Characterizing Wheel-Soil Interaction Loads using Meshfree Finite Element Methods: A Sensitivity Analysis for Design Trade Studies

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A wheel experiencing sinkage and slippage events poses a high risk to planetary rover missions as evidenced by the mobility challenges endured by the Mars Exploration Rover (MER) project. Current wheel design practice utilizes loads derived from a series of events in the life cycle of the rover which do not include (1) failure metrics related to wheel sinkage and slippage and (2) performance trade-offs based on grouser placement/orientation. Wheel designs are rigorously tested experimentally through a variety of drive scenarios and simulated soil environments; however, a robust simulation capability is still in development due to myriad of complex interaction phenomena that contribute to wheel sinkage and slippage conditions such as soil composition, large deformation soil behavior, wheel geometry, nonlinear contact forces, terrain irregularity, etc. For the purposes of modeling wheel sinkage and slippage at an engineering scale, meshfree finite element approaches enable simulations that capture sufficient detail of wheel-soil interaction while remaining computationally feasible. This study implements the JPL wheel-soil benchmark problem in the commercial code environment utilizing the large deformation modeling capability of Smooth Particle Hydrodynamics (SPH) meshfree methods. The nominal, benchmark wheel-soil interaction model that produces numerically stable and physically realistic results is presented and simulations are shown for both wheel traverse and wheel sinkage cases. A sensitivity analysis developing the capability and framework for future flight applications is conducted to illustrate the importance of perturbations to critical material properties and parameters. Implementation of the proposed soil-wheel interaction simulation capability and associated sensitivity framework has the potential to reduce experimentation cost and improve the early stage wheel design process.

I. Introduction

Since the 90's, JPL has enjoyed highly profiled success in the arena of robotic, rover exploration missions. During the recent Mars Exploration Rover (MER) missions, the Spirit rover suffered compromised mobility due to wheel sinkage in soft Martian regolith. Combined with other failure mechanisms, compromised mobility due to wheel-soil interaction resulted in the ultimate demise of Spirit after a very successful run. Preceding the landing of the Mar Science Laboratory - JPL's most recent planetary rover, the project

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conducted several sloped drive tests in the Mojave desert. One such test is shown in relation to the JPL benchmark wheel-soil interaction problem in Fig. 1. Although these experiments sought to replicate the in situ operational conditions of the rover on Mars, it is costly and sometimes impossible to vary test conditions related to soil composition. In a simulation environment, a sensitivity analysis capability can be developed using LS-Dyna and its associated metamodel based LS-OPT to simulate the soil-wheel interaction event in a variety of off-nominal conditions. Trade studies produced by the developed sensitivity analysis capability can produce more robust wheel designs and guide experimentalists in developing a test program. Experimentation can work hand in hand with the developed simulation capability to reduce overall risk during the planning and operational phases of rover missions.

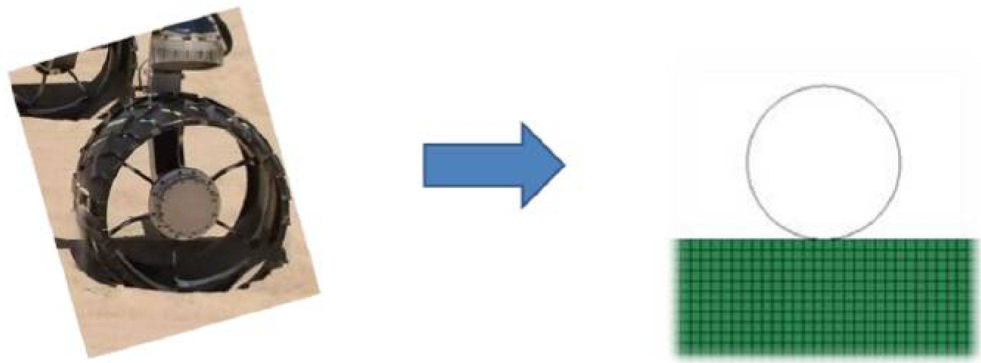

Figure 1. Mars Science Laboratory (MSL) sloped drive test on dry, loose sand (left) shown with JPL benchmark wheel-soil interaction simulation (right)

