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Vehicle-wet snow interaction: Testing, modeling and validation

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Abstract

For a vehicle interacting with snow, whether dry or wet, uncertainties exist in the mechanical properties of snow, and in the interfacial properties between the tires of the vehicle and snow. For dry snow, these uncertainties have been studied recently using methods within a statistical framework employing a simple stochastic tire-snow interaction model and several validation metrics. Wet snow is more complicated and much less studied than dry snow, especially for tire-snow interaction. In this paper, the authors used a physical tire-snow interaction model and a similar statistical framework as was used to analyze dry snow, and presented results of calibration and validation of the interaction model for wet snow in conjunction with new test data based on a single test run with the assumption that it would provide needed sampling points for statistical analysis. Four local and global statistical validation metrics were used to assess the physical and statistical models with good results. Comparison between wet and dry snow, based on a single test run, shows that the former has a lower interfacial coefficient of friction, and a higher drawbar pull than the latter.

Keywords: Wet snow; Dry snow; Drucker–Prager; Drawbar pull; Torque; Validation metrics; Calibration; Stochastic; Uncertainties; Friction

1. Introduction

The interaction of a vehicle with soft terrains, such as snow and soil, is complicated due to the uncertainties in the material properties of the terrain, and in the frictional contact properties at the interface of the vehicle and terrain. For snow, the uncertainties stem from many aspects of the material properties due to the influence of microstructure, water content, thermal and snow deposition environment, fragmentation of the snow slab, as well as properties at the tire-terrain interface, the 3-D terrain profile such as the varying depth of snow (Lee and Liu, 2005) which is difficult to obtain accurately and cost effectively. Additional discussions regarding uncertainties for tire-snow interaction are given in Lee (2013).

Whereas for soils, a single-wheel type of test bed has often been used in a laboratory setting, known as the soil-bin method, it is not feasible for natural snow due to the many aspects of uncertainties mentioned above. Traditional soil-bin type of approach could be categorized as *physical modeling* in that an idealized situation is designed for the testing. For example, the soils are typically remolded such that they may differ from those that are in situ. A single wheel is also typically used such that the effects of the chassis of the vehicle as well as the potentially complicated vehicle maneuvers could not be taken into consideration which may differ significantly from the performance of a full vehicle in the field. In addition, interfacial properties between a tire and soil in the soil bin may not reflect those in the field experienced by the full vehicle. The aim of the traditional approach, as in most physical models, is usually to *reduce* the variations of test parameters under idealized conditions. Although physical modeling can be useful to understand the effects of some

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Nomenclature

$\bar{\sigma}$	von Mises stress (Pa)
β	friction angle for Drucker–Prager criterion (deg)
ϵ^p	volumetric plastic strain
μ	friction coefficient
ω	angular velocity (rad/s)
σ_n, τ	normal and shear stress acting on tire (Pa)
θ	angular position of tire-snow contact point (deg)
θ_0	maximum angular contact position (deg)
b	tire section width (m)
c, ϕ	cohesion (Pa), friction angle (deg) of Mohr–Coulomb yield criterion
c_1, c_2, c_3	hardening constants of Drucker–Prager yield criterion
F_x	drawbar pull (N)
F_z	vertical force on tire (N)
$F_{\tau x}$	shear force (traction) (N)
f_{rr}	rolling resistance coefficient
i_x	longitudinal slip
j_x	longitudinal shear displacement (m)
K_{shear}	shear deformation modulus (cm)
N	number of test data points used in statistical methods
p	hydrostatic pressure (Pa)
p_a	location of cap of Drucker–Prager yield criterion (Pa)
p_d	cohesion for Drucker–Prager criterion (Pa)
r	radius of tire (m), number of parameters for calibration
R_x	motion resistance (N)
T_{app}, M_y	torque applied on wheel (N m)
v	longitudinal velocity (m/s)
z, z_0	deformation of snow, maximum deformation of snow (sinkage) (m)
CI	confidence interval
DP	Drucker–Prager yield criterion
GP	Gaussian Process
LHS	Latin Hypercube Sampling

parameters, the applicability of physical modeling, which is deterministic in nature, to field situations is seldom discussed.

Our approach (Lee et al., 2006; Li et al., 2007, 2009), on the other hand, attempts to assess statistically the effects of a multitude of uncertainties that occur simultaneously during vehicle maneuver as opposed to the approach in physical modeling where only one parameter is changed at a time. In other words, in our work, the traditional causal effects of parameters are not explored but only the effects due to the *ranges* of parameters are assessed.

Consequently, during testing, the goal is, for a given type of snow, to explore a wide range of vehicle maneuvers such as speed, and longitudinal slip that are available for the vehicle and the terrain using a human driver. During vehicle traversal, the values of parameters of the vehicle-terrain interaction are usually different at different times. Consequently, the data in current time is considered to be independent from the previous time and subsequent time. Thus, a single test, under nominally similar snow conditions, is considered to be sufficient as being representative statistically.

Recently, uncertainties for dry snow have been characterized via the calibration and validation of a stochastic tire-snow interaction model in conjunction with new test data (Lee et al., 2012; Lee, 2013) using an instrumented vehicle within a flexible statistical framework using several validation metrics. To the best of our knowledge, the work in Lee (2013) is the first time that a stochastic tire-snow interaction model has been calibrated and validated.

It should be noted that although the term validation is commonly used in literature but oftentimes used without qualification and not associated with validation metrics. In this paper, the approach to validation follows recent progress in the field of verification and validation (ANSI/ASME V& V 10-2006,).

Relative to dry snow, wet snow is a more complicated material whose properties are much less known (Colbeck, 1979a, 1982; Techel et al., 2011). Most of the studies on wet snow focus on physical properties such as water retention (Morris and Kelly, 1990; Denoth, 1999), and snow metamorphism over a long period of time (Colbeck, 1979b; Denoth, 1982). Fewer studies have focused on the mechanical properties of wet snow discussed in Salm (1982), Izumi and Akitaya (1985), and Techel et al. (2011); additional references can be found in Techel et al. (2011). In particular, the authors are not aware of phenomenological plasticity-type of material models, such as the model in Haehnel and Shoop (2004) for dry snow, and the many models for unsaturated soils reviewed in Sheng (2011), for wet snow. By using a simplified plasticity model, to be discussed in Section 2, there's an uncertainty of the parameters used in the material model in addition to an uncertainty of the values of model parameters.

As far as the authors are aware, there have been no dedicated studies of the interaction of wet snow with a vehicle in literature especially involving the characterization of uncertainties – the purpose of this paper. The aims of this paper are to develop a stochastic model, to calibrate model parameters using new test data, and to assess the quality of models using validation metrics, as well as to study the similarities and differences between dry and wet snow.

The rest of the paper is organized as follows. The simple tire-snow interaction model, including the material model, is given in Section 2. The statistical methods are summarized in Section 3. Experimental procedures are presented