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Prediction of Tractive Performance of Tracked Vehicles Using a Computer Simulation Model

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Abstract: A mathematical model was developed for estimating the mechanical interrelation between characteristics of soil and main design factors of a tracked vehicle, and predicting the tractive performance of the tracked vehicle. Based on the mathematical model, a computer simulation program (TPPMTV) was developed in the study. The model considered the continuous change in tension for the whole track of a tracked vehicle, the analysis of shape and tension of the track segment between sprocket and first roadwheel, and the side thrust on both sides of grouser by the active earth pressure theory in predicting the tractive performance of a tracked vehicle. Also, the model contained not only sinkage depth of the track but the pressure distribution under the track in analyzing the side thrust. The effectiveness of the developed model was verified by performing the drawbar pull tests with a tracked vehicle reconstructed for test in loam soil with moisture content of 18.92%. The predicted drawbar pulls by the model were well matched to the measured ones. Such results implied that the model developed in the study could estimate the drawbar pulls well at various soil conditions, and would be very useful as a simulation tool for designing a tracked vehicle and predicting its tractive performance.

Keywords: Mathematical model, Tracked vehicle, Tractive performance, Computer simulation, Drawbar pulls

Introduction

The tractive performance of tracked vehicle operated on various terrains is greatly influenced by soil-track interaction. In the past decades, many studies have been conducted to investigate the interrelation between soil and track. The major concerns of the studies were the mechanical characteristics of soil on which tracked vehicles were operated, and the distribution of normal and shear stress associated with soil-track interaction. Such a research approach was suggested by Bekker (1956, 1969), and then many related researches have been reported in this area (Wong, 1989; Okello, 1994).

Based upon the studies, it is possible to predict the tractive performance of tracked vehicles for a given terrain condition and use the prediction for optimum design of a tracked vehicle with improved performance. Therefore, the object of the study were to develop a mathematical model for estimating the mechanical interrelation between characteristics of soil and main design factors of tracked vehicles and predicting their tractive performance, and to implement a computer simulation program for executing the mathematical model.

Traction Model

For a tracked vehicle inclined with an angle δ, the entry angle α_1 of the first roadwheel is determined by the sinkage Z_{0_1} and the radius r of roadwheel on the assumption that there exists initial sinkage (status 1 in Fig. 1). When the soil surface, however, is located above the point α_0 on the roadwheel due to the large sinkage Z_{0_2}, the track segment above the point receives a soil reaction. Therefore, the tension of the track segment increases by the reaction and its shape changes from the straight to a curve (status 2 in Fig. 1). As the result, the initial entry angle α_1 of the first roadwheel changes to α_1' and the angle α_0, which is associated with the point on the sprocket at which the track and the sprocket are separated, varies to an angle α_{fsp}. Thus, the shape of the track segment would change from status 1 to status 2 in Fig. 1.

At the status 2 in Fig. 1, the total track segment osculating on the sprocket from the angle α_0 through α_{fsp} can be represented by adding a finite number of track elements with an infinitesimal length Δl as shown in Fig. 2. On considering the force equilibrium

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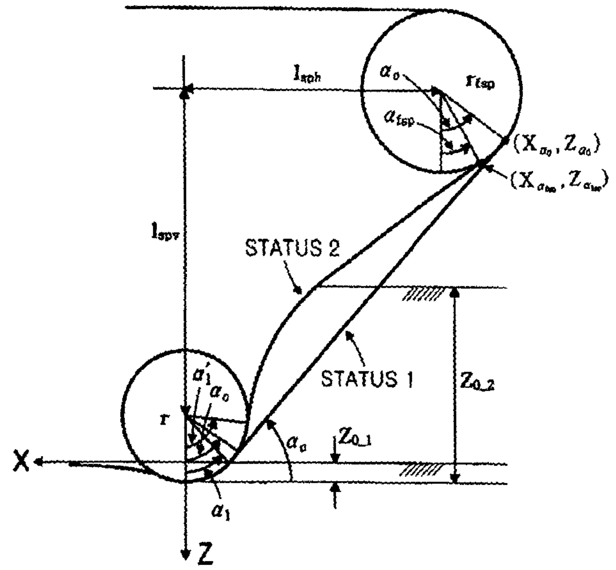

Fig. 1 The change in shape of track segment with the depth of sinkage.

