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Using a modified version of the Magic Formula to describe the traction/slip relationships of tyres in soft cohesive soils

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Abstract

The tractive force/slip relationships of pneumatic tyres are required as inputs to vehicle performance prediction models such as the NATO Reference Mobility Model. They can also be used to calculate the tractive efficiency and work output of vehicles such as farm tractors, especially important when the vehicles are performing high drawbar pull operations; the effects of altering tyre size, tyre pressure and ballast can be predicted. The so-called Magic Formula is widely used for describing the force/slip relationships of pneumatic tyres on hard road surfaces. The coefficients in the Magic Formula are derived from experimental measurements. Relationships are then developed to describe the coefficients as functions of normal load on the tyre. The paper describes how the Magic Formula can be adapted to describe the tractive force/slip relationships of tyres in soft cohesive soils. The coefficients are made functions of Mobility Number instead of normal load. Mobility Number is an empirical system for estimating the tractive performance of tyres in soft soils at a single value of slip. The method could be extended to cover lateral tyre forces or other soil types if suitable experimental data is available.

Keywords: Tyres; Soft soil; Traction/slip relationships; Magic Formula; Mobility Numbers

1. Introduction

The tractive force/slip relationships of tyres are required as inputs to vehicle performance prediction models such as the NATO Reference Mobility Model (NRMM) [1]. Here the objective is to determine the maximum average speed a military vehicle can achieve over various terrains. The tractive force of the tyres is required to overcome the various resistances acting on the vehicle and slip is required to calculate the vehicle speed.

The force/slip relationships also enable the tractive efficiency and work output of vehicles such as farm tractors to be estimated. This is important when the vehicles are performing tillage and similar high drawbar pull operations. The effects of altering tyre size, tyre pressure and ballast can be predicted.

The objective of the paper is to show how the Magic Formula, widely used for describing the force/slip properties of tyres on hard surfaces, can be adapted to represent the force/slip characteristics of tyres in soft soils.

2. Force/slip characteristics

2.1. Basic definitions

Fig. 1a shows the forces, torque and speeds that are normally measured on a tyre during tractive performance trials. Figs. 1b and 1c show the equivalent free body diagrams for the wheel in the tractive and free rolling conditions. In the driving condition T is the input torque, F_T is the pull or net tractive force developed by the tyre, W is the vertical applied load and R the vertical ground reaction. In the free rolling condition T is zero and F_T becomes F_R, the rolling resistance force, and acts in the opposite direction.

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Nomenclature

b	tyre width	r_s	static radius of tyre
B, C, D, E	primary coefficients in the Magic Formula	r_r	rolling radius of tyre on a hard surface
c_t	cohesion from triaxial test	R	normal reaction of tyre at ground surface
C_G	gross traction coefficient	s	longitudinal slip
C_R	rolling resistance coefficient	s_v	shear stress from simple shear vane
C_T	net traction coefficient	S_H, S_V	horizontal and vertical shifts in the Magic Formula
C_{TP}	peak net traction coefficient		
CI	Cone Index	T	Input torque
d	tyre diameter	v	forward velocity of the wheel
F_G	gross tractive force	W	vertical load on the wheel
F_R	rolling resistance force	x, X	slip parameters in the Magic Formula
F_T	net tractive force	x_m	slip at peak force in the Magic Formula
h	tyre section height	y, Y	force parameters in the Magic Formula
N_{CT}	Mobility Number for cohesive soils (Turnage)	δ	tyre deflection on a hard surface
N_{CM}	Mobility Number for cohesive soils	ω	rotational speed of the wheel
r_e	effective tyre radius		

$$\frac{T}{r_e} = F_G \tag{1}$$

F_G is termed the gross tractive force acting horizontally at the contact patch. r_e is the effective radius of the tyre. Therefore:

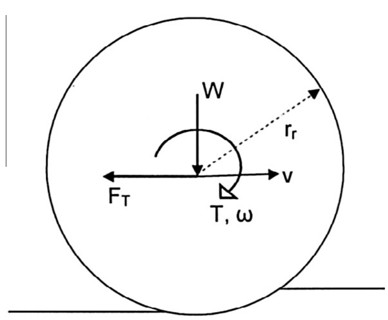

Fig. 1a. Forces, torque and speeds measured on a wheel during traction testing.

$$F_R = F_G - F_T \tag{2}$$

The tyre forces are normally converted to a non-dimensional form by dividing by the vertical load on the tyre W as follows:

$$\frac{F_T}{W} = C_T \quad \text{the net traction coefficient} \tag{3}$$

$$\frac{F_G}{W} = C_G \quad \text{the gross traction or torque coefficient} \tag{4}$$

$$\frac{F_R}{W} = C_R \quad \text{the rolling resistance coefficient} \tag{5}$$

Slip s is defined as follows:

$$s = \frac{\varpi r_e - v}{\varpi r_e} \quad \text{or} \quad 1 - \frac{v}{\varpi r_e} \tag{6}$$

where ω is the angular velocity of the wheel, v is the forward speed of the wheel. Further consideration of r_e is covered in Section 5.3.

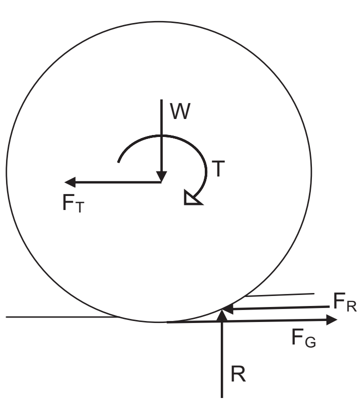

Fig. 1b. Free body diagram for a wheel in the traction condition.

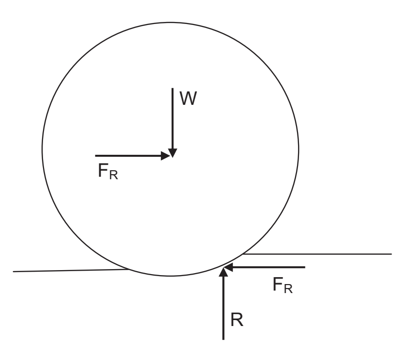

Fig. 1c. Free body diagram for a wheel in the free rolling condition.