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GUIDANCE FOR STANDARDS APPLICABLE TO THE DEVELOPMENT OF NEXT GENERATION NATO REFERENCE MOBILITY MODELS (NG-NRMM)

Edition A, Version 1

JULY 2021

NORTH ATLANTIC TREATY ORGANIZATION

ALLIED MODELLING AND SIMULATION PUBLICATION

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NATO LETTER OF PROMULGATION

16 July 2021

1. The enclosed Allied Modelling and Simulation Publication AMSP-06, Edition A, Version 1, GUIDANCE FOR STANDARDS APPLICABLE TO THE DEVELOPMENT OF NEXT GENERATION NATO REFERENCE MOBILITY MODELS (NG-NRMM), which has been approved by the nations in the NATO MODELLING AND SIMULATION GROUP, is promulgated herewith. The agreement of nations to use this publication is recorded in STANREC 4813.

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EXECUTIVE SUMMARY

1. The NATO Reference Mobility Model (NRMM) is a simulation tool aimed at predicting the capability of a vehicle to move over specified terrain areas with specified conditions. NRMM was developed and validated by the U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) and Engineer Research and Development Center (ERDC) in the 1960s and 1970s, and has been revised and updated through the years. [Note: In 2018 TARDEC was reorganized within the U.S. Army Combat Capabilities Development Command (CCDC) and was renamed Ground Vehicle Systems Center (GVSC).] It was originally used to facilitate comparisons between vehicle design candidates by assessing the mobility of existing vehicles under specific terrain scenarios, but has subsequently and most recently found expanded use in support of complex decision analyses associated with vehicle acquisition and operational planning support. A NATO Exploratory Team (AVT-ET-148) (Dasch and Jayakumar, 2018) and its follow-on Research Task Group (AVT-248) (Dasch and Jayakumar, 2020) have developed an approach to upgrade this key modelling and simulation (M&S) tool to account for modern M&S methods. This document provides guidance defining the Next-Generation NRMM (NG-NRMM) capabilities under a unifying open architectural framework.

2. A NATO standard is necessary to address the latest mobility modelling and simulation (M&S) tools that are used for planning the NATO nations' military vehicle operations, and to support vehicle acquisition and design using common mobility metrics. Currently, the NATO Reference Mobility Model is the only NATO recognized numerical modelling tool for accomplishing these objectives, but it is broadly augmented and supplanted with other methods because it is understood to be inherently limited and difficult to adapt.

3. This standard builds upon and expands the original valid basis for the legacy NRMM to define the Next-Generation NRMM to be any mobility M&S capability that produces map-based probabilistic mobility predictions of ground and amphibious vehicles through interoperation of M&S tools that include:

a. Geographic information systems (GIS) software,
b. 3D Physics-based vehicle dynamics,
c. Terramechanics models for off-road operations
d. Autonomous control M&S software, as well as
e. Uncertainty Quantification (UQ) software for probabilistic M&S

4. The combat vehicle and automotive industries, as well as the various NATO national labs already use these M&S tools. Through this standard, a ground vehicle mobility modelling and simulation architectural specification is established. The standard is applicable to the full range of ground vehicle geometric scales and running gear morphologies. It addresses: 1) standard M&S methods; 2) modular interoperability,

portability, and future expansion; 3) uncertainty quantification; and 4) verification, validation and benchmarks appropriate to multiple levels of theoretical, geometric, and numerical model resolution.

5. Since this open architecture basis for an NG-NRMM related standard is the initial release, a significant list of gaps and challenges are also identified. It is expected that this guidance provides the framework whereby all future efforts can be planned to become additive and complementary to the long-term goals to support NATO nations' operational readiness and acquisition processes.

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CHAPTER 1 INTRODUCTION

1.1. BACKGROUND

The NATO Reference Mobility Model (NRMM) is a simulation tool aimed at predicting the capability of a vehicle to move over a terrain with specified characteristics. NRMM was developed and validated by the U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) and Engineer Research and Development Center (ERDC) in the 1960s and 1970s, and has been revised and updated through the years. It was originally used to facilitate comparisons between vehicle design candidates by referencing the mobility of existing vehicles under specific terrain scenarios, but has subsequently and most recently found expanded use in support of complex decision analyses associated with vehicle acquisition and operational planning support. A NATO Exploratory Team (AVT-ET-148) (Dasch and Jayakumar, 2018) and its follow-on Research Task Group (AVT-248) (Dasch and Jayakumar, 2020) have developed an approach to transform this key modelling and simulation (M&S) tool into an M&S standard that allows for use of a broad and diverse range of modern M&S methods. This document provides guidance defining the Next-Generation NRMM (NG-NRMM) capabilities under a unifying open-architectural framework and follows the NATO standards development process provided in AAP-03(K) “Directive for the Production, Maintenance and Management of NATO Standardization Documents” (AAP-03, 2018).

1.2. PURPOSE

An NG-NRMM related standard is necessary to address mobility modelling and simulation (M&S) tools that are used for planning the NATO nations’ military vehicle operations and to support vehicle acquisition and design using common mobility metrics. Currently, the NATO Reference Mobility Model (NRMM) is the only NATO recognized numerical modelling tool for accomplishing these objectives, but it is broadly augmented and supplanted with other methods because it is understood to be fundamentally limited and difficult to adapt. This standard refines and expands the original valid basis for the legacy NRMM to define the Next-Generation NRMM (NG-NRMM) to be **any mobility M&S capability that produces map-based probabilistic mobility predictions of ground and amphibious vehicles through interoperation of M&S tools** that include: geographic information systems (GIS) software, physics-based vehicle dynamic, terramechanical, and autonomous control M&S software, as well as uncertainty quantification software for probabilistic M&S performance predictions.

1.3. SCOPE

1. These M&S tools have already been adopted by the combat vehicle and automotive industries, as well as the NATO nations' national labs. Through continued development of this standard, NG-NRMM will become a ground vehicle mobility modelling and simulation architectural specification applicable to the full range of ground vehicle geometric scales and running gear morphologies. It will address

a. Standard M&S methods
b. Modular interoperability, portability, and future expansion
c. Uncertainty quantification
d. Verification, validation and benchmarks

applied across the full range of theoretical, geometric, and numerical model resolution.

CHAPTER 2 ARCHITECTURAL SPECIFICATIONS

1. A Next-Generation NATO Reference Mobility Model (NG-NRMM) is broadly defined to be any mobility analysis capability that predicts land and amphibious vehicle mobility, through coordinated interoperation of geographic information systems (GIS) software, physics-based vehicle dynamic modelling and simulation (M&S) capable of using terramechanics for soft soil interaction, autonomous control systems, and uncertainty quantification for probabilistic performance predictions. The nominal summary level mobility metrics generated by a NG-NRMM capability shall be GO/NOGO, Speed-Made-Good and Motive Efficiency. These summary level metrics can be composed of any number of mobility contributing and controlling factors.

2. NG-NRMM software tools should predict both the summary level vehicle mobility metrics, as well as their contributing factors, on any given terrain map for operational analysis and mission planning purposes, to include selecting the optimum vehicle path based on the mission requirements.

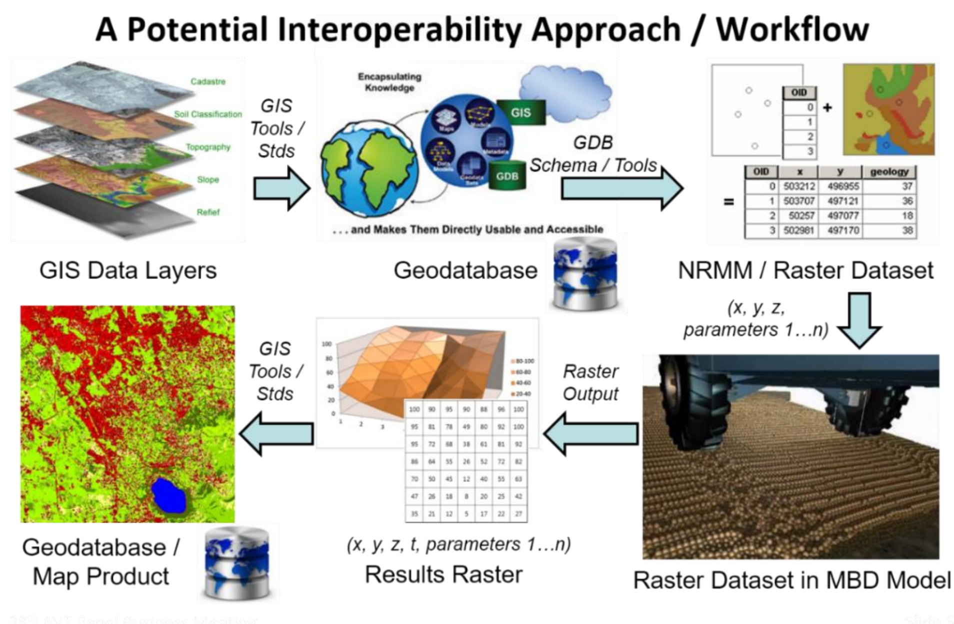

Figure 2.1: Data Flows and File Types in NG-NRMM.

3. Figure 2.1 shows a high level description of the data flows and file types in NG-NRMM. Standard GIS tools and processes are used to organize geospatial data into the File Geodatabase schema. The data is then be exported from the File Geodatabase to an intermediate "terrain file" format. Currently, a modified NRMM Code 11 (or, "MAPTBL") or GeoTIFF (Geographic Tagged Image File Format) format is used (see Annex A.1). To be compatible with modern GIS data services, the structure of this is also described by a unified modelling language (UML) data model (see Annex A.2).

4. The format is either modified Code 11 MAPTBL as shown in Annex A or XML/GML (extensible markup language/geography markup language) using an XML schema definition (XSD) as shown in Annex B, corresponding to the data model. The modified NRMM Code 11 (Ahlvin and Haley, 1992) input format in Annex A.1 provides for backwards compatibility to the legacy NRMM data files. Each terrain file contains important environmental characteristic data needed to assess vehicle mobility. All terrain feature data is incorporated and preserves all relevant spatial information to provide cartographic visualization and route analysis capabilities.

2.1. GEOGRAPHIC TERRAIN DATA PROVIDED AS INPUT TO MOBILITY M&S

1. From a broad array of GIS data, NG-NRMM terrain data input files shall be specifically constructed and formatted to support probabilistic mobility predictions. The following minimum set of 24 characterizing attributes should be included as data fields in the NG-NRMM terrain data:

a. Surface* soil type, encoded as an integer corresponding to a Unified Soil Classification System (USCS, NRMM variable KUSCS)
b. Surface bulk density (g/cm^3)
c. Surface soil moisture content by weight (%), (NRMM variable TMOIST)
d. Surface soil temperature, Degrees Celsius
e. Land Use, (NRMM variable LUSE) encoded as an integer corresponding to a Multinational Geospatial Co-Production Program (MGCP) land cover descriptor
f. Surface soil layer depth
g. Surface roughness (RMS Wave number)
h. Sub-surface soil type, encoded as an integer corresponding to a Universal Soil Classification Code (USCS, NRMM variable KUSCS)
i. Sub-surface bulk density (g/cm^3)
j. Sub-surface soil moisture content by weight (%), (NRMM variable TMOIST)
k. Sub-surface soil temperature, Degrees Celsius
l. Statistical type for surface soil type value (i.e., majority)
m. Statistical type for surface bulk density value (i.e., maximum, mean, minimum)
n. Statistical type for surface soil moisture content value (i.e., maximum, mean, minimum)
o. Statistical type for surface soil temperature value (i.e., maximum, mean, minimum)
p. Statistical type for land use value (i.e., majority, most intense)
q. Statistical type for surface soil layer depth (i.e., maximum, mean, minimum)
r. Statistical type for surface roughness (i.e., maximum, mean, minimum)
s. Statistical type for sub-surface soil type value (i.e., majority)

t. Statistical type for sub-surface bulk density value (i.e., maximum, mean, minimum)
u. Statistical type for sub-surface soil moisture content value (i.e., maximum, mean, minimum)
v. Statistical type for sub-surface soil temperature value (i.e., maximum, mean, minimum)

2. Tags for each value identify the source of the data as measured (m), inferred (i), legacy (c), or notional (n). Inferred data shall provide the inference algorithm (see Bullock, 1994). Also Annex C is an example of inference models relating to soil moisture and terrain strength, a nascent area of research.

a. Tag for surface soil type data source (i.e., m, i, c, n)
b. Tag for surface bulk density data source (i.e., m, i, c, n)
c. Tag for surface soil moisture content data source (i.e., m, i, c, n)
d. Tag for surface soil temperature data source (i.e., m, i, c, n)
e. Tag for land use data source (i.e., m, i, c, n)
f. Tag for surface soil layer depth data source (i.e., m, i, c, n)
g. Tag for surface roughness data source (i.e., m, i, c, n)
h. Tag for sub-surface soil type data source (i.e., m, i, c, n)
i. Tag for sub-surface bulk density data source (i.e., m, i, c, n)
j. Tag for sub-surface soil moisture content data source (i.e., m, i, c, n)
k. Tag for sub-surface soil temperature data source (i.e., m, i, c, n)

* Surface typically refers to the upper 0-6” (0-15.2 cm) of soil.

3. Elevation data will also be necessary and will require special consideration. Elevation data will be used to construct the surface upon which simulated vehicles are run and will allow for the calculation of slope, aspect, and potentially ride quality, either at simulation run time or through pre-processing. Very high-resolution elevation data can identify small obstructions and greatly improve the estimation of ride quality, but it will require greater computing resources to process and greater effort to obtain. Coarse resolution elevation data is easier to obtain and requires fewer resources to process, but may omit abrupt changes in topography or small obstructions. A consideration when selecting appropriate levels of spatial resolution is that in order to model or simulate the interaction of components of a vehicle’s running gear with the environment, the resolution of these input data must be smaller than the dimension of the modelled vehicle’s running gear (e.g., wheel diameter) by a factor of 10, ideally, and a minimum of a factor of 5 required to capture a full harmonic cycle in the terrain profile with wavelength equal to running gear dimension. In practice, it has been found that combining high-resolution elevation data with other data layers may result in a combined data set that is too large to process. Because of this, high-resolution elevation data should be provided to the simulation environment as a separate stand-alone data set. While elevation data are typically shared as rasters in TIFF or GeoTIFF format, larger elevation data sets may be

shared more efficiently using the Triangulated Irregular Network (TIN) format. The TIN format is a more efficient format that results in smaller file sizes and allows for a variable density of elevation points. The TIN format is similar to, and can be converted into, the mesh formats commonly used in 3D modelling environments.

4. High-resolution elevation data in raster or TIN format may be resampled or decimated to a lower-resolution version to reduce file sizes and lower computing requirements. Elevation data sets of different resolutions may also be combined into a single TIN data set, where sparsely spaced low-resolution data points are replaced by densely spaced high-resolution data points where they are available.

5. It is likely that multiple geospatial data sets will need to be combined to produce data to populate all the necessary characterizing attribute fields. Data sets of the highest spatial resolution available should be used to obtain these characterizing attributes, but they do not all need to be the same spatial resolution. All data sets included should use, or be projected into, a common coordinate system. It will also be necessary to document the uncertainty of each input characterizing attribute as an attribute for each feature, or as an associated layer, for each input geospatial data set. This uncertainty data type should include a value for horizontal spatial resolution in metres, and measurement variance within each feature, due to feature aggregation or measurement error, represented as a standard deviation.

6. Input GIS layers should be prepared such that only necessary data fields are included and geometries should be dissolved to combine any neighboring features having identical attributes. Some GIS software systems provide tools to enforce topological rules for collections of vector data, allowing data layers to be ranked in order of their precision. Boundaries of less precise layers may be shifted to match the nearby boundaries of more precise layers, while the precision and boundaries of more precise layers are preserved. Often, attribute values from source data sets will need to be recoded to match the recommended NG-NRMM data model. An example data model is included in Annex A.

7. While input GIS layers will likely include raster and vector format data, these data will typically need to be converted into a collection of either all raster or all vector format prior to use in the M&S environment, but this can vary between M&S systems.

8. If all raster format is used, a raster layer will need to be created for each characterizing attribute. It is recommended to use a common template raster to create each individual raster layer, as it is critical that all raster layers share the same origin, extent, and resolution.

9. If all vector format is used, each individual GIS layer shall be combined together through a process such as a union, resulting in a single GIS layer that is a combination of the geometries and attributes of two or more input layers. Raster format layers may be converted to vector format and included in this process. After all GIS layers have been combined, final preparation should be performed on this layer to remove unnecessary attributes and geometries should be dissolved to combine any neighboring features

having identical attributes. If topology tools are available in the GIS software system in use, these should be used to remove slivers or gaps in data, and improve the quality of the combined data.

10. Regardless of the GIS layer format used, the final step in preparation of a NRMM MAPTBL terrain file format is to generate Numbered Terrain Units (NTUs) representing regions of homogenous characterizing attributes. The MAPTBL file is an ASCII raster format where each pixel represents the NTU ID of that area.

11. Additionally, a table of characterizing attributes is generated in text format, where each row represents the attributes for one terrain unit. When following the vector data format example above, each feature in the fully processed and dissolved layer of combined inputs represents a unique NTU. The schema of this terrain file table is described in Annex A.1. The AVT-308 Cooperative Demonstration of Technology (CDT) (Letherwood et al., 2020) developed a geo-processing script with a user-defined template raster to extract NTUs and create the ASCII raster file. This script also generated the associated text format attribute table. A benefit of a user-defined template raster is that data can be output at a variety of extents and resolutions, while still maintaining the original source data at the highest possible resolution. The size and resolution of this template raster affects the size of the generated terrain file, the fidelity of characterizing attributes, and ultimate predictions. A higher resolution raster with smaller pixels will capture small obstacles or features in the landscape but results in a larger file requiring more resources to process. A lower resolution raster needs fewer resources to process, but may omit landscape features smaller than the pixel size.

12. Many M&S systems may not require the generation of a MAPTBL format terrain file or combined attribute table. Alternatively, the data described in the terrain file may be stored in an XML/GML format as described in Annex B.

13. Some systems may have the capability to accept input characterizing attribute data as individual raster files, each representing a single characterizing attribute. It is recommended that these individual raster files be generated in GeoTIFF format. It is critical that all of the individual raster layers share the same origin, extent, and resolution. The CDT also developed a geoprocessing script to export GeoTIFF format rasters for each characterizing attribute in a vector format terrain data set.

14. While several data formats including the ESRI Geodatabase Feature Classes (ESRI, 2020), ASCII rasters, text, TIN, and GeoTIFFs have been described above, these are certainly not the only acceptable formats to transfer data into M&S systems. Other formats including XML and GML formats are discussed in section 2.1.2, and many M&S systems may include functionality to import data in other formats not discussed.

15. The legacy NRMM terrain file in ASCII format, Code 11 MAPTBL, has been modified to accommodate the minimum requirements listed above. The detailed file specification is included in Annex A.1.

2.1.1. Input Data Schema

1. NG-NRMM tools for GIS shall use the product specifications, encoding formats and application schemas for military geospatial data; and it is built upon generic and abstract standards for geographic information defined by the International Organization for Standardization (ISO TC/211) and the Open Geospatial Consortium (OGC).

2. The following will be supported:

   a. Feature Attribute Coding Catalog-Plus (FACC+) data model schema [with eventual migration to DGIWG (Digital Geographic Information Working Group) Feature Data Dictionary-Plus (DFDD+)]
   b. NG-NRMM XML/GML shall build upon the XSD standard of W3C (World Wide Web Consortium) incorporating GML standards of OGC for spatial reference. The XSD defining the data format is derived from the UML data model [see Annex B].
   c. Legacy NRMM Code 11 MAPTBL [see Annex A.1]

2.1.2. Input Data Formats

1. Input data files will be developed using the process shown in Figure 2.1 involving the following file types: File Geodatabase, a modified NRMM Code 11 MAPTBL via ASCII ("flat file"), GeoTIFF, XML/GML following the schema defined in Annex B, TIN (Triangulated Irregular Network) elevation data, and Metadata in XML format following ISO 19139 (templates exist in ArcGIS). All data sets should use the Universal Transverse Mercator (UTM) coordinate system with linear units of metre.

2. The MAPTBL format is a legacy ASCII format that stores geospatial data and attribution in three different files.

   a. *.ASC file which is an ASCII raster format of Numbered Terrain Units (NTUs) and their spatial location
   b. *.PRJ file which stores the geospatial coordinate system description of the .ASC file
   c. *.TER file which stores the attributes of each NTU following the data model described in Annex A

3. NTUs are conceived as areas much larger than the vehicle for which probabilistic terrain attributes (e.g., slope, aspect, roughness, etc.) are valid assumptions. Higher-resolution terrain data shall be treated as an independent GIS layer for specific areas where it is available.

4. The GeoTIFF raster format represents each descriptive attribute as a single image. A GeoTIFF image should be produced for each descriptive attribute listed in section 2.1.

5. The XML/GML format is an alternative to the MAPTBL format, and shall include all attributes listed in section 2.1 in a single file, following the schema defined in Annex B. High-resolution elevation data should be provided in TIN format, either within a file

geodatabase, or as an x-y-z ASCII, binary, or XML file. All data should include metadata in XML format for each file following ISO 19139 standards or its replacement.

2.1.3. Input Environment Scenario Data

An optional environment-defining scenario data input file shall have the same format as the terrain data file. One example is non-permanent, weather-related conditions that modify terrain response. The scenario file attribute values will be customized to produce the required environment-defining scenarios supporting the particular end use.

2.2. MOBILITY M&S OUTPUT TO GEOGRAPHIC MAP OVERLAYS

Summary mobility metrics, as well as their contributing factors, shall be computed by the NG-NRMM mobility M&S tools for each NTU and/or GIS based terrain discretization unit. The summary mobility metrics are, at a minimum, trafficability (single pass GO/NOGO), Speed-Made-Good and Motive Efficiency. Further, each of these shall include probabilistic predictions. Detailed definitions of the individual mobility contributing factors and the aggregating algorithmic basis for combining them should be transparent and available to the users and consumers of the output data. The legacy NRMM factors and aggregating algorithms in the NRMM operational module are accepted as a minimum baseline, but probabilistic mobility and terrain property related metrics for map plotting from an NG-NRMM capability shall be defined by each end use. Ideally, any NG-NRMM will include a module to tailor multifactor aggregating algorithms to each end use. That aggregating module of the NG-NRMM will preserve backward compatibility to the NTU-based input and output data files while also migrating to GIS-based data.

2.2.1. Formats

For any given implementation of a NG-NRMM, there may be hundreds of possible output variables. Therefore, consistent with the modular open-system architecture principles of NG-NRMM standards, actual output files may be expanded or otherwise tailored to meet the intended use. Consistent with the minimal output metrics mentioned above, and as an example from legacy applications, Annex D provides a notional example output file. As a minimal set, in addition to the integer value GO/NOGO (1=GO, 0=NOGO) data fields, three Speed-Made-Good data fields (upslope, downslope, cross slope), and Motive Efficiency data field, there shall be five data fields for the variance of each of these standard mobility metrics. The Annex D example also includes 13 additional real valued data fields per NTU in raster format as an example of allowance for custom tailoring of each application. The notional example of an ASCII output file, provided in Annex D, is an Excel file available for download from NATO STO at https://www.sto.nato.int/pages/natostandards.aspx.

2.2.2. Trafficability (GO/NOGO)

Trafficability is the ability of a vehicle to traverse a given area of terrain. It shall be expressed as a binary result indicating success (GO) or failure (NOGO). Using available data that quantify variability of terrain properties, probabilistic trafficability metrics shall be developed. The subordinate reasons (e.g., controlling factors) for results and their respective limits shall be made available in the GIS output file. The algorithms supporting the results shall be fully documented.

2.2.3. Speed-Made-Good

1. Speed-Made-Good is the maximum speed a given vehicle can traverse an NTU. Each application may require a tailored detailed definition. For example, slope dependence can be averaged out to yield a single performance metric that is omni-directional-- (i.e., “omni-speed”) or the results can be provided as a triplet including upslope, cross slope, and downslope speed limits. When using omni-speed, all three data fields will be equal, having the omni-speed average value. Each end use of an NG-NRMM shall be fully transparent regarding the definition and detailed algorithm used for Speed-Made-Good.

2. Using available data that quantify variability of terrain properties, probabilistic Speed-Made-Good metrics shall be developed. The subordinate reasons (e.g., controlling factors) for results and their respective limits shall be made available in the GIS output file. The algorithms supporting the results shall be fully documented.

2.2.4. Motive Efficiency

Motive Efficiency is any measure of energy efficiency. Using available data that quantify variability of terrain properties, probabilistic motive efficiency metrics shall be developed. The subordinate reasons (e.g., controlling factors) for results and their respective limits shall be made available in the GIS output file. The algorithms supporting the results shall be fully documented.

2.3. VEHICLE SYSTEM MODELS

NG-NRMM will take advantage of 3D multibody dynamics (MBD) modelling and simulation to represent the vehicle at a level of fidelity and model resolution consistent with the requirements of the mobility modelling end use. MBD computer codes are the core numerical simulation technology that have enabled almost all modern users of mobility models to accurately represent almost any vehicle at any desired level of fidelity with respect to the vehicle’s mechanical architecture and behavior. Further, there are numerous commercial MBD simulation codes and their application to vehicle dynamics has been one of their primary applications. Thus, almost all MBD codes are tightly integrated with the additional simulation capabilities required to model the vehicle power trains and suspensions, embedded control systems, and most importantly, their interaction with terrain. Since the commercial automotive industry has already driven extensive development and validation of these MBD tools for on-road mobility, this standard will focus on applications of MBD to off-road mobility that is important to military vehicle applications--more specifically, the vehicle-terrain interaction models.

2.4. TERRAMECHANICS

1. NG-NRMM must utilize vehicle-terrain interaction models, also known as terramechanics models that are geometrically and mechanically consistent with their end use application and are theoretically extensible across a range of vehicle and terrain environment scales and morphologies. NG-NRMM terramechanics models must include the terrain elasto-plastic response to bearing and tractive repetitive loads using models that can be correlated to available in-situ geospatially mapped and remotely sensed terrain characteristics. All terramechanics models require empirical measurement and calibration of models of soil effects at some level of resolution. NG-NRMM models are categorized below as "Simple" and "Complex" based on the increasing level of resolution at which the physics of the soil response is modelled. Figure 2.2 shows the spectrum of models. Simple Terramechanics computes a normal and tangential force at the running gear based on application of bearing and traction experimental results at the scale of the running gear. Complex Terramechanics uses full three-dimensional deformation and flow dynamic soil models and experiments with the soil discretized at least at the scale of the tire tread or track grouser.