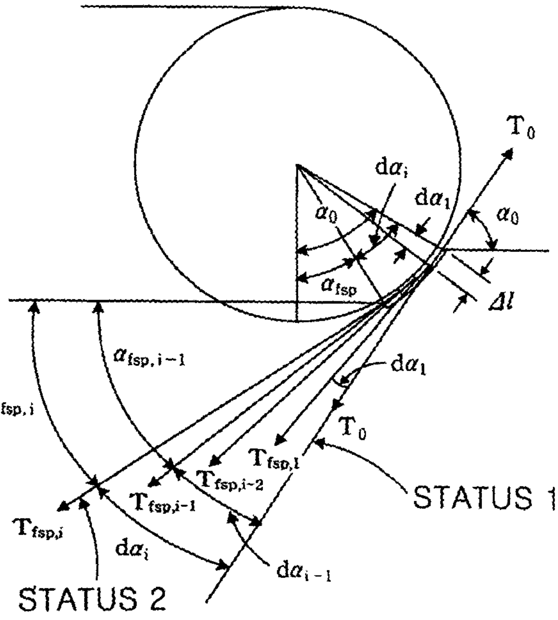

Fig. 2 The analysis of tensions acting on the track elements on the sprocket.

at the first through the first element for the track segment on the sprocket between the angle α₀ and an arbitrary angle $\alpha_{fsp,i}$, the equilibrium equation for each element can be represented by equation (1). Thus, the tension of a track element separated at an arbitrary location on the sprocket is determined from equation (1).

$$T_{fsp,i}\cos d\alpha = T_{fsp,i-1} + b\int_{\frac{\pi}{2}-\alpha_{fsp,i-1}}^{\frac{\pi}{2}-\alpha_{fsp,i}} \tau(\theta)\cos[\theta-(\frac{\pi}{2}-\alpha_{fsp,i-1})]r_{fsp}d\theta$$

$$+b\int_{\frac{\pi}{2}-\alpha_{fsp,i-1}}^{\frac{\pi}{2}-\alpha_{fsp,i}} p(\theta)\sin[\theta-(\frac{\pi}{2}-\alpha_{fsp,i-1})]r_{fsp}d\theta \quad (1)$$

where

$T_{fsp,i}$ = the tension of ith track element separated from the sprocket
($T_{fsp,0}=T_{\alpha 0}=T_0$; T_0 is the initial tension of track segment)

$\alpha_{fsp,i}$ = the angle of ith track element separated from the sprocket with respect to the horizontal
($\alpha_{fsp,i}=\alpha_0 \quad d\alpha_i$, $\alpha_{fsp,0}=\alpha_0$)

$d\alpha_i$ = the angle change of ith track element on the sprocket with respect to the initial angle α₀
($d\alpha=d\alpha_1=\frac{\Delta l}{r_{fsp}}\times 1$, $d\alpha_2=\frac{\Delta l}{r_{fsp}}\times 2$, …, $d\alpha_i=\frac{\Delta l}{r_{fsp}}\times i$)

Δl = the length of a track element

b = the width of the track

In order to determine the change in shape and tension of the track segment between the sprocket and the first roadwheel, we can assume again that the track segment be represented as a summation of a finite number of track elements with an infinitesimal length Δl (Fig. 3).