NASA mobility engineers require better design tools. Wheel ground pressure is currently the primary scaling tool, but has already been shown to be inadequate in scaling from the 180 kg MER rovers to the 900 kg MSL rover. In addition, rover operation teams are often in need of assessing stability on smooth or soft slopes. Particularly treacherous is the prospect of drilling while on such slopes where slipping could break a drill bit or cause a jamming event. Finally, energy efficiency of the rovers can be improved through better wheel design. Every Watt freed from driving requirements becomes available for science and navigational computing.

Previous simulation work done in collaboration with JPL involving wheel-soil interaction has focused on developing stand-alone tools that can model sinkage and slippage. Zhou et al.[1] developed the Artemis simulation software for use in operation of the NASA Mars Exploration Rovers (MER). Artemis combines commercial multibody dynamics software with subroutines that introduce the classical Bekker-Reece-Wong[2]-[3] equations of wheel terramechanics. The classical equations limit the usefulness to medium-slip, low-sinkage conditions. The Artemis software is used in conjunction with a single-wheel testbed at the Massachusetts Institute of Technology to validate models and explore automated Bekker parameter estimation. A similar commercial product is available from Carnegie Mellon Simulation Labs,[4] which has been demonstrated in Mars rover simulations. Beyond NASA and the Mars rovers, Ding et al.[5] provide a thorough review of planetary wheel-soil research prior to 2011. Of note, the German Space Agency (DLR) has developed simulation tools for their own rovers, which include Bekker-based mechanics, multibody rover dynamics, and deformable 3D terrain maps.[6] Within any of the above simulations, there are continuing efforts to keep updating the semi-empirical terramechanics equations with real Mars data[7] and Earth-based microgravity experiments[8]-.[9]

Several efforts[10]-[13] have been made to model the MER wheels with Discrete Element Modeling (DEM). These are physics-based models with up to millions of interacting particles, and are thus computationally expensive in comparison to the Bekker-based formulations. EDEM is a commercial software with DEM capabilities that have looked at case studies for Lunar mobility.[14]

Previously, a benchmark wheel-soil interaction problem was developed to validate simulation methodologies.[15] This paper implements the benchmark wheel-soil interaction problem in the commercial code environment taking advantage of LS-Dyna's recent advancements in meshfree simulation, particularly SPH elements. Once the problem is simulated in the LS-Dyna environment, a metamodel based sensitivity analysis which varies critical simulation parameters can be conducted using LS-OPT.

II. Model Development

The simulation model developed for this study required implementation of both explicit time integration methods and advanced algorithms for material contact. To allow for future full fidelity modeling, it was desired to stay within a continuum mechanics framework to maintain feasibility of such simulations. Meshfree methods were used to qualitatively capture high deformation behavior. These characteristics of model development led to the selection of LS-Dyna as the candidate analysis tool.

A. Wheel-Soil Benchmark Problem

The purpose of the wheel-soil benchmark problem is to compare the performance of different analytical tools on a standardized problem that can be the basis for two fundamental events of importance to rover mobility: (1) wheel traverse and (2) wheel sinkage. The critical dimensions related to the wheel and the soil 'sandbox' are illustrated in Fig. 2.

