against rollover due to loss of tire contact with the ground at the uphill rear tire. Thus, i_o was discussed considering the contact condition of the uphill rear tire of the example tractor in this study. Furthermore, tractor vertical and lateral vibration characteristics were analyzed basing on the entire COG of the tractor.

RESULTS AND DISCUSSION

The influence of the track width ratio on tractor overturning risk over time is presented in Fig. 4. With the track width ratios in the 0.5–2.0 range, a generally increasing trend of i_o can be seen with the values of R_t in ascending order (note that a zero value of i_o indicates loss of stability). There are two main regions of interest shown in Fig. 4. The first one starts from the beginning of simulation, indicating that the uphill front tire is passing over the bump. The second region of interest, which is much more obvious than its counterpart, represents the obstacle–surmounting passage of the uphill rear tire. The values of i_o approaching zero give the essential reason that results to the initiation of rollover. From the results, we found that for small values of R_t, i_o was extremely unstable and the tractor would lose stability when the uphill rear tire was passing over the bump. Such unsteadiness rapidly reduces with increases in R_t. For high track width ratios, the variation of i_o was found to be minor throughout all the obstacle–surmounting periods. Ac–cordingly, the tractor is not supposed to face an overturning problem under the corresponding condition.

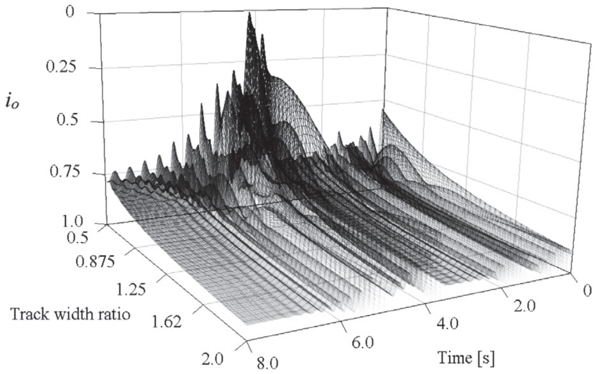

Fig. 4. Effect of track width ratio on tractor overturning index (i_o).

As Fig. 5 shows, track width ratio was found to have negligible effect on tractor vertical ac–celeration. It is clear that the amplitudes of the vertical acceleration throughout the four obsta–cle–surmounting periods of the tractor nearly stay at the same level. However, low track width ratios were discovered to slightly influence the acceleration amplitude after the uphill front and rear tires have passed over the bump. Furthermore, for the values of R_t in the low range, vertical acceleration was found to fluctuate as the track width ratio increases.

Tractor lateral acceleration at the entire COG influenced by the track width ratio is shown in Fig. 6. Similar to Fig. 5, the effect of the track width ratio on the acceleration amplitude is mi–nor. However, low ratios were found to greatly affect the steadiness of the acceleration values. Moreover, a lightly decreasing trend of acceleration was observed during the obsta–cle–surmounting passage of the uphill front tire. As the track width ratio rises, lateral accelera–tion converges to zero more rapidly. In addition, there are three main regions of interest refer–ring to acceleration amplitude, which differs from the results revealing four regions as shown in Fig. 5.

Compared with Fig. 4, the variations in wheel base ratio result in more intense changes in the stability of the tractor, as shown in Fig. 7. Especially, for the wheel base ratios under 2.0, the contact condition between the uphill rear tire and the ground appears to be highly unstable. An increase in tractor speed or slope angle may immediately lead to loss of contact and draw the tractor into a rollover mode. From an overall perspective, however, increasing the wheel base ratio enhances tractor stability against rollover. Moreover, i_o becomes increasingly stable and converges to the value of 1 (the initial stable status) more rapidly after the tractor has passed over the bump as the wheel base ratio increases, which implies the improved tractor ability of resisting the disturbance due to external exciters. Accordingly, the tractor can easily returns to a stable state and regains sufficient stability to support operations at higher speeds or on steeper slopes.

Changes in vertical acceleration due to the variations in wheel base ratio is shown in Fig. 8. It is clear that an

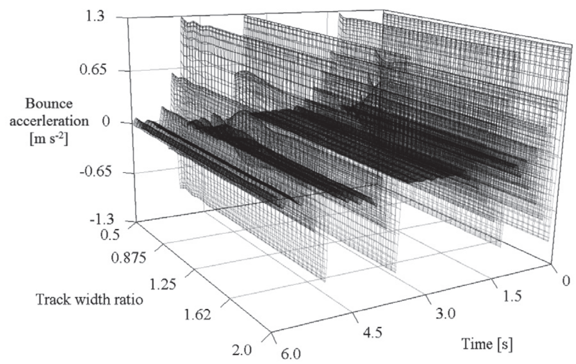

Fig. 5. Effect of track width ratio on bounce acceleration.