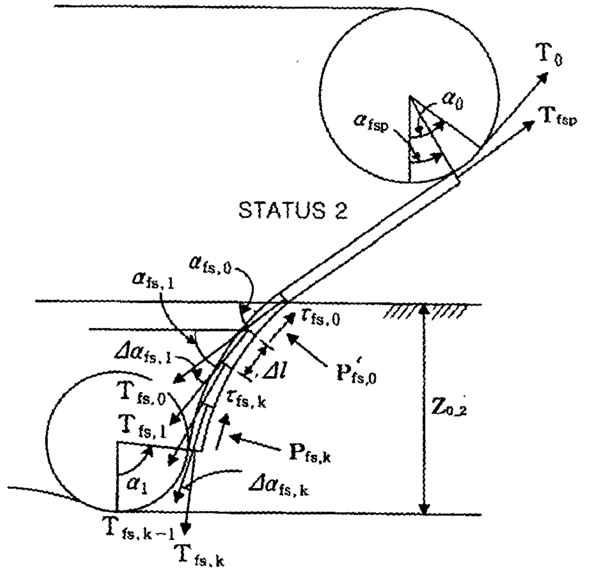

Fig. 3 Forces acting on elements of track segment between sprocket and first roadwheel.

Then, the force equilibrium for each track element can be represented as follows.

$$T_{fs,k} \cos \Delta\alpha_{fs,k} = T_{fs,k-1} + b\Delta l \tau_{fs,k-1} \qquad (2)$$

$$T_{fs,k} \sin \Delta\alpha_{fs,k} = b\Delta l p_{fs,k-1} \qquad (3)$$

where

$T_{fs,k}$ = the tension of kth track element on the track segment between the sprocket and the first roadwheel

$T_{fs,k-1}$ = the tension of (k-1)th track element on the track segment between the sprocket and the first roadwheel ($T_{fs,0} = T_{fsp}$)

$\Delta\alpha_{fs,k}$ = the angle difference between (k-1)th and kth track element

$\tau_{fs,k-1}$ = the shear stress acting on (k-1)th track element

$p_{fs,k-1}$ = the vertical normal stress acting on (k-1)th track element ($\tau_{fs,k-1} = p_{fs,k-1} = 0$ at $Z \leq 0$; the Z coordinate of a track element lies above the ground)

The coordinates (X, Z in Fig. 1) and the tension of an arbitrary track element between the sprocket and the first roadwheel at a certain escape angle($\alpha_{fsp,i}$) on the sprocket can be calculated by applying the equations (2) and (3) iteratively. The application of three equations (1), (2) and (3) is based on a trial and error approach because the escape angle is also unknown at the initial stage. Thus, the iteration of three equations stops when two conditions are satisfied at the same time while iterating. The one condition is that the coordinates of a certain element calculated by continuously increasing the number of track elements from the first through the arbitrary element are coincident to the predetermined perimeter coordinates of the first roadwheel. The other is that the calculated slope of the arbitrary track element is the same as the actual one (the tangential of the first roadwheel) at the coincident point on the first roadwheel. Based on this approach, the escape angle of track element separated from the sprocket, the entry angle into the first roadwheel, the shape and the tension at an arbitrary location of the track segment can be obtained simultaneously.

For a tracked vehicle with n roadwheels, the shape of the whole track can be determined by expanding the approach to all roadwheels and track segments with the equations (1), (2) and (3). In addition, the vertical and the horizontal force, moment equilibrium in the whole track of the vehicle should be examined at this stage of simulation. With changing slope and sinkage of the vehicle, the examining process continues until three equilibrium conditions are satisfied. The motion resistance, thrust and drawbar pull of the tracked vehicle can be estimated at a complete equilibrium.

In this study, not only the thrust occurred under the track but the side thrust on both sides of grousers was considered in predicting the tractive performance of tracked vehicles. When there exists a pressure (p) at an arbitrary point under the track, the horizontal stress on sides of the track exerted by soil between grousers was calculated by applying the active earth pressure theory. In case of including friction (ø) and cohesion (c) of soil, the side shear stress per unit length on both sides of one track can be represented by the following Mohr-Coulomb equation.

$$T_{side} = 2\ (ch + P_A \tan ø) \qquad (4)$$

where

P_A = the active earth pressure acting on the side of track along with the grouser height(h)

P_A = $[\frac{\gamma h^2}{2} + ph] \tan^2[45° - \frac{\phi}{2}] - 2ch \tan[45° - \frac{\phi}{2}]$

γ = unit weight of soil

By integrating the equation (4) on the whole length of track, the total side thrust (H_{side}) acting on both sides of two tracks can be represented by equation (5).