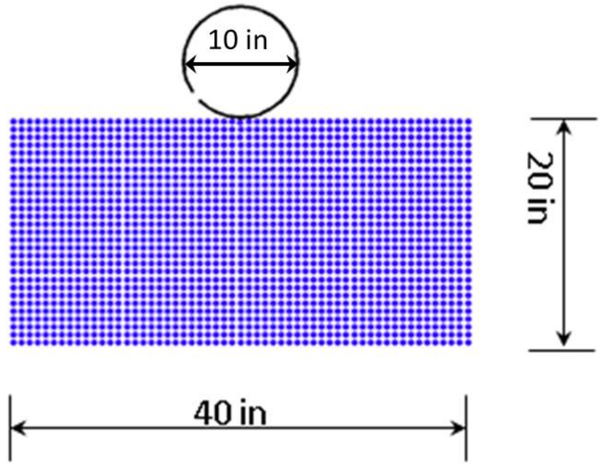

Figure 2. Wheel-Soil Benchmark Problem and Dimensions

Due to the availability of laboratory data for triaxial soil tests, the soil was modeled using the MAT_005 (MAT_SOIL_AND_FOAM) material formulation in LS-Dyna. The input to this material model calls for volumetric strain values (logarithmic scale) and pressures corresponding to those values that come from hydrostatic traixial soil tests. A specific soil sample was tested by Schwer and the data successfully generated material models in studies by Bojanowski et al. that show good agreement with experimental results. The density, ρ, shear modulus, G, and the bulk modulus for unloading, K, were determined to be 2350 kg/m^3, 34.5 MPa, and 15.0 MPa respectively. Test data from the triaxial soil tests is reprinted in Fig. 3

From the test data, the yield function coefficient a_2 was determined using a procedure implemented by Fasanella et al. to model soil impacts for the Orion Landing System. A soil material's shear strength envelope described by second invariant of the stress tensor, J_2, can be expressed as a quadratic representation of pressure. This yields the following equation for the deviatoric perfectly plastic yield function:

$$\phi = J_2 - (a_0 + a_1 p + a_2 p^2) \tag{1}$$

On the yield surface the following is true,

$$J_2 = \frac{1}{3}\sigma_D = a_0 + a_1 p + a_2 p^2 \tag{2}$$

where σ_D is the stress difference between confining pressure, σ_c and axial pressure, σ_a and computed from test data by Eq. 3.

$$\sigma_D = \sigma_c - \sigma_a \tag{3}$$

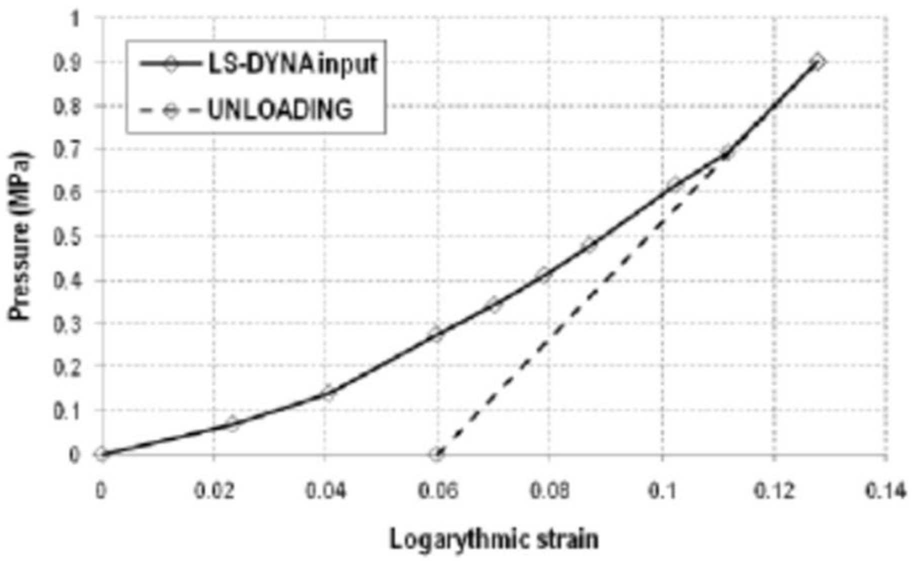

Figure 3. Hydrostatic triaxial test data and LS-Dyna inputs to material model

Assuming a linear relationship between σ_D and p which is true for low cohesion soils, then

$$\sigma_D = mp \tag{4}$$

where m is a slope fit from triaxial test data.

