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Improved sinkage algorithms for powered and unpowered wheeled vehicles operating on sand

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Abstract

Modeling and simulation of vehicles in sand is critical for characterizing off-road mobility in arid and coastal regions. This paper presents improved algorithms for calculating sinkage (z) of wheeled vehicles operating on loose dry sand. The algorithms are developed based on 2737 tests conducted on sand with 23 different wheel configurations. The test results were collected from Database Records for Off-road Vehicle Environments (DROVE), a recently developed database of tests conducted with wheeled vehicles operating in loose dry sand. The study considers tire diameters from 36 to 124 cm with wheel loads of 0.19–36.12 kN. The proposed algorithms present a simple form of sinkage relationships, which only require the ratio of the wheel ground contact pressure and soil strength represented by cone index. The proposed models are compared against existing closed form solutions defined in the Vehicle Terrain Interface (VTI) model. Comparisons suggest that incorporating the proposed models into the VTI model can provide comparable predictive accuracy with simpler algorithms. In addition to simplicity, it is believed that the relationship between cone index (representing soil shear strength) and the contact pressure (representing the applied pressure to tire-soil interface) can better capture the physics of the problem being evaluated.

Keywords: Vehicle off-road mobility; Sand; Traction; Sinkage; Vehicle Terrain Interface (VTI); Database Records for Off-road Vehicle Environments (DROVE)

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1. Introduction

Off-road vehicle performance is analyzed based on design parameters such as tire size, suspension, weight distribution, and distribution of power to the tires to select an optimum combination to support off-road mobility. Comparison of off-road vehicle performance is based on tire design, clearance, traction control, and weight (Priddy, 1999). Mobility improvements often adversely affect changes in the vehicle design related to transportability,

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Nomenclature

δ	tire deflection
ΔMR_{j+1}	change in motion resistance for each additional pass of the vehicle
ΔCI_{j+1}	change in cone index for each additional pass of the vehicle
ΔZ	change in total sinkage, Z
A, B	empirical curve fit constants
b	tire section width
CI	soil strength, cone index
CP	contact Pressure
d	tire section diameter
DBP	drawbar pull
G	shear Modulus
h	tire section height
i	ith tire component
k_c	cohesive modulus of the soil
k_ϕ	frictional modulus of the soil
j	jth pass of wheel
LC	chord length of wheel on ground
$LC1$	chord distance of a tire resting on a rigid surface
m	effective number of previous passes of a wheel
MR	motion resistance force for steered and non-steered wheels
n	exponent of the vertical soil deformation related to soil type
n_a	number of tires per axle for a vehicle
$N_{sz,u}$	sand numeric for sinkage defined for unpowered wheels
$N_{sz,p}$	sand numeric for sinkage defined for powered wheels
P	tire inflation pressure
p	pressure on area under the wheel or track
Q	torque applied to the tire
s	wheel slip; used synonymously for longitudinal wheel slip
SSF	soil Strength Correction Factor
T	traction force for a steered or non-steered wheel
V_v	forward velocity of the vehicle
V_W	theoretical velocity of the wheel
W	vertical wheel load for non-steered wheels
z	sinkage of vehicle wheel assembly

fuel consumption, survivability, and occupant protection. The procurement and design stage of off-road vehicles is often based on models such as the NATO Reference Mobility Model (NRMM) (Ahlvin and Haley, 1992; Vong et al., 1999) and the Vehicle Dynamics (VehDyn) Model (Creighton et al., 2009; McKinley, 2014). The Vehicle Terrain Interface (VTI) model is used as a library within the VehDyn model to assess the traction (T), slip (s), motion resistance (MR), and sinkage (z) of a vehicle traversing linear segments of off-road terrain. The VehDyn model is a preprocessor for vehicle files used in the NRMM. The NRMM is used to assess vehicle performance over areas which may consist of 100's of km^2. Both NRMM and VehDyn use a series of closed formed solutions and finite difference models to define forces at the tire-soil interface.

The NRMM and VehDyn define vehicle immobilization in terms of a threshold average velocity. As a tire sinks into the ground, horizontal MR forces are subtracted from the available T force and the vehicle speed is degraded. For the VehDyn model, a vehicle speed remaining below 0.02 m/s for 10 time steps would indicate immobilization, where a typical time step is 0.001 s. For small robotic vehicles climbing vertical obstacles, the number of time steps is increased, thereby scaling time steps to vehicle size. The NRMM supports speed maps, while the VehDyn and VTI models support time step analyses of vehicle performance over linear segments of terrain. The VehDyn and VTI models also support preprocessing vehicle files for the NRMM to define obstacle negotiation and ride dynamics.

In off-road mobility, torque (Q) applied to the wheel is not often the limiting factor and immobilization of a vehicle occurs due to shearing of soil under the tire. Consequently, the basis for off-road mobility models is the algorithms defining the soil shear strength. Different methods have been used to measure soil strength for mobility analyses. Early work by Bekker (1951, 1969) provided the fundamental framework used today for off-road vehicle engineering. The soil shear strength parameters needed for the Bekker model are typically measured by plate load tests in the laboratory and can be difficult to obtain quickly in the field.

There are practical limitations on the number of plate load tests that can be performed on a vehicle test lane to obtain Bekker's model parameters. Alternatively, cone index (CI) is obtained from the cone penetrometer test. Soil strength in the NRMM and VehDyn is defined in terms of CI. The maximum depth of penetration used for the trafficability cone penetrometer is 1 m (Hetherington and Littleton, 1987; Bozdech and Ayers, 2011), providing incremental measurements of soil strength throughout the zone of significant vehicle stress (i.e., tire pressure bulb).

The CI was introduced in the 1940s as a mechanism to supplement plate load tests. The CI was a more expedient method and provided rapid spatial data along with incremental measurements for the depth of penetration. Shear strength parameters in terms of cohesion and angle of internal friction for a given soil type were found to correlate with CI (Baladi and Rohani, 1979; Baylot et al., 2012). Fig. 1a and b illustrate an example of manual and automated cone penetrometers, respectively. As demonstrated in Fig. 1a, a manual vertical force is applied to the proving dial connected to the cylindrical shaft, which is attached to the cone. Penetration resistance readings are taken at prescribed