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Simple Terramechanics Models and their Demonstration in the Next Generation NATO Reference Mobility Model

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ABSTRACT

In 2014, a NATO Applied Vehicle Technology (AVT) Exploratory Team 148 (ET-148) was formed to explore the development of an improved Next-Generation NATO Reference Mobility Model (NG-NRMM)[1]. A development path forward was identified and initiated in a subsequent NATO research task group (AVT-248) to implement ET-148 recommendations. One key area for improvement was the vehicle-terrain interaction (Terramechanics) models defining important performance metrics for off-road performance in differing soils, and environmental conditions. The near term implementation focuses on existing "Simple" Terramechanics models as a practical improvement to the incumbent NRMM Cone Index (CI) empirically based method, without requiring the computational power of the large scale complex discrete element model (DEM) methods that are the targeted long term solution. Practical approaches and limitations to the implementation of these existing Simple Terramechanics models in 3D vehicle models are described along with parameter identification approaches and their limitations.

INTRODUCTION

The ultimate demonstration of a NG-NRMM simulation capability under the broad scope of it's requirements, is depicted in Figure 1 wherein terrain mechanical properties are one of many overlaid geographically distributed features that affect vehicle mobility. Based on the terrain properties, mobility will be computed and expressed and displayed as a map of GO/NOGO capability and maximum speeds attainable across a given region of interest. Soft soil effects are one of the primary attributes affecting vehicle mobility and are a foundational capability required in both the current NRMM and the NG-NRMM. The cone penetrometer and it's CI metric holds a practical and intuitive appeal for linking terrain strength to vehicle performance. Unfortunately, a cone penetrometer is not a very close physical analog to vehicle running gear bearing and tractive load interactions with soil, and it is dimensionally insufficient to characterize the independent development of tractive and bearing loads as well as the properties and processes involved in the development of soil strength. The dual development path focusing on existing models under the title "Simple Terramechanics" and the longer term higher fidelity objective approach entitled "Complex Terramechanics" allows for theoretical and numerical approaches that are still under development and which overcome theoretical and practical limitations of existing Terramechanics models using fully 3D continuum failure and flow models

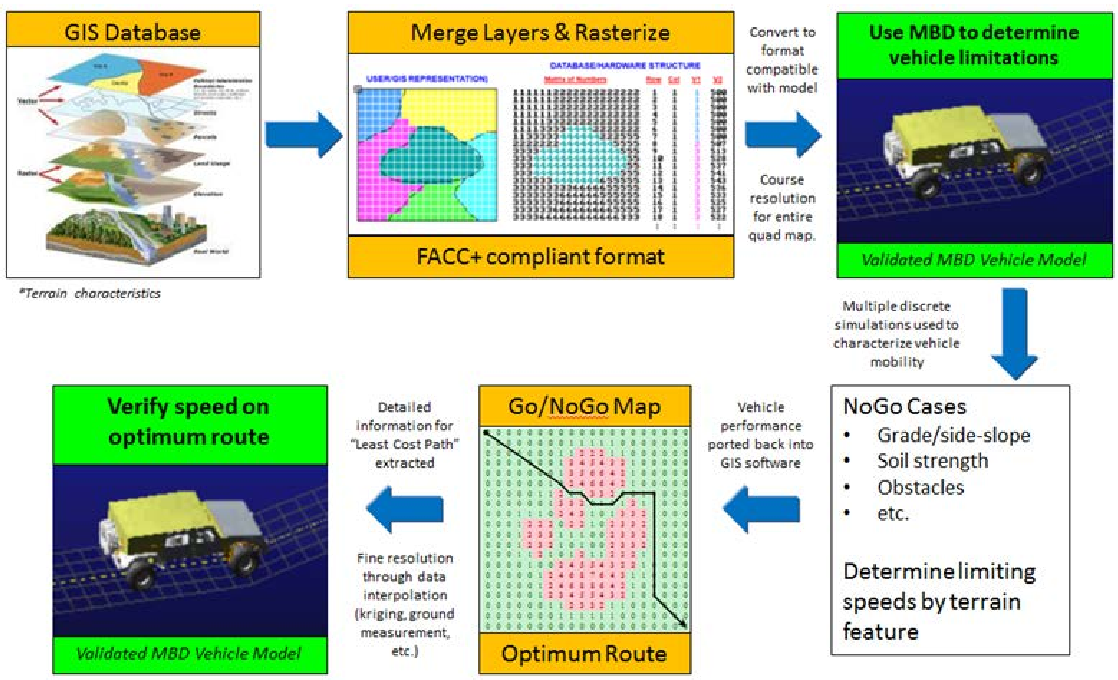


Figure 1: Full Featured NG-NRMM Simulation Begins with GIS based data, predicts mobility and maps it back onto the terrain as an additional GIS parameters[2]