Finally, substituting Eq. 4 into Eq. 2 and for $a_0 = a_1 = 0$, the following expression for a_2 is achieved

$$a_2 = \frac{1}{3}m^2 \tag{5}$$

where p is calculated experimentally by

$$p = \frac{\sigma_a + 2\sigma_c}{3} \tag{6}$$

Given the test data, the yield function coefficient for the soil used in the following simulations was $a_2 = 0.602$. This parameter will prove to be important in the ensuing sensitivity analysis results in Section IV.

B. Simulation Paradigm

Meshfree methods avoid mesh distortion, entanglement difficulties, and numerical stability issues associated with conventional Lagrangian finite element meshing.[15] A meshfree simulation framework specializes in dealing with problems that have excessive deformation and/or complex failure mechanisms (ie. wheel sinkage event). Meshfree methods have been successfully applied to a wide array of large nonlinear deformation and contact/impact problems. The foundation of the method is based on kernel approximation theory and readers are referred to Chen *et al.* for a detailed explanation of the methodology.

In order to validate the benchmark problem implementation in LS-Dyna and ensure that the contact interface and friction parameters were defined properly, a wheel traverse case over a soil sandbox was simulated. The contact interface was defined using CONTACT_AUTOMATIC_SURFACE_TO_SURFACE and the friction coefficient between the soil and wheel was 0.4. The MAT_005 soil constitutive model was selected for the simulation due to its numerically stability and the availability of experimentally obtained material parameters.[17]

III. Baseline Simulation Results

A contour plot of the downward pressure in the soil domain is shown in Fig. 4 while the wheel is rolling on the surface with an angular velocity of 2π rad/sec (cw) for 0.25 sec. The centerline of the soil sandbox is marked to show translation of the wheel.

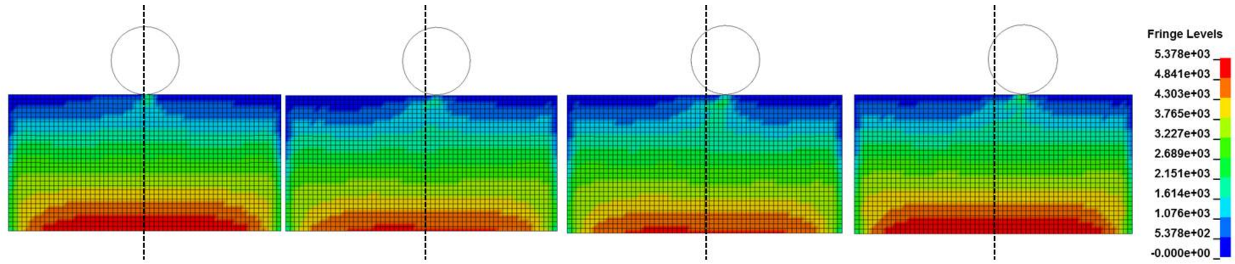

Figure 4. Wheel traverse simulation results showing pressure in the soil (Pa) as the wheel rolls on the surface

Following the wheel traverse case, an 8 second simulation involving both sinkage and slippage of the wheel in the same soil material model was performed. However, in order to capture the high deformation behavior, SPH elements were used. To improve computation time, a hybrid approach was employed with the outer portion of the sandbox discretized by a coarse Lagrangian soil mesh and the inner portion near the wheel-soil contact interface comprising a fine SPH soil domain. An additional contact surface was defined in between the SPH soil and the Lagrangian soil. The wheel was compressed into the soil at 0.6 in/sec while spinning at a rate of 1 rad/sec (ccw). Simulation time on a 64-bit machine running on 16 quad-core processors with 128 GB of total RAM was 1 hr 22 min and 37 seconds by the use of the hybrid formulation.

In can be observed from Fig. 5 which shows 6 simulation snapshots (at 0, 1.5, 3, 4.5, 6, and 8 seconds) that the SPH nodes qualitatively display a high degree of deformation while maintaining a numerically stable configuration. In the bottom right snapshot at 8 seconds, there exists a small amount of piled up soil near the SPH-Lagrangian boundary - a feature difficult to capture without a meshfree formulation. Also, the wheel undergoes some translation due to the effect of both sliding and slipping as it is being compressed into the bed of SPH nodes. The sinkage and slippage effects shown in Fig. 5 fulfill the objectives of the benchmark problem.