	Quantum Mechanics	Molecular Dynamics	Micro-scale Model Complex Terramechanics	Macro-Scale Model Complex Terramechanics	Height Field Model Simple Terramechanics	Height Model Simple Terramechanics	Vehicle Cone-Index Empirical Model
Fidelity	Very high →						Very low
Description	Sub-atomic to atomic scale models	Molecular scale model	Soil grains individually modeled	Soil particles lumped to form a virtual particle or a finite element (e.g. DEM or FEM)	Terrain is divided into vertical cells. For each cell height and state of stress are stored. A Bekker-Wong-Janosi type pressure-sinkage-traction-slip model is used for each cell.	Normal stress and slip are used to calculate sinkage and tractive force using a Bekker-Wong-Janosi type model.	Vehicle-scale empirical steady-state model based on the Cone Index (implemented in NRMM / NRMM-II)
Terrain discretization	3D	3D	3D	3D	2D or 1D	0D	0D
Discretization scale	Sub-atomic scale	Molecular scale	Soil grain	Tread-block	Tread-block or Running gear	Running gear	Vehicle scale
Deformation/flow directions	3D	3D	3D	3D	1D - Vertical or 2D - Vertical + Horizontal	1D - Vertical	1D - Vertical
Number of Soil DOFs for vehicle mobility applications	$>10^{20}$	$\sim10^{18}$	$10^{14} – 10^{11}$	$10^{7} – 10^{6}$	$10^{4} – 10^{3}$	1	0
Current Computational Cost	Prohibitive	Prohibitive	Years of HPC time.	6 hours to 1 week	Minutes/ real time	Faster than real time	Faster than real time
Current state of development	Unknown how to take the model to the macro-scale	Taking the model to the macro-scale requires more research because the soil consists of many materials	More research is needed to understand the micro-mechanical soil interaction forces	More research is needed to improve, calibrate, and validate the soil models	More research is needed to improve, calibrate, and validate the soil models	More research is needed to improve, calibrate, and validate the soil models	Implemented in NRMM/NRMM-II

Figure 2.2: Spectrum of Terramechanics Models Levels of Resolution.

2. Terrain properties for each unique terrain type should be collected in a complete characterization suite to include:

a. USCS or other soil type: ASTM D2487 (2011) and ASTM C136 (2019)

b. For hard surfaces, the type of surface material must be specified including concrete, asphalt, or brick for paved roads and gravel or compacted dirt for unpaved roads.
c. Moisture content (MC) by weight, measured by ASTM D4643 (2017)
d. Sample as-tested total (wet) bulk density (or dry density with MC, sand cone ASTM D1556 (2015); drive cylinder ASTM D2937 (2017); or nuclear densometer ASTM D6938 (2017)). Nuclear densometer readings should use a probe depth of 15 cm (6 inches).
e. Maximum total bulk density, derived from a Standard Proctor compaction test, ASTM D698 (2012)
f. Liquid and Plastic limits (ASTM D4318, 2017) for plastic soils (i.e., the Atterberg Limits)
g. Saturation Test for non-plastic soils
h. Specific Gravity test
i. Soil strengths expressed as cohesion and internal friction angle using triaxial shear testing. Use consolidated drained ASTM D7181 (2020) for sand and ASTM D4767-11 (2020) for consolidated undrained triaxial compression test for cohesive soils.
j. For the dilatancy (volumetric) response and deviatoric (shear) response Mohr-Coulomb failure theory parameters at four moisture levels:
    (1) near dry (~half of Proctor Optimal MC (POMC))
    (2) at POMC
    (3) at 0.95 times liquid limit (LL), or saturation at field density (SatMC) for non-plastic soils
    (4) 0.5·(LL + POMC) for plastic soils, or
    (5) 0.5·(SatMC + POMC) for non-plastic soils
k. Top two strength-determining layer depths
l. Temperature of layers
m. Cone index at the 0-6” and 6-12” layer depths
n. Land Use (MGCP land cover descriptors)
o. Rock and vegetative/organic material (i.e., roots, grass mats, etc.) content
p. Confining and drainage conditions

3. It is also recommended that the terramechanics models have the ability to include the following terrain features:

a. Heterogeneous terrains. Those are terrains, which in addition to soil, have other embedded components such as boulders, rocks, stones and/or large roots. The discrete terrain component can be specified by its size, shape, and spacing distributions as well as its mechanical properties including the friction coefficient with the vehicle running gear.
b. Multilayered soil. Each layer can have a specified thickness and its own set of mechanical properties. It is recommended that the terramechanics models support at least two soil layers. The layers can include for example:

a tilled soil layer on top of compacted soil; an organic muskeg layer on top of compacted soil; or a snow and/or ice layer on top of soil.

c. Snow and ice melting and refreezing effects on friction and adhesion to the running gear.

d. Bodies of water and water-covered terrains. The model should be able to account for the following effects:

(1) Water resistance to the vehicle motion due to water viscosity and inertia

(2) Soft soil bottom that can include: soft organic soil, sand, or gravel

(3) Transition of the vehicle from solid terrain to flooded terrain and vice versa

e. Vegetation covered terrains. Vegetation models can include the following:

(1) Effect of vegetation roots (below ground vegetation) on soil strength

(2) Effect of ground vegetation such as low grass/shrubs and fallen leaves on soil strength and friction coefficient between the running gear and the terrain

(3) Models of above ground vegetation including compliant stems such as grass, bushes, and most crops, semi-compliant stems such as small-trees and some types of crops (stem diameter <2 in), and stiff stems such as medium and large trees (stem diameter >2 in)

(4) Above ground vegetation models should be able to account for:

(a) Vegetation override force for one stem at any vehicle speed. The override force must be smaller than the force which causes permanent deformation to the vehicle body.

(b) Vegetation resistance force at any vehicle speed while the vehicle is going over a field of stems

(c) Above ground vegetation can be specified using the following physical parameters: (1) vegetation type (using for example the U.S. National Vegetation Classification - usnvc.org); (2) number of stems per unit area (or average distance between stems); (3) stem length distribution; (4) stem diameter distribution. From those physical parameters the following mechanical parameters can be experimentally calibrated then used to model for the vegetation mechanical response: (1) friction coefficient between the vegetation stem and the vehicle; (2) stem axial and bending stiffness as a function of stem diameter; (3) stem axial and bending damping as a function of stem diameter; (4) breaking strength of a stem under axial and bending loads as a function of stem diameter; (5) maximum axial force and bending moment required to pull a stem from the soil as a function of stem diameter and soil conditions (type, moisture, and temperature).

f. Complex terrain topography can include:

(1) Terrain vertical height as a function of the X and Y horizontal terrain coordinates. The X-Y resolution should be smaller than the smallest dimension of the vehicle running gear (such as tire or track wheel radius).
(2) Sloped terrains: positive/negative long slopes and side slopes
(3) Roughness specified by the spectrum of wave height (amplitude) versus wave length in two directions. It is recommended that the smallest wave length be about 1/10th the running gear size (tire or track wheel radius).

g. Natural obstacles including rocks and fallen trees and/or branches (similar in size or larger than about a quarter of the radius of the vehicle tires or track wheels). Smaller obstacles can be modelled as part of the heterogeneous soil and/or as terrain roughness.

h. Urban obstacles including poles, walls, fences, debris, other vehicles, and small structures

2.4.1. Simple Terramechanics for Soft Terrain

1. NG-NRMM Simple Terramechanics (ST) models are those that depend upon complementary calibrating experimental methods that are geometrically similar and physically analogous to vehicle running gear interaction with soft terrain (Dasch and Jayakumar, 2020). The nominal approach uses a bearing limit response model and a separate complementary tractive mechanical development response model that includes dependence on bearing stress, terrain cohesive (or adhesive), and frictional properties and running gear slip.

a. The nominal ST analytical model must predict both bearing and tractive performance of vehicles on deformable terrain.
(1) Elasto-plastic repetitive load response model tracks permanent terrain substrate normal and tangential deformations via some means such as a height field model
(2) Height field model: a discretized terrain model that tracks deformation by using a vertical height and/or shear displacement dynamic state variables at each discrete terrain point or cell

b. For hard surfaces and hard off-road terrain where terrain-vehicle response is dominated by the vehicle running gear, no terrain discretization and permanent terrain deformation tracking is required, but surface-specific traction response characteristics (friction ellipse, friction vs. slip curve) must be provided.

c. The complementary experimental method must have demonstrated repeatability with associated statistical uncertainty characteristics to support probabilistic M&S.

d. An evolving Terramechanics Database of ST modelling parameters is provided in Annex E for NG-NRMM with soft terrain modelling parameters. This Annex collects available data relating to terramechanics models typically measured using Bekker value meter (i.e., "bevameter") techniques. The data are collected from a wide variety of sources in an EXCEL file available for download from NATO STO at https://www.sto.nato.int/pages/natostandards.aspx. This database has standard consistent sets of bevameter-derived pressure-sinkage and shear characteristics (Bekker, 1969; Bernstein, 1913; Reece, 1965; Wong, Garber and Preston-Thomas, 1984). The Terramechanics Database is also intended to be adaptable to account for future innovations to be inclusive of multiple terrain layer characterization and also any unknown future model innovation and development such as slip-sinkage model parameters. Standard bevameter pressure-sinkage should be measured as follows:

(1) On mineral terrain with at least two different plate sizes, and will consist of at least two scaling parameters and a power law exponent

(2) On muskeg with at least one plate size, and will consist of scaling parameters for an appropriate pressure-sinkage relationship

(3) On snow with at least two different plate sizes, and will consist of scaling parameters for exponential relationships that represent the behavior of a snow pack with frozen ground at the base

(4) On all terrain types measure the repetitive load-unload permanent deformation characteristics with at least two parameters such as a linear stiffness and stiffness progression parameter

e. Bevameter based shearing characteristics of terrain, also in Annex E, include maximal shear strength and a shear stress-shear displacement relationship that characterize the tractive interface between the terrain and the vehicle running gear (e.g., wheel, tire, track, rubber-pad track, walking foot, etc.). The maximal shear strength should consist of a cohesion (or adhesion) constant and a friction angle. The measurements should be made using the bevameter shear annulus device with applied normal pressures that are as close as practicable to the applicable maximum bearing pressure that will be experienced by the vehicles to be modelled. The shear stress vs. shear displacement relationship shall include parameters to represent the standard exponential curve fitting relationship as originally described in Janosi and Hanamoto (1961), and further elaborated and described in Senatore and Iagnemma (2011), Shoop (1993), and Wong and Preston-Thomas (1983). Ideally, separate measurements should be made for:

(1) Internal shearing characteristics of the terrain (of interest, for example, when tracks or tires have grousers or lugs that cause one

portion of the terrain to shear relative to another portion of the terrain itself)

(2) Rubber-terrain shearing characteristics (of interest, for example, when rubber tires or rubber components on tracks interact with the terrain so that shearing occurs between the rubber and the terrain)

(3) Any other type of shearing characteristics (e.g., vehicle-belly shearing) that may be needed to characterize the development of tractive forces on the vehicle-terrain interface

f. When a bevameter process is being planned for use to acquire ST terrain response data:

(1) The suite of geotechnical terrain properties listed in Section 2.4 shall also be measured to characterize the terrain.

(2) For pressure-sinkage bearing capacity measurements:

(a) The contact area of the plate (or of the largest plate when two or more plates are used) should be in the same order of magnitude as the contact area of the tire, track link or other element (e.g., walking foot) on the vehicle to be modelled.

(b) Measurements should be made up to pressures that are approximately two times the applicable bearing pressure that will be experienced by the vehicles to be modelled with specific parameters.

(c) When two or more plate sizes are used, the areas of the largest and smallest should differ by approximately a factor of two.

(d) The rate of application of the pressure load shall be documented as well as the pressure relaxation or sinkage creep at the maximum pressure level.

(e) Pressure-sinkage power law parameters can be developed using the weighted least squares data fitting methods. An example is described in Wong (1980).

(f) Higher order polynomials and piecewise data fitting methods are also allowed, as well as custom weighting methods that focus on an operational pressure range (Jayakumar et al., 2014).

(3) Ensembles of repeated identical measurements should be employed whenever possible and the ensemble statistics (mean and standard deviation) near the operational pressures used for uncertainty estimates.

(4) For shear ring measurements to get running-gear to terrain interface friction angle, cohesion/adhesion, and initial slope for the exponential parameters:

(a) At least three normal pressures shall be used including the nominal local running gear (wheel or track link (or pad)) static bearing pressure, plus two more: one at 50% of nominal bearing pressure and a second at 150% of nominal bearing pressure, as practicable.

(b) The parameter for characterizing the exponential shear stress-shear displacement relationship developed by Janosi and Hanamoto (1961) shall be derived from shear ring test data using the least squares fitting as described in the reference (Senatore and Iagnemma, 2011).

g. When a wheel load sensor test vehicle is being planned for use to acquire running gear level ST terrain response data (Shoop, 1993):

(1) The suite of geotechnical soil properties listed in Section 2.4 shall also be measured to characterize the terrain.
(2) Vehicle primary physical characteristics shall be reported.
(3) Instrumentation shall be fully described for both bearing/normal load response as well as traction/shear response.
(4) Pavement tests shall be performed to demonstrate sensor calibration
(5) Tire-terrain response decoupling methods or assumptions shall be fully described.
(6) Correlation of single wheel response to full vehicle response shall be developed when possible.
(7) Data should be collected for different normal bearing loads if possible
(8) Rolling resistance based methods should clearly state contact patch assumptions.
(9) Contact patch assumptions should be validated by direct measurement where possible.
(10) Terrain parameters derived from data obtained using a wheel (or vehicle) as a probe (instrument) are dependent on the model of wheel-terrain interaction used. Strictly speaking, the terrain parameters so obtained can only be applied to predicting performances of other types of wheels using the same wheel-terrain interaction model and may not be applicable to predicting wheel performance using other types of wheel-terrain interaction models.

h. When ST models are developed by inference from ST running gear data or from closed form soil mechanics footing bearing equations and/or other fundamental geotechnical tests and properties (Karafiath and Nowatski, 1978):

(1) The suite of geotechnical soil properties listed in paragraph 2.4 shall also be measured (or developed from references) to the greatest extent possible to characterize the soil.

(2) Analytical assumptions and background theory shall be cited for each bounding property or characteristic.

(3) Numerical assumptions and background theory shall be cited for all interpolations and extrapolations.

(4) A notional model for inferring ST parameters for any soil type and moisture content using linear interpolation of consistent, but notional, ST parameter sets for a range of soil types and moisture content values is provided as an example of the eventual goal of the ST database development (Annex E).

i. To facilitate the transition from past measurements of mobility, whenever possible, correlated measurements of Cone Index and Remolded Cone Index should also be measured. Whenever possible, NG-NRMM predictions of GO/NOGO soft soil performance should be compared to predictions using legacy metrics of performance such as Vehicle Cone Index (VCI) or Mean Maximum Pressure (MMP) (Priddy and Willoughby, 2006). A review of using VCI and MMP as vehicle mobility metrics is presented in Wong et al., (2020).

2.4.2. Complex Terramechanics

1. NG-NRMM Complex Terramechanics (CT) models are full three-dimensional dynamic soil models capable of accounting for the three-dimensional deformation/flow of the soil including both elastic and plastic (permanent) deformation under any three-dimensional loading condition/motion of a vehicle running gear/surface (or in general any solid rigid or flexible object). Accounting for three-dimensional soil deformation/flow includes, for example, prediction of: rut depth/width/shape, rut side wall height, and bulldozing of the soil in front of the vehicle running gear. The soil discretization in Complex Terramechanics models must be smaller than the tire tread block spacing or track grouser spacing in order to be able to accurately resolve the interaction forces between the vehicle and the soil at that scale and the important effect of tread/grouser design and depth on soft soil vehicle mobility. Typical Complex Terramechanics models include: continuum models such as the finite element method (FEM); and particle models such as the: Discrete Element Method (DEM), Smoothed Particle Hydrodynamics (SPH), or Material Point Method (MPM). The Complex Terramechanics models must have the following capabilities:

a. Accurately predict the 3-D interaction forces exerted by the soil on a solid object that is spatially moving in any arbitrary desired path with respect to the soil. Those include tractive (tangential) and bearing (normal) forces.

b. Accurately predict the primary vehicle mobility measures of interest to the end-users: GO/NOGO, Speed-Made-Good, and Motive Efficiency. Subfactors contributing to the primary mobility metrics could include: fuel consumption, engine torque/power, wheel sinkage, available drawbar pull, transmitted vibration power to the vehicle's occupants/payloads, vehicle components' dynamic stresses, maximum braking distance, and vehicle stability, etc.

c. Account for the effect of compaction on the soil quasi-static shear strength (including soil internal friction and cohesion). This includes accounting for the effect of the current hydrostatic stress and previously applied hydrostatic stress on the soil shear strength.

d. Account for the change in soil bulk density as a function of hydrostatic stress (soil compaction state).

e. Account for adhesion of the soil to the vehicle surfaces.

f. It is also desirable to account for the following higher order mechanical effects such as:
   (1) Effect of shear strain rate on soil shear strength (soil viscosity)
   (2) Effect of normal strain rate on soil normal bearing strength (soil damping)
   (3) Soil dilation (including reduction of bulk density and shear strength) after tilling type loading (shearing and tension)

g. Accurately predict soil mechanical response for small-scale (e.g., piston-cylinder compression test, confined and unconfined shear cell, triaxial cell, penetrometer, bevameter, wheel-on-soil test, etc.) and full-scale (e.g., drawbar pull) terramechanics experiments. Those experiments can be modelled using the complex terramechanics software tool (high-fidelity soil/multibody dynamics models) and the Complex Terramechanics soil model parameters can be adjusted/calibrated such that the simulation response matches the experimental response.

h. Accurately represent the mechanical response of worldwide soils including:
   (1) All soil types. A soil can be classified under a certain soil type based on its grain size distribution and proportion of the different mineral and organic chemical substances in the soil. It is currently recommended to use the USCS soil classification system in the NG-NRMM. However, using the USCS soils with significantly different mechanical properties (friction angle, cohesion, bulk density, etc.) can map to the same soil type. Therefore, more research is needed to develop a soil classification system that is more suitable for vehicle mobility applications.
   (2) The effect of the following on the soil mechanical properties:
      (a) Moisture at and between all Atterberg limits
      (b) Temperature
      (c) Compaction state (measured using bulk density)

2.4.3. Complex Terramechanics Tests

1. Compressibility: Hydrostatic Pressure versus Bulk Density

2. Objective: Obtain the hydrostatic pressure versus bulk density for a soil type at a specified moisture content and temperature (Figure 2.3).

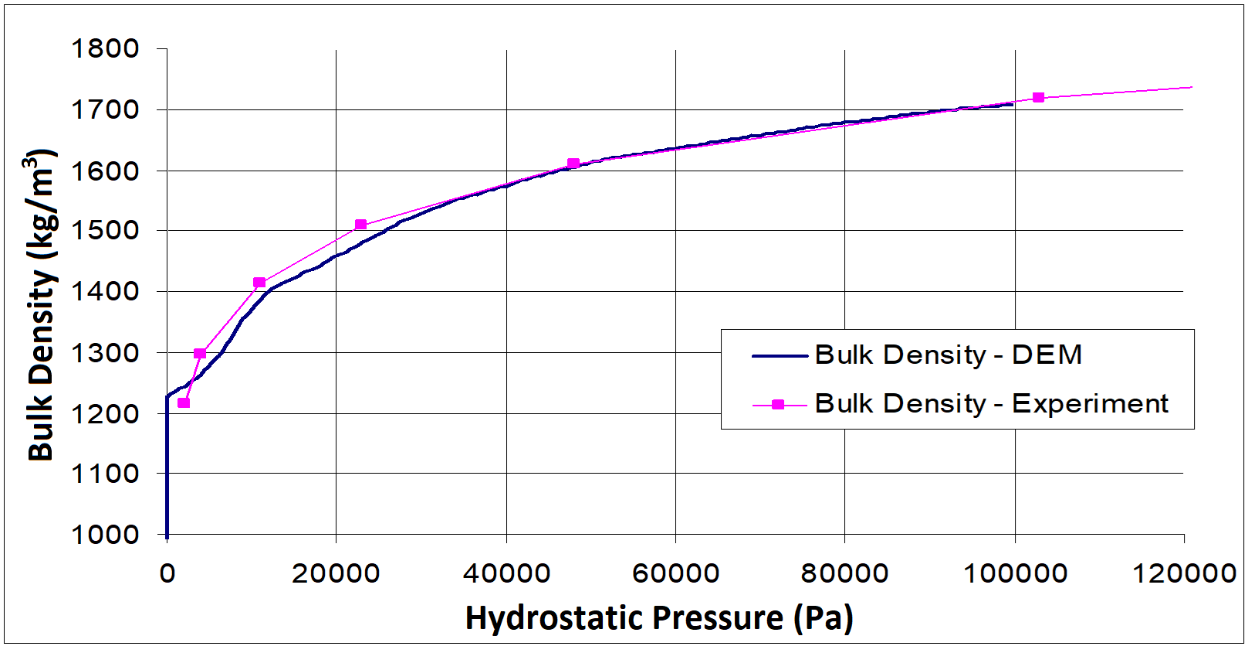

Figure 2.3**:** Example Hydrostatic Pressure versus Bulk Density Plot.

3. Test Apparatus: The test can be performed using one of the following test apparatuses:

a. Triaxial or hydrostatic pressure cell (Figure 2.4) with equal normal stress along three axes. The test is used to measure the hydrostatic pressure versus material volume (which can then be used to calculate the bulk density).

b. Piston-cylinder (Figure 2.5), confined uniaxial compression cell. The test is used to measure the normal pressure versus displacement of the piston. (The material volume of the soil can be calculated using the height of the soil in the cylinder).

Bulk density = Material mass / Material volume

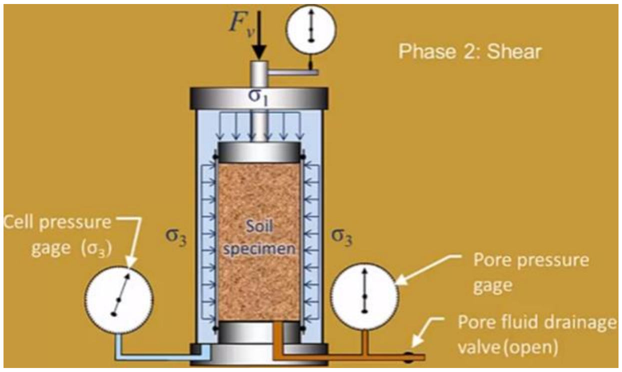

Figure 2.4: Triaxial Cell.

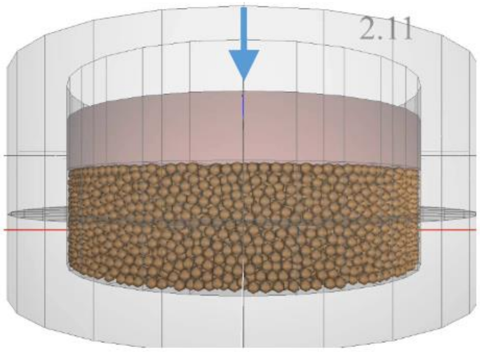

Figure 2.5: Piston-cylinder Confined Uniaxial Compression Cell.

4. Test steps:

   a. Loosen/till the soil to the lowest possible bulk density before loading it into the test cell.
   b. Slowly load the soil into the test cell and avoid compressing the soil while loading it.
   c. Measure the mass of the soil loaded into the test cell.
   d. Measure the initial volume of the material with zero pressure.
   e. Increase the pressure in small steps (say 5% steps of the maximum value σ_{max}). For each step measure the volume of the material. Then plot bulk density versus hydrostatic pressure (Figure 2.3).
   f. Notes: The maximum hydrostatic pressure (σ_{max}) should be equal to double the maximum pressure that the vehicle tire (or track pad) exerts on ground.

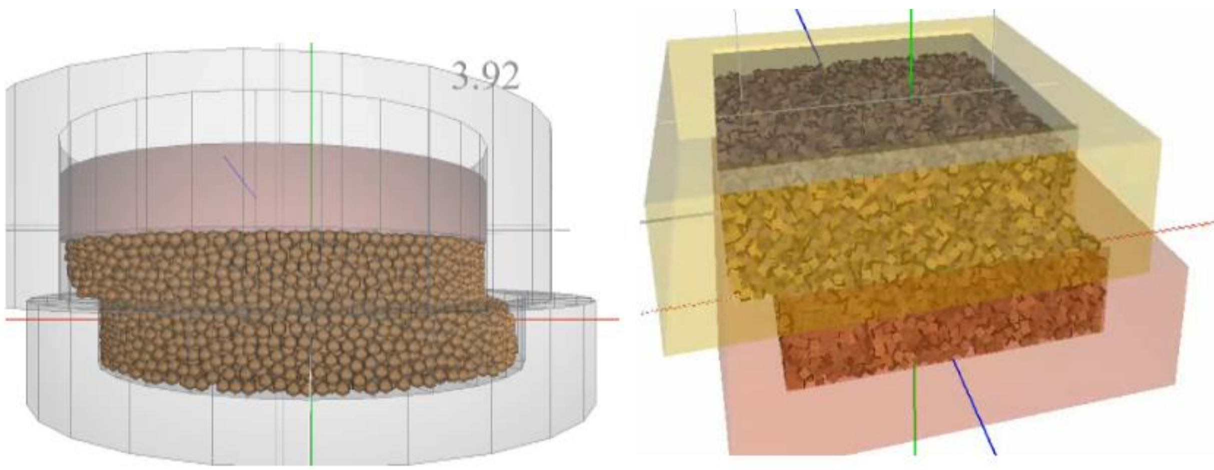

Figure 2.6: Circular and Square Shear Cells.

5. Shear Test: Measure Cohesion, Friction, and Effect of Pre-Stress

6. Objective: Use a confined shear cell (Figure 2.6), an unconfined shear cell, a bevameter or a triaxial cell (Figure 2.4) to measure the soil shear strength versus normal stress for soil samples that have been previously subjected to a normal pre-stress (Figure 2.6). This test measures the following soil mechanical properties:

   a. Cohesion (soil shear strength at zero normal stress)
   b. Friction angle (slope) of the lines in Figure 2.7
   c. Effect of pre-stress (or soil compaction/plastic deformation) on soil cohesion and friction.
   d. This test should be performed for each soil type and at each moisture content and temperature.

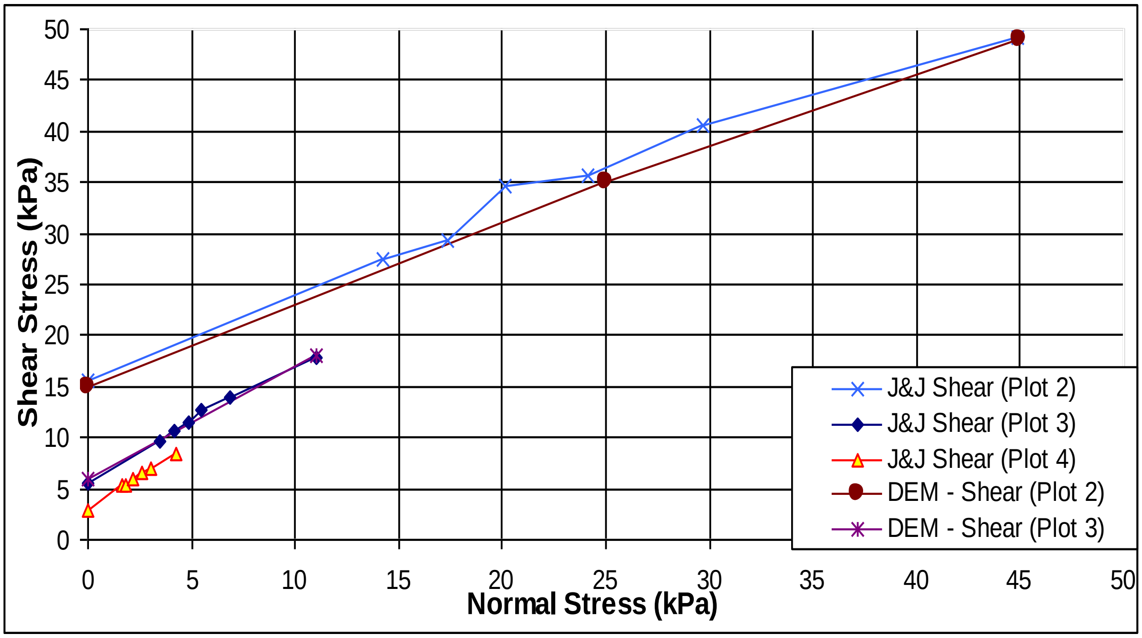

Figure 2.7: Example Maximum Shear Stress (Soil Shear Strength) versus Normal Stress Plot for Different Normal Pre-Stress Values Obtained Using a Shear Cell. The Normal Pre-Stress Value is the Maximum Normal Stress for each Line Plot. The Soil Cohesion Strength is the Intercept Point of each Line Plot with the Y-axis. The Soil Friction Angle is the Angle of each Line Plot with the X-axis.