Figure 2 depicts the spectrum of Terramechanics models beginning with the incumbent NRMM Cone Index (CI) empirically based method and ranges up to the Complex Terramechanics models, with Simple Terramechanics models providing a practical middle ground compromise solution between the limitations and challenges of those two extremes.

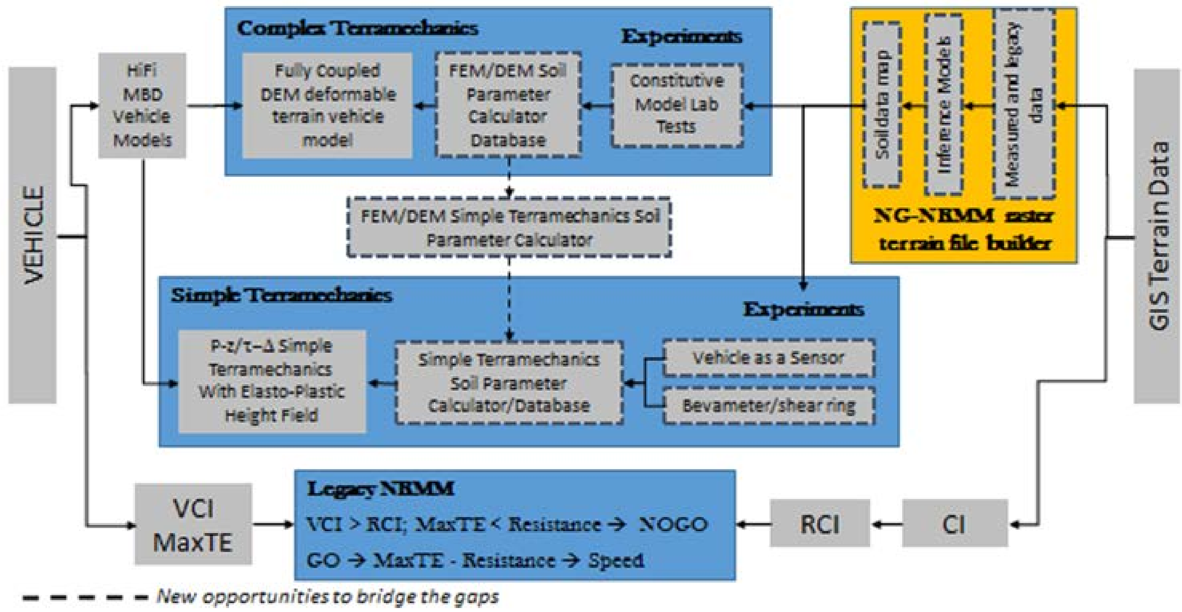


Figure 2: Replacing the Cone Index (CI) methods used in the current NRMM, simple Terramechanics models bring the full 3D mechanics of vehicles together with existing Terramechanics to provide a means for calculating critical mobility metrics on soft soil that are foundational components in the higher level mobility aggregated predictions of feasible trafficability (GO/NOGO regions) and maximum speed attainable.

SIMPLE TERRAMECHANICS

Pressure-sinkage testing using bearing stress platens, combined with grouser enhanced shear rings for tractive stress (both assumed to be geometric analogs of the vehicle running gear) are the most widely used improvement to the CI methods for characterizing soil strength [3,4]. Dimensionally, there are at least 5 independent parameters determined by the calibrating experiments. For bearing pressure, these are commonly represented as "p-z" *equations where p is the bearing pressure* under the platen that is pushed into the soil, z is the platen sinkage, and **k** and **n** are the best fit parameters in the equations that have taken several forms over the years. Originally Bernstein [3] proposed the following power law form of the plastic limit pressure:

$$p = kz^n$$

Bekker added the effects of a primary running gear dimension, b, typically the width:

$$p = \left(\frac{k_c}{b} + k_\varphi\right) z^n$$

where $\mathbf{k_c}$ and $\mathbf{k_\phi}$ are intended to capture the cohesive and frictional soil strength effects. Wong [5] developed the experimental data reduction methodology for parameter identification and the elasto-plastic model of repetitive unload re-load cycles augmenting the Bekker model (see regime D in Figure 3). In combination, these are known as the Bekker-Wong model and must include the constants associated with the slope of the elastic unload/load in regime D.