$$H_{side} = 2 \int_0^l \tau_{side} \cos \theta \, dl \qquad (5)$$

Field Test

The effectiveness of the developed model was verified by performing drawbar pull tests with a tracked vehicle reconstructed for test in loam soil with moisture content of 18.92%. In the study, the number of roadwheels, the initial track tension and the vehicle weight were selected as design factors of a tracked vehicle for drawbar pull test. The basic test was

Table 1 Design conditions of vehicles for drawbar pull test

Vehicle \ Factors	Initial track tension	Vehicle weight	Roadwheel number	Difference to reference
Reference vehicle	0.49 kN	5.39 kN	4	
Vehicle Ⅱ	0.98 kN	5.39 kN	4	Initial track tension
Vehicle Ⅲ	0.49 kN	5.39 kN	3	Roadwheel number
Vehicle Ⅳ	0.49 kN	4.606 kN	4	Vehicle weight

conducted with a reference vehicle having four roadwheels, the initial track tension of 0.49kN and the vehicle weight of 5.39kN. To verify the model at various design conditions, three different types of vehicles were reconstructed by changing one of three selected factors on the reference vehicle; three roadwheels, initial track tension of 0.98kN and vehicle weight of 4.606kN (Table 1). The model was implemented to a computer simulation program named TPPMTV. The drawbar pulls predicted by the model were compared with the ones measured by field tests.

Results and Discussion

Fig. 5 through Fig. 8 show the results of drawbar pull tests at various slips for reference vehicle, vehicle II, vehicle III and vehicle IV, respectively. In the figures, the points represent the measured drawbar pulls and the solid line shows the predicted ones obtained by using the model and the computer simulation program TPPMTV. The figures show that the predicted drawbar pulls with changing slip were similar to the measured ones in the whole range of slip for all the four vehicles.

Table 2 shows the determinant coefficients (R^2) and the regression coefficients between the predicted and the measured drawbar pulls for four vehicles. For the reference vehicle, vehicle II, vehicle III and vehicle IV, the values of R^2 between the predicted and the measured drawbar pulls were 0.7033, 0.7623, 0.7362 and 0.8341, respectively. Also, the regression coefficients were 1.039, 1.059, 0.9958 and 1.1533, respectively, so

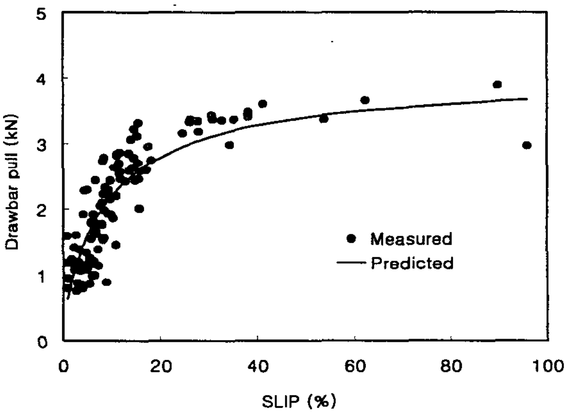

Fig. 5 Predicted and measured drawbar pulls with slip for vehicle Ⅱ.

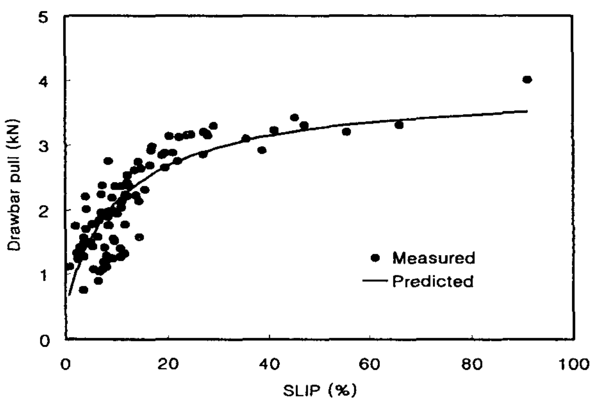

Fig. 4 Predicted and measured drawbar pulls with slip for reference vehicle.