7. Test steps:

   a. Set $a = 0$.
   b. Set $b = 0$.
   c. Loosen/till the soil to the lowest possible bulk density before loading it into the test cell.
   d. Slowly load the soil into the test cell without compressing it.
   e. Apply an initial uniform normal stress $\sigma_0 = a\ \sigma_{max}$ that will compress the soil and increase its strength.
   f. Remove the normal stress i.e. set the normal stress to zero. Then, apply a normal stress of b σ_0.
   g. Slowly shear the soil sample and record the shear displacement versus shear stress, then find the maximum shear stress. This is the shear strength of the soil. Then, plot a point on the σ_0 line: maximum shear stress versus $b\ \sigma_0$.
   h. Set $b = b + 0.33333$, then go to step c. Go to step i when $b > 1$.
   i. Set $a = a + 0.33333$, then go to step b. End the process when $a > 1$.
   j. Note: Maximum pressure (σ_{max}) should be equal to double the maximum pressure that the vehicle tire (or track pad) exerts on ground.
   k. Note: For some tests (such as bevameter) the applied normal stress on the soil cannot be zero. In that case a small normal stress, which is enough to fully engage the grousers in the soil, can be applied.

l. Minimum number of test points = 1 + 3 × 4 = 13 (for a certain soil type at a certain moisture content and temperature). More test points can be used to better measure the soil shear strength as a function of the normal pre-stress and currently applied normal stress.

8. Penetrometer

9. A penetrometer test can be used to measure the soil internal friction angle if the soil cohesion is known or the soil cohesion of the friction angle is known. The penetrometer can be a standard 30° cone penetrometer (see Figure 2.8) or any other type such as a rectangular plate, a flat cylinder, or a hemisphere.

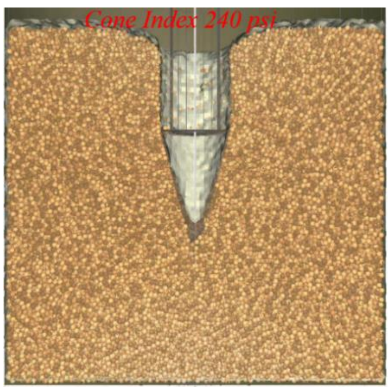

Figure 2.8: Simulation of a Cone Penetrometer.

10. Objective: Use a penetrometer to find the maximum normal pressure during penetration at a prescribed slow speed (quasi-static load). The penetration pressure is equal to the penetration force divided by the maximum cross-section area of the penetrometer.

11. Test procedure:

a. Set a = 0.
b. Loosen/till the soil to the lowest possible bulk density before loading it into the test bin.
c. Slowly load the soil into a test bin without compressing it.
d. Apply an initial uniform normal stress $\sigma_0 = a\ \sigma_{max}$ that will compress the soil and increase its strength.
e. Remove he normal stress, i.e., set the normal stress to zero.
f. Slowly insert the penetrometer in the soil at a constant speed and record the maximum penetration force, then calculate the corresponding pressure. Plot this pressure value versus the initial normal stress σ_0.
g. Set $a = a + 0.33333$, then go to step b. End the process when $a > 1$.
h. Note: Maximum pressure (σ_{max}) should be equal to double the maximum pressure that the vehicle tire (or track pad) exerts on ground.

2.5. AUTONOMOUS VEHICLES

1. The NG-NRMM capabilities must include and embrace modelling of vehicle intelligence (VI) related components and their physics in order to allow autonomous vehicle mobility modelling as a foundational architectural goal. To accomplish this the NG-NRMM capability must:

a. Be capable of modelling every conceivable ground vehicle physical morphology
b. Provide models of environment sensors commonly used by autonomous systems and environment attribution to support sensor models
c. Broaden the definition of environment to include definitions of objects, agents, atmospheric conditions, and communication networks
d. Allow for multiple levels of model resolution to support computational burden trade-offs
e. Embrace stochastic modelling and database development necessary to support VI algorithms
f. Recognize a hierarchical and skills-based sliding scale of VI, autonomy, and control
g. Develop applicable VI related mobility metrics for M&S Verification and Validation (V&V) and accreditation

2.5.1. Sensors for Vehicle Intelligence

NG-NRMM should include models of all sensing systems used for VI and autonomous control. NG-NRMM shall include common sensors including automotive radar, global positioning systems (GPS), inertial measurement unit (IMU), electro-optical cameras, and light detection and ranging (LIDAR). The unique capabilities of each sensor system should be accurately characterized and interact with environment attributes to predict effectiveness of the sensor in different environments and conditions.

2.5.2. Environment Data

1. NG-NRMM shall provide environment attribution to support the characterization of a sensor's perception of the environment. The environment should include definition of the terrain and its material attributes, any objects in the environment, any agents operating in the environment, the current conditions including lighting and weather, and the presence and capabilities of communication networks supporting command-and-control (C2), vehicle-to-infrastructure (V2I), and vehicle-to-vehicle (V2V) communication.

a. Object and Agent Representations: In addition to interacting with the terrain, autonomous vehicles must perceive and respond to objects and agents in the environment. Objects may be natural objects such as boulders and trees or manmade objects such as jersey barriers and buildings. Objects such as traffic lights and swinging gates may have simple behaviors that change the state of the object and affect the autonomous vehicles response to the object. Agents, or actors, represent humans, animals, or vehicles that move through the environment according to their own complex behaviors.

b. Objects and agents share many attributes. The primary difference between objects and agents is the agent's ability to move itself through the environment and the complexity of the agent's behaviors. The simplest representation shall include the position and dimensions of the object or agent. The detailed geometry of the object or agent shall be defined by a mesh and an associated material. Physics data including mass, surface friction, compressibility, and more shall be associated with the objects to support modelling of physical interactions between the vehicle and the objects in the environment. Some objects may have parts that move (e.g., the swinging arm of a gate). Controllers describe the behavior of objects in the environment. Changes in behavior may be driven by time or other changes in the environment. For example, a gate may automatically open when a vehicle approaches the gate.

c. Material Attributes: NG-NRMM environment data shall include material attributes to support analysis of VI sensing capabilities. Material attributes define how the object is perceived by the sensors. Different sensors may require different material attributions. For example, electro-optical cameras typically detect light in the visible spectral range (400 to 700 nm) while LIDAR uses beams above the visible range (905 nm and 1550 nm).

2.5.3. Metrics

1. The NG-NRMM shall include the ability to uniquely adapt standard mobility metrics to assess the effectiveness of the VI and control features of increasingly intelligent vehicles. Broad examples of these include the following:

a. Look ahead speed limit: analogous to the classic NRMM driver visibility speed limits, this is a combined metric of the effects of sensor, actuators, signal/network latency and computational delay and their interaction within the scenario-terrain-vehicle dynamics and can be decomposed to address relative and multiple contributory effects.

b. Generalized customizable ride quality limits: analogous to current human ride quality assessments, but extended to the unique components of the intelligent vehicle, its functions, or its payload.

c. Speed through an offset corridor: analogous to the NATO Lane Change test, this metric proposes to adapt the geometry to measure speed VI local path following capability through parameterized local plan view anomalies or obstacles.

d. Soft soil limit sensing: an extension to soft soil performance for vehicles with sensor feedback and soft soil hazard avoidance algorithms. One simple example of this is traction control systems.

2.6. UNCERTAINTY QUANTIFICATION

1. For uncertainty quantification (UQ) in NG-NRMM, full stochastic information of terrain variables, e.g., mean, standard deviation, variance, distribution of elevation and soil properties, as well as vehicle variables, such as weight, tire pressure, tread wear, etc., must be utilized and analyzed for their effects on reliability-based mobility maps (Adams et al, 2019; Choi et al., 2018). If full stochastic information of the soil properties is not available, then the best available measurement data should be used with statistical methods to determine the best representative distribution of each soil property. Additionally statistical correlation between soil properties should be studied and considered (Noh et al., 2008). Consideration of correlation is critical when generating realizations from the distributions in order to generate physically correct realizations, this was found during the Cooperative Demonstration of Technology for NG-NRMM event (Letherwood et al., 2020). The following two steps, as shown in Figure 2.9, are recommended for generating reliability-based mobility maps (Speed-Made-Good and GO/NOGO).

a. Step 1. Modeling of Terrain Variability: Use of variabilities of geostatistical data such as terrain elevation and soil physical property parameters to model input distributions.

b. Step 2. Generation of Reliability-Based Mobility Maps: Propagation of geostatistical data uncertainty through mobility models for generation of reliability-based mobility maps (Adams et al, 2019; Choi et al., 2018).

2.6.1. GIS Data

In the beginning of Step 1, as shown in Figure 2.9, the GIS data layers can include satellite data, manual observations, soil type and geological maps, as well as estimated or known measurement errors. The GIS data include elevation, slope, soil composition, soil cohesive strength, soil friction coefficient, bulk density, temperature, moisture content, etc. Currently, the GIS data are available only in lower resolution, which may not be sufficient to meet the modelling and simulation needs.

2.6.2 Variability Models of Terrain Variables

To generate the distribution of the slope at each point, GIS elevation raster realizations data can be created and the corresponding slope calculated. For the soil property parameter variabilities, the data obtained from geotechnical databases for each of the soil types need to be used to generate the distribution types with certain confidence value range. Variabilities shall be modelled using appropriate statistical distribution types and their parameters. If any of those terrain variables are correlated, then copula shall be used to model the correlation (Noh et al., 2008). In addition to the physical variability, GIS data uncertainties may also include other variabilities such as known measurement error, estimated variation based on measurement type, terrain, etc.

2.6.3. Propagation of Uncertainty

NG-NRMM shall estimate the propagation of terrain variabilities obtained in Step 1 into the predictions of mobility to yield reliability-based mobility maps as shown in Step 2 of Figure 2.9. A typical reliability analysis requires Monte Carlo Simulation (MCS). For uncertainty quantification, no less than 10,000 MCS samples at each pixel location may be required to generate high-resolution mobility maps with a high level of reliability (e.g., higher than 90%). Therefore, it is desirable to utilize Design of Experiments (DOE) and surrogate models for computational efficiency (Adams et al, 2019; Choi et al., 2018). The surrogate model for the maximum speed of a vehicle is a function of soil properties and slope. This surrogate model represents the vehicle model. Using the surrogate model, uncertainty quantification and inverse reliability analyses can be carried out for the typical mobility metrics such as Speed-Made-Good and GO/NOGO.

2.6.4. UQ Verification and Validation

NG-NRMM UQ capabilities shall demonstrate their respective level of V&V maturity (see Chapter 3) using a suitably defined benchmark problem for development of reliability-based mobility maps.

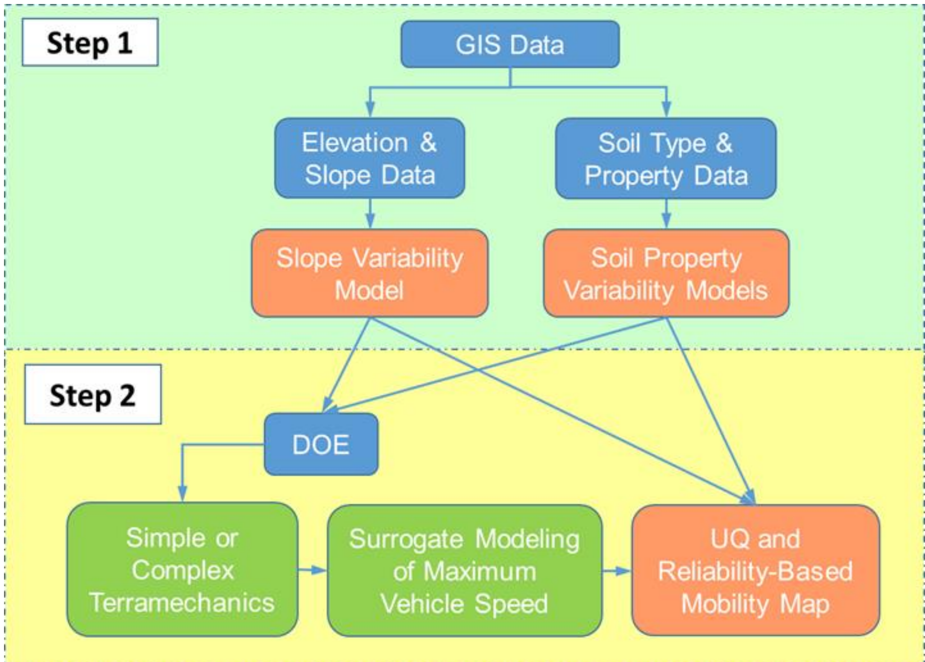

Figure 2.9: Framework of Developing Reliability-Based Stochastic Mobility Map.

CHAPTER 3 VERIFICATION AND VALIDATION (V&V)

1. Beginning with the overarching guidance from NATO's Terminology Database (NATOTerm, 2020) and SISO-GUIDE-001.1-2012, Guide for Generic Methodology for Verification and Validation (GM-VV) to Support Acceptance of Models, Simulations, and Data (SISO, 2012), NG-NRMM V&V requires tailoring based on the specific challenges intrinsic to mobility models. This tailoring leverages the more specific definitions derived from historical sources including U.S. Army Pamphlet 5-11 (Pamphlet 5-11, 2014), which defines:

2. Verification. The process of determining that a model or simulation implementation and its associated data accurately represent the developer's conceptual description and specifications.

3. Validation. The process of determining the degree to which a model or simulation and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model.

4. Accreditation and/or acceptance criteria are not addressed by this standard. These shall be defined by each M&S intended end use (Pamphlet 5-11, 2014) and end user.

5. Because mobility models and simulations development efforts typically occur opportunistically and incrementally over time, it is necessary to establish a scale for capability and maturity of NG-NRMMs that supports and recognizes this. Thus, this standard includes a V&V Capability Maturity Scale as well as specific benchmark data sets whereby the progress and relative merits of any given NG-NRMM M&S capability may be demonstrated and quantified.

6. NG-NRMM validation requires test events measuring vehicle dynamics and terramechanics useful for the prediction of on- and off-road mobility simulation metrics that support acquisition, design and operational planning. The list of test events defined by this standard is intended as a common baseline and not intended to be exhaustive. Additional events supportive of specific vehicle mobility challenges should be included as necessary to establish a model's validity.

7. Furthermore, three benchmarks have been provided that implement the recommended test events for three different vehicles. These benchmarks were derived to include the following:

   a. Test and simulation guidelines adhering to existing standards
   b. Vehicle benchmark performance data sets for detailed on- and off-road test models of test events useful for model calibration and validation that include:
      (1) Vehicle physical characterization datasets

(2) Soil data, both in-situ and geotechnical lab data, applicable to the benchmark events
(3) Vehicle dynamic performance data in measured environments

3.1. CAPABILITY MATURITY SCALE

1. Recognizing that most NATO nations' mobility models are evolving and cumulative developments that span decades and must leverage real world data acquisition events opportunistically, a maturity scale is recommended that allows for useful comparisons of capability across the full range of developmental maturity. Thus, the following progressive scale shall establish NG-NRMM V&V maturity:

Table 3-1: NG-NRMM Verification and Validation Maturity Scale.

Level	Term	Definition
1	Demonstration	Demonstration of a correct implementation of a theoretically and conceptually consistent model
2	Parameter Sensitivity Demonstration	Verification that a change in performance prediction associated with a change in system parameters is consistent with theory and physics principles
3	Independent User Verification	Independent user demonstration of results that correlate well to the results independently obtained by the original model advocate and/or developer
4	Cross Code Verification	Good correlation with results obtained using another accepted mobility simulation code
5	Calibration	Calibration to a real vehicle test data set
6	Validation	Blind correlation to a real vehicle test data set
7	Parameter Variation Validation	Blind correlation to a real vehicle test data set with a change in system parameter(s)

2. The V&V demonstrations shall use a set of discrete mobility events from the test and evaluation communities that measure the various different factors comprising GO/NOGO, Speed-Made-Good, and Motive Efficiency for typical ground vehicles. These events, combined with specific vehicle, terrain and actual measured performance data sets establish the benchmarks that can be used to demonstrate an NG-NRMM M&S V&V maturity and capability.

3.2. V&V BENCHMARK VEHICLES

1. Three vehicles are benchmarked, one tracked vehicle and two wheeled vehicles. The vehicles and data are representations of vehicle types with the varying levels of

complexity and challenge for off-road mobility prediction. The three vehicles are listed here in order of data availability.

(a) A tracked Armored Personnel Carrier, APC: Vehicle and test data available as shown in Annex F
(b) A 4x4 high-mobility Wheeled Vehicle Platform with advanced suspension, WVP: Vehicle and test data available as shown in Annex G
(c) A Fuel Efficiency Demonstrator – Alpha, FED-A: Vehicle and test data available as shown in Annex H

3.2.1. Tracked Vehicle (TV) Benchmark Summary

Annex F includes data defining a tracked vehicle representing an armored personnel carrier (APC) type vehicle. The data are collected from various publicly available sources as indicated in the Annex. Additional reasonable assumptions were made to complete all additional vehicle parameters that were necessary to construct complete vehicle numerical models with enough resolution to predict performance on the mobility events defined in section 3.3. The publicly available sources also give vehicle performance data (i.e., test data) for a limited number of the defined events. These can also be used for V&V purposes.

3.2.2. Wheeled Vehicle Platform (WVP) Benchmark Summary

Annex G is a compilation of vehicle model parameters and test results for a 4X4 wheeled vehicle that is representative of an actual prototype vehicle designed and built by the Nevada Automotive Test Center. The vehicle has advanced suspension design such as adjustable ride height and hydraulic-based roll stiffness. Furthermore, the vehicle has off-road treaded tires representative of off-road performance. The original detailed input data are available in a spreadsheet for download from the NATO STO site at https://www.sto.nato.int/pages/natostandards.aspx.

3.2.3. CDT Wheeled Vehicle Benchmark Summary

Annex H is a compiled summary of the vehicle model input data, terrain model input data and test results for a 4x4 wheeled vehicle known as the Fuel Efficiency Demonstrator – Alpha (FED-A). The FED-A vehicle was originally designed and built by a contractor-led team of the industry partner Ricardo, Inc. and the Ground Vehicle Systems Center (GVSC), formerly U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC). The FED–A vehicle was selected to be used for the NATO AVT-308 Cooperative Demonstration of Technology for NG-NRMM Development held at Keweenaw Research Center (KRC)/ Michigan Technological University in Houghton, MI in September 2018 (Letherwood et al., 2020).

3.3. BENCHMARK MOBILITY EVENTS

The following mobility test events cover the key mobility factors that should be included in a NG-NRMM and are based on existing accepted testing standards, operating procedures and recommendations. Some enhancements to existing test procedures are also described in order to capture the detailed data necessary for V&V of the specific mobility factor models. Where appropriate, the differences between wheeled and tracked vehicle test procedures are indicated throughout the event descriptions. Each event also includes surface type assumptions and, where applicable, the detailed soil model parameters are included in the benchmark data sets compiled in Annexes F, G and H.

3.3.1. Steering Performance

1. Wall to wall (WTW) turn radius in accordance with AVTP 03-30 (1991). Compute the maximum diameter of a plan view trace of vehicle chassis outer most points that will impinge upon a wall of any height and thus prevent the turn maneuver, turning at least 360° on a paved surface (mu=0.8). Repeat in the counterclockwise direction. Wheeled Vehicle Platform (WVP) Benchmark: use slow speed full maximum steer angle. Tracked vehicle (TV) benchmark use neutral axis spin maneuver at slow speed, maximum steer input (drive right track in reverse and left track in forward direction to achieve a clockwise vehicle spin). Repeat in the counterclockwise direction.

2. Steady state cornering (SSC): per SAE J266 (1996), asphalt skid pad (friction coefficient, mu = 0.8), 100 feet turn radius, starting at 5 mph increase velocity at constant acceleration rate to achieve approximate expected max speed in 100 seconds. Continue acceleration until loss of traction or unable to maintain turn radius. Plot turn angle and vehicle roll angle vs lateral acceleration. Repeat to get both right and left turns.

3. Double lane change (DLC) paved: Determine max attainable speed per AVTP 03-160W (1991), hard surface, mu= 0.8. The test course gate spacing is based on the vehicle dimensions, run from left to right in plan view (i.e., offset force left turn evasive maneuver). WVP: Constant speed (within ±1 mph); Use steering angle time history as model input for the maneuver (test data provided), maintain constant speed, test course dimensions provided, open differentials. Judge the event as “Passed” if vehicle goes through the course without hitting any cones. Conduct test in 5 mph increments from 10 mph to maximum speed, use 1-mph increments within 10 mph of max speed, maximum speed determined by contact with "virtual cone" (any lane exceedance) or loss of control. Outputs are roll, pitch, yaw angles and rates, lateral acceleration, tire 3DOF forces, path of each wheel, and limiting speed. TV: use both unlimited power assumption and user provided direction and speed control loops subject to power train limits provided in vehicle data. Provide maximum attainable speed and reason for speed limit.

4. Double lane change gravel: Determine max attainable speed per AVTP 03-160W (1991), hard surface, mu=0.5.

5. Open-Loop Steering event (OLS). Perform open loop steering test for vehicle steady state behavior validation on paved surface, mu = 0.8. Following recommendations in SAE J266 (1996) discrete constant steering wheel angle test, the vehicle is driven straight at each selected test speed. The steering wheel is turned to a mechanical stop until steady state conditions occur for at least 3 seconds. The test yields transient as well as steady state response for comparison with simulation. Similar standard for heavy vehicles: ISO 14792:2011.

3.3.2. Side Slope Stability (SSS)

1. TOP 2-2-610 (2009) serves as a guideline.

2. Paved (mu=0.8) surface serpentine steerable slope speed limit: Determine maximum 30% side slope speed maneuverable. For the purpose of vehicle mobility model V&V, this is implemented as the maximum speed on a 30% side slope for which the vehicle can traverse across a 30% side slope, first in a straight path line for 20 m, then execute a downhill obstacle avoidance maneuver in less than 30 m of traverse path length, around a 3-m wide obstacle while recovering to the original straight line path and elevation on the slope.

3. Deformable terrain serpentine steerable 20% side slope speed limit. Determine maximum speed for obstacle avoidance (per 3.3.2.2 description) on a 20% side slope on deformable terrain. For the tracked vehicle benchmark this is the LETE sand defined in Table F.15.

4. For the WVP data set, determine max speed negotiable for (mu=0.4) 30% side slope obstacle avoidance maneuver. Outputs: roll, yaw, steer angles and rates, lateral acceleration, tire 3DOF forces, speed, path of each wheel, and limiting speed.

3.3.3. Grade Climbing

1. TOP 2-2-610 (2009) serves as a guideline for this event.

2. Max steerable/brakeable up slope and down slope. For paved (mu=0.8) surface determine max up slope and down slopes for which a 3-metre wide obstacle avoidance maneuver can be executed in 30 m of path length while recovering original path line.

3. Speeds on grades. Determine maximum speed on grades up to maximum steerable up slope.

4. Deformable terrain grade limits and speeds (initial benchmark on dry sand). Determine maximum steerable up slope and down slopes and maximum speed on grades up to the maximum up slope. For the tracked vehicle benchmark this is the LETE sand defined in Table F.15.

5. For WVP data set, determine maximum slope attainable for straight line motion where loss of forward motion is defined as failure. Assume sand with properties from the WVP data set.

3.3.4. Ride Quality

1. All terrain for ride quality testing is assumed non-deformable. Outputs: speed vs absorbed power for each terrain and the 6-watt ride limiting speed.

2. Random terrain ride limiting speeds: Determine 6-watt ride limiting speeds due to vertical driver accelerations on standard 2D profiles provided. (Annex F, G, H).

3. Half-round obstacle ride limiting speeds: Determine 2.5 g ride limiting speeds due to vertical driver accelerations on standard half-round profiles from 4” to 12” in height (=radius).

4. ISO 8608 (2016), ISO 2631-1 (1997), TOP 1-1-014 (2012), and Lins (1972) serve as guides for these events.

3.3.5. Obstacle crossing

1. Assume all hard ground surfaces with $\mu = 0.8$.

2. Step climb height limit: determine maximum traversable height in forward direction, using TOP 2-2-611 (1980) as a guide.

3. Gap crossing limits: determine maximum gap traversable in forward direction, using TOP 2-2-611 (1980) as a guide.

4. Trapezoidal fixed barrier limits: determine traversability limits for obstacles parameterized by trapezoidal slope angle, barrier height, and barrier top surface width. Assume 12 different obstacles generated by the combinations resulting from the following obstacle parameter values: height: 30”; top widths: 6”, 30”, 140”; up angles: 16°, 26°, 38°, 68°.

5. Trapezoidal ditch crossing limits: determine traversability limits parameterized by trapezoidal slope angle, ditch depth, and ditch bottom surface width. Assume 12 different ditch obstacles generated by the combinations resulting from the following obstacle parameter values: depth: 30”; bottom widths: 6”, 30”, 140”; down angles (for ditch obstacles): 16°, 26°, 38°, 68°.

6. MOUT limits (rubble pile, crater). Test data N/A (not available).

3.3.6. Off-road trafficability

1. Single-pass soil strength limit. Determine maximum gross vehicle weight traversable in one pass including reversing back through the path per standard VCI measurement methods. Test data N/A

2. Multi-pass soil strength limit. Determine max GVW traversable for 50 passes (forward and reverse). Test data N/A

3. Drawbar Pull (DBP) versus slip using constant speed, slowly varying slip test method and using TOP 2-2-604 (2007) as a guide where applicable. Slip s is defined as $s = \frac{(r\omega - v)}{r\omega} 100\% = \left(1 - \frac{v}{r\omega}\right) 100\%$, where r is the wheel effective radius, or for tracked vehicles, the sprocket pitch radius, v is the vehicle speed and ω is the rotational speed of the wheel. The nominal zero slip conditions under which the rolling radius is determined should be stated regarding the surface (non-deformable or deformable) and power state (powered or towed).The objective of the test is to uniformly populate the DBP versus slip curve by keeping test vehicle speed constant while slowly increasing wheel rotational speed to achieve a uniform sweep of slip from zero to the maximum attainable by the powertrain. For constant gear ratio powertrains, the slip attainable at constant test vehicle speed is limited by maximum RPM available in the given gear. Therefore, the test has two phases that can be carried out in direct continuation of each other. The constant speed phase, and a slowly decelerating phase to populate the rest of the DBP-slip curve. The latter part can be omitted if testing area is limited and the maximum DBP already has been established by the constant speed phase. Select a suitable constant desired forward speed in the lowest gear range of the transmission. Recommended constant speed in the range of 3 - 8 kph, or as deemed appropriate for the vehicle and terrain combination available. The test is recommended to be performed with transfer case and differentials locked. Based on the speed selected, the maximum attainable slip can be estimated from gear ratio and maximum engine RPM given the vehicle will not be power limited. The DBP test can be run with transfer case and differentials unlocked if desired, but is typically not needed for maximum DBP testing. Instrumentation is recommended to include wheel rotational speeds and torques (if available), vehicle chassis forward speed (differential GPS or fifth wheel), pitch/roll/yaw rates and linear accelerations. Testing should at a minimum include:

a. For wheeled vehicles, determine the effective wheel radius to obtain the theoretical speed in the given gear for reporting the results. It is of high importance to be clear about the effective radius used in the reporting for comparison between test and simulation and between different simulation sources. The choice of radius will shift the DBP curve horizontally on the DBP versus slip plot. Three radii measurements are recommended to be established:

(1) Report tire un-deformed radius as per tire specifications.