$$\mathbf{k_{unload} = k_0 + A_{unload}\, z_{unload}}$$

where $\mathbf{k_0}$ and $\mathbf{A_{unload}}$ are developed from multiple repetitive load experiments. Later, Reece proposed the Bekker-Wong-Reece form

[6] of the plastic limiting bearing envelope:

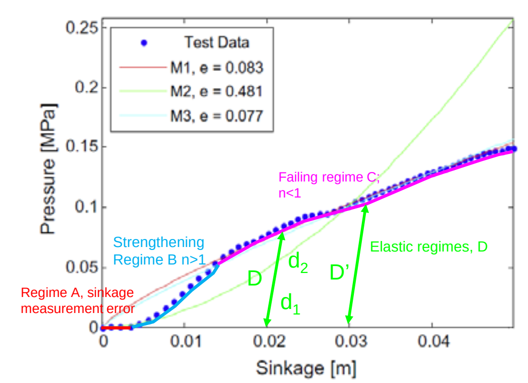
$$\boldsymbol{p} = \left(\boldsymbol{k'}_{\boldsymbol{c}} + \boldsymbol{b}\boldsymbol{k'}_{\boldsymbol{\varphi}}\right)\left(\frac{\boldsymbol{z}}{\boldsymbol{b}}\right)^{\boldsymbol{n}}$$

where the coefficients have slightly different units and meaning with the potential to account for geometric scale more effectively [6]. When combined with a shear response model developed from measurements using an annular ring shear device [7], they form the basis of most modern Simple Terramechanics models. Analytically, shear stress-shear displacement, "τ-j", equations were proposed and demonstrated by Janosi and Hanamoto[7] in the following simplest form:

$$\tau = [c + p \tan \phi\,](1 - e^{(-j/k)})$$

Where $\boldsymbol{\tau}$ is shear stress, $\boldsymbol{j}$ is shear slip, $\boldsymbol{k}$ is a exponential function constant, $\boldsymbol{c}$ is cohesion and $\boldsymbol{\phi}$ is soil internal friction angle. They have been validated at the vehicle level for both tracked vehicles [5] and wheeled vehicles [7], and can take other more complex mathematical forms when necessary.

For deformable soils, a common analytical construct of all Simple Terramechanics models must be some means of tracking permanent deformation and modifying the soil response due to the effects of compaction and flow as well as sheared soil layers (i.e., slip-sinkage). This typically requires a discretization of the soil substrate into cells for which the sinkage and shear states are numerically computed and tracked. This general construct has been described in [8] and [9] in the context of Vehicle Terrain Interface (VTI) real-time models for simulators, but is commonly known in recent engineering analysis implementations as a "height field" local terrain model [10], discussed later and shown in Figure 4.



Sample estimation for 5-cm plate.

Figure 3: Data from [8] shows that the Bekker-Wong model includes procedures for parameter identification from test data and, most importantly, recognition of the elastic unload/reload portions of the response, D and D'[5,13] . Regime A is sinkage measurement error offset to the onset of actual soil loading; Regime B is the compacting of loose soil so the soil is strengthening and n>1; The transition to Regime C is an inflection point with changing exponent, toward n<1 in regime C, which is soil bearing failure controlled by the growth of shear slip line fields in the far field. Thus the model parameter identification is dependent upon peak pressure regime in the specific vehicle application for which it will be used.