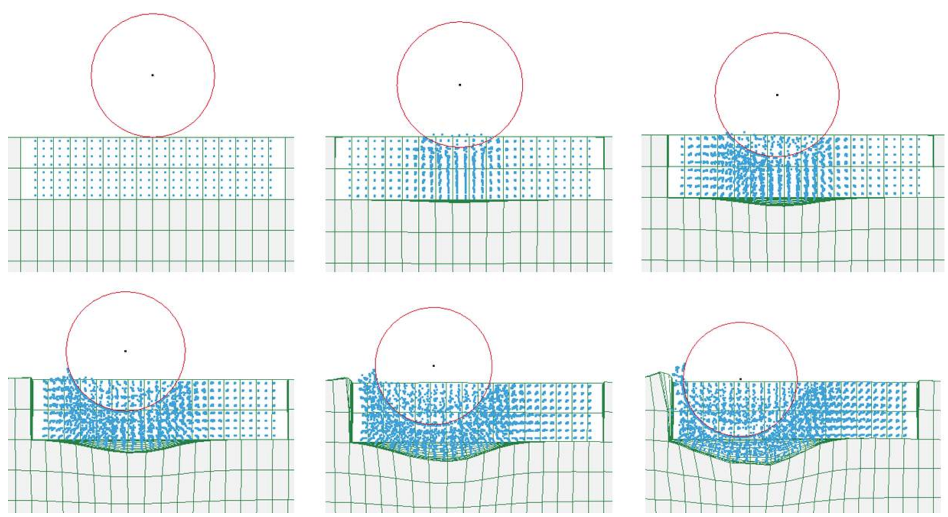

Figure 5. Benchmark wheel-soil interaction problem implementation using a hybrid approach with SPH elements

IV. Sensitivity Results

Using LS-OPT, a sensitivity study was performed using the nominal hybrid wheel-soil interaction model. The resultant vertical force at the wheel soil interface was defined as the model response or output. The soil parameters that were selected for the sensitivity study are shown in Table 1 along with their lower and upper bound dispersion values. The range of variation corresponds to a $+/-10\%$ variation from the nominal values.

Table 1. Variables used for sensitivity study (units mm-sec-tonne)

Variable	Description	Nominal	Lower Bound	Upper Bound
rho	Soil density	2.35e-09	2.115e-09	2.585e-09
k	Soil unloading bulk modulus	15.024	13.521	16.526
g	Shear modulus	34.474	31.026	37.921
a_2	Yield surface coefficient	0.602	0.542	16.526
fpres	10% Uncertainty applied to pressure data	1	0.9	1.1
fstrain	10% Uncertainty applied to log strain data	1	0.9	1.1

A linear polynomial metamodel surface defined by Eq. 7 was sufficient for the sensitivity study of $m = 5$ different parameters. The approximate linear response surface was fit by LS-Opt using Eq. 8. The accuracy of the metamodel is plotted in Fig.7 showing a reasonable RMS error of 2% computed using Eq. 9 where $n = 11$ is the number of sample points. Sample points were selected by the D-Optimal sampling algorithm which determined that 11 points were needed from the full $m!$ space of possible parameter combinations because they comprise a minimum set to describe the linear polynomial metamodel surface.

$$y = \eta(\mathbf{x}) = \beta_0 + \sum_{i=1}^{m} \beta_i x_i + \epsilon \tag{7}$$

$$\widehat{y} = \beta_0 + \sum_{i=1}^{m} \beta_i x_i \tag{8}$$

$$\epsilon_{RMS} = \sum_{k=1}^{n} \sqrt{\frac{(y_k - \widehat{y}_k)^2}{n}} \tag{9}$$