(2) Determine effective rolling radius at the tested tire pressure measured for 10 revolutions by measuring travelled distance.

(3) In some cases rolling radius can also be measured directly from the instrumentation by measuring absolute traveled distance and individual wheel rotation.

b. Motion Resistance:

(1) Hard surface: Test instrumentation accuracy by measuring slip generated to overcome towed running gear motion resistance on a level, hard, obstacle-free surface at the selected constant slow test

speed. Run the motion resistance test on a hard surface with the vehicle in neutral to get the motion resistance without internal gearing resistance. Perform a self-propelled run without DBP to determine driven slip values.

(2) Soft Soil: Repeat the tow test in the soft-soil test area on a level obstacle-free surface. If space is available, repeat the self-propelled test in the soft soil test area as well.

(3) Coast down testing methods of motion resistance can also be used if instrumentation limits preclude the methods above.

c. Drawbar Pull Test:

(1) <u>All Vehicles Phase One:</u> Assuming the drawbar is horizontally oriented and attached at the rear hitch location, initiate the test with both load and test vehicle at same speed to produce zero drawbar pull slip. Keep the load-vehicle at the selected test speed, and increase test vehicle drivetrain speed at a constant slow rate that does not induce pitch dynamics (i.e., slow enough that instantaneous states are approximately equivalent to steady state conditions). The rate at which the drivetrain speed is increased will determine the population density and uniformity of the drawbar pull versus slip curve and thereby produce improved data spacing. A drivetrain speed controller can be applied if available for improved test results. Limiting condition will be stall for underpowered vehicles or max drivetrain speed in the selected gear for overpowered vehicles.

(2) <u>Over-Powered Vehicles Continuation Phase Two:</u> If space is available, continue the generation of the drawbar pull versus slip phase to 100% slip for overpowered vehicles. Two options are available: 1) continue the test but now decrease the speed of the test vehicle at a constant rate until reaching 0 kph. This is achieved by slowing down the load vehicle at a low constant deceleration to achieve near steady-state condition. Data can be inertia corrected if needed in this phase but should not be necessary if the deceleration is low (<0.05 g); 2) a higher gear can be selected to further populate the drawbar pull slip curve and then repeat Phase 1 method to achieve the immobilized vehicle at 100% slip.

4. Annex F presents validation/calibration data for the APC tracked vehicle benchmark. Wheeled vehicle test data are presented in Annexes G (Wheeled Vehicle Platform) and H (FED-A).

5. Reporting of the results. The following output time histories are recorded: engine speed, engine torque, vehicle speed, individual wheel rotational speeds, individual wheel torques and the DBP force.

6. DBP coefficient versus slip curve: The DBP coefficient is defined as the ratio of DBP tow force divided by vehicle weight. DBP coefficient is plotted as a function of average wheel longitudinal slip.

3.3.7. Model Validation Definitions for DBP and MR:

1. Use the powered and towed motion resistance coefficients on hard ground and soft soil to determine two motion resistance coefficients. As described in Wong (2008a), drawbar pull *DBP* is the horizontal force available at the drawbar, and is equal to the difference between the tractive effort *TE* (a horizontal force developed by the running gear along the vehicle-terrain interface) and the sum of a number of resisting forces $\sum MR$.

$$DBP = TE - MR$$

DBP: Drawbar Pull force;

TE = Total_Tractive Effort force;

$\sum MR$ = ∑ Motion Resistance forces

2. Similar to the case for DBP, the TE coefficient is defined as the ratio of the TE force divided by vehicle weight, and the $\sum MR$ coefficient is defined as the ratio of $\sum MR$ force divided by vehicle weight.

3. The resisting forces acting on an off-road vehicle include the following – more details are provided in Wong (2008a) regarding each of these.

4. *Internal Resistance of the Running Gear:* For wheeled vehicles this is mainly due to tire hysteresis. For tracked vehicles, hysteresis losses inside the track, and interaction of the track with the drive sprockets, guide pins and rollers are all significant contributors to this internal resistance.

5. *Resistance Due to Vehicle-Terrain Interaction:* This includes the resistance due to compacting the terrain and the bulldozing effect. It is normally the most significant resistance for off-road vehicles, and its prediction is thus a key element of NG-NRMM models.

6. *Ground Obstacle Resistance:* Obstacles such as stumps and stones cause a resistance to forward motion of an off-road vehicle.

7. *Grade Resistance:* As described in Wong 2008b, this resistance is equal to the vehicle weight times the sine of the grade angle, and is often approximated (for small angles) by the weight times the tangent of the grade angle, or weight times the grade in percent. This is a very significant factor, and is the reason it is important to conduct field tests on level surfaces, or properly take the grade into account.

8. *Aerodynamic Resistance*: For off-road vehicles operating at speeds below 48 kph (30 mph), aerodynamic resistance is not usually a significant factor. The aerodynamic effects of operating at higher speeds can be evaluated using the methods described in Wong (2008a).

9. Each of the individual resisting forces described above has a corresponding resistance coefficient that is defined as the ratio of the resistance force divided by vehicle weight.

10. In the hard ground motion resistance test described above, the internal resistance of the running gear coefficient is evaluated by measuring the force required to tow the vehicle on a level, hard, obstacle-free surface and dividing it by the vehicle weight. If the NG-NRMM simulation model has a model of internal resistance of the running gear, this result can be compared with the model prediction. If not, then this result can be provided as input to the model.

11. In the self-propelled motion resistance test described in under 3.3.6, the track slips or tire slips required to move the vehicle forward on the surface are the result of the running gear having to overcome the internal resistance of the running gear, and the results should be compared to simulation model estimates of the slips required to move the vehicle forward on this surface.

12. In the level, obstacle-free, soft soil, towed vehicle motion resistance test described under 3.3.6, the towing force must overcome the internal resistance of the running gear and the resistance due to vehicle-terrain interaction. This combined resistance force (of the internal resistance of the running gear and the resistance due to vehicle-terrain interaction) can be divided by the vehicle weight to get a corresponding combined resistance coefficient. Subtracting the internal resistance of the running gear coefficient that was measured above gives the resistance due to vehicle-terrain interaction coefficient, and the result can be compared to simulation model estimates of this.

13. In the soft soil, self-propelled motion resistance test described under 3.3.6, the track slips or tire slips required to move the vehicle forward are the result of the running gear having to overcome the internal resistance of the running gear and the resistance due to vehicle-terrain interaction. The results should be compared to simulation model estimates of the slips required to move the vehicle forward in a self-propelled manner on this soft soil surface.

14. In the soft soil, drawbar pull-slip tests described under 3.3.6, the internal motion resistance of the running gear coefficient and the resistance due to vehicle-terrain interaction coefficient have already been defined in the steps above. Accordingly, the results of the drawbar pull-slip tests at each slip allow the tractive effort coefficient predicted at that slip to be combined with the measured internal resistance of the running gear coefficient and the measured resistance due to vehicle-terrain interaction coefficient, and produce a predicted drawbar pull coefficient that can be compared with the drawbar pull coefficient measured at that slip. This provides a strong evaluation of the simulation model's ability to estimate tractive effort, resistance to motion, and drawbar pull coefficients on this terrain.

3.3.8. Motive Efficiency

1. Motive Efficiency is defined as Gross Path-Dependent Terrain Induced Motion Resistance (also known as: Terrain Induced Motion Resistance for Fuel Economy), using AVTP 03-10 (1991) as a guide:

a. On-road. For a given 3D path loop, defined in Figure 3.1, determine net terrain dependent motion resistance coefficient. Note that all vehicle intrinsic losses are ignored or assumed constant for this test event.

b. Off-road deformable terrain. For a given 3D path loop defined in Figure 3.1, determine net terrain induced motion resistance coefficient. Note that all vehicle intrinsic losses are ignored or assumed constant for this event.

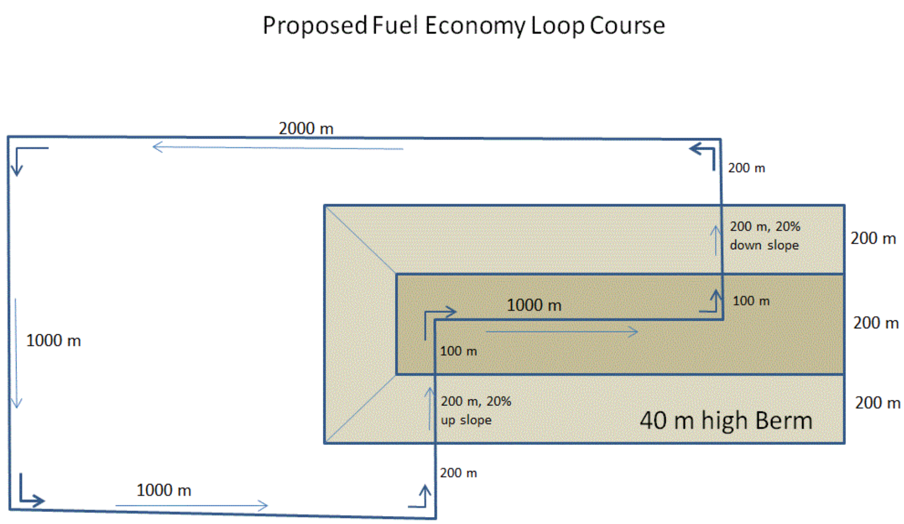

Figure 3.1: Fuel Economy (Motive Efficiency) Course Dimensions, 90° Turns Must Be Executed within a 15 m Wall to Wall Corner.

2. Figure 3.1 provides a theoretical motive efficiency course. Actual courses for this purpose exist in many of the NATO nation's test sites. Substitution of these actual test courses is preferred where possible.

3.3.9. Amphibious Operations. Test Data N/A

1. Vehicle amphibious mobility is an area for future development of this standard. Examples of amphibious performance metrics for which NG-NRMMs should be predictive are:

a. Fording depth
b. Speed in calm water
c. Sea state limit
d. Speed in waves

3.3.10. Autonomous Vehicle. Test Data N/A

1. Autonomous vehicle mobility is an area for future development of this standard. Examples of autonomy performance metrics for which NG-NRMMs should be predictive are:

   a. Look ahead speed limit
   b. Speed through an offset corridor
   c. Soft soil limit sensing

CHAPTER 4 OPERATIONAL READINESS AND GAPS

1. The purpose of this chapter is to provide a roadmap toward a more complete and comprehensive methodology that can be implemented successfully to support NATO-wide operational capabilities. A framework is required so that future activities can become additive and complementary to the long-term goal of supporting operational readiness and acquisition processes through a common mobility modelling methodology as defined within NG-NRMM.

2. From an operational planning standpoint, the methodology to aggregate and combine multiple mobility limiting factors into a single higher level metric such as GO/NOGO, Speed-Made-Good, or Motive Efficiency must be made readily available and compatible with existing terrain and vehicle data products. These outputs, in a simplified formats are currently available in the existing mobility models in use for Operational Planning. Modeling practitioners have the ability to treat these limiting factors as layered filters, adding or removing operationally relevant parameters to create a composite map of only their parameters of interest. However, the next generation of physics-based approaches will require higher fidelity terrain and vehicle data in order to output these limiting factors. To address this gap a survey was used to assess the ability of the operational units in various NATO nations to provide and utilize the required information.

4.1. OPERATIONAL READINESS

4.1.1. Data Transport Integration

1. In the current and future operational environments, it is imperative that forces and systems communicate across various units, share information, and assist operational mission planners as events play out on the battlefield. The communication of this information includes operational parameters at various time scales (from immediate action, to longer term force planning for example) and may involve two or more NATO nations. In addition to standardized Command and Control architectures, data transport and integration will require implementation of common data repositories and integrated delivery of data sets to users in the field. As such, data architectures are required for future operations in virtually all battlefield functions. While such battlespace structures must be resolved at the NATO/DOD level, next-generation mobility models can benefit and support the required fidelity and precision of that data to provide accurate prediction of wheeled and tracked vehicle mobility. NG-NRMMs and their associated analytical structures will identify the precision required to achieve specific levels of accuracy for the prediction of overall mobility and the determination of optimum maneuver corridors.

2. Additionally, the solution should begin with support of acquisitions, as NG-NRMMs are employed using a cradle to grave philosophy. Key vehicle data and required capability are established during the vehicle development and acquisition processes. Additional data is gathered during upgrades to legacy systems that should be easily integrated to

the NG-NRMM solution. This detailed vehicle, vehicle subsystem and terrain interaction analysis is validated during operational test and deployment. The proven simulation environment which meets the intent of NG-NRMM can be provided to the operational component and utilized in near real-time applications to support optimum maneuver decisions. Prediction of friendly and opposition force vehicle mobility can be achieved within this structure. Annex I provides a general discussion of how NG-NRMM and subsets of the primary tool can be deployed to successfully support operational needs.

4.1.2. Operational Survey

1. Tactical and combat vehicle mobility has always been key to ensuring the operational success of expeditionary forces for all NATO member nations. Work has been ongoing to better quantify mobility capability in recent years, particularly in light of the substantial increase in gross vehicle weight as well as axel/track element loading due to the need for additional protection and firepower systems. Analytical tools and near real-time situational awareness provided by satellite, remote sensing and other sources are available to individual units as well as the broader force.

2. To determine how such analytical tools can be best employed, it is appropriate to identify how these tools are currently deployed or considered by the operational planners. This is of particular interest with the deployment of vehicles with advanced mobility capabilities, allowing successful maneuver through areas previously avoided and the availability of near real-time operational information provided by Unmanned Aerial Systems (UAS) and other remote sensing technology resources. A survey and questionnaire (Annex J) was provided to NATO operational planners to determine both the need and readiness to implement solutions represented by this NATO standard and the intent of NG-NRMM solutions.

3. A notional concept of employment has been developed within an operational vignette as provided in Annex I. Annex I provides examples of how the integrated mobility measurement and analysis tools could be deployed in support of the Intelligence Preparation of the Battlefield (IPB) process. The questionnaire, survey and concept of employment sought to recognize the broad range of tactical and combat vehicle capabilities found among the NATO members.

4. Based on the AVT-248 work on Operational Readiness (Dasch and Jayakumar, 2020) the operational planners were queried as to the potential application and associated use of the tools identified as NRMM2, NG-NRMM simplified and NG-NRMM complex. Whereas NRMM2 is a defined software product, NG-NRMM solutions are taken to be those that conform to this NATO Standard and a variety of solutions have been proposed but are not yet widely developed or fully validated. Therefore, the approach taken with the operational planners was to determine the potential value of the NG-NRMM approach and whether the NATO community was aware of currently established data environments for key terrain and vehicle parameters required for successful implementation.

5. The following summary is based on the input from more than 60 participants responsible for operational planning from a broad range of NATO Nations. [Note: Research in this area will continue and be included in the AVT-327 Final Report.]

4.1.3. Survey Responses

In an effort to identify the importance of the various elements that currently make up the parameters that influence operational planning, each of the respondents was asked to rate the significance of the individual survey metrics. The rating scale was one through five with one being the least and five being the most important. The summarized values are identified below.

(blue)	Most Important
(green)	Moderately Important
(yellow)	Least Important

Table 4.1: Survey Results – Average Ranking of Importance.

Terrain Data	AVE
Elevation / Slope	4.6
Terrain Roughness	4.0
Soil Type	3.9
General type (USDA / USGS)	3.8
Seasonal effects (e.g., moisture, winter)	4.4
Terramechanics parameters	3.5
Soil sinkage	3.7
Soil shear strength	3.4
Land Cover / Usage	4.2
Road Network	4.4
Building material	4.0
Road width / number of lanes	4.5
Geometry (curves / banks)	4.3
Hydrography (streams / rivers)	4.6
Aerial Photography	4.3
Obstacles	4.5
Geometry	4.3
Density	4.3
Forest Characteristics	3.8
Stem size	3.9
Stem spacing	3.8
Climate Effects	4.2

Vehicle Data	**AVE**
Tire Analysis	3.0
Importance of proper tire selection for the vehicle	3.3
Importance of a range of operational tire pressures as a function of terrain conditions	3.2
Ability to operate the vehicle at reduced tire pressures to gain mobility	3.3
Ability to incorporate a run-flat system with the tire and measure the effect of the run-flat	3.1
When considering the tire as a component of the overall vehicle how do you consider the following parameters?	
Weight	3.4
Spring rate	2.8
Damping	3.0
Contact area / lug geometry	3.3
Pacejka coefficients	2.9
Other? Please describe.	3.3
Suspension Analysis	2.9
Weight of the suspension and axle system	3.3
Total wheel travel	3.4
Ability to adjust suspension performance for the condition (e.g., off-road operation versus on-road stability)	3.4
Adjustable ride height suspension and the impact on mobility	3.1
On-road stability and the use of anti-roll bars	3.4
Chassis Analysis	3.5
Impact of the total weight of the vehicle system	4.3
Overall geometry including angle of approach, departure and break-over angles	3.9
Model Outputs	**AVE**
GO/NOGO for single vehicle	4.1
GO/NOGO for multiple vehicles	4.6
Speed across terrain	3.8
Time to a given destination	3.8
Confidence levels	3.9
Vehicle handling	3.0
Ride quality as it impacts the operator, weapons systems or payload	2.8
Ability to negotiate a particular slope (longitudinal or side slope)	3.9
Ability to negotiate a specific obstacle (downed timber, urban rubble, irrigation ditch, etc.)	3.7
Other (please describe)	4.2

4.1.4. Detailed Response to Survey Questions

1. Terrain Data
   a. *What devices or approach do you typically utilize when obtaining terrain measurements prior to a training maneuver?* 100% of all respondents to date indicated they obtained direct measurement and/or remote sensing data suitable for application in NG-NRMM even when operating in established maneuver training areas. Many forces utilized some type of precursor vehicle thereby combining critical data including moisture content, sinkage, motion resistance, slip and other critical parameters to support NG-NRMM and "vehicle as a sensor" applications. None of the respondents indicated the use of advanced tools such as the bevameter.
   b. *Utilization of Cone Penetrometer / Precursor Vehicle:* All of the respondents indicated that they currently used some type of direct measurement device. About 50% either used a cone penetrometer or similar method and the others relied on a precursor vehicle and identification of rut depth or wheel slip.
   c. *Experience with Deployed Vehicles in Similar Conditions or Operational Events:* All of the respondents indicated that they rely on experience with deployed vehicle systems in similar conditions. Generally, all indicated that they had specific units (combat engineers, etc.) who were responsible for this activity and would report back through their chain of command.

2. Vehicle–Terrain Interaction
   a. *Access to Any Predictive Tools for the Terrain:* About 30% of the respondents indicated that they were actively using a predictive tool to establish maneuver corridors, but in all cases completed this analysis well in advance of the operational event.
   b. *Do you have access to tools that combine terrain and vehicle information for the purpose of operational planning?* All of the respondents indicated that they did have access to tools. Generally, the predominance of the non-US respondents referenced some type of ArcGIS based tool and a generic application of expanded terrain information. The more advanced implementation of information was focused on specific obstacles (primarily NOGO or avoidance) and on threat location. Vehicle performance was included primarily based on prior operational experience with the vehicle system.
   c. *Simplified Analysis:* All respondents indicated that through their IPB process the risk of operation was determined and generally assessed as GO, SLOW GO and NOGO areas. A predominance of respondents indicated that they attempted to estimate the performance of the Threat Forces and compared their maneuver corridors to threat vehicle movement. Many identified the recent emphasis on mobility and operation in winter/spring thaw conditions. Sinkage, slope and obstacle avoidance were primary metrics and the

analysis was predominantly focused on GO/NOGO and route clearance multi-pass.

d. *Use terrain and vehicle data Information for operational decisions.* The majority of respondents indicated that the vehicle configuration, velocity, tire pressure selection, recommendation for maneuver corridor, selection of drive train configuration, anticipated fuel usage based on conditions (slope, motion resistance, in motion versus stationary time, etc.) were determined based on the simplified analysis and the outcome of the IPB.

e. *Empirical Analysis / NATO Reference Mobility Model Usage:* Within the operational context identified through the vignettes, outside of US forces, there was no acknowledged significant utilization of NRMM2 during the IPB process. There was, however, significant use of the key metrics for terrain and vehicle that are directly applicable to the NG-NRMM approach, including slope, soil strength based on observed vehicle sinkage, measured cone penetrometer, mean maximum pressure for the selected vehicle at a given tire pressure, etc. Generally the available terrain data was 30-metre resolution and maneuver corridors relatively wide.

f. *Simple Terramechanics:* Approximately 50% of respondents indicated that they applied some type of analysis tool either developed through their in-country process (University, Military Research and Development, etc.) or as might be provided by other forces during joint operations IPB planning. The remaining indicated an approach that appeared to be more empirically based. Some indicated that they had developed analysis that utilized the precursor vehicle and its performance combined with some soil strength measurements (cone penetrometer, estimated soil density and moisture content, etc.) in a manner that generally reflects the “vehicle as a sensor” methodologies. None of the respondents indicated any use or application of "Bekker Wong" /bevameter prediction methods during the IPB process.

g. *Vehicle as a Sensor:* The predominance of the respondents indicated that they used forward vehicles as sensors to identify and then send near real-time condition data to the operating unit. Many identified that forward platforms were responsible to provide relevant mobility information to support Company level maneuver decisions, which were subsequently provided to the Brigade / Battalion.

h. *Information Collected Informs Operational Decisions:* All indicated that they used the data collected to inform operational speed, vehicle configuration, maximum payload for mission, and tire pressure settings within the Central Tire Inflation System (CTIS) if the vehicle was so equipped, as part of the IPB. Assessment of in-place bridge weight limits remains a continued limitation for operational planners.

3. Simulation Outputs to Support Operational Planning

a. *Terrain and Mobility Analysis Completed Well in Advance of Operation:* All respondents indicated that regardless of the type of terrain and vehicle analysis that was conducted, this effort was always performed well in advance of the operation. The failure to recognize current or near current conditions was acknowledged as a limitation. The potential for unsuccessful operations in certain adverse mobility areas was acknowledged due to the inability to more rapidly adjust or adapt small unit maneuver corridors using current and projected future conditions.

4. The responses provided by the operational planners clearly indicate the capability currently exists to gather the necessary data within their currently available operational planning systems to achieve the intended capability provided by NG-NRMM as described within this NATO Standard. However, there remains a number of action items for the NG-NRMM community to achieve and subsequently implement the capability necessary for success within the operational community.

4.2. IMPLEMENTATION AND GAPS

1. Success at the operational level requires single, higher-level metrics for vehicle system mobility such as GO/NOGO, Speed-Made-Good, Dash Speed and Motive Efficiency (fuel economy, logistic support, etc.). Currently, NG-NRMM does not provide a detailed recommendation for the methodology to aggregate and combine multiple mobility limiting factors. However, NG-NRMM defines the necessary format for terrain, vehicle, and vehicle/terrain interaction data sets to achieve these objectives.

2. Specific applications should be governed by the principle that the fidelity and granularity of the various data sets (terrain, vehicle, vehicle terrain interaction, etc.) match the intended application of the simulation. For example, accuracy of mobility predictions required for determination of maneuver corridors should be based on more rigorous analytical methods.

4.2.1. Resolution of Data Sources

1. Elevation data is widely available at 3 arcsecond and 1 arcsecond (~90 m and ~30 m) resolution (e.g., shuttle radar topography mission (SRTM) data). While this may be appropriate for a large-scale study (Battalion to Division level maneuver), this fidelity and granularity is not sufficient for vehicle design development or local maneuver decisions. Terrain data resolution must be commensurate with the applied vehicle dynamic mobility analysis. Based on the study and research completed by the various NATO NG-NRMM committees, a recommended notional terrain and corresponding vehicle scale is shown in Table 4.2), along with common implementation cases.

Table 4.2: Suggested Fidelity by Implementation.

Implementation	Terrain Resolution	Vehicle Resolution
Vehicle Design and Development. Final acquisition and confirmation of compliance with stated performance requirements in a controlled environment	10 centimetres Detailed soil strength and parameter data	High-resolution on important parts for current simulation (e.g., deformable structure, FEA/DEM tire models, etc.)
Deployed Company avenues of approach. Operation supported by direct terrain measurement for directed maneuver event	1 metre resolution Detailed soil strength and parameter data based on direct measurement augmented by remote sensing	Substantially increased granularity and fidelity of vehicle subsystems compared to traditional 2D simulation tools. 3D MBD physics-based model which retains both time domain and frequency domain accuracy converted to a surrogate model to reduce run time.
Brigade/Battalion avenues of approach. Operation supported by near real-time remote sensing systems and historic terrain data	10 metre resolution Broader soil moisture and density, representative soil shear strength, reduced detail relative to subsurface soil strength	Reduced vehicle subsystem detail commensurate with terrain roughness resolution 3D MBD simulation converted to surrogate simulation, energy management simulation (e.g., motion resistance, sinkage, tractive force speed, etc.)
Division pre-planning. Primarily historic terrain data with varying fidelity	30 metres with known infrastructure data	Vehicle system capability data. Simplified vehicle performance data. Data commensurate with terrain resolution. Limited physics-based parameters. Better than NRMM – MBD model converted to simplified surrogate model to aid in reduced run time to rapidly support multiple engagement scenarios.

2. High-resolution terrain data is typically difficult to obtain and may not be appropriate for near real-time simulations used to support operational decisions. Key terrain parameters that directly impact vehicle mobility (soil strength, moisture content, slope, etc.) are expected to be provided with relatively high-resolution for all analysis efforts. High-resolution terrain and vehicle data is appropriate when defining core vehicle competencies and for setting performance boundaries prior to maneuver events. For

some characteristics (e.g., elevation) remote sensing techniques can be used to generate high-resolution data or to augment existing satellite or historic operational area measurements. These remote sensing data sets are augmented by direct measurement, as noted in the table above. However, other techniques that involve analysis of the uncertainty or error, such as kriging or data inferencing, may be necessary for parameters for which the uncertainty/error of the existing data is such that accurate predictions cannot be obtained. When inferencing techniques are used, these should be noted in the terrain data file. Also, the certainty of the estimate should be carried through in the uncertainty quantification effort.

3. As identified by the operational planners, there is no current use of soil strength measurement devices such as the bevameter in the field. There is no planned use for the future. However, all the operational elements deploy precursor or other systems that would meet the criteria of "vehicle as a sensor" whereby the measured response of the vehicle (sinkage, wheel slip, tractive force as defined by the torque management system as part of a digital backbone, etc.) can be used to characterize terramechanical strength of terrain. Combined with the validated and verified 3D MBD simulation of the vehicle, the terramechanical strength estimates can provide the necessary vehicle terrain interaction data elements required for successful implementation of NG-NRMM. At the Company level, "vehicle-as-a-sensor" data are augmented by direct contact and remote sensing of soil parameters and terrain.

4.2.2. Data Availability Typical for the Operational Mission Planner

1. Global data is available for some elements such as elevation, soil type, and land cover. These open data sets are often low resolution. Soil type and land cover are often vector formats that require processing to combine with raster layers. High-resolution data (one metre or smaller) may be available for initial vehicle development and research elements but are atypical within the operational environment, even at the Company level. Demonstration of real-time or near real-time data acquisition from the operational environment through the use of remote sensing systems continues. The architectural specifications section of this document describes how this data can be integrated into a consistent set of input files, which can then be used in concert with the vehicle physics-based simulations to achieve an accurate prediction of operational capability. Compatibility of the data sets regardless of resolution becomes essential for the success of the operational deployment of the NG-NRMM solutions. High-resolution multi-band satellite images are available; with processing these can be used to infer land cover, vegetation density, etc. The process to achieve the implementation of this data needs to be established and therefore represents an existing gap for the successful implementation of NG-NRMM.