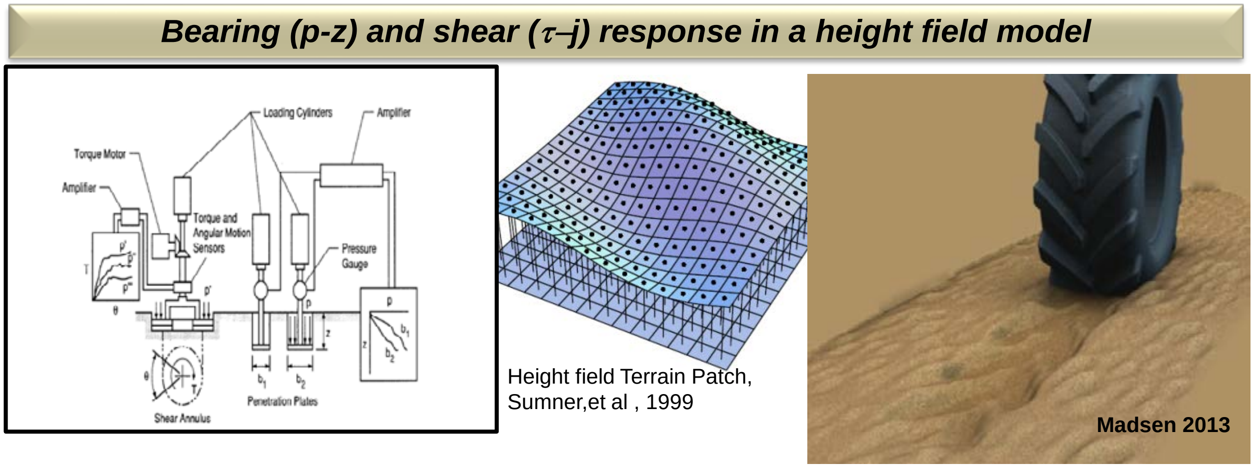


*Figure 4: The classic Bekker-Wong-Janosi (BWJ) Terramechanics models (e.g., pressure-sinkage (**p-z**), shear stress-shear displacement (**τ-j**)), along with associated bevameter [4] experimental methods, are the most widely developed model suite that improves upon cone index approach and are ready for immediate application in NG-NRMM when implemented in the context of a terrain height field model [9- 13]*

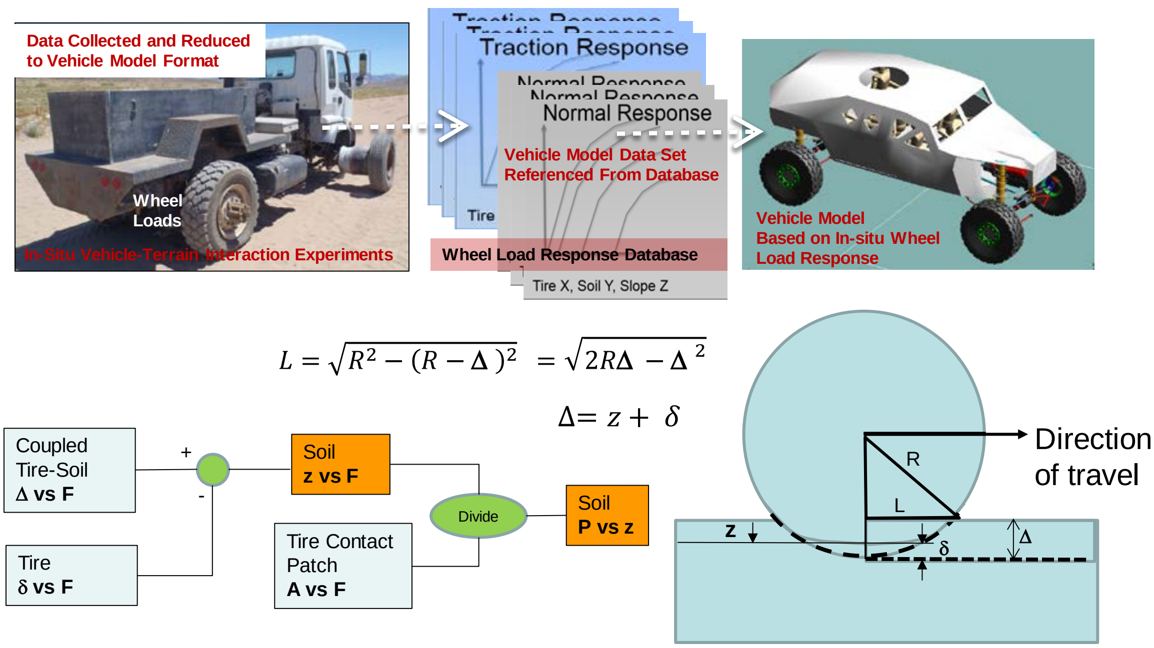


Figure 5: The advent of low cost on-board sensor suites such as 6DOF wheel load sensors have been proposed as the basis for empirical on-vehicle real-time collection and characterization of bearing load and traction load responses to terrain that takes advantage of superior repeatability, automated data collection, data reduction, and database development to build running gear level models of Terramechanical response based on lookup tables directly from the response measurement database [14,15].