Once the metamodel surface is fit to within an acceptable error tolerance, the sensitivity results can be illustrated by computing the dimensionless quantity in Eq. 10 where x_i^{max} is the lower bound of the i^{th} parameter in Table 1 and x_i^{min} is the upper bound of the i^{th} parameter in Table 1.

$$\Delta y_i = \frac{\partial y}{\partial x_i}(x_i^{max} - x_i^{min}) \tag{10}$$

The linear ANOVA based sensitivity results showing quantities computed using Eq. 10 are shown in Fig. 6. The most significant driver of the response is shown to be variable, a_2, which is a yield surface parameter specific to the experimental soil modeling. The soil density (rho) and bulk modulus (k) did not comparatively play as much of a role in the variation of the force response.

Finally, Fig. 8 shows the resultant force as function of time for all varied parameter simulations. The contour bar at the right of the plot highlights the parameter value of a_2 in each simulation. The max values of resultant force for all the varied simulations ranges from approximately 23 kN to 38 kN. The results demonstrate approximately 27% max uncertainty in force for off-nominal conditions underscoring the criticality of accurately determining the yield surface parameter.

V. Conclusion

The wheel-soil benchmark problem developed at JPL was implemented in a commercial code environment using the meshfree capability enabled by LS-Dyna software. The model was shown to produce qualitatively realistic results for both a wheel traverse case and a wheel sinkage case. Due to the uncertainty in the variance of in situ bulk material properties of soil, a metamodel based sensitivity study was conducted using LS-OPT. It was found that the resultant interface wheel contact force was most sensitive to the a_2 parameter which relates pressure to the Druker-Prager yield function. This parameter was fit from experiments performed in a previous study, but emphasizes the importance of the accuracy in its determination. Although the sensitivity study showed a range of dispersion in the max resultant force on the wheel of 23 to 38 kN, it is possible to