2. Within an operational context, it is anticipated that mission planning at the Division level will utilize historic data with relatively low resolution to establish maneuver intent. This maneuver intent is then analyzed and implementation planned at the Brigade or Battalion level. At this point, specific maneuver assets, logistic support and other details are determined. As noted, throughout the development of the NG-NRMM approach inclusion of more detailed infrastructure (roads, bridges, water gaps, etc.) is identified. As

described in the attached vignette description (Annex I), maneuver decisions are then implemented at the Company level. It is at the Company level, with their specific tracked and wheeled assets, that the full implementation of NG-NRMM using near real-time environmental and threat data is anticipated to be most valuable and feasible. Assets are available at the Company level to provide ground truth level information for the terrain based on either direct measurement or remote sensing. At this point, accurate prediction of specific maneuver corridors are established and the range of NG-NRMM tools and methods can be employed utilizing "vehicle as a sensor."

3. As Defense organizations within NATO develop common data repositories for multiple battlefield purposes, NG-NRMM must be structured to enable use of scalable fidelities/accuracies in those data fields. As the core analysis is based on very high fidelity terrain-to-vehicle interaction, the accuracy of the operational metrics using lower resolution/lower fidelity data combined with imbedded uncertainty quantification can be implemented with near real-time operational knowledge. Currently, the specifics of the data fidelity and accuracy have not been established throughout NATO and DOD organizations and the NATO Standard provides a basic framework for this activity. Substantial effort remains to achieve full implementation.

4. It will be useful for the NG-NRMM proponents to determine desired formats and database structures in parallel with developers of the enterprise level DOD/NATO data repositories, as data intensive algorithms will be necessary to support development of future robotic and autonomous systems (RAS) negotiating the terrain surface. Since NG-NRMM will generate a robust mobility prediction based on terramechanics and the specifics of the vehicle terrain interaction, it is a reasonable expectation that NG-NRMM can serve as a backbone for ground RAS movement in off-road terrains. As this NATO Standard sets forth the structure for how terrain information will be provided, prioritization of these data elements as a function of the application of this data in an operational context remains to be established.

4.2.3. Terrain Data Implementation Gaps

1. In an operational context, identification of slope characteristics needs to have sufficient granularity to account for obstacles or surface roughness that impact vehicle performance and mobility. When the optimum maneuver path is identified, variability due to additional traffic, changing obstacles, continuing environmental events, etc. must be evaluated conservatively. For example, slope resolution to +/- 5 degrees may be sufficient, reducing terrain data volume and analytical processing time. Significant effort remains to determine these optimal parameters in a given NG-NRMM implementation in an operational context. While all the elements are present to support the required level of terrain data resolution and fidelity, the specific methodology for validation of a given implementation remains to be established.

2. The legacy NRMM Code 11 MAPTBL format provided in Annex A, otherwise known as MAP-11, is an ASCII text format for representing GIS data. This has been expanded for new NG-NRMM layers. The format is human readable and editable with common spreadsheet software. However, as an ASCII format, the file size can become

very large with a large area or fine resolution. Also, because it is easily edited it is also easily corrupted. This format was chosen primarily for two reasons: 1) backward compatibility with legacy NRMM, and 2) readability for a variety of software packages from both the GIS and MBD domains.

3. Due to the established limitations of the MAP-11 format, it is appropriate to investigate other formats that may be both more compact and more secure. Because numerous layers need to be considered simultaneously, the file type should be limited to raster options and exclude vector. The CDT-1 effort used GeoTIFF as the alternate format. This is a native format for most GIS software, but presented some challenges relative to integration with the vehicle-based 3D MBD tools. In the 3D MBD environment, GeoTIFF creates an extended simulation run time because the whole file must be loaded into memory during the simulation. This is not acceptable within an operational environment. Other formats offer advantages in the simulation environment. An example is the HDF5 format. The structure of these files offers unlimited dimensions (layers) as well as dynamic access to smaller portions of the files. Subsets of the file can be loaded into the simulation software as the vehicle moves along a traverse.

4. A possible future solution to be considered is to declare GeoTIFF as the common data exchange and storage format. However, at or near simulation run time, that data set can be translated into a different format prior to implementation within the overall NG-NRMM simulation. The Open Source Geospatial Foundation offers a software utility known as the Geospatial Data Abstraction Library (GDAL). This utility can be used to translate from GeoTIFF into numerous other formats (currently 55 options).

5. For any given collaboration effort among multiple nations or organizations, these terrain data set issues require resolution to successfully deploy NG-NRMM. While the NATO Standard provides a recommended approach, tailored approaches are also allowed in the NG-NRMM framework.

6. Additional effort is required to better refine the process to review available soil specific data and develop the necessary terramechanics parameters to support the standard terrain data formats identified. The tasks include: 1) determine physical relationships that relate known parameters to the parameters required for successful simulation validation and verification, thereby overcoming the need for deployment of unique soil measurement devices; 2) establish a methodology so that each NATO member provides in-country data that may be developed during commercial or defense projects; 3) establish a validation process to leverage emerging remote-sensing technologies that can provide essential terrain data. As the emerging non-contact remote sensing technologies expand to include the full range of environmental conditions (wet/dry, direct sunlight/shaded/night, bare ground/vegetation), a multidimensional database may be required to properly relate these parameters and the associated hyperspectral analysis to the required soil strength parameters.

4.2.4. Vehicle Data

1. The NATO Standard identifies that the representation of the vehicle within the 3D MBD environment must be commensurate with the intended accuracy that will occur after integration with the terrain data. This capability must be established through the execution of standard maneuvers on a non-deformable surface. This traditional approach is essential to confirm that the simulation can accurately represent the speed, acceleration, braking, steering, stability, ride quality, maneuverability, etc. of the vehicle prior to the introduction of the complexity of deformable soil, slopes, vegetation, typical obstacles, etc. The ability of the 3D MBD simulation tools to accomplish this task was well proven through the efforts of AVT-248 and CDT-1. However, a standard set of maneuvers and performance metrics for the purpose of validation and verification has not yet been established within the NATO community. The overall success of NG-NRMM will depend on the ability to describe a broad range of vehicle attributes in a common format similar to that proposed for the terrain parameters.

2. The criteria for ride quality measurement needs to be defined. Currently a broad range of definitions exist. Some rely on a two-dimensional approach, relying solely on vertical input to the driver, gunner and commander. Others follow the three-dimensional approach identified within the ISO standard. Further, some operational components rely on the definition of the operational terrain based on a two-dimensional, single value RMS measurement metric, while others acknowledge that the vehicle and the terrain are three-dimensional producing vertical, longitudinal and lateral loads that impact ride quality and hence the determination of Speed-Made-Good, dash speed and maximum safe operational speed. The criteria for these metrics need to be resolved to a common data format so that the metrics provided to the operational planners represent a common approach within the NATO forces.

3. As noted in the survey responses from the operational planners, the significance of tire performance, proper inflation pressure, and proper load deflection, is essential to successful maneuver. Currently there is a significant lack of appropriate tire data available to the community, a problem recognized throughout the various work that has led to this NATO Standard. The lack of accurate tire performance data in deformable soils and the inability to successfully represent tire mechanics within the simulation environment remains a significant gap, which must be addressed in future efforts.

4. The NATO Standard acknowledges the potential significance of uncertainty associated with terrain measurement. Data gaps exist due to variation of geospatial and soil parameter data. Temporal and spatial variability of the terrain must be addressed to ensure successful operational planning implementation. Additional effort is required to address the impact of measurement methodology on the accuracy of the data and the impact on the final mobility predictions. Standardization of GIS data collection methods and interpolation techniques will reduce variability. Uncertainty quantification tools must be applied as indicated within the NATO Standard.

4.2.5. Validation and Verification

1. The NATO Standard provides a basic list of test events appropriate for the validation of the vehicle dynamic performance on non-deformable surfaces and subsequently test events involving operation on deformable surfaces, which would be performed on soils representative of the conditions anticipated for the operation of the vehicles. Figure 4.1 generally identifies the role of these validation events as it would apply to simulations that get used in an operational context.

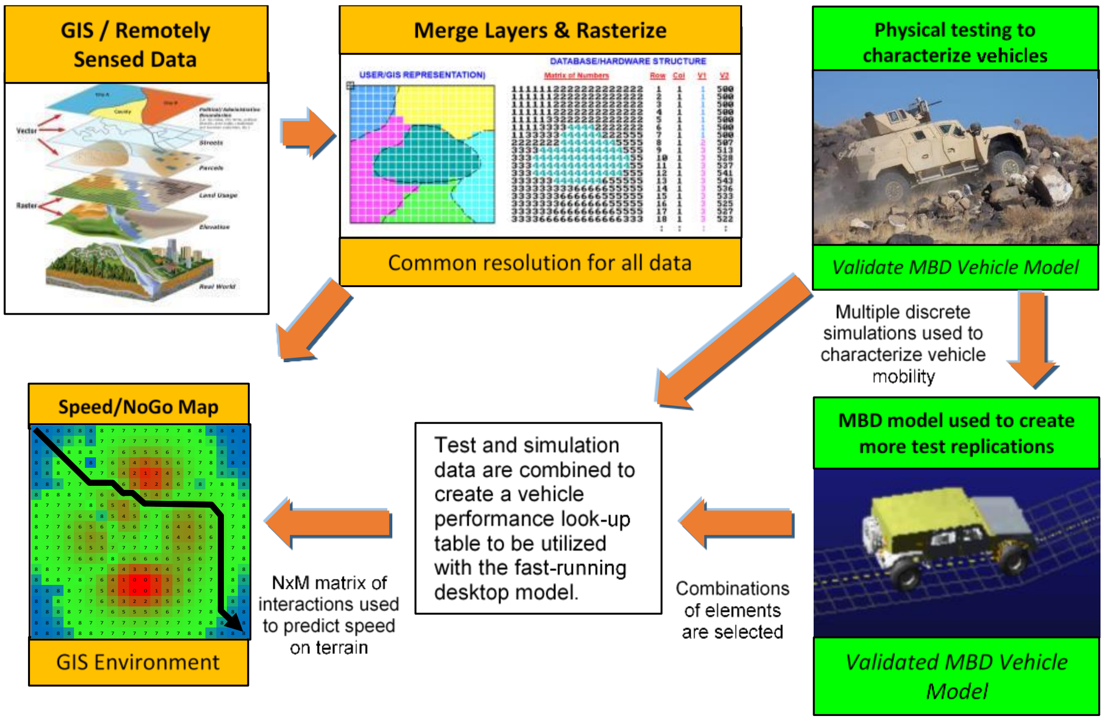

Figure 4.1: Validation of Vehicle Dynamic Performance.

2. Although significant validation work has been accomplished in the development of the NATO Standard, additional effort remains which must be addressed to achieve full implementation of NG-NRMM in support of operational maneuver decisions.

3. Accurate mobility prediction in a deformable soil, slippery environment, which includes sinkage, obstacle override, vegetation override and complex maneuver on an uneven surface, remains to be successfully demonstrated.

4. The running gear level terramechanics model most commonly employed outside of cone index is the Bekker-Wong model for sinkage with the Janosi-Hanamoto method for shear strength (1961). The primary model limitation is that the sinkage parameters are related to the specific vehicle contact area. Thus the parameters are not completely generic or universal. Secondly, the parameters are calculated normal to the soil. Applying the sinkage coefficients on sloped terrain requires a combination of the sinkage and shear models, which has not been demonstrated.

5. The soil parameter data availability remains a significant shortfall in efforts to apply quasi-continuum level terramechanics. This higher fidelity approach requires significantly more detailed soil parameter and vehicle terrain interaction data. Detailed, measured soil response is often necessary to calibrate the required parameters as described within the NATO Standard. Once these values are established, the uncertainty of the measurement and prediction must then be applied to the operational conditions.

6. The challenge of modelling and tracking the forces on millions of nodes/particles presents computational limitations. Currently the implementation of such methods cannot be deployed in an operational environment and the analysis is limited to expert users. Future applications of artificial intelligence technologies may substantially improve the efficiency of these methodologies. Such methodologies would first need to gain acceptance within the vehicle development and acquisition communities in order to provide the necessary data that could then be applied in a “fast-running model” approach required for operational planning.

7. Additionally, refinement of the detailed elements associated with these and other factors are anticipated to become the purview of follow-on efforts to this NATO Standard. Coordination with other groups involved in standards development that address critical inputs to NG-NRMM will be required. This will include how elements such as terrain roughness are defined and represented, how ride quality and dynamic response are defined and quantified, how specific tests beyond traditional dynamic lane change or braking are conducted, etc.

8. The NATO Standard identifies the list of validation and verification methods for NG-NRMM that reflect current activities. The predominance of the test events are conducted on non-deformable surfaces or are based on test methods established for paved/reinforced surface performance. Implementation for operational planning requires that the vehicle maneuvers over deformable terrain for various soil types and moisture contents be fully assessed. Obstacle negotiations should address positive and negative events on soft soil conditions and include vegetation override and maneuver. Additional work is required to establish repeatable methods that can then be used to validate and verify those predictions within NG-NRMM.

9. The Maturity Scale identified within the document represents an appropriate range relative to the accuracy and applicability of potential NG-NRMM tools. Regarding implementation in order to support operational planning, a Level 6 or Level 7 is necessary to successfully provide the confidence required by operational planners as noted in the summary of responses to the questionnaire and the associated vignette describing how the capability of NG-NRMM could be implemented. The current recommended level of test and available data for the purpose of validation and verification remains below the requirement, particularly for tracked vehicle performance. As such, substantial effort remains to both demonstrate the process and define the necessary steps to achieve validation and verification for NG-NRMM.

10. The soil types identified for off-road trafficability are based on historic analysis (e.g., LETE sand, Muskeg and snow) and correlation to the predominant soil types faced by operational planners has not been established. Additional soil conditions representative of the environment faced by operational planners should be considered to ensure accurate representation of tracked and wheeled vehicle performance throughout all performance maneuver capabilities.

11. The application of NG-NRMM to the predicted performance of autonomous vehicles is essential to defining the interoperability between these systems and manned vehicles for operational planners. The ability to determine where such platforms can operate using onboard sensors will be critical to successful deployment. Requirements to describe environment, scenario, vehicle, and autonomy are the responsibility of AVT-341.

   a. Benchmark metrics will be developed to assess verification and validation different from manned vehicles as described in this NATO Standard.
   b. Sensor and autonomous control system database and benchmarks will be developed and may be added to NG-NRMM data repositories.

12. As identified within this document and the associated annexes, along with the investigations and research that have been performed under the auspices of various NATO technical groups, the ability to analyze and accurately predict vehicle capability within the framework of NG-NRMM for operational purposes has been established. Challenges remain to successfully implement these demonstrated techniques and solutions to the benefit of operational planners.

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CHAPTER 5 CONFIGURATION MANAGEMENT

5.1. CHANGES TO THIS STANDARD

1. This standard is developed and maintained using the following process:

   a. Anyone may propose changes to this AMSP-06 document based on the scope of NG-NRMM outlined in section 1.3. Proposals will be submitted along with a Technical Activity Proposal (TAP) dealing with revision of the AMSP-06 with regard to proposed changes. Submissions shall be sent to the NATO STO AVT Panel via e-mail avt@cso.nato.int.

   b. After approval by NATO Science and Technology Board, the respective Technical Activity must follow the standard's revision procedure as per AAP-03(K) (2018).

5.2. GIS, TERRAIN, SOIL and VEHICLE TEST STANDARDS

1. Changes required for NG-NRMM to the DFDD+ will be submitted to the International Change Control Board to ensure data harmonization and interoperability or added as non-standard data "+". Likewise the following governing standards and their on-going impacts on NG-NRMM results files will be continuously harmonized:

   a. AGeoP-11 EDITION A (2018) - NATO Geospatial Information Framework (NGIF)
   b. ISO 19103 (2015) – Conceptual schema language
   c. ISO 19109 (2015) – Rules for application schema
   d. ISO 19115 (2003) – Metadata
   e. ISO 19117 (2012) - Geographic Information – Portrayal
   f. ISO 19126 (2009) – Profile – FACC Data Dictionary
   g. ISO 19135 (2015) - Procedures for registration of geographical information items
   h. ISO/TS 19139-1 (2019) Geographic Information – XML Schema Implementation
   i. TIFF (2017) Tagged Image File Format
   j. GeoTIFF Format Specification, GeoTIFF Revision 1.0 (2017)
   k. ASTM C136 (2019) Sieve Analysis
   l. ASTM D698 (2012) Maximum total bulk density (derived from a Standard Proctor compaction test)
   m. ASTM D4643 (2017) Moisture content (MC)
   n. ASTM D1556 (2015) Density by sand-cone method
   o. ASTM D2487-11 (2011) Soil Classification
   p. ASTM D2937 (2017) Density by drive-cylinder method

q. ASTM D6938 (2017) In-Place density and water content by nuclear densiometer
r. ASTM D4318 (2017) Liquid and Plastic limits for plastic soils
s. ASTM D2216 (2019) Saturation Test for Non-plastic soils
t. AVTP 03-10 (1991) Fuel and oil consumption.
u. AVTP 03-30 (1991) Steering and Maneuverability
v. AVTP 03-160W (1991) Dynamic Stability.
w. AVTP 03-170 (1993) Suspension Performance.
x. SAE J266 (1996) Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks.
y. TOP 1-1-014A (2012) Ride Dynamics, April 2012.
z. TOP 2-2-604 (2007) Test Operation Procedure: Drawbar Pull.
aa. TOP 2-2-610 (2009) Gradeability and Side Slope Performance.
bb. TOP 2-2-611 (1980) Standard Obstacles, June 1980.

5.3. UNITS, DATE AND TIME

5.31. Units

1. It is acknowledged that much of the available data originates from a variety of sources from many parts of the world. As such, various measurement unit systems, used in the past and currently, are to be expected. Even in this document, such sources have largely retained the measurement units of the original work without an overall attempt to translate these into SI.

2. The International System of Units (SI), commonly known as the metric system, is the international standard for measurement. This is the recommended unit system to use in all future NG-NRMM work. It is strongly preferred that all new work, such as data collection, data reporting, analytical models, model outputs, etc. be created, processed and reported using the SI unit system. It is vitally important to ensure that all engineering quantities are correctly represented with appropriate units. Where parameter values are non-dimensional quantities, it is equally important to state that this is so. Where it is necessary to report values in different unit system, the results produced using SI are suitably post-processed to convert to the desired unit system.

3. The importance of establishing and using SI as the unit system cannot be over-stated. Incorrect application of mid-stream unit conversions creates the potential for serious errors that must be avoided.

5.32. Date and Time

1. The controlling specification is ISO 8601 (2019) Data elements and interchange formats - Information interchange - Representation of dates and times. ISO 8601 is the recommended date standard for NG-NRMM. The standard allows for a concise and unambiguous representation of the year, month and day using a YYYY-MM-DD date

format. Given the global nature of NG-NRMM, it is important to adopt a date standard that is internationally recognized and functional.

2. Universal Time Coordinated (or UTC) is the primary time standard by which the world regulates time. Again, given the global nature of NG-NRMM, and great potential for time sensitive information captured in many international time zones, it is recommended that all data that is time-stamped be done using the UTC standard. This is necessary to avoid any confusion as to the time or period elapsed since the data was recorded.

3. Date/time standards may need different levels of granularity. W3C (1997) specifies six levels of granularity ranging from lowest level of year only (YYYY) to the highest level with fractions of a second (YYYY-MM-DDThh:mm:ss.s).

5.4. MOBILITY BENCHMARK EVENT STANDARDS

Changes to the benchmark events will be subject to the applicable referenced standards contained in their definitions. Participation in those complementary standards definition efforts and harmonization thereof will be pursued by the NG-NRMM Verification and Validation subgroup.

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CHAPTER 6 REFERENCES

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CHAPTER 7 ACRONYMS

Acronym	Meaning
2D	Two-Dimensional
3D	Three-Dimensional
AAP	Allied Administrative Publication
AMSP	Allied Modelling & Simulation Publication
AEI	Aerodynamic ET Index
AOI	Area of Interest
AO	Area of Operation
AOR	Area of Responsibility
APC	Armored Personnel Carrier
ARB	Anti-roll bar
ARL	U.S. Army Research Laboratory
ASCII	American Standard Code for Information Interchange
ASTM	American Society for Testing and Materials
AVT	NATO Applied Vehicle Technology
AVTP	NATO Allied Vehicle Testing Publication
BW	Bekker-Wong
C2	Command and Control
CAC	Combined Arms Company
CAE	Computer-Aided Engineering
CCDC	U.S. Army Combat Capabilities Development Command
CCIR	Commander’s Critical Information Requirement
CDT	NATO Cooperative Demonstration of Technology
CG	Center of Gravity
CPG	Churchill Proving Grounds
CSO	Collaboration Support Office
CSU	Colorado State University
CT	Complex Terramechanics
CTIS	Central Tire Inflation System
CV	Coefficient of Variation
DBP	Drawbar Pull
DDI	Deep Drainage Index
DEM	Discrete Element Method
DEM	Digital Elevation Model
DFDD+	DGIWG Feature Data Dictionary-Plus
DGIWG	Digital Geographic Information Working Group
DIGEST	Digital Information Exchange Standard
DLC	Double Lane Change
DOD	US Department of Defense
DOE	Design of Experiments
DOF	Degrees of Freedom

DTED	Digital Terrain Elevation Data
EMT+VS	Equilibrium Moisture from Topography, Vegetation and Soil
ERDC	U.S. Army Engineer Research and Development Center
ET	NATO Exploratory Team
ET	Evapotranspiration
FACC+	Feature and Attribute Coding Catalog-Plus
FEA	Finite Element Analysis
FED-A	Fuel Efficiency Demonstrator - Alpha
FEM	Finite Element Method
GDAL	Geospatial Data Abstraction Library
GCVW	Gross Combined Vehicle Weight
GeoTIFF	Geographic Tagged Image File Format
GIS	Geographic Information System
GML	Geography Markup Language
GPS	Global Positioning System
GVSC	U.S. Army CCDC Ground Vehicle Systems Center
GVW	Gross Vehicle Weight
HDF	Hierarchical Data Format
KPH	Kilometre per hour
KRC	Keweenaw Research Center
IMU	Inertial Measurement Unit
IPB	Intelligence Preparation of the Battlefield
ISO	International Organization for Standardization
LCA	Lower Control Arm
LETE	Land Engineering Test Establishment
LFI	Lateral Flow Index
LIDAR	Light Detection and Ranging
LL	Liquid Limit
M&S	Modeling and Simulation
MAPTBL	A NRMM Code 11/ Map 11 format
MBD	Multibody Dynamics
MC	Moisture Content
MCS	Monte Carlo Simulation
MCOO	Modified Combined Obstacle Overlays
METT-T	Mission, Enemy, Terrain, Time, and Troops
MGCP	Multinational Geospatial Co-Production Program
MMP	Mean Maximum Pressure
MOI	Moment of Intertia
MOUT	Military Operations in Urban Terrain
MPH	Miles per Hour
MPM	Material Point Method
MR	Motion Resistance
MTU	Michigan Technological University
NATC	Nevada Automotive Test Center

NATO	North American Treaty Organization
NGIF	NATO Geospatial Information Framework
NG-NRMM	Next-Generation NATO Reference Mobility Model
NMSG	NATO Modelling and Simulation Group
NRMM	NATO Reference Mobility Model
NSO	NATO Standardization Office
NTU	Numbered Terrain Unit
NTVPM	Nepean Tracked Vehicle Performance Model
OGC	Open Geospatial Consortium
OLS	Open-Loop Steering
POMC	Proctor Optimal Moisture Content
PSRI	Potential Solar Radiation Index
RAS	Robotic and Autonomous Systems
REI	Radiation Evapotranspiration Index
RMS	Root Mean Squared
RMSD	Root Mean Square Deviation
RPM	Revolutions per Minute
RTG	NATO Research Task Group
SAE	Society of Automotive Engineers
SATMC	Saturated Moisture Content
SAVI	Soil Adjusted Vegetation Index
SI	International System of Units
SMAP	Soil Moisture Active Passive
SPH	Smoothed Particle Hydrodynamics
SRTM	Shuttle Radar Topography Mission
SSC	Steady State Cornering
SSS	Side Slope Stability
ST	Simple Terramechanics
STANAG	NATO Standardization Agreement
STANREC	NATO Standardization Recommendation
STO	NATO Science and Technology Organization
TAP	Technical Activity Proposal
TARDEC	U.S. Army Tank Automotive Research Development and Engineering Center (now GVSC)
TC	Technical Committee of ISO
TE	Tractive Effort
TIFF	Tagged Image File Format
TIN	Triangulated Irregular Network
TOP	Test Operations Procedure
TV	Tracked Vehicle
UAS	Unmanned Aerial Systems
UCA	Upper Control Arm
UML	Unified Modeling Language
UQ	Uncertainty Quantification

USCS	Unified Soil Classification System
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USNVC	United States National Vehetaion Classification
UTC	Universal Time Coordinated
UTM	Universal Transverse Mercator
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VCI	Vehicle Cone Index
V&V	Verification and Validation
VI	Vehicle Intelligence
VIPER	Vehicle Inertial Properties Evaluation Rig
VSDC	Vehicle Systems Development Corporation
VTW	Vehicle Test Weight
W3C	World Wide Web Consortium
WCS	Web Coverage Service
WD	Wheel Drive
WFS	Web Feature Service
WVP	Wheeled Vehicle Platform
WTW	Wall to Wall
XML/GML	Extensible Markup Language/Geography Markup Language
XSD	XML Schema Definition

ANNEX A TERRAIN AND SOIL DATA MODEL

1. The data model of NG-NRMM input data originates from the legacy “MAPTBL” terrain data input format (A.1). On this basis a UML data model was designed that began as an exact translation of the properties and items of the modified Code 11 MAPTBL terrain data input format. This NG-NRMM data model, provided in the UML format (A.2) typically used by modern data modelers and developers, provides a formal definition of the data model including additional attributes to facilitate more advanced models and simulation development. Geospatial data developers should follow the data model described in A.2 when developing input terrain data sets for NG-NRMM applications.

2. Section A.1 features a full description of the MAPTBL terrain data input format, A.2 describes the UML data model that originates from the contents of A.1.

A.1. MODIFIED CODE 11 MAPTBL TERRAIN DATA INPUT FORMAT

Section A.1 and its parts describe the MAPTBL Terrain Data Input Format as was defined at the beginning of the NG-NRMM development process. Terrain data developed for the 2018 Cooperative Demonstration of Technology, and used for development of the recommended GIS process described in this document, was formatted using the following definition. While this format was extended to enable more advanced terramechanics models and simulations, it is the root of the current recommended extended terrain data model. This format definition is provided here because it provides detailed descriptions of descriptive attribute items, and provides a background upon which the current data model was developed.

A.1.1. ASC ASCII Raster Format

1. The ASCII Raster Format is a raster-based thematic image of Numbered Terrain Units (NTUs). These are identifiers of terrain units that are matched up to the NTU field in the associated .TER file described below.

NCOLS xxx
NROWS xxx
XLLCENTER xxx | XLLCORNER xxx
YLLCENTER xxx | YLLCORNER xxx
CELLSIZE xxx
NODATA_VALUE xxx
row 1
row 2
...
row n

Where:

Table A.1: ASCII Raster Format Parameters.