All of the analytical methods that apply p-z and s-j equations are based on integrations of the normal and shear stress distributions over the geometric soil-running gear contact areas. These methods are ubiquitous in multi-body vehicle dynamics with off-road Terramechanics models.

Experimental methods based on wheel load sensing technology have been proposed and implemented that reduce the experimental effort and geometric similarity gap of the standard bevameter [14, 15]. They directly measure load and wheel center in-soil deflection Δ for a given soil condition. As shown in Figure 5, the empirical **F-Δ** relationship (normal force versus normal wheel center displacement) is then derived from known tire force-deflection relationships (**F-δ)** by decoupling the curve to identify only the soil force-sinkage curve (**F-z**) and finally the soil pressure-sinkage curve (**p-z**). Using tire contact patch models, these relationships are directly used in the vehicle dynamic model which must have at least a separate tire ring body defined to enable tire and soil deflection decoupling. The traction relationship (thrust vs. wheel slip) is also directly measured and ported to the vehicle model. Shown in Figure 5, this proposed method is called a "running gear level" Terramechanics model [14,15].

The fundamental assumptions and limitations of both of these Simple Terramechanics methods and their analytical constructs are:

1) bevameter platens and shear rings are good stress state surrogates for the vehicle tires and tracks (p-z, s-j models only)
2) the soil is unconfined, homogeneous and deep enough to be unaffected by boundary effects
3) coupling between the bearing and traction strength components is either negligible, or explicitly accounted for using a slip-sinkage model[13]
4) vertical height field discretization models can be used to account for plastic flow
5) accuracy progressively degrades for smaller terrain profile geometric features below the geometric scale of the platen or characteristic wheel footprint length [16]
6) due to effects of gravity on soil strength and increased coupling of shear and bearing capacity, accuracy progressively degrades with increasing slope [14]

Vehicle As A Sensor

The running gear level models and methods of parameter identification are derived from observations indicating that the most accurate method for modeling the strength of terrain in response to vehicle forces is to measure the loading of a vehicle of similar nominal ground pressure. For example surrogate or scout vehicles can be helpful for predicting vehicle performance of even much larger vehicles [14].

While on-board sensors to measure wheel loads for traction and resistance are the most obvious approach [14,15], vehicle sensors have been also used as indicators of weather or road conditions [17]; for classifying terrain types for planetary rovers [16,18] and recently, cameras and digital image correlation have been used for rut depth, tire slip and profiling [19-22] in all types of terrain [23].

For rut depth and motion resistance on-vehicle sensors, there is a unique opportunity to develop an alternative to the bevameter for soil characterization support of Simple Terramechanics models. These opportunities derive from the fact that vehicle running gear bearing strength obeys a mathematical form described by the Bernstein power law. First, notice that these can be used to derive a simple approach to a bearing strength model parameter identification, provided that measurements of rolling resistance, μ_{soil} ,and rut depth , z_s , can be made by the vehicle's on-board sensors, or other means.

By integrating the bearing force through the process of compaction to the equilibrium sinkage, a direct equation for the compaction work done can be derived.

$$Work = \mu_{soil} Wl = \int_0^{z_s} 2blkz^n dz = 2blk\left[\frac{z_s^{n+1}}{n+1}\right]$$

If the work due to vehicle powertrain and running gear internal resistance is known and all other soil related losses such as bulldozing are negligible, this equation can be combined with the original pressure-sinkage relationship applied to all vehicle wheels for the gross weight of the vehicle:

$$W = 2NbLkz^n$$

where N is the number of axles, b is running gear width and L is the contact patch length over which the compaction occurs. Substitution of this equation into the work equations yields an equation for the soil compaction work motion resistance coefficient.