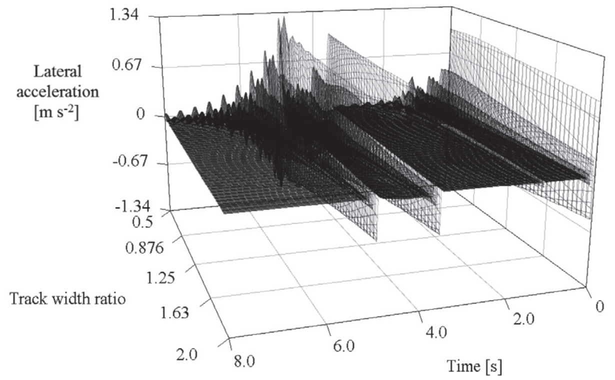

Fig. 6. Effect of track width ratio on lateral acceleration.

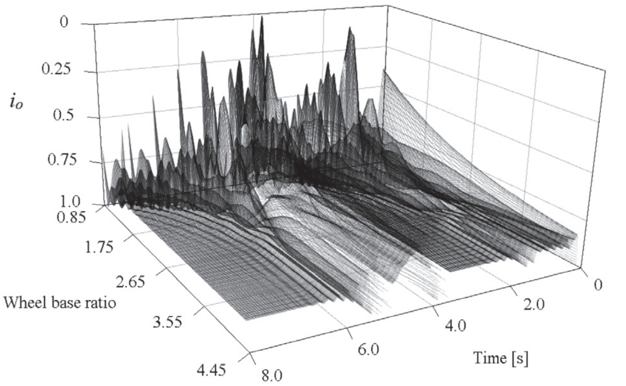

Fig. 7. Effect of wheel base ratio on tractor overturning index (i_o).

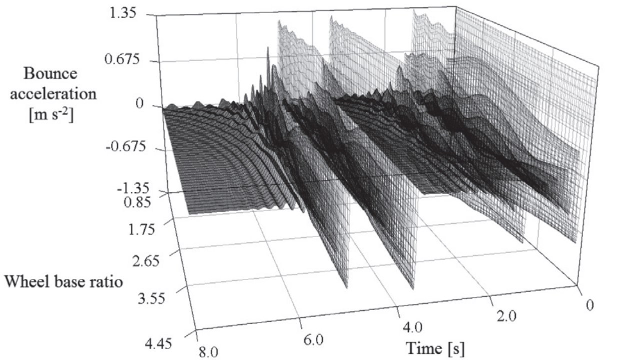

Fig. 8. Effect of wheel base ratio on bounce acceleration.

increase in wheel base ratio helps gradually reduce the acceleration amplitude to a small extent. For the wheel base ratios under the value of 2.0, R_w was found to have a fluctuant effect on determining the amplitude of vertical acceleration. There is a generally decreasing trend of acceleration with increases in R_w. Although the wheel base ratio was not found to sig–nificantly affect the acceleration amplitude, higher ratios certainly change the vibration charac–teristics by shortening time duration of stabilizing the tractor after a disturbance. Furthermore, different from the results shown in Fig. 6, R_w was found to have nearly negligible influence on lateral acceleration.

CONCLUSIONS

Two key parameters of the tractor geometry: track width ratio and wheel base ratio were con–sidered as the factors influencing tractor stability against rollover and introduced into the mathematical model developed by Li *et al.* (2015). We investigated tractor stability characteris–tics from the aspects of rollover initiation, vertical and lateral accelerations.

According to the results, the increases in both R_t and R_w appear enhance the tractor ability of resisting loss of contact between the uphill rear tire and the ground, while the decreases in them have a reverse effect. It was also found that greater values of R_w helped stabilize the tractor more rapidly. The same effect was discovered for the parameter of R_t and R_w resulting in the lateral and vertical accelerations, respectively. Furthermore, as the estimated results show, R_t and R_w have negligible effects on the vertical and lateral accelerations, respectively. Therefore, for the higher values of R_t and R_w, it mainly improves tractor stability by restraining the sensitive tire from lifting up and shortening the recovery time after experiencing a disturbance.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support received from the China Scholarship Council.

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