Parameter	**Description**	**Requirements**
NCOLS	Number of cell columns.	Integer greater than 0.
NROWS	Number of cell rows.	Integer greater than 0.
XLLCENTER or XLLCORNER	X coordinate of the origin (by center or lower left corner of the cell).	Match with Y coordinate type.
YLLCENTER or YLLCORNER	Y coordinate of the origin (by center or lower left corner of the cell).	Match with X coordinate type.
CELLSIZE	Cell size.	Greater than 0.
NODATA_VALUE	The input values to be NoData in the output raster.	Optional. Default is -9999.

A.1.2. PRJ ASCII Raster Spatial Reference Support File

The PRJ support file stores the coordinate system information for the .ASC raster file above.

A.1.3. TER Terrain File

1. A tabular format for terrain data input is devised as format Code 11, MAPTBL. This format provides the capability to enter the terrain data information in a space-delimited spreadsheet with the terrain data items being in fields (columns), and the terrain units as records (rows). The first row of the tabular input designates the specific terrain items. The remaining “header” are marked as comments, starting with a “!” and may include, date and time created, author, contact info, etc. After general comments are the field header metadata, marked with “!#”. These rows describe the field (columnar) data in the remaining table. The first row after the field header metadata are the field headers. They are in order (left to right) delimited by a space character. The remaining rows are the .TER file’s data section, and contain the actual data values in order noted in the field headers.

2. First Record: The first row of the file is the line with the number of data records in the file, the format type, and an up-to 60 character description of the file. The first record is the "Standard" NRMM terrain file heading as follows:
<NTU> <KTYPE> <TERID>

Table A.2: Standard NRMM Terrain File Heading (First Record of TER file).

Item	**Format**	**Description**
NTU	Integer	Number of terrain units (rows in .TER file's Data Section)
KTYPE	Integer	Terrain file type & format code (Must be 11 for this format)
TERID	Text (Length = 60)	Alphanumeric title/description

Example:

53544233 11 Monterey California AOI-27JUN2015

Where:

a. NTU = 53544233
b. KTYPE = 11
c. TERID = Monterey California AOI-27JUN2015

Other KTYPE formats were supported in earlier versions of NRMM, but only Code 11, MAPTBL, is supported in this description.

3. General Comments: The general comment rows start with a "!" character. The rest of the line is treated as text comment and are not processed.

4. Field Header Metadata: Information about each field included in the data table is included in the TER file's header. Each line is initialized with a "!" comment marker followed by a "#" character to identify a field metadata row. The next string is the FIELD_NAME as it exists as the first line of the data values section of the file. This should contain any special characters or spaces. Separating the name from the metadata tags list is a colon ":". Currently three metadata tags exist for the fields:
a. FIELD_DESCRIPTION
b. DEFAULT_VALUE
c. DATA_SOURCE_TYPE

5. The FIELD_DESCRIPTION is a single sentence describing the data field. The DEFAULT_VALUE is the value that the row/field will receive in the absence of data. Note

that a string “NULL” may be used in place of a number or other value as a “No Data” default flag. Earlier versions of NRMM did not support this flag and are forced to use a numeric value. Common values for earlier NRMM are 0 or -9999.

6. DATA_SOURCE_TYPE tag determines how the value was collected. This tag has five values:

a. MEASURED: the source was directly measured or calculated from a measured source.
b. INFERRED: the source was estimated or interpolated from single or multiple sources.
c. LEGACY: the supporting source was built for previous versions of NRMM standard.
d. NOTIONAL: the data value is extrapolated or estimated from non-source data for fields that do not yet have a consistent data source available. This allows the modelling and simulation software to function with required data that does not yet exist.
e. UNKNOWN: a general flag for data that was captured or obtained without knowledge of origin.

7. The end user should have the option to scrub or deselect NOTIONAL data sources from processing for non-simulated exercises.

Format of each field line:

!# <FIELD_NAME>:[<FIELD_DESCRIPTION>, <DEFAULT_VALUE> , <DATA_SOURCE_TYPE>]

Table A.3: Field Header Metadata.

Item	Description	Values
FIELD_NAME	Name of the field	Text
FIELD_DESCRIPTION	Description of the field	Text
DEFAULT_VALUE	Default value used if no value exists	Various
DATA_SOURCE_TYPE	Source condition	Text • m = MEASURED • i = INFERRED • c = LEGACY • n = NOTIONAL • u = UNKNOWN

Example:

!# SHAPE_LENGTH:["boundary length","NULL","m"]

The following terrain data input items may be specified via this input method.

Table A.4: NRMM Terrain Data Inputs.

Item Name	Default Value	Units	Type	Item Description	Earliest NRMM Version [1]
ACTRMS	0	Inches	Double	Surface roughness	2.8.2
AREA	0	km^2	Double	Patch area	2.8.2
BRDGMLC(1) BRDGMLC(2) BRDGMLC(3) BRDGMLC(4)	4*0		Integer	Bridge MLC (1) – type 1, one-way, wheeled (2) – type 2, two-way, wheeled (3) – type 3, one-way, tracked (4) – type 4, two-way, tracked	2.8.2
CI(1) CI(2)	cone index: (1) – 0-6 inches (2) – 6-12 inches	psi	Real	Cone index value	2.8.2
CLUTTER	0	Code	Integer	Road lane width restriction 0 – no effect 1 – reduced by 10% 2 – reduced by 6 ft 3 – reduced by 8 ft 4 – greater of 8 ft reduction or 75% > 4 – minimum of all lane widths	2.8.2
CRVSPD		Mph	Double	Curve speed limit	2.8.2
DBROCK	99.9	Inches	Double	Depth to bedrock	2.8.2
DFREEZ	0	Inches	Double	Depth of freezing	2.8.2
DIST	0	km	Double	Road terrain unit length	2.8.2
DSNOW	0	Inches	Double	Depth of surface snow	2.8.2
DTHAW	0	Inches	Double	Depth of thawing	2.8.2
EANG	0	Radians	Double	Super-elevation angle	2.8.2
ELEV	0.0	Meters	Double	Elevation at surface	2.8.2
GRADE	0.0	Percent	Double	Slope of surface	2.8.2
IMTYPE (NOT USED)	0	Code	Integer	Material type 0 – not given 1 – soil 2 – concrete 3 – bituminous (asphalt) 4 – crushed rock 5 – gravel 6 – shale	2.8.2
IOST	1 (avoidable)	Code	Integer	Obstacle avoidability 1 – avoidable 2 – not avoidable	2.8.2

IROAD	0 (cross country)	Code	Integer	Road type 0 – off road 1 – super highway 2 – primary road 3 – secondary rod 4 – trail	2.8.2
ISCOND	0 (use scenario)	Code	Integer	Surface condition 0 – not given, use scenario value 1 – normal 2 – slippery 3 – flooded 4 – snow 5 – snow on ice	2.8.2
IST		Code	Integer	NRMM soil model code: 1 – fine grained 2 – coarse grained 3 - muck	2.8.2
ITURNLR	0	Code	Integer	Curve turn direction 0 – not given 1 – left -1, 2 - right	2.8.2
IURB	4	Code	Integer	Urban code 1 – village 2 – town 3 – city 4 – normal on/off-road 5 – canal 6 – river 7 – lake	2.8.2
KUSCS	5	Code	Integer	Soil type 1 – SW 2 – SP 3 – SM 4 – SC 5 – SMSC 6 – CL 7 – ML 8 – CLML 9 - CH 10 – MH 11 – OL 12 – OH 13 – water 14 – pavement 15 – rock 16 – GW 17 – GP	2.8.2

				18 – GM 19 – GC 20 - Pt	
KWI	3	Code	Integer	Wetness Index (SMSP) 0 – arid 1 – dry 2 – average 3 – wet 4 – saturated 5 – water logged	2.8.2
LOCHARD	.TRUE.	Logic	Boolean	Overhead clearance type	2.8.2
LTRAFFIC(NLANES)	MLANES*0	Code	Integer	Traffic flow direction 1 – forward 2 – reverse 3 – two-way	2.8.2
LUSE	0	Code	Integer	Land Use classification (various types)	2.8.2
NI	8	Number	Integer	No. vegetation classes Max = 9	2.8.2
NLANES	1	Number	Integer	No. traffic lanes	2.8.2
NTU	1	Number	Integer	Terrain unit number	2.8.2
NUNITS	1	Number	Integer	Number of terrain units	2.8.2
OBAA	3.14159	Radians	Double	Obstacle approach angle	2.8.2
OBH	0.0	Inches	Double	Obstacle height	2.8.2
OBL	0.0	Inches	Double	Obstacle length	2.8.2
OBS	999.0	Inches	Double	Obstacle spacing	2.8.2
OBW	0.0	Inches	Double	Obstacle width	2.8.2
OHCLEAR	0.0	Inches	Double	Overhead clearance	2.8.2
RADC	5730.0	Inches	Double	Road curvature radius	2.8.2
RCIC(1,1) RCIC(1,2) RCIC(2,1) RCIC(2,2) RCIC(3,1) RCIC(3,2) RCIC(4,1) RCIC(4,2)	8*750.0	PSI	Double	Seasonal Soil Strength 1,1 – dry, 0” – 6” 1,2 – dry, 6” – 12” 2,1 – average, 0” – 6” 2,2 – average, 6” – 12” 3,1 – wet, 0” – 6” 3,2 – wet, 6” – 12” 4,1 – wet-wet, 0” – 6” 4,2 – wet-wet, 6” – 12”	2.8.2
RDA(1) RDA(2) RDA(3) RDA(4) RDA(5) RDA(6) RDA(7)	12*3600.0	Inches	Double	Recognition distance by month: 1 – January 2 – February 3 – March 4 – April 5 – May 6 – June	2.8.2

RDA(8) RDA(9) RDA(10) RDA(11) RDA(12)				7 – July 8 – August 9 – September 10 – October 11 – November 12 - December	
RDBDANG(1) RDBDANG(2)	2*0.0	Radians	Double	Road embankment angle 1 – left side 2 – right side	2.8.2
RDBDHGT(1) RDBDHGT(2)	2*0.0	Inches	Double	Road embankment height 1 – left side 2 – right side	2.8.2
RDBDWID(1) RDBDWID(2)	2*0.0	Inches	Double	Road embankment width 1 – left side 2 – right side	2.8.2
RDSHWID(1) RDSHWID(2)	2*0.0	Inches	Double	Road shoulder width 1 – left side 2 – right side	2.8.2
RDSTRNGS(1,1,1) RDSTRNGS(1,1,2) RDSTRNGS(1,2,1) RDSTRNGS(1,2,2) RDSTRNGS(2,1,1) RDSTRNGS(2,1,2) RDSTRNGS(2,2,1) RDSTRNGS(2,2,2) RDSTRNGS(3,1,1) RDSTRNGS(3,1,2) RDSTRNGS(3,2,1) RDSTRNGS(3,2,2)	12*0.0	PSI	Double	Road soil strengths 1,1,1 – roadway, left side, 0-6” 1,1,2 – roadway, left side, 6-12” 1,2,1 – roadway, right side, 0-6” 1,2,2 – roadway, right side, 6-12” 2,1,1 – shoulder, left side, 0- 6” 2,1,2 – shoulder, left side, 6-12” 2,2,1 – shoulder, right side, 0-6” 2,2,2 – shoulder, right side, 6-12” 3,1,1 – roadbed, left side, 0-6” 3,1,2 – roadbed, left side, 6-12” 3,2,1 – roadbed, right side, 0-6” 3,2,2 – roadbed, right side, 6-12”	2.8.2
RDSTYPS(3,2)	6*0	Code	Integer	Road soil types 1 – left side 2 – right side	2.8.2
S(1) S(2) S(3) S(4) S(5) S(6) S(7) S(8) S(9)	9*3936.0	Inches	Double	Stem spacing, each class S(1) = 0.49 S(2) = 1.67 S(3) = 3.15 S(4) = 4.73 S(5) = 6.30 S(6) = 7.88 S(7) = 9.25 S(8) = 12.42 S(9) = 99.0	2.8.2

SD(1) SD(2) SD(3) SD(4) SD(5) SD(6) SD(7) SD(8) SD(9)	0.49,1.67,3.15,4.73,6.30,7.88,9.25,12.42,99.0	Inches	Double	Stem average diameters SD(1) = 0.49 SD(2) = 1.67 SD(3) = 3.15 SD(4) = 4.73 SD(5) = 6.30 SD(6) = 7.88 SD(7) = 9.25 SD(8) = 12.42 SD(9) = 99.0	2.8.2
SDL(1) SDL(2) SDL(3) SDL(4) SDL(5) SDL(6) SDL(7) SDL(8) SDL(9)	0.98,2.36,3.94,5.51,7.09,8.66,9.84,15.0,99.0	Inches	Double	Stem maximum diameters SDL(1) = 0.98 SDL(2) = 2.36 SDL(3) = 3.94 SDL(4) = 5.51 SDL(5) = 7.09 SDL(6) = 8.66 SDL(7) = 9.84 SDL(8) = 15.0 SDL(9) = 99.0	2.8.2
SIGMA	0.1	g/cm^3	Double	Snow density	2.8.2
SNOMCH	Scenario = .false.	Code	Boolean	Snow inferencing	2.8.2
TMOIST	0.0	Percent	Double	Thawing soil moisture content	2.8.2
TSPDMAX(1) TSPDMAX(2)	2*1760.0	In/sec	Double	Restricted clearance speeds 1 – bridge/tunnel/roadway speed limit 2 – VHGTMAX interference speed limit	2.8.2
TUID	BEST UNIT	Text		Terrain unit id.	2.8.2
TWIDMIN	0.0	Inches	Double	Roadway minimum width	2.8.2
WD	0.0	inches	Double	Depth standing water	2.8.2
WLANES(NLANES)	NLANES*0.0	inches	Double	Road lane widths	2.8.2
ENG_C	0.0	psi	Double	Cohesion	3.0
ENG_G	0.0	psi	Double	Elastic shear modulus	3.0
ENG_GAMMA	0.0	lb/ft^3	Double	Total unit weight	3.0
ENG_PHI	0.0	degrees	Double	Friction angle	3.0
EXTFRICT	0.0	degrees	Double	External friction angle	3.0
CPRIS	0.0	psi	Double	Soil prism cohesion	3.0
DELTAPRIS	0.0	degrees	Double	Soil prism external friction angle	3.0
GAMMAPRIS	0.0	lb/ft^3	Double	Soil prism unit weight	3.0
PHIPRIS	0.0	degrees	Double	Soil prism friction angle	3.0

TEMP	295.4	Degrees (K)	Double	Soil temperature in degrees Kelvin	NG
ASPECT	-1 (flat surface)	Degrees	Double	Direction in degrees of surface normal vector -1.0 – 360.0.	NG
SSL			Double	First significant strength layer depth	NG
SSL2			Double	Second significant strength layer depth	NG
KUSCS2	5	Code	Integer	KUSCS associated with SSL2	NG
TMOIST2	0.0	Percent	Double	TMOIST associated with SSL2	NG
TEMP2	295.4	Degrees (K)	Double	TEMP associated with SSL2	NG
BULKDNS	0	g/cm^3	Double	Values measuring soil bulk density.	NG

[1] - The "Earliest NRMM Version" column lists the legacy NRMM software version, starting with 2.8.2, that the field is supported. So 2.8.2 is supported on 2.8.2 and possibly 3.0, while 3.0 is supported on 3.0, but not NG-NRMM (NG). NG-NRMM is not supported on 2.8.2 or 3.0.

8. Field Header. The row after the File Header Metadata, which is the first row without a "!" starting character, is the file header row. This is a space delimited list of the fields (columns) to follow in the data section. Each of the field names in the Field Header Metadata section is in this list. The order of the fields is the order of the data columns to follow.

<field_1> <field_2> <field_3> <field_4> <field_5> … <field_n>

Example:

NTU ASPECT BULKDNS CI(1) CI(2) DBROCK GRADE IOST IROAD ISCOND KUSCS KWI NLANES OBH OBL TMOIST USCS ELEV LUSE

9. Data Section: The subsequent rows in the file store the actual data values, separated by spaces. The number of data rows is the number of NTUs listed in the First Record. The order of the values is the same as the order of fields in the File Header. Because of the nature of the delimiting character the data values will NEVER contain a space as this would cause a shift in field values and corrupt data values.

<row_1_field_1> <row_1_field_2> <row_1_field_3> <row_1_field_4> … <row_1_field_n>

<row_2_field_1> <row_2_field_2> <row_2_field_3> <row_2_field_4> … <row_2_field_n>

<row_3_field_1> <row_3_field_2> <row_3_field_3> <row_3_field_4> … <row_3_field_n>

<row_4_field_1> <row_4_field_2> <row_4_field_3> <row_4_field_4> … <row_4_field_n>

…

<row_m_field_1> <row_m_field_2> <row_m_field_3> <row_m_field_4> … <row_m_field_n>

Example:

1 0.0 0.1 0.0 0.0 201.0 9.0 0 0 1 20 2 0 0.0 0.0 12.0 PT 329.336222 0

2 0.0 0.1 0.0 0.0 201.0 12.0 0 0 1 20 2 0 0.0 0.0 12.0 PT 329.031422 0

3 0.0 0.1 0.0 0.0 201.0 12.0 0 0 1 20 2 0 0.0 0.0 12.0 PT 328.879022 0

4 360.0 0.1 0.0 0.0 201.0 12.0 0 0 1 20 2 0 0.0 0.0 12.0 PT 328.802822 0

5 0.0 0.1 0.0 0.0 201.0 12.0 0 0 1 20 2 0 0.0 0.0 12.0 PT 328.802822 0

6 360.0 0.1 0.0 0.0 201.0 9.0 0 0 1 20 2 0 0.0 0.0 12.0 PT 328.879022 0

A.2. UML DATA MODEL

Geospatial data developers should use the following data model when developing input terrain data sets for NG-NRMM applications.

A.2.1. UML Data Model - Feature Types

1. This section describes a data model for NG-NRMM as a basis for the storage and the exchange of data on terrain and soil. The data model is described in UML-Syntax and uses the ISO 19136 (2020) standard of TC 211. It is at first instance an exact translation of the properties and items that are defined in Annex A.1 for the modified Code 11 MAPTBL terrain data input format, which was then modified to adapt the structure to recent demands.

2. As shown in the MAPTBL data of ANNEX A.1, Numbered Terrain Units (NTUs) have a variety of features and properties that can be fit into a data model. Organizing these into feature types and attributes will result in a data model that enables broader use of various data sources and data as a service. Below is an example of one possible data model implementation.

3. The properties of NG-NRMM can be split into static and dynamic properties and thus described by two feature types to make independent changes on each of them feasible. The data model in essence consists of these two feature types, as well as two feature types for describing the information of the header and the field header metadata in case they are required for the sake of interoperability. Two additional feature types were included to enable the exchange of data on uncertainty by services. One is for the uncertainty of elevation that may be handled independently from other parts of the data and the other for correlation described by copula. Copula may be linked to values of static or dynamic properties.

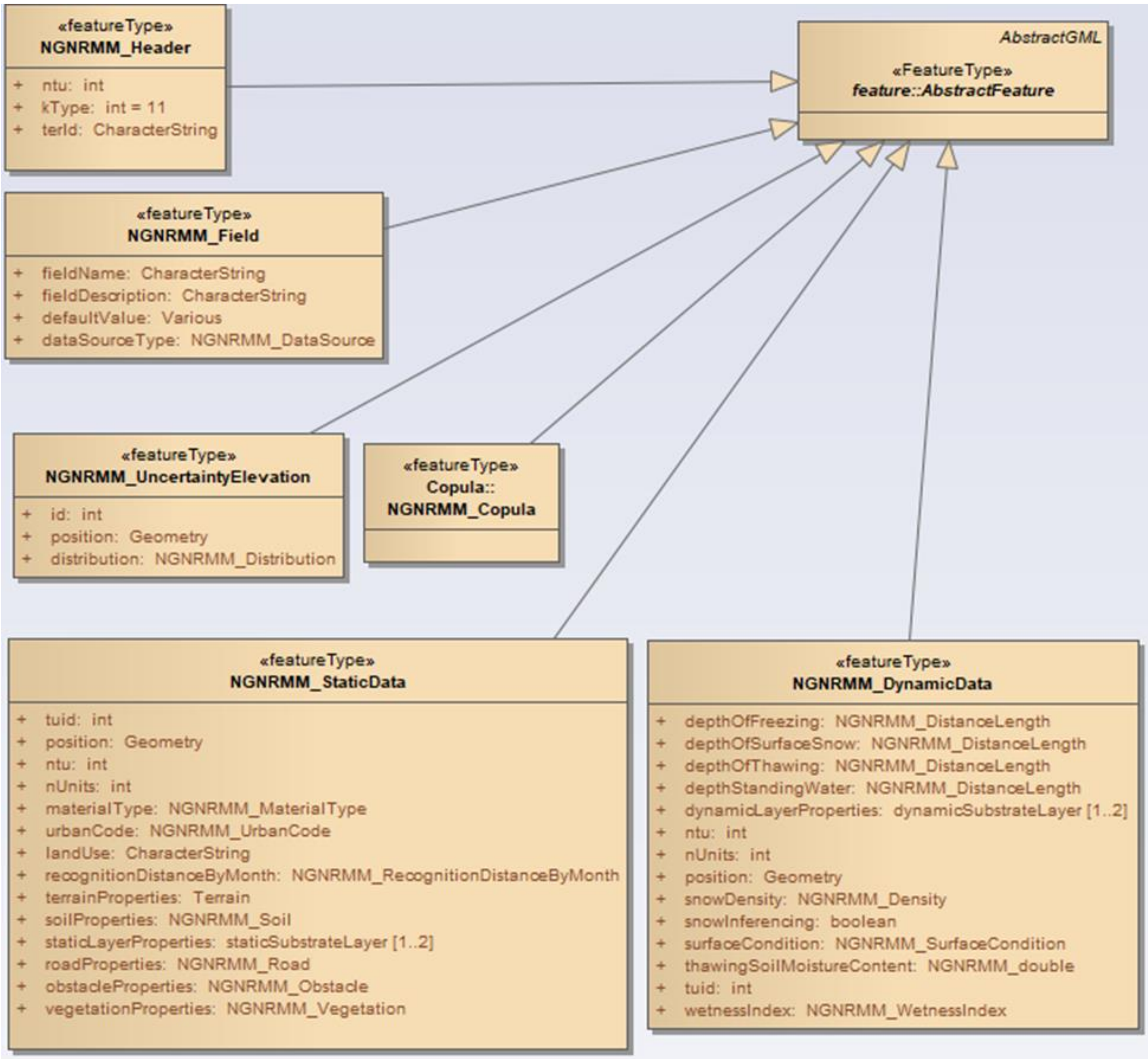

Figure A.1: Feature Types of the NG-NRMM Data Model Derived from the GML Type AbstractFeature.

4. The feature types of the NG-NRMM data model inherit a standardized set of further attributes from the feature type *AbstractFeature* of the OGC-GML/ISO 19136 (2020) standard, which is necessary for the standardized exchange of data according to the Web Feature Service (2020) standard of OGC.

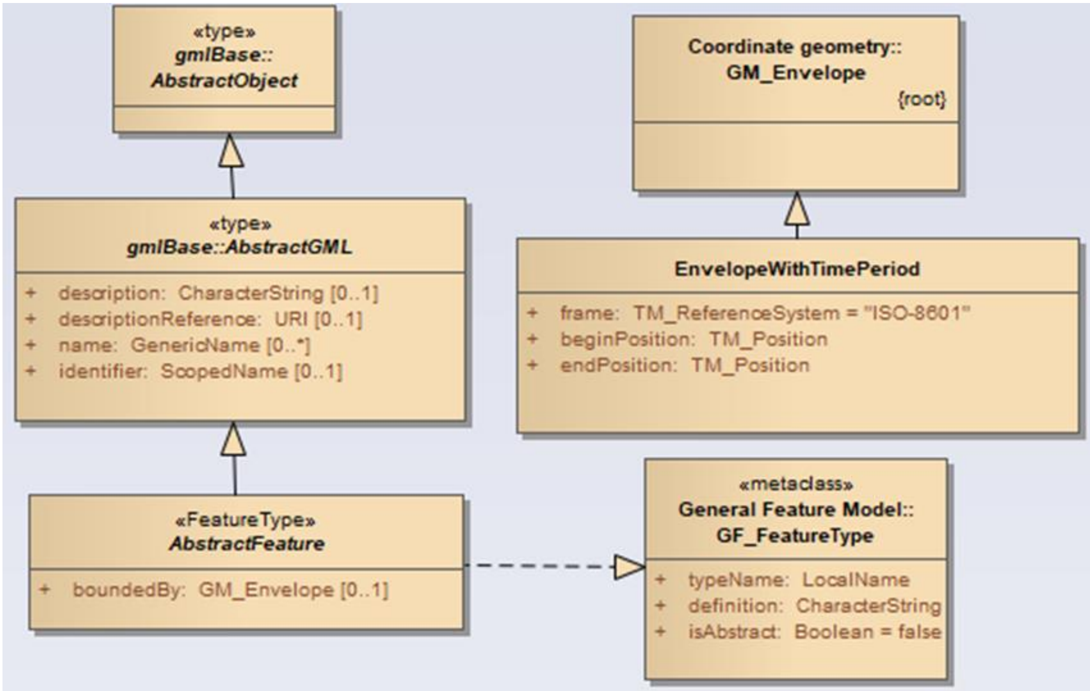

Figure A.2 : Excerpt of OGC-GML/ISO 19136 (2020) Standard Showing Substantial Attributes of the GML Type AbstractFeature.

A.2.2. UML Data Model – Data Types

1. The properties of the NTUs are described by the attributes of the feature type. There are three kinds of attributes used in the NG-NRMM data model. The first are direct attributes that are of a basic type such as int, double, boolean or string. The second are enumerations, which are used for properties that have a fixed range of possible values. The third kind are attributes that are of a complex data type.

2. Complex data types define not a single value but a structure that itself may consist of several attributes. They are used to organize the data model hierarchically by aggregating properties of the same topic like terrain, soil, roads, obstacles or vegetation. Furthermore the use of complex data types is reasonable if a set of attributes is employed multiple times. For instance the data type “NGNRMM_staticSubstrateLayer” may be populated multiple times in a data set for each layer of soil. The complex data types of the attributes of the feature types shown in Figure A.1 are shown in more detail in the following figures.

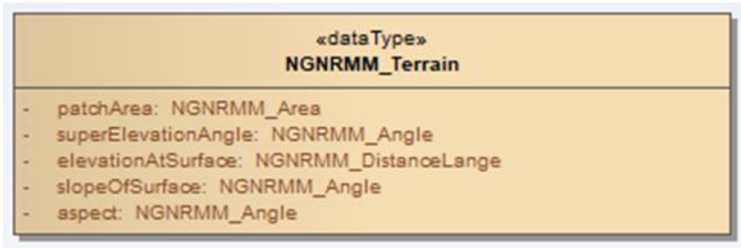

Figure A.3: Complex Data Type NGNRMM_Terrain.

3. Data on terrain may also be exchanged in the form of raster data. In this case the data type “NGNRMM_Terrain” is not required and probably not populated in the data set.

Figure A.4: Complex Data Types Used by the Features Types Directly.

4. Some of the attributes of the complex data types in Figure A.4 are of a basic type or are enumerations. But some, in turn, are of a complex data type themselves. These next level complex data types are shown in Figure A.5. This way a hierarchy of data types organizes the properties of the NTUs into a tree-like structure. This structure is not shown graphically in UML notation, but by relating the name of the type of an attribute and the name of the corresponding complex data type.