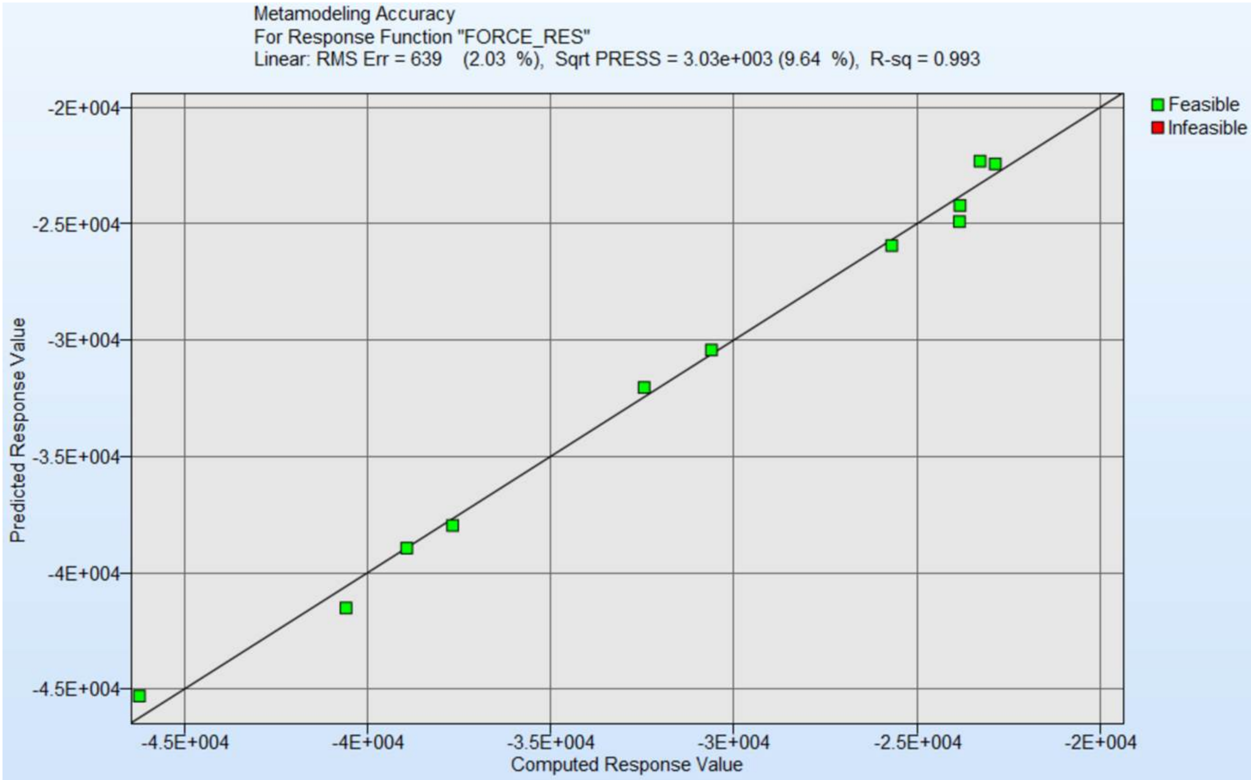

Figure 6. Accuracy of linear polynomial metamodel fit

reliably envelope these loads given the uncertainty. These loads are differentiable from conventional design loads because they not only determine strength capability, but they carry with them information related to wheel performance (ie. spin rate). Future work will involve increasing the complexity of wheel design to resemble existing flight hardware.

Acknowledgments

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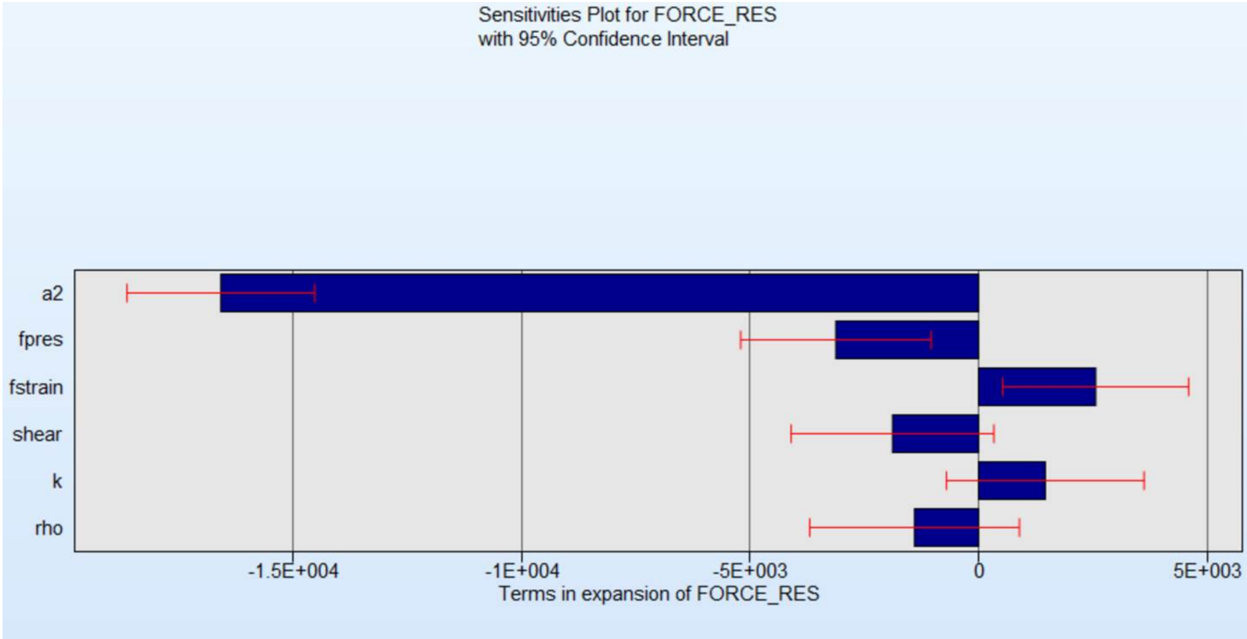

Figure 7. Sensitivity of variable with respect to result wheel-soil interface force (dimensions normalized)

