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Comparison of discrete element method and traditional modeling methods for steady-state wheel-terrain interaction of small vehicles

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Abstract

A simulation study was conducted to evaluate three terramechanics methods for predicting single wheel performance of small vehicles on granular terrain. Traditional Bekker-type terramechanics methods do not consider the soil profile, soil dynamics, or transient wheel dynamics, which can be important factors in vehicle performance. The 'dynamic Bekker' method treats the wheel as a free body and discretizes the soil into grid regions, which allows for multibody dynamics simulations on more complex soil profiles. Another option is to use the discrete element method (DEM), which makes fewer assumptions but requires significantly more computation time. Before these methods can be evaluated in dynamic conditions, they must first be tested in steady-state conditions. Single-wheel experiments were performed on Mojave Martian Simulant to evaluate performance at various slip ratios. Similar tests were simulated using traditional Bekker, dynamic Bekker, and DEM. Each method was tuned to match direct shear and pressure-sinkage tests performed on the same soil. While Bekker-type methods only require curve-fitting to determine soil parameters, the discrete element method was tuned by simulating the soil tests with varying parameters. The results from this study show DEM can better predict wheel performance both qualitatively and quantitatively, though at a considerably higher computation cost.
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Keywords: Discrete element method; Terramechanics; Small vehicles; SUGV

1. Introduction

Small autonomous and unmanned ground vehicles continue to increase in importance for many industries, from planetary exploration to military defense. Examples include the highly visible NASA Mars rovers Sojourner, Spirit, Opportunity, and Curiosity, as well as commercial products like the PackBot by iRobot, and research platforms like the P-A3T by Mobile Robot, the RMP400 by Segway Robotics, and many others. These vehicles require significantly fewer resources compared to manned vehicles while reducing risks to human life. The use of unmanned vehicles, including small vehicles, is likely to increase as advances are made in autonomy technologies. Given the critical nature of the tasks these vehicles are given, it is crucial they maintain their mobility.

Terramechanics methods can aid in the design and operation of small vehicles to help ensure they do not become immobilized due to limited traction or energy depletion. The most common terramechanics method is the Bekker

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Nomenclature

Symbol	parameter units
β	coefficient used to relate damping ratio to collision time of particles (–)
$\gamma_{n/t}$	normal/tangential viscoelastic damping coefficient (N-s/m)
γ_r	rolling viscoelastic damping coefficient (N-m/s)
$\boldsymbol{\Delta\theta}_r$	relative rotation vector (rad)
$\boldsymbol{\Delta\omega}_r$	relative angular velocity vector (rad/s)
$\boldsymbol{\Delta s}_t$	tangential displacement vector for the duration of particle contact (m)
$\boldsymbol{\Delta T}_r^k$	change in rolling resistance stiffness torque (N-m)
δ	overlap length of two particles (m)
θ	angle along wheel-soil interface (rad)
θ_{eq}	equivalent front-region contact angle for rear-region (rad)
$\theta_{f/r}$	wheel-soil entry/exit angle (rad)
θ_m	position of maximum radius stress (rad)
μ_c	coulomb static yield coefficient (–)
$\mu_{r,eff}$	effective rolling resistance coefficient (-)
μ_r	Rolling resistance coefficient (–)
$v_{i/j}$	poisson ratio of particle i/j (–)
σ	normal pressure (N/m^2)
τ	shear stress (N/m^2)
τ_{res}	Mohr–Coulomb residual shear stress (N/m^2)
ϕ	angle of internal friction (rad)
ω	wheel angular velocity (rad/s)
$a_{0,1}$	Bekker coefficients for θ_m (–)
b	wheel width (m)
b_{plate}	plate width (m)
c	soil cohesion (Pa)
e	coefficient of restitution (–)
$\boldsymbol{F}_{n/t}$	hertzian normal/tangential friction forces (N)
F_{normal}	normal force of wheel (N)
G_{eff}	effective shear modulus (Pa)
I_{eff}	effective moment of inertia (kg-m^2)
j	soil displacement due to shearing (m)
K	Bekker shear modulus coefficient (m)
k	Bekker pressure-sinkage parameter (N/m^2)
$k_{n/t}$	Normal/tangential elastic spring coefficient (N/m)
k_r	rolling elastic spring coefficient (N-m)
$M_{i/j}$	mass of particle i/j (kg)
n	Bekker pressure-sinkage exponent (–)
$\boldsymbol{n}_{ij}$	unit vector connecting the centers of two overlapping particles (–)
$R_{i/j}$	radius of particle i/j (m)
r	wheel radius (m)
s	slip ratio (–)
$\boldsymbol{T}_r$	rolling resistance torque (N-m)
$\boldsymbol{T}_r^{k/\gamma}$	rolling resistance stiffness/damping torques (N-m)
$\boldsymbol{v}_{n/t}$	normal/tangential component of the relative velocity of two particles (m/s)
v_x	wheel linear velocity in direction of travel (m/s)
v_j	shear displacement rate (m/s)
Y_{eff}	effective Young's modulus (Pa)
$Y_{i/j}$	Young's modulus of particle i/j (Pa)
z	soil sinkage (m)

method, discussed in greater detail in Section 2.1. This method, the product of many researches over decades, provides predictions of wheel performance given the soil properties, wheel geometry, and loading conditions under the assumption of steady-state operations. During off-road locomotion the vehicle's dynamics couples with an irregular soil profile, can generate more complex wheel-soil interactions than assumed in the Bekker method. Among the possible options, two commonly used alternative models are discussed in this paper: the dynamic Bekker method and the discrete element method (DEM). These methods, described in detail in the following sections, allow for multibody dynamics simulations on complex soil profiles.

Each terramechanics method has advantages and disadvantages; no method is ideal for all situations. It is important then to determine when a given method should be chosen and understand its limitations compared to other methods. In this paper three common terramechanics methods, the Bekker method, dynamic Bekker method, and DEM, are evaluated by comparing the predicted performance of a small wheel driving on Mojave Martian Simulant at steady state. The parameter values needed for each method were obtained by performing direct shear and pressure-sinkage soil tests. Evaluations were made based on quantitative and qualitative accuracy, and computation efficiency.

2. Terramechanics methods

The three terramechanics methods, the Bekker method, dynamic Bekker method, and the discrete element method, are each described in the following sections.

2.1. Bekker method

The limitations and difficulties of purely empirical or theoretical terramechanics methods led researchers to create semi-empirical models. M.G. Bekker, a pioneer in the field during the 1950s and 1960s, created semi-empirical equations for wheel performance which are the basis for