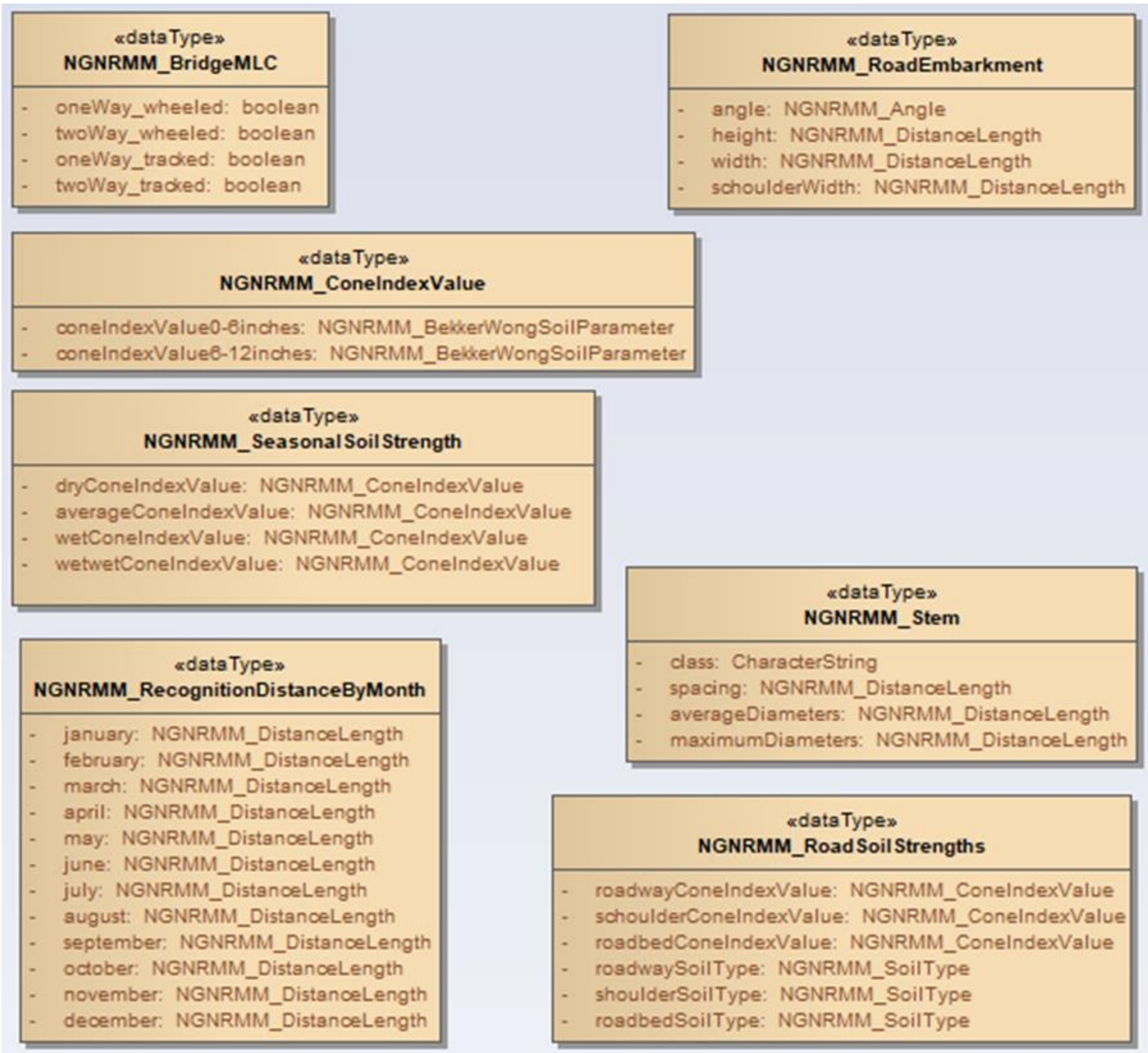

Figure A.5: Lower Level Data Types Used by the Complex Data Types Shown in Figure A.4.

A.2.3. UML Data Model – Enumerations

Enumerations are suitable for properties that have a fixed range of possible values. The enumerations used by the above feature types and data types are shown in Figure A.6.

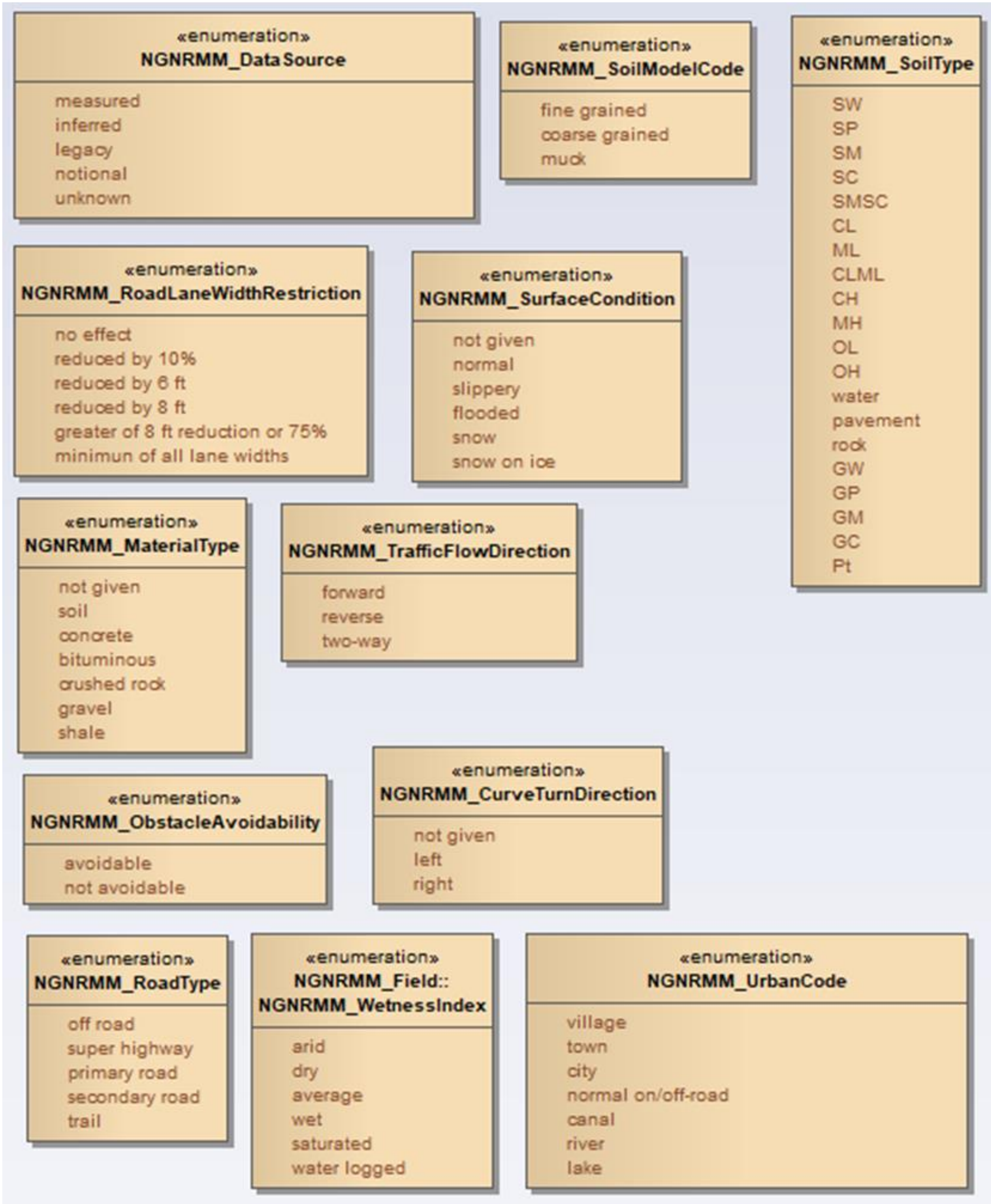

Figure A.6: Enumerations of the NG-NRMM Data Model.

A.2.4. Naming Conventions

1. The names of feature types, data types and enumerations use the prefix NGNRMM. This indicates that these types belong to the NGNRMM data model, in case applications make use of several different data models.

2. The NTU attribute names in camel case notation are obtained from the description of the corresponding items of the modified Code 11 MAPTBL terrain data input format. The item description rather than the item name is used to increase readability.

A.2.5. Uncertainty

1. For values of numerical type, information about uncertainty can be handled by the NGRNMM data model. The following relates to Figure A.7. To describe uncertainty a special data type, *NGNRMM_Doub*le, is employed. This data type consists of two attributes. The first, named *value*, is of type *double* and contains the value itself. The second attribute holds information about a distribution describing the deviation of the value. Additionally, a reference to a feature that describes the correlation by use of a copula may be set. In a populated data set the information on uncertainty is not mandatory, hence the possible cardinality of 0. Thus, a value may be populated without any uncertainties.

2. Several data types for all sorts of quantities are derived from the data type *NGNRMM_Doub*le, e.g., NGNRMM_DistanceLength, and thus inherit all the properties concerning uncertainty. Each of these derived data types consist of one attribute *unit* that denotes the unit of the value. There are different data types for different quantities so that each of them may have an individual enumeration of possible units of measure. The intention is that one may choose the unit according to the measurement taken for a certain value without the need of immediate transformation, which may otherwise be a source of error. However it is recommended to use SI units whenever possible.

3. The deviation of a value can be described by a distribution. Accordingly, the attribute *uncertainty* of the data type *NGNRMM_Double* is of type *NGNRMM_Distribution*. Figure A.8 shows that *NGNRMM_Distribution* is of a special union type. This means that only one of its attributes can be used at a time. It is either a normal distribution, a Weibull distribution or any of the many others shown in Figure A.8.

4. For each of these distributions there is a data type that defines the distribution's corresponding attributes. For a normal distribution this is simply the standard deviation. For Weibull and Gamma distributions, it is the shape and the scale and so forth. All *NGNRMM_Distribution* data types have a *standardDeviation* attribute in addition to the distribution shape, scale, and other parameter attributes. For distributions that have more than one mathematical definition, e.g., that defines the distribution, the standard deviation value can be used to determine which mathematical definition the parameter values correspond to.

5. Instances of the data type *NGNRMM_Double* may have a link to a feature of type *NGNRMM_Copula*. Its structure is shown in Figure A.9. Several individual copulas are derived from the main feature type for the sake of inheriting the reference to *NGNRMM_Double*. All copulas have an attribute named *tau*. The reason why there are individual copulas, though they all have the same parameter *tau,* lies in the different types of correlation and constraints on the range of the *tau* parameter.

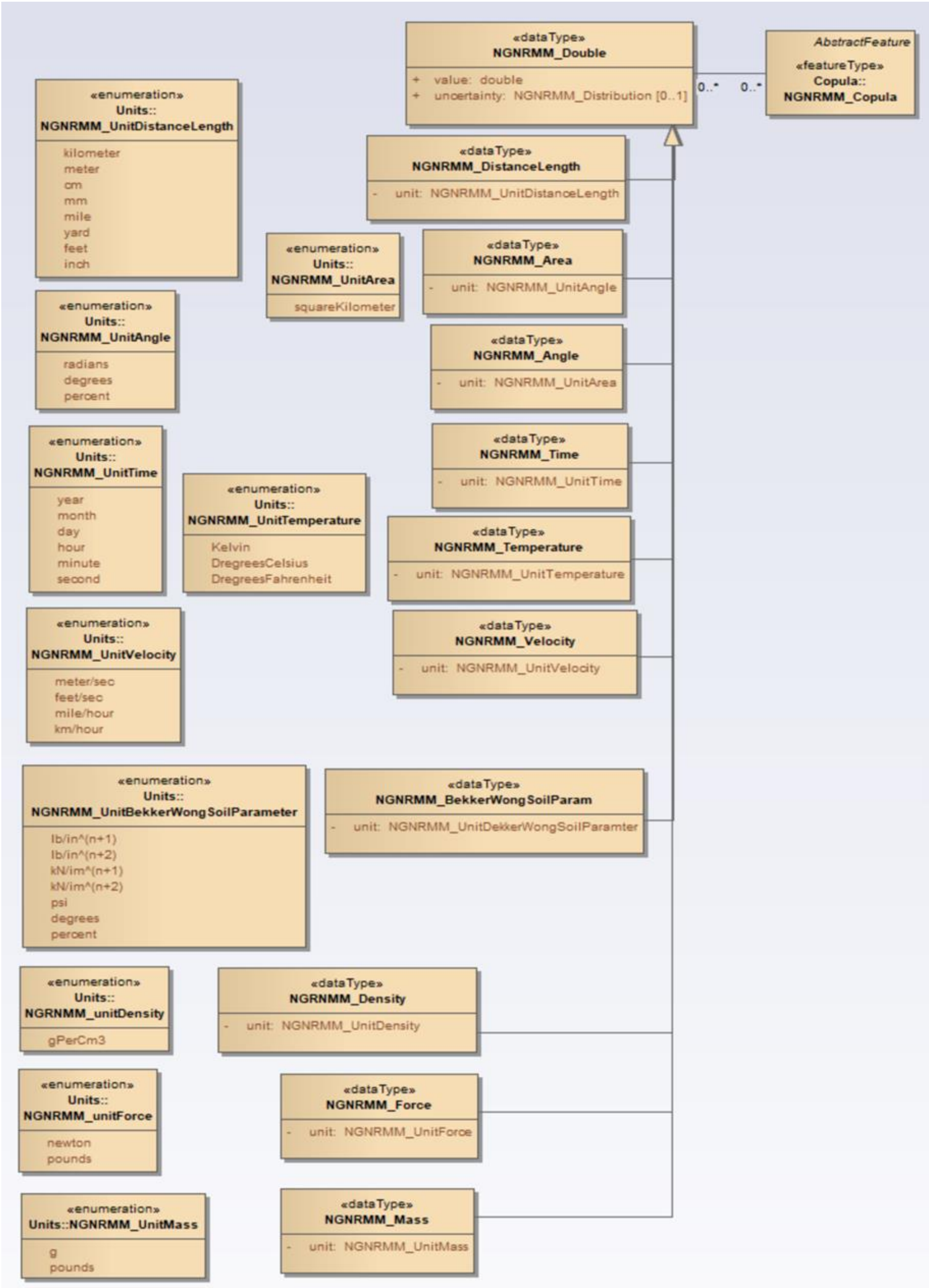

Figure A.7: Data Types of Double Values each with an Enumeration of Possible Values Derived from Abstract Data Type NGNRMM_Double to Incorporate Uncertainty.

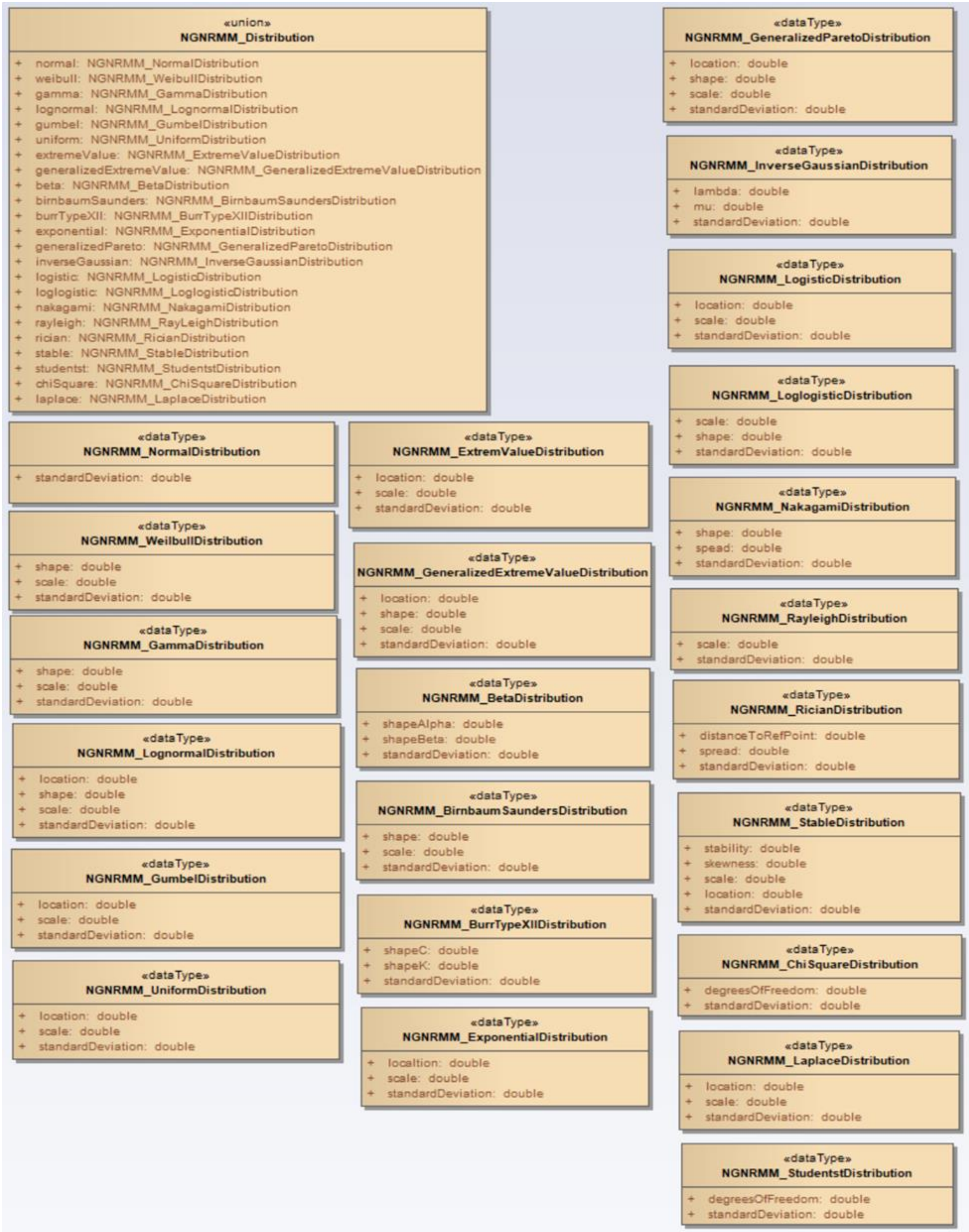

Figure A.8: Distributions for Describing Uncertainty.

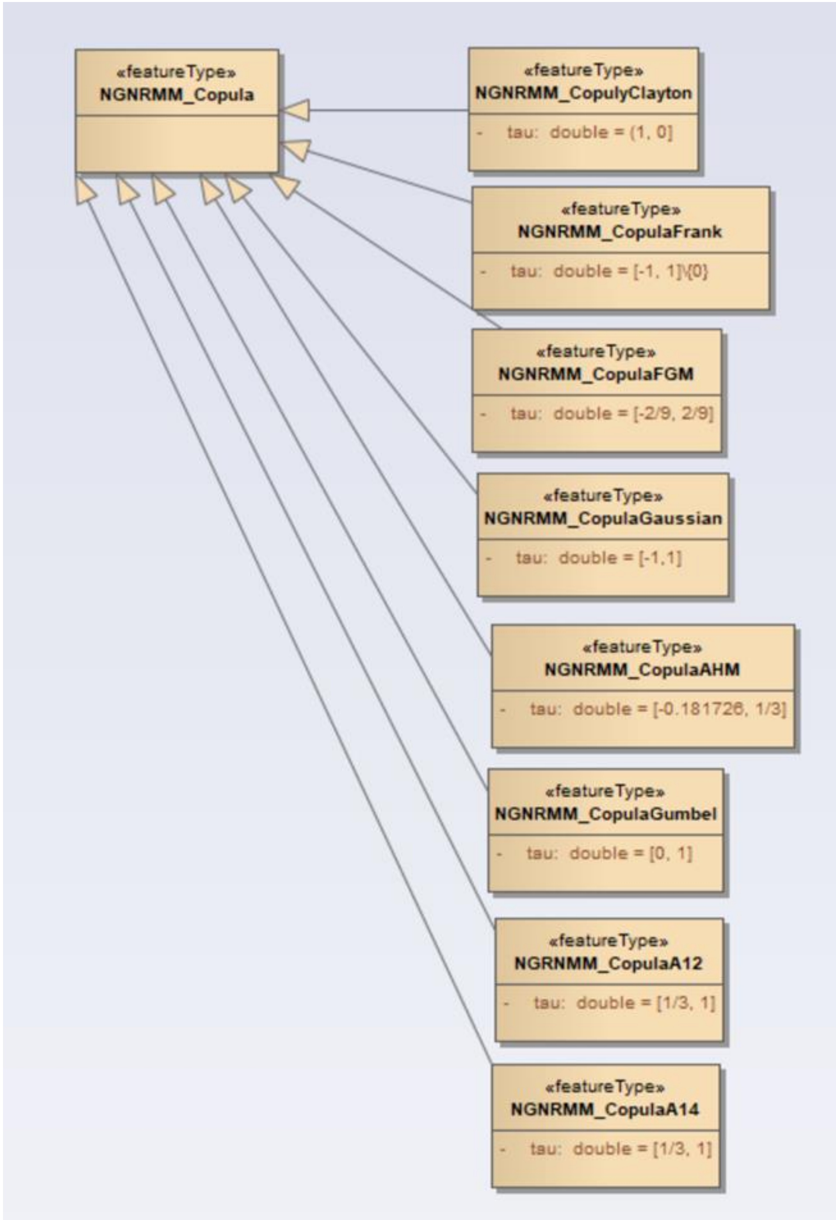

Figure A.9: Copulas for Describing Correlation.

A.2.6. Spatial Reference

1. The NGNRMM data model provides different options for spatial reference of the NTUs. One of them is the attribute *position*, that both feature types of the NTUs provide. This attribute can either be of the type *GM_PointRef* or *GM_PolyhedralSurface*. The first option corresponds to the modified Code 11 MAPTBL terrain data input format where NTUs are each located at a point of a raster. The opportunity to have spatial reference through a surface instead is provided as well, for purposes of usability.

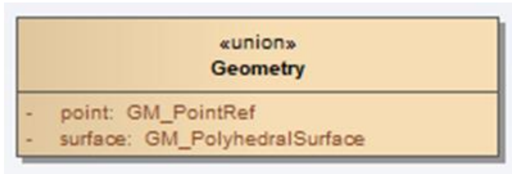

Figure A.10: Union of *GM_PointRef* and *GM_PolyhedralSurface.*

2. Both *GM_PointRef* and *GM_PolyhedralSurface* are part of the GML data model (ISO 19136, 2020).

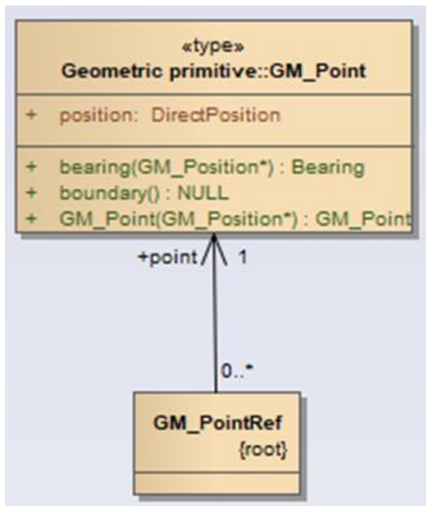

Figure A.11: Excerpt of OGC-GML/ISO 19136 (2020) Standard Showing the Definition of *GM_Pointref.*

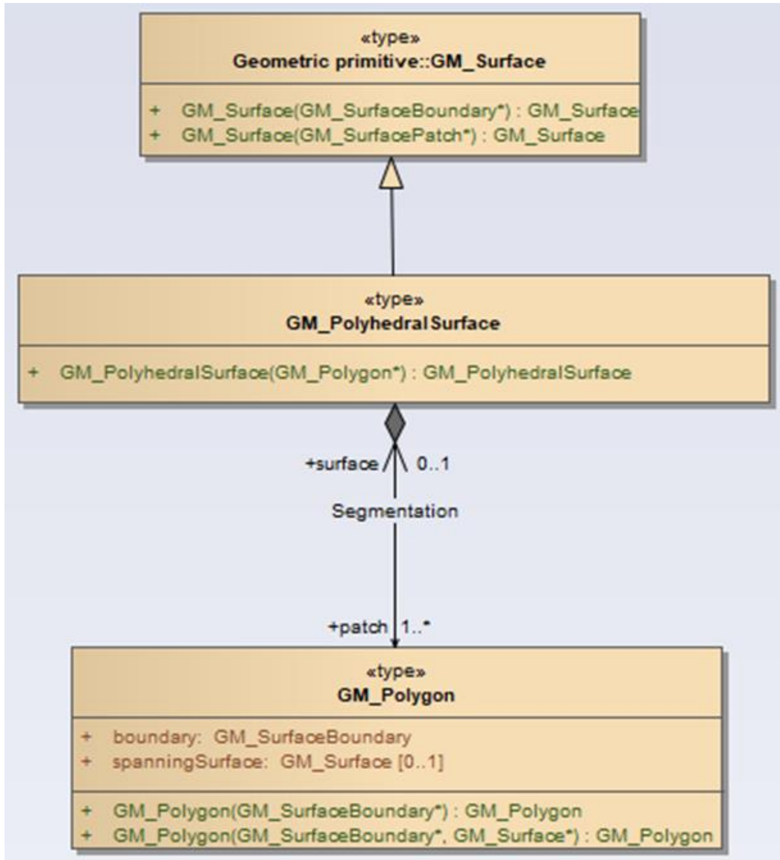

Figure A.12: Excerpt of OGC-GML/ISO 19136 (2020) Standard Showing the Definition of *GM_PolyhedralSurface.*

3. Another option for spatial referencing would be the use of a georeferenced raster data set. This can be provided by a Web Coverage Service (2020) for example. In this case each point of the raster data is linked to the *Terrain Unit ID* (*tuid*) of an NTU, which allows the corresponding NTUs to be resolved.

A.2.7. Elevation Data

1. The NGNRMM data model delivers a data type *NGNRMM_Terrain*. This data type aggregates all properties of modified Code 11 MAPTBL terrain data input format dealing with terrain. Its main use is to provide a structure for the conversion of data into modified Code 11 MAPTBL file from a populated NG-NRMM data set.

2. Instead of using this structured terrain data it could also be provided as a separate raster data set of elevation data by use of a WCS.

A.2.8. Uncertainty of Elevation Data

1. Uncertainty of elevation data is handled by a special feature type named *NGNRMM_UncertaintyElevation*. It consists of three attributes.

a. *id*: This is for the case that spatial reference is provided by a raster data set that may have the same resolution as the raster data set with the elevation data itself.
b. *position*: This is a second option for spatial reference by use of a polygon area.
c. *distribution*: Describes the kind of distribution and the quantity of uncertainty.

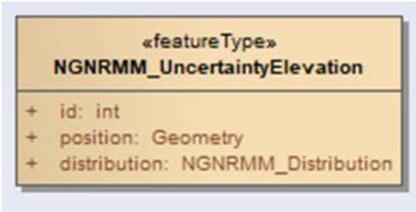

Figure A.13: Feature Type for the Description of Uncertainty of Elevation.

A.3. REFERENCES

1. ASC ASCII Raster Format (http://resources.esri.com/help/9.3/arcgisdesktop/com/gp_toolref/spatial_analyst_tools/esri_ascii_raster_format.htm) Accessed 12/19/2017

2. How Slope Works (http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-slope-works.htm) Accessed 7/31/2017

3. How Aspect Works (http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-aspect-works.htm) Accessed 7/31/2017

4. ISO 19136-1. 2020. Geographic Information - Geography Markup Language (GML).

5. Unified Modeling Language. 2020. In Wikipedia, The Free Encyclopedia. Retrieved 27.03.2020. from https://de.wikipedia.org/wiki/Unified_Modeling_Language.