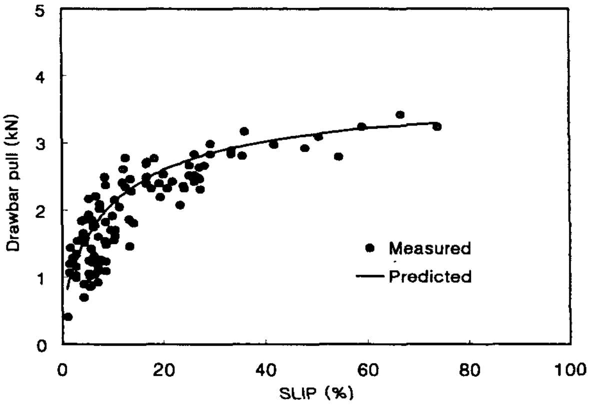

Fig. 6 Predicted and measured drawbar pulls with slip for vehicle Ⅲ.

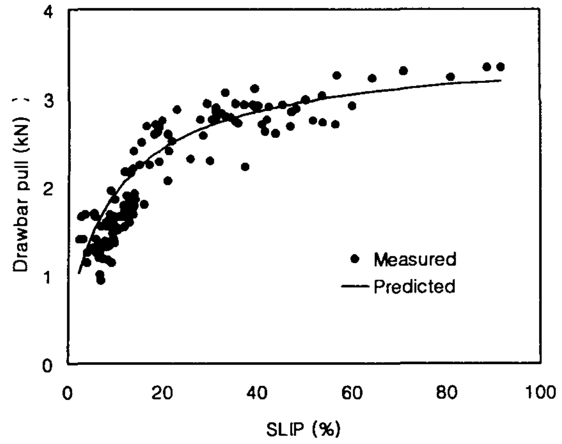

Fig. 7 Predicted and measured drawbar pulls with slip for vehicle Ⅳ.

that the predicted drawbar pulls were well matched to the measured ones in the whole range of slip. Such results implied that the model developed in the study could estimate drawbar pulls well at various soil conditions, and would be very useful as a simulation tool for designing a tracked vehicle and predicting its tractive performance.

Table 2 The determinant and the regression coefficients for drawbar pull test

Vehicle	Determinant coefficient (R^2)	Regression coefficient
Reference vehicle	0.7033	1.0390
Vehicle Ⅱ	0.7623	1.0594
Vehicle Ⅲ	0.7362	0.9958
Vehicle Ⅳ	0.8341	1.1533

Conclusions

This study was conducted to develop a mathematical model of estimating the mechanical interrelation between characteristics of soil and main design factors of tracked vehicles and predicting their tractive performance, and to implement a computer simulation program for executing the mathematical model. The developed model has the following characteristics.

1. The continuous change in tension for the whole track of a tracked vehicle was included in the analysis of a soil-track system.
2. In order to apply the model for a soil-track system with deep sinkage, the analysis of shape and tension of the track segment between the sprocket and the first roadwheel was included in the model.
3. The side thrust on both sides of grouser as well as the thrust occurred under the track was considered in predicting the tractive performance of a tracked vehicle. The horizontal stress on sides of the track exerted by soil between grousers was calculated by applying the active earth pressure theory. Also, the model contained not only sinkage depth of the track but the pressure distribution under the track in analyzing the side thrust.

For four different types of vehicles, the predicted drawbar pulls with changing slip were similar to the measured ones in the whole range of slip. The regression coefficients were 1.039, 1.059, 0.9958 and 1.1533, respectively, so that the predicted drawbar pulls were well matched to the measured ones in the whole range of slip. Such results implied that the model developed in the study could estimate the drawbar pulls well at various soil conditions, and would be very useful as a simulation tool for designing a tracked vehicle and predicting its tractive performance.

References

Bekker, M. G., 1956, Theory of land locomotion. University of Michigan Press.

Bekker, M. G., 1969, Introduction to terrain vehicle system. University of Michigan Press.

Okello, J. A., 1994, Prediction and experimental validation of the field tractive performance of a rubber track unit. Journal of Agricultural Engineering Research, 59(2):163-171.

Wong, J. Y., 1989, Terramechanics and off-road vehicles. Elsevier Publishers.