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A unified equation for predicting traction for wheels on sand over a range of braked, towed, and powered operations

George L. Mason [a], James M. Williams [a,b], Farshid Vahedifard [a,b,*], Jody D. Priddy [c]

[a] Center for Advanced Vehicular Systems (CAVS), Mississippi State University, Mississippi State, MS 39762, USA
[b] Dept. of Civil and Environmental Engineering, Mississippi State University, Mississippi State, MS 39762, USA
[c] U.S. Army Engineer Research and Development Center (ERDC), 3909 Halls Ferry Road, Vicksburg, MS 39180. USA

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ABSTRACT

Vehicle traction between the wheel and the ground surface is a critical design element for on-road and off-road mobility. Adequate traction in dry sand relates to the vehicle's ability to negotiate deserts, sand dunes, climb slopes, and ingress/egress along beaches. The existing traction equations predict values for only one mode of operation (braked, towed, or powered). In this article, we propose a unified algorithm for continuous prediction of traction over a range of braked, towed, and powered operations for wheels operating on sand. A database of laboratory and field records for wheeled vehicles, entitled Database Records for Off-road Vehicle Environments (DROVE), was used to develop the proposed algorithm. The algorithm employs the ratio of contact pressure to cone index as a primary variable to develop fitting parameters for a relationship between slip and traction. The performance of the algorithm is examined versus the measured data and is also compared against two alternative equations. The new equation showed higher correlation and lower error compared to the existing equations for powered wheels. The proposed equation can be readily implemented into off-road mobility models, eliminating the need for multiple traction equations for different modes of operation.

1. Introduction

Off-road vehicle design and analysis, as well as optimal route planning, require the prediction of key traction parameters. The net traction, or drawbar pull (DBP), is often optimized for design or path selection purposes. The DBP is the pulling force produced by the gross traction (T) after taking the motion resistance (MR) forces acting on the wheel into account. The tractive performance is a function of the size of the contact patch of the tire on the soil surface, the torque acting on the tire, and the slip (i) experienced during operation. This contact area of the tire on the ground is a function of the tire's effective radius and sinkage (z) (Mason et al., 2016). Traction tests in the past have been conducted to evaluate the effects of changes in velocity (Coutermarsh, 2007), steering (Durham, 1976), and variations in tire characteristics (Turnage, 1995). Likewise, MR is affected by velocity, slip, turning, loading, tire inflation pressure, and sinkage (Taghavifar and Mardani, 2013; Coutermarsh, 2007; Brixius, 1987; Sharma and Pandey, 2001). Due to the number of considerations required, prediction of tractive forces remains a key area of study.

A variety of methods, including empirical relationships, semi-empirical relationships, or physics-based discrete element or finite element numerical models, use soil-tire inputs for prediction of tractive forces (Tiwari et al., 2010; Taheri et al., 2015; Du et al., 2017). While the physics-based models provide high fidelity results and allow consideration of the many forces acting on the tire, their computational cost and need for a significant number of input parameters make such methods difficult to implement. Therefore, empirical and semi-empirical relationships have often been used to correlate more easily obtained measurements to vehicle performance. Many proposed empirical algorithms rely on a dimensionless wheel mobility number (Hegazy and Sandu, 2013). The mobility number is typically comprised of tire and soil characteristics, which drive the tire traction models that have been developed (e.g., Brixius, 1987; Elwaleed et al., 2006; Maclaurin, 2014). Several of these empirical and semi-empirical relationships have been implemented in the Vehicle Terrain Interface (VTI) model, a high-resolution empirical model that addresses the interactions at the traction-terrain element interface. The VTI serves as a practical tool to support virtual prototyping of off-road vehicles

* Corresponding author at: Dept. of Civil and Environmental Engineering, Mississippi State University, Mississippi State, MS 39762, USA.

E-mail addresses: mason@cavs.msstate.edu (G.L. Mason), jmw835@msstate.edu (J.M. Williams), farshid@cee.msstate.edu (F. Vahedifard), Jody.D.Priddy@usace.army.mil (J.D. Priddy).

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Nomenclature

δ	tire deflection [m]	G	cone index gradient [kN/m^2]
A	fitting parameter related to intercept [–]	h	tire section height [m]
B	fitting parameter related to slope [–]	i	slip [%]
b	tire section width [m]	MR	motion resistance [–]
B_n	Brixius number [–]	N_s	sand numeric [–]
C	fitting parameter related to inflection point [–]	Q	torque [N m]
CA	area of tire contact patch [m^2]	T	gross traction [–]
CI	cone index [kPa]	V_a	actual wheel velocity [m/s]
CP	contact pressure [kPa]	V_t	theoretical wheel velocity [m/s]
d	tire overall diameter [m]	W	wheel load [kN]
DBP	drawbar pull [–]	z	sinkage [m]

without the computational cost of the larger models, a valuable part of the computer-aided design process. Evaluation of VTI algorithms using the Database Records for Off-road Vehicle Environments (DROVE) indicated a need for further improvement of traction equations (Vahedifard et al., 2016, 2017).