$$\mu_{soil} = \left[\frac{z_s}{NL(n+1)}\right]$$

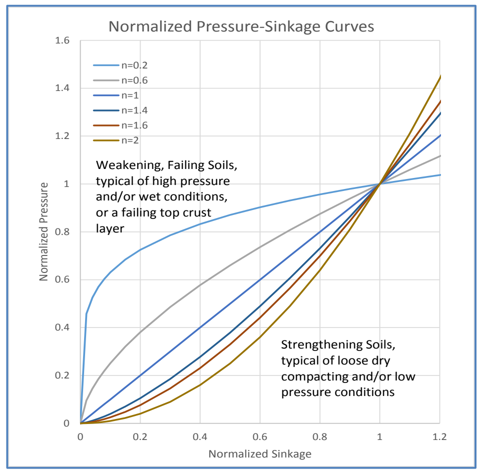
Solving for the bearing strength exponent, n,

$$n = \left[\frac{z_s}{NL\mu_{soil}}\right] - 1$$

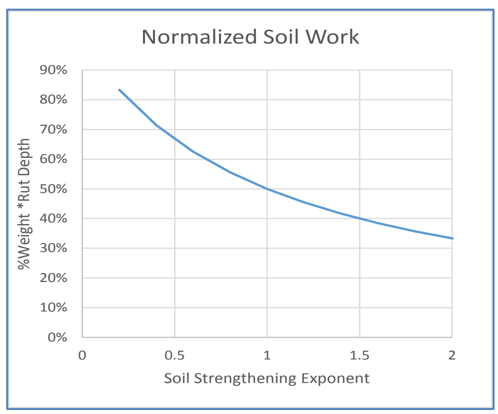
A coast down experiment on any soil of interest can be used to determine μ_{soil}

$$\mu_{soil} = \left(\frac{V^2}{2gd} - \mu_{vehicle}\right)$$

Where V is the initial velocity, d is the coast down distance, g is gravitational constant and $\mu_{vehicle}$ is the vehicle powertrain rolling resistance, determined by coast down experiments on pavement. It should also be noted that load sensors on the front axle wheels could be used to directly measure the resistance load and the equations adjusted for a single axle load. In this latter mode of operation, the vehicle could stream soil parameters continuously to a live route database. In either mode, the p-z equation constants become averages over a large path length rather than single geographic point estimates.



(6a)



(6b)

*Figure 6: Pressure-sinkage (6a) and soil work curves (6b) normalized to equilibrium wheel load and rut depth show how the exponent **n** can have a qualitative correlation to soil natural density and moisture content states. Actual bevameter data published in various sources [4,5,13,24] generally agrees well with these observations.*

The soil work is the integral under the pressure load (assuming constant area) curves shown in Figure 6a. Consistent with intuition, for values of n > 1 are typical of loose dry soils undergoing compaction, and "n < 1" soils are descriptive of soils that have reached compaction limits and are failing due to internal shearing in their far field. It should be noted that a thin hard top crust will also behave like a "n<1" soil, but then subsequently under further sinkage, transition to a "n>1" behavior as the deeper lower layer is loose and not compacted (see Figure 7).

Having thus first determined the bearing strength exponent, **n**, the bearing strength coefficient **k**, can be determined using the rut depth, $\mathbf{z_s}$, the nominal wheel load, and Bernstein's equation, multiplied by the contact patch area.

The second useful implication that can be derived from observations of the parametric behavior of the Bernstein power law as it applies to particular soil types and states is illustrated in Figure 6b, where typical exponent values associated with their soil strength trends are shown. Note that soil work is smaller for larger values of **n**. This is typical of a loose dry soil that strengthens progressively with higher bearing loads, primarily due to compaction.

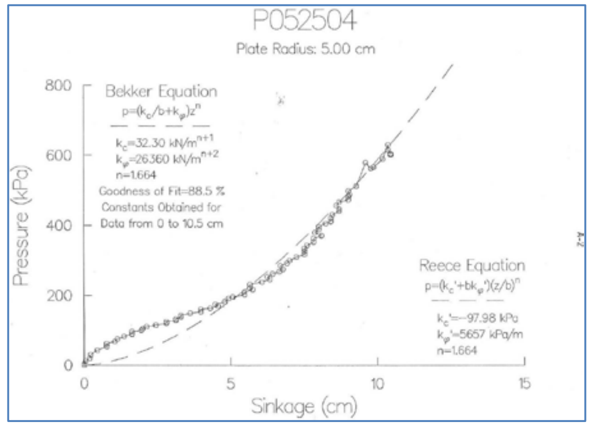


Figure 7: Pressure-sinkage data from a soil with an apparently weak top layer and loose deep under layer [24]