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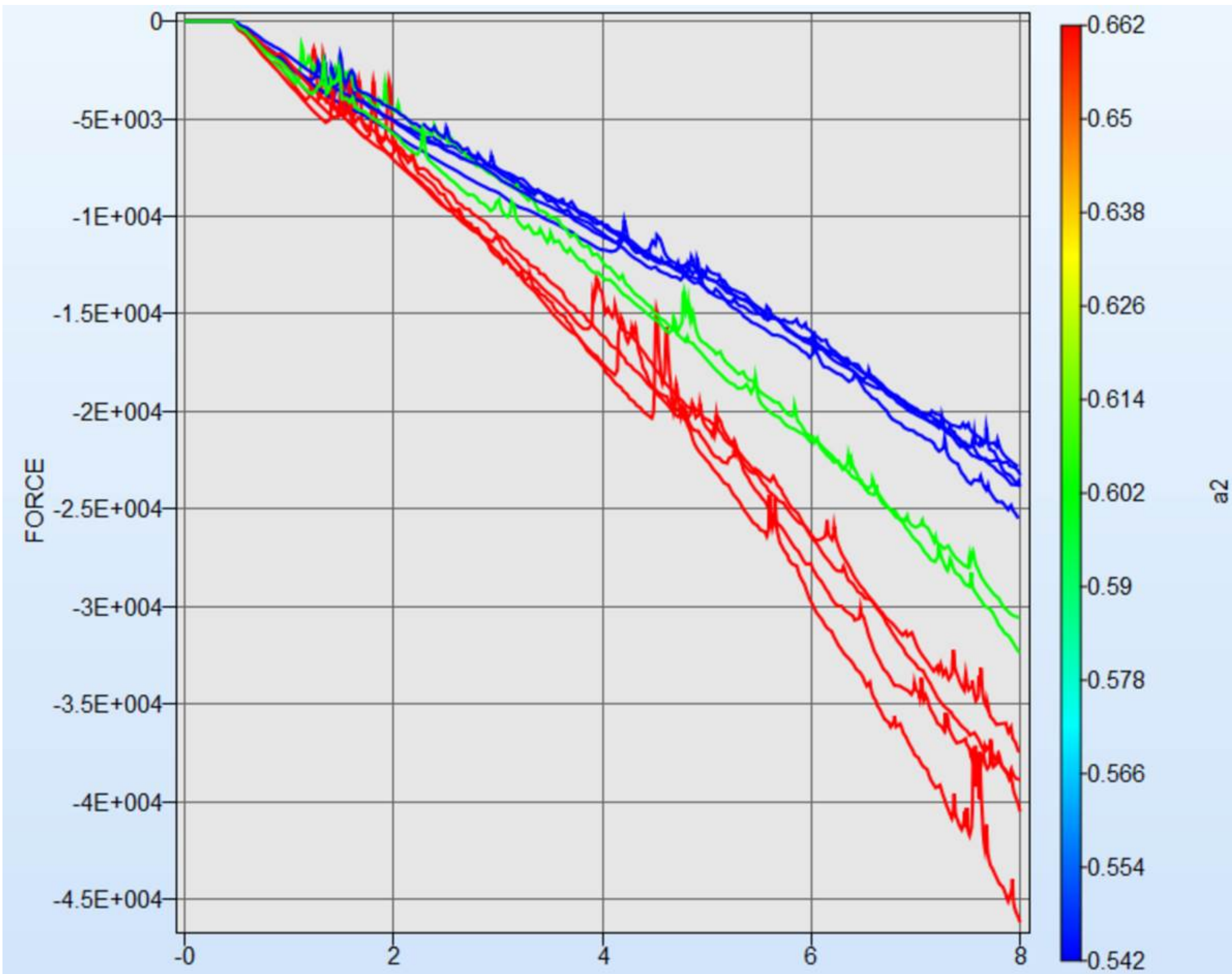

Figure 8. Resultant wheel-soil interface force history for all simulations (kN)