The majority of existing traction equations predicts values for only one mode of operation. This work presents a new, unified algorithm that can continuously predict traction over a range of braked, towed, and powered operations for wheels operating on sand. This feature eliminates the need for using multiple equations found in other empirical models such as the VTI. The new algorithm is developed using laboratory and field records available in the DROVE dataset. Previous studies using DROVE have already proposed new calibrations for existing VTI equations (Dettwiller et al., 2017, 2018), as well as new equations for z (Mason et al., 2016) and MR (Williams et al., 2017), but this work is the first to apply DROVE to the development of a new traction equation. The proposed equation takes a continuous s-shaped form for the traction-slip relationship. The y-intercept, slope, inflection point, minimum, and maximum values are required to establish the gross traction-slip relationship. Such information can be determined using a variety of methods including empirical relationships based on test data or the application of discrete element models. For the purpose of this work, the filtered DROVE dataset was used to develop relationships between these fitting parameters and the ratio of contact pressure (CP) to cone index (CI). Information on the DROVE dataset used is provided in the following section. The form of the equation and its development are then presented. For comparison and evaluation of the proposed equation, existing traction equations are also presented and their performance is compared to the new equation.

2. Database Records for Off-road Vehicle Environments 1.0 (DROVE)

A substantial number of test results are required to test and develop prediction equations. A recently created database, DROVE (Vahedifard et al., 2016, 2017), containing historic test data was selected to provide the necessary information. The first version of DROVE (DROVE 1.0) includes records for field and laboratory tests of wheeled vehicles conducted on dry sands (Vahedifard et al., 2016) and wet clays (Vahedifard et al., 2017). Each test record includes all relevant information known about an individual test. DROVE records commonly contain tire parameters such as tire width (b), diameter (d), section height (h), deflection (δ), and load (W) corresponding to a given set of performance records over a given soil strength. Typically, recorded performance parameters included at least one of the key traction parameters (DBP or MR), z, i, and torque (Q). Soil strength for DROVE records is in terms of CI for the top 150 mm of soil. Coarse-grained predictive equations often use the gradient of cone index (G). For the top 150 mm, dividing CI by 3.47 provides an approximate G value (Turnage, 1995). The test records in DROVE 1.0 were conducted over Yuma sand, river wash sand, and mortar sand over the course of several decades. The gradation of these sands is shown in Fig. 1. Each of the sands was dry (less than 1% moisture content by weight) throughout all test records.

For this study, the sand dataset from DROVE 1.0 (Vahedifard et al., 2016) was filtered to remove records that did not include torque (Q). This was done to ensure that each record used in the development of the new equation could have an approximate measured gross traction coefficient value based on the radius, Q, and W (Priddy, 1999):

$$\frac{T}{W} = \frac{Q}{(d/2)W} \tag{1}$$

This approximation was used in place of measured gross traction as the DROVE database, and does not contain direct records of gross traction. These filtered data were then used to develop and test a new equation. In order to evaluate the developed equation's performance, existing traction equations were applied to the same dataset and the root mean square error (RMSE) of each of the predictions against the measured values was determined.

3. Selected functional form

The theoretical correlation between slip and the traction has been proposed by a number of authors (e.g., Wismer and Luth, 1973; Karafiath and Nowatzki, 1978) and is illustrated in Fig. 2. For the purposes of this work, the relationship considers traction as a coefficient produced by dividing the gross traction by the applied load. The traction-slip relationship can be most easily described as an "s-shaped" curve. In addition to the conceptual relationship, illustrative figures of the braked and powered operation are also presented in Fig. 2. The transition zone in Fig. 2 is the region in which the tire may be operating in the powered, towed, or braked mode, and additional information regarding its operation would be necessary to determine which mode is active. The conceptual trends depicted in Fig. 2 demonstrate a curved function with horizontal asymptotes at the minimum and maximum traction values. The exact placement of these values is dependent upon the contact pressure of the wheel and the soil strength.

Existing traction prediction methods are often valid for only a single mode of operation (i.e., braked, towed, or powered). However, the ability to predict the tractive forces in all three modes of operation is necessary. Therefore, a characteristic curve equation, based on the continuous theoretical relationship illustrated in Fig. 2 would be ideal. Due to the theoretical shape of this