However, as **n** gets smaller, it becomes more characteristic of a weaker soil, or weak crust layer, for which the bearing strength is almost asymptotically limited. These observations are consistent with the equations describing soil motion resistance which is only dependent upon the strength exponent, **n**, the rut depth, $\mathbf{z_s}$, and the characteristic contact patch length, **L**. Given the correlations between exponent **n** and soil states shown in Figure 6, it is best to underestimate **n**. Given the dependence upon **L**, it is therefore important that this parameter be conservatively estimated so that **n** is not overestimated. Based on the wheel sinkage geometry shown in Figure 8, a conservative estimate for **L** based on wheel radius and sinkage is:

$$L = \sqrt{R^2 - (R - z)^2} = \sqrt{2Rz - z^2}$$

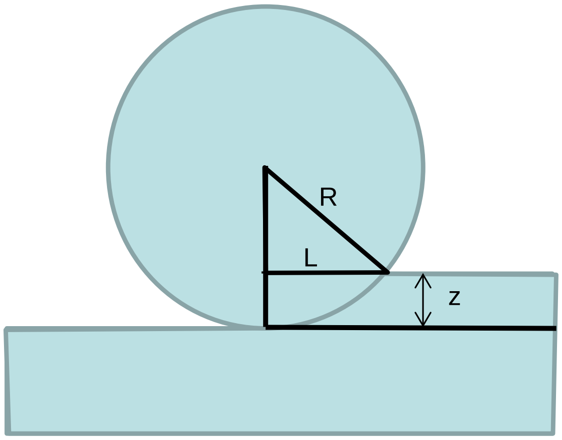


Figure 8: Example of a Contact patch calibrating length, L, estimation for a rolling wheel.

For tracked vehicles, track pad length is usually not a good nominal estimate for **L** for increasing rut depths, so the method of Figure 8 is suggested where the road wheel radius is an effective radius augmented by the track thickness.

Thus Simple Terramechanics p-z relationships cannot always be extrapolated to pressure loading regimes beyond those for which the model data were measured, and if the data exhibit transitions such as that shown in Figures 3 and 7, the model parameters must be adjusted for the new pressure magnitude regime.

AVT-248 OUTCOMES

The primary outcomes of the AVT-248 Simple Terramechanics efforts will be:

1) a draft NATO standard recommendation (STANREC) defining simple terramechanics models in NG-NRMM, and

2) a prototypical demonstration of a simple terramechanics model operating in the context of a complete end-to-end mobility prediction that begins with mapped geographic information systems (GIS) data of some sample terrain and produces a GIS based map of trafficability and maximum speed attainable for a specific vehicle. Specific plans for these are described in the Appendix.

Standards inclusively cast a broad net, yet rigorously seek to drive improvement upon the legacy incumbent cone index methods for Terramechanics. Furthermore, they will provide common data interoperability and assumptions assuring easy coordination and collaboration among NATO countries for mobility studies and actual operations. Standards establish a non-preferential basis that allows all countries to continue to take advantage of their legacy data and capabilities. Thus it will also promote and drive Terramechanics innovation and research among M&S industry and academia. Finally, over the long term it will seek to align virtual proving ground standards with the NATO physical test community.

Terramechanics Draft standards:

1. Analytical methods must predict both bearing and tractive performance of vehicles on deformable terrain
2. terrain response to the vehicle must include both normal response (e.g., either pressure-sinkage or force deflection) and tangential/traction response (e.g., drawbar pull vs slip or tractive stress vs shear strain) that includes and tracks permanent deformations
3. The computational method, including

idealization, discretization and scale assumptions for normal and shear stress distributions over the running gear interacting geometry surface assumptions shall be explicitly described and supported by a consistent repeatable experimental method analogously similar to the geometric scale of the running gear.

4. For deformable terrains, the discretization and permanent deformation tracking model (e.g., elasto-plastic height field) shall be explicitly described, consistent with and supported by the experimental method.
5. The experiments used to develop model parameters shall be repeated to determine model parameter variance
6. For hard surface off road terrain where terrain-vehicle response is dominated by the vehicle running gear, no terrain discretization and permanent deformation tracking is required.
7. Should be implementable in commercial 3D multibody dynamics codes
8. A height field is a discretized terrain model for use with multibody dynamics codes and a simple terramechanics model that tracks deformation by using a vertical height dynamic state variable at each terrain cell along with appropriate interpolation across cells.
9. GIS Interoperability: Standard GIS mapped output parameters for a Simple Terramechanics model minimum required:
    a. GO/NOGO
    b. Speed made good
10. Simple Terramechanics Model Input data from any GIS data source minimum required

    ST: USCS soil type
    MC: moisture content
    ρ: density
    T: temperature
    d: First significant strength layer depth

Database Development.

Methods to derive or infer additional data will have to be developed to meet the needs for current Simple Terramechanics models. These derived or inferred data requirements are:

c cohesion
ϕ internal friction angle
j shear strength exponent
n bearing strength exponent
k_ϕ bearing strength frictional constant
k_c bearing strength cohesive constant
K_0 bearing elastic reload stiffness
A_u bearing elastic progressive stiffening
$K_{\phi 2}$ 2nd layer frictional bearing strength
K_{c2} 2nd layer cohesive bearing strength
n_2 2nd layer bearing strength exponent
File1,File2 empirical data filenames,links

These data will populate a specific Simple Terramechanics database separate from standard terrain files coming from GIS. At the higher level, the NG-NRMM STANREC will require expandable open interfaces to permit additional GIS interoperable data fields to account for future development.

These key input/output relationships and parameters have been defined to help drive the software interface and data base requirements, as well as future development opportunities in terrain strength characterization from GIS based data. Fundamental to this effort are the several competing methods whereby the Simple Terramechanics model parameters (or the running gear model databases) are to be inferred, derived or developed from the available GIS remotely sensed data, or other augmenting GIS data. In addition to the vehicle as a sensor efforts already described, these methods include large scale cooperative efforts to collect broad spectrum field test traditional single point bevameter data [24], as well as analytical methods leveraging Complex Terramechanics models and their relationships to GIS mapped soil types and moisture contents. As was depicted in the dashed boxes connecting the Complex and Simple Terramechanics approaches shown in Figure 2, the latter include the development of fundamental soil strength numerical models (e.g. Finite or Discrete Element Models (FEM/DEM)), that can successfully predict running gear, bevameter and shear ring response across the necessary spectrum of soils and environmental conditions [25-27].

CONCLUSIONS

The NATO AVT-248 subcommittee on Simple Terramechanics plans to conclude its work in 2017 by establishing the initial STANREC and supplying prototypical demonstrations of GIS based end-to-end mobility modeling that incorporate existing Simple Terramechanics models. At this point in time, data bases and sources of measured data are a patchwork of efforts and data. Many are not supported with repeated measurements for analysis of variance. However, the methods and machinery are available and in use. Combined with the promise of on-board parameter estimation, Simple Terramechanics methods have become the de facto standard for multi-body vehicle dynamic models of off-road mobility. When coupled with specific vehicle test benchmarks [1,5,15], this will establish a vehicle terrain interaction modeling method for Next Generation NRMM that is verified and validated to be capable for predictive analysis of vehicle mobility for operational analysis, acquisition, and vehicle design.

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APPENDIX

Prototype demonstrations of Simple Terramechanics models generating GIS map based mobility predictions are being planned by several organizations involved in the NATO AVT248 committee, including Nevada Automotive Test Center (NATC), the South African Council for Scientific and Industrial Research (CSIR), and the National Research Council Canada (NRC). For example, the NRC Canada will use the development of a Supplementary Module for the Nepean Tracked Vehicle Performance Model (NTVPM), a Simple Terramechanics software package developed by Wong [5] to model the interaction of tracked vehicles on soft soil. The new Supplementary Module will adapt NTVPM to provide predictions of tracked vehicle performance on deformable terrain in place of the existing NRMM module. This includes adding powertrain capabilities and calculating the speed-made-good due to deformability of the terrain. The Supplementary Module will provide the speed-made-good due to operation on deformable terrain directly to the GIS database, as part of a complete end to end mobility prediction. The capabilities of the Supplementary Module may be extended to include the prediction of vehicle operating fuel economy and other performance metrics, if needed.