6. Web Feature Service (WFS). 2020. http://www.ogc.org/standards/wfs. Retrieved 27.03.2020.

7. Web Coverage Service (WCS). 2020. http://www.ogc.org/standards/wcs. Retrieved 27.03.2020.

ANNEX B DATA SCHEMA

B.1. EXTENDED SCHEMA DEFINITION

1. The schema of the NG-NRMM data model is provided by an Extended Schema Definition (XSD) (2020), which is a W3C standard. The XSD schema definition of NG-NRMM is derived from the UML (2020) data model of NG-NRMM. This section explains the structure of the NG-NRMM-XSD. It does not include the full content of the XSD as this can be gathered from the XSD files themselves.

2. The inclusion of standardized structures of ISO 19136 (2020) into the NG-NRMM-XSD is handled similar to the way the UML data model of NG-NRMM makes use of data types from the standard ISO 19136. The schema definition of NG-NRMM imports schema definition files of W3C and OGC to incorporate the corresponding schema types and elements. These imports are defined in the header section of the NG-NRMM schema file.

```
<?xml version="1.0" encoding="UTF-8"?>
<schema xmlns=http://www.w3.org/2001/XMLSchema
            xmlns:gml=http://www.opengis.net/gml/3.2
            xmlns:xlink="http://www.w3.org/1999/xlink"
           .xmlns:ngnrmm="http://www.sto.nato.AVT-327.ngnrmm_namespace"
            xmlns:wfs="http://www.opengis.net/wfs/2.0"
            targetNamespace="http://www.sto.nato.AVT-327.ngnrmm_namespace"
            elementFormDefault="qualified">
<!— The URLs above do not relate to active web sites
<import namespace="http://www.opengis.net/gml/3.2" schemaLocation="opengis/gml/3.2.1/feature.xsd"/>
<import namespace="http://www.opengis.net/wfs/2.0" schemaLocation="opengis/wfs/2.0/wfs.xsd"/>
```

3. The data structure of the schema is described by use of XML-elements, XML-simple types and XML-complex types. There is one XML-element each for a feature type of the UML data model.

```
<!-- Elements of metadata of header and fields -->
<element name="NGNRMM_Header" type="ngnrmm:NGNRMM_HeaderType"
            substitutionGroup="gml:AbstractFeature"/>
<element name="NGNRMM_Field" type="ngnrmm:NGNRMM_HeaderType"
            substitutionGroup="gml:AbstractFeature"/>
<!-- Elements of the data model for static properties like soils and land use and more dynamic properties
like moisture and temperature This means two different types of NTUs one for static and one for dynamic
properties -->
<element name="NGNRMM_StaticData" type="ngnrmm:NGNRMM_StaticDataType"
            substitutionGroup="gml:AbstractFeature"/>
<element name="NGNRMM_DynamicData" type="ngnrmm:NGNRMM_DynamicDataType"
            substitutionGroup="gml:AbstractFeature"/>
```

4. The *substitutionGroup gml:AbstractFeature* indicates that the feature types of the UML data model inherit from the class *AbstractFeature*. This way they inherit all the properties that are required to behave like a proper GML-Object and thus be exchangeable by standardized OGC services.

5. The structure and the attributes of the UML data model are denoted by XML-complex types. Here is one example for *NGNRMM_StaticDataType*.

```
<complexType name="NGNRMM_StaticDataType">
  <complexContent>
    <extension base="gml:AbstractFeatureType">
      <sequence>
        <element name="tuid" type="integer" minOccurs="0"/>
        <element name="position" type="gml:GeometryPropertyType" minOccurs="0"/>
        <element name="ntu" type="integer" minOccurs="0"/>
        <element name="nUnits" type="integer" minOccurs="0"/>
        <element name="materialType" type="ngnrmm:NGNRMM_MaterialType" default="not given"
minOccurs="0"/>
        <element name="urbanCode" type="ngnrmm:NGNRMM_UrbanCodeType" default="normal
on/off-road" minOccurs="0"/>
        <element name="landUse" type="string" minOccurs="0"/>
        <element ref="ngnrmm:RecognitionDistanceByMonth" minOccurs="0"/>
        <element ref="ngnrmm:Terrain" minOccurs="0"/>
        <element ref="ngnrmm:Soil" minOccurs="0"/>
        <element ref="ngnrmm:StaticSubtrateLayer" minOccurs="0" maxOccurs="2"/>
        <element ref="ngnrmm:Road" minOccurs="0"/>
        <element ref="ngnrmm:Vegetation" minOccurs="0"/>
        <element ref="ngnrmm:Obstacle" minOccurs="0"/>
      </sequence>
    </extension>
  </complexContent>
</complexType>
```

6. The attributes of the UML data model are denoted by XML-elements. The *extension base gml:AbstractFeatureType* indicates that the complex type inherits additional elements from the complex type *gml:AbstractFeatureType* of the standardized GML schema description. The XML-element *position* is of the type *gml:GeometryPropertyType* that is delivered by GML and included via one of the imported XSDs as well. The type *gml:GeometryPropertyType* provides a standardized structure for geometry.

7. Those attributes of the UML data model that are of a complex data type correspond to XML-elements that have a reference (element ref=) to the corresponding XML-complex type instead of a simple type. In general data types of the UML data model correspond to complex types in XML schema. One example for this is the *NGNRMM_SoilType*. This complex type again has an element *ConeIndexValue* of a complex type *NGNRMM_ConeIndexValueType*.

```
<complexType name="NGNRMM_SoilType">
    <sequence>
        <element name="surfaceRoughnessInches" type="double" default="0" minOccurs="0"/>
        <element name="coneIndexValue" type="ngnrmm:NGNRMM_ConeIndexValueType"
minOccurs="0"/>
        <element name="depthToBedrockInches" type="double" default="99.9" minOccurs="0"/>
        <element name="soilModelCode" type="ngnrmm:NGNRMM_SoilModelCodeType"
minOccurs="0"/>
        <element name="seasonalSoilStrength" type="ngnrmm:NGNRMM_SeasonalSoilStrengthType"
minOccurs="0"/>
        <element name="cohesionPSI" type="double" default="0.0" minOccurs="0"/>
        <element name="elasticShearModulusPSI" type="double" default="0.0" minOccurs="0"/>
        <element name="totalUnitWeightLbPerft3" type="double" default="0.0" minOccurs="0"/>
        <element name="frictionAngleDegrees" type="double" default="0.0" minOccurs="0"/>
        <element name="externalFrictionAngleDegrees" type="double" default="0.0" minOccurs="0"/>
        <element name="soilPrismCohesionPSI" type="double" default="0.0" minOccurs="0"/>
        <element name="soilPrismExternalFrictionAngleDegrees" type="double" default="0.0"
minOccurs="0"/>
        <element name="soilPrismUnitWieghtLbPerFt3" type="double" default="0.0" minOccurs="0"/>
        <element name="soilPrismFrictionAnglleDegrees" type="double" default="0.0" minOccurs="0"/>
    </sequence>
</complexType>
<complexType name="NGNRMM_ConeIndexValueType">
        <sequence>
                <element name="coneIndexValue0-6inchesPSI" type="boolean" minOccurs="0"/>
                <element name="coneIndexValue6-12inchesPSI" type="boolean" minOccurs="0"/>
        </sequence>
</complexType>
```

8. The enumerations of the UML data model correspond to XML-simple types.

```
<simpleType name="NGNRMM_MaterialType">
        <restriction base="string">
                <enumeration value="not given"/>
                <enumeration value="soil"/>
                <enumeration value="concrete"/>
                <enumeration value="bituminouos"/>
                <enumeration value="crushed rock"/>
                <enumeration value="gravel"/>
                <enumeration value="shale"/>
        </restriction>
</simpleType>
```

B.2. XML/GML DATA SET

1. XML is an ASCII file format. It uses tags to provide a certain structure for the data. This structure can be validated against the XSD, which is denoted in the file. In this case

the XSD is based on the XSDs of the GML standard. So a NG-NRMM XML data set has the structure of a GML feature collection. The members of a GML feature collection can be those XML-elements that have *gml:Abstractfeature* as substitution group, which is the case for all relevant features of the NG-NRMM.

Example:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<gml:FeatureCollection gml:id="_ca105e52-d664-4b23-bc23-5126783bc670f"
        xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
        xmlns:gml="http://www.opengis.net/gml/3.2"
        xmlns:ngnrmm="http://www.sto.nato.AVT-327.ngnrmm_namespace"
        xsi:schemaLocation=" http://www.sto.nato.AVT-327.ngnrmm_namespace ng-nrmm.xsd">
        <!-- Example of Static Data-->
        <gml:featureMember>
         <ngnrmm:NGNRMM_StaticData gml:id="_ca105e52-d634-4b23-bc23-5126783bc670f">
          <ngnrmm:tuid>12345</ngnrmm:tuid>
          <ngnrmm:position>
           <gml:Point>
             <gml:pos srsName="urn:ogc:def:crs:EPSG:6.6:4326" srsDimension="2">6.7
49.76</gml:pos>
           </gml:Point>
          </ngnrmm:position>
          <!-- FACC+ MGCP -->
          <ngnrmm:landUse>EA010</ngnrmm:landUse> <!-- would mean agriculture -->
          <ngnrmm:StaticSubstrateLayer>
           <ngnrmm:soilTypeUSCS>Pt</ngnrmm:soilTypeUSCS> <!-- peat -->
           <ngnrmm:bulkDensityGperCm3>2000</ngnrmm:bulkDensityGperCm3>
           <ngnrmm:layerDepth>6</ngnrmm:layerDepth> <!-- inches -->
          </ngnrmm:StaticSubstrateLayer>
          <ngnrmm:StaticSubstrateLayer>
           <ngnrmm:soilTypeUSCS>Pt</ngnrmm:soilTypeUSCS> <!-- peat -->
           <ngnrmm:bulkDensityGperCm3>2200</ngnrmm:bulkDensityGperCm3>
           <ngnrmm:layerDepth>6</ngnrmm:layerDepth> <!-- inches -->
          </ngnrmm:StaticSubstrateLayer>
         </ngnrmm:NGNRMM_StaticData>
        </gml:featureMember>
        <gml:featureMember>
         <ngnrmm:NGNRMM_DynamicData gml:id="_ca105e52-d634-4b43-bc23-5126783bc670f">
          <ngnrmm:tuid>12345</ngnrmm:tuid>
          <ngnrmm:position>
           <gml:Point>
            <gml:pos srsName="urn:ogc:def:crs:EPSG:6.6:4326" srsDimension="2">6.7
49.76</gml:pos>
           </gml:Point>
          </ngnrmm:position>
          <ngnrmm:DynamicSubtrateLayer>
           <ngnrmm:moistureContentPercent>50</ngnrmm:moistureContentPercent>
           <ngnrmm:temperatureKelvin>298</ngnrmm:temperatureKelvin>
          </ngnrmm:DynamicSubtrateLayer>
          <ngnrmm:DynamicSubtrateLayer>
```

```
            <ngnrmm:moistureContentPercent>48</ngnrmm:moistureContentPercent>
            <ngnrmm:temperatureKelvin>296</ngnrmm:temperatureKelvin>
          </ngnrmm:DynamicSubtrateLayer>
        </ngnrmm:NGNRMM_DynamicData>
      </gml:featureMember>
</gml:FeatureCollection>
```


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ANNEX C EXAMPLE INFERENCE METHOD FOR SOIL MOISTURE AND STRENGTH

C.1. SOIL MOISTURE ESTIMATION OVERVIEW

1. A research team associated with NATO AVT-248[1] has developed (and is continuing to develop) an Equilibrium Moisture from Topography, Vegetation and Soil (EMT+VS) model for application to NG-NRMM soil moisture estimation. This model downscales remotely-sensed or modelled coarse resolution (5 – 40 km) soil moisture to tactical resolutions (< 100 metres) based primarily on topographic and vegetation cover information (Ranney et al., 2015). Coarse soil moisture and topographic (e.g. terrain elevation) information are required EMT+VS inputs while fine-resolution vegetation (Soil Adjusted Vegetation Index – SAVI) and soil type information can also be input, if available.

2. Unlike conventional hydrologic models, the EMT+VS model does not iterate through time, so it requires no initial or historical conditions and it can be applied rapidly to large regions (e.g., 150 km by 150 km regions in 3-4 minutes). It also can be applied to any selected date or even hypothetical moisture conditions. The parameters it requires can be estimated from global data sets, which means that it is applicable to data-limited environments. Yet it can accept additional data if such data is abundant.

3. The EMT+VS model calculates soil moisture using a mathematical structure that is similar to earlier approaches (Busch et al., 2012; Werbylo et al., 2014) but the equations are built on conceptual descriptions of vadose zone[2] hydrology. The model estimates soil moisture by considering the water balance in the soil layer for the land area *A* that drains through the edge of a fine-resolution grid cell. Four processes (see Figure C.1) can add or remove water from that layer: infiltration, deep drainage, lateral flow, and evapotranspiration or ET:

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[1] Drs. Jeffrey Niemann, Andy Jones and Joseph Scalia of Colorado State University (CSU) along with Mssrs. Mark Cammarere and Keith Gemeinhart of Technology Service Corp (TSC).

[2] The **vadose** zone, also termed the **unsaturated** zone, is the part of Earth between the land surface and the top of the phreatic zone, the position at which the groundwater (the water in the soil's pores) is at atmospheric pressure.

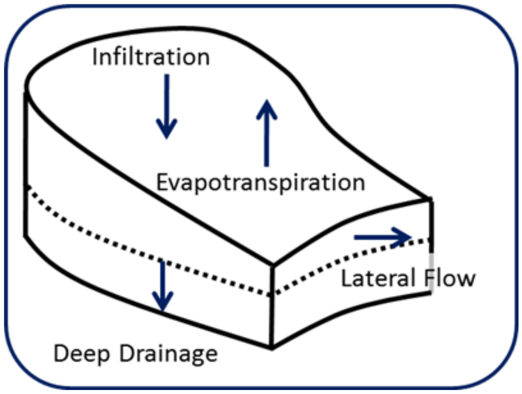

Figure C.1: Four Hydrologic Processes Considered in EMT+VS Model.

a. **Infiltration *F*** is described using a simple approach that accounts for orographic effects on precipitation and interception of precipitated water by vegetation. Orographic precipitation is described using the elevation, slope, and topographic aspect when the topography is represented at intermediate (~7 km) resolution. This intermediate resolution has been shown to exhibit the strongest relationship between topographic attributes and precipitation patterns (Daly et al., 1994; Cowley et al., 2016).

b. **Deep drainage *G*** describes the loss of water to deeper soil layers or groundwater. It is described using Darcy's Law under the assumption that gravity controls the vertical hydraulic gradient (i.e., using a percolation assumption). Unsaturated hydraulic conductivity is described using the Campbell equation (Campbell, 1974).

c. **Lateral flow *L*** describes the movement of water to lower locations on a hillslope. Lateral flow is also described using Darcy's Law under the assumption that the lateral hydraulic gradient is a function of the topographic slope. The thickness of the soil layer is modelled as a function of topographic curvature (Heimsath et al., 1999).

d. **Evapotranspiration *ET*** model begins with a supplied spatial-average value or coarse grid of potential ET values. The local potential ET is then calculated by inferring spatial variations in temperature from the local elevation. This approach was compared to a full Penman-Monteith estimation method and found to produce very similar results (Cowley et al., 2016). The local potential ET is then partitioned into a potential evaporation and a potential transpiration using the fractional vegetation cover *V*. The fractional vegetation cover is also used to reduce soil evaporation in response to shading of the soil. The ET is then partitioned into a radiation ET term and an aerodynamic ET term using the Priestley-Taylor assumption (Priestley and Taylor, 1972). Spatial variations in insolation are described using the Potential Solar Radiation Index (PSRI), which depends primarily on the topographic slope and aspect along with the latitude (Dingman, 2002).

4. A summary of the model is provided below, but a detailed description and evaluation of the model are published in the scientific literature (Coleman and Niemann, 2013; Ranney et al., 2015; Alburn et al., 2015; Cowley, et al., 2017; Hoehn et al., 2017).

Using the equations for *F*, *G*, *L* and *ET* to describe the hydrologic processes, the soil moisture is determined using a novel solution strategy (Coleman and Niemann, 2013).

The strategy calculates the local (or fine-resolution) soil moisture θ as a function of the spatial-average soil moisture $\bar{\theta}$. The spatial-average soil moisture $\bar{\theta}$ can be provided as a single value or a coarse resolution grid of values (e.g., from a land-surface model like Noh et al. (2008) or a remote-sensing product like SMAP (Entekhabi et al., 2010). A series of exact analytical solutions are obtained for soil moisture under the assumption that each of the outflow terms in the water balance dominates. Once these analytical solutions are found, the final soil moisture is determined by a weighted average of the analytical solutions, where the weights are the magnitudes of the outflow terms in the water balance. The final soil moisture estimate is:

$$\theta = \frac{w_G \theta_G + w_L \theta_L + w_R \theta_R + w_A \theta_A}{w_G + w_L + w_R + w_A}, \quad \text{(C-1)}$$

where θ_G, θ_L, θ_R, and θ_A are the analytical soil moisture estimates if deep drainage, lateral flow, radiation ET, and aerodynamic ET dominate, respectively. The weights w_G, w_L, w_R, and w_A control the importance of θ_G, θ_L, θ_R, and θ_A to the final estimate of θ.

The soil moisture when deep drainage dominates is:

$$\theta_G = \bar{\theta} \frac{\mathrm{DDI}}{\overline{\mathrm{DDI}}}, \quad \text{(C-2)}$$

where DDI is the deep drainage index, and $\overline{\mathrm{DDI}}$ is the spatial-average of the DDI. The DDI is a spatial pattern that primarily depends on the fractional vegetation cover *V*. The DDI is one way that the model introduces fine-resolution variations in the soil moisture pattern. The soil moisture when lateral flow dominates is:

$$\theta_L = \bar{\theta} \frac{\mathrm{LFI}}{\overline{\mathrm{LFI}}}, \quad \text{(C-3)}$$

where LFI is the lateral flow index and $\overline{\mathrm{LFI}}$ is the spatial-average of the lateral flow index. The LFI is a spatial pattern that depends both on the fractional vegetation cover V and on topographic attributes (drainage area A, slope S, and curvature κ). The LFI also can introduce fine-resolution variations in soil moisture. The soil moisture when the radiation ET term dominates is:

$$\theta_R = \bar{\theta} \frac{\mathrm{REI}}{\overline{\mathrm{REI}}}, \quad \text{(C-4)}$$

where REI is the radiation ET index and $\overline{\mathrm{REI}}$ is the spatial-average of the REI. The REI is a spatial pattern that depends primarily on the elevation Z, PSRI Ip, and vegetation cover V. The soil moisture when the aerodynamic ET term dominates is:

$$\theta_A = \bar{\theta} \frac{\mathrm{AEI}}{\overline{\mathrm{AEI}}}, \quad \text{(C-5)}$$

where AEI is the aerodynamic ET index and $\overline{\mathrm{AEI}}$ is the spatial-average of the AEI. The AEI is a final spatial pattern that depends primarily on the elevation Z and vegetation cover V. The contributions of θG, θL, θR, and θA to the weighted average are calculated from:

$$w_G = \left(\frac{\bar{\theta}}{\text{DDI}}\right)^{\gamma_v} \quad \text{(C-6)}$$

$$w_L = \left(\frac{\bar{\theta}}{\text{LFI}}\right)^{\gamma_h} \quad \text{(C-7)}$$

$$w_R = \left(\frac{\bar{\theta}}{\text{REI}}\right)^{\beta_r} \quad \text{(C-8)}$$

$$w_A = \left(\frac{\bar{\theta}}{\text{AEI}}\right)^{\beta_a} \quad \text{(C-9)}$$

5. These weights vary in time because $\bar{\theta}$ is expected to vary in time (see Figure C.2). As $\bar{\theta}$ changes, the weights emphasize different spatial patterns, which produces soil moisture patterns with different spatial structures. The ability of the EMT+VS model to produce temporally unstable patterns is important because some soil moisture patterns exhibit this behavior (Western et al., 1999) but most estimation and downscaling methods do not. Figure C.3 shows a sample EMT+VS output for the Monterey Bay sample data set area in California that was stood up by the GIS Terrain and Mobility Map team for AVT-248 (Dasch and Jayakumar, 2020). This sample result used a USGS 30 m Digital Elevation Model (DEM) with coarse soil moisture estimates from SMAP (~9 km resolution) and SAVI information derived from 30 m LandSat data. Soil type information was not included as an EMT+VS input.

6. In addition to the spatial average soil moisture estimation model described above, the research team is also currently updating the model to produce estimates of soil moisture uncertainty.

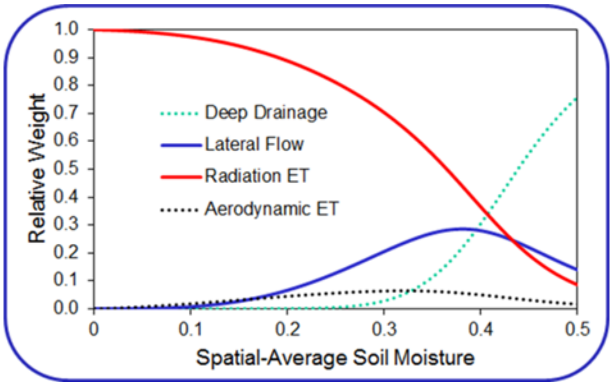

Figure C.2: Relative Importance of the Four Hydrologic Processes with Spatial-Average Soil Moisture.

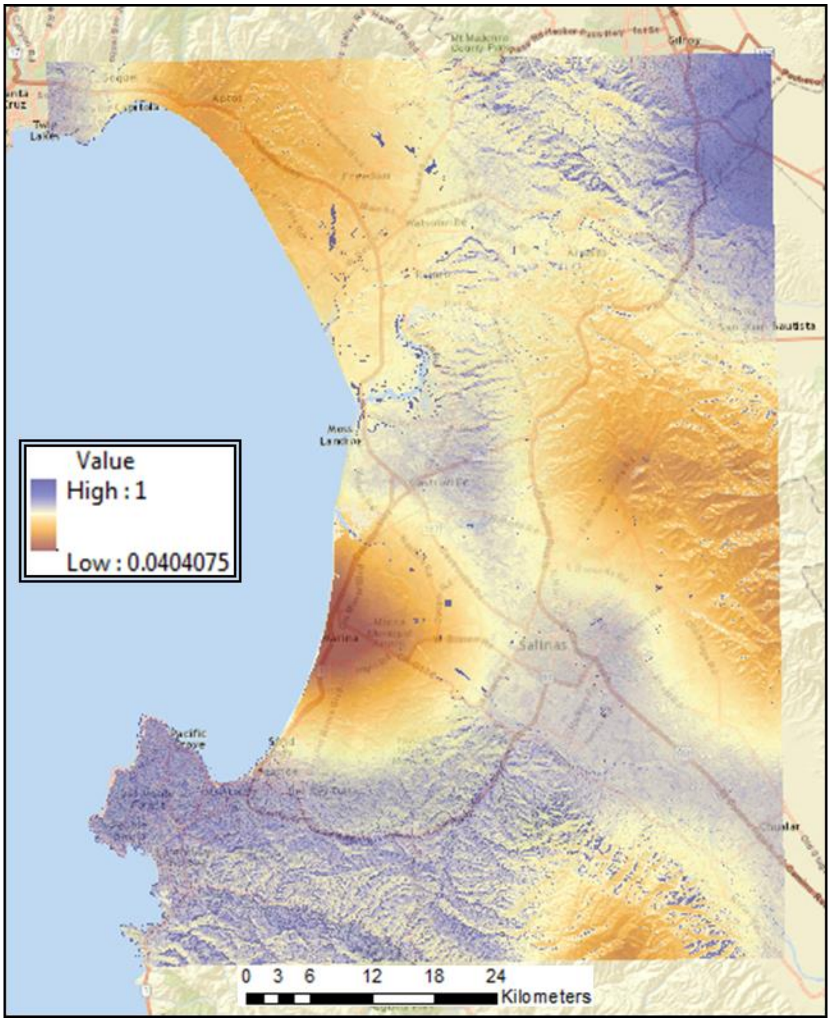

Figure C.3: Sample 30 m EMT+VS Output for Monterey Bay, CA Sample Area.

7. While the members of the research team representing CSU have been developing the EMT+VS model itself, those members representing TSC have been implementing the model processes in a combination of the C# and Python programming languages, and packaging them in a map-centric application. The EMT+VS model process chain is shown in Figure C.4, while Figure C.5 shows a screen shot of the map-centric tool interface. In Figure C.4, the blue italicized text indicates user-provided inputs to the EMT+VS process chain including AOI (an Area of Interest rectangle).

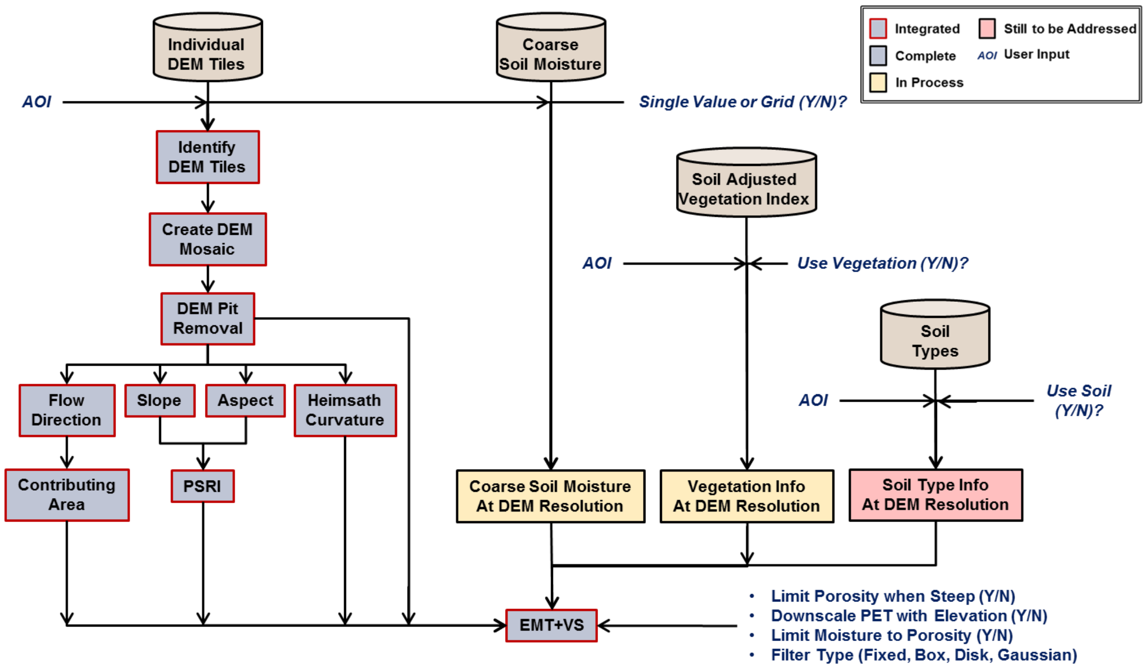

Figure C.4: EMT+VS Model Process Chain.

Figure C.5: EMT+VS Soil Moisture Estimator Map-Centric Application Interface.

8. Sample intermediate EMT+VS results for the Fort Pickett Army National Guard installation near Blackstone, VA are shown in Figure C.6 – while final results (DEM mosaic and fine-resolution soil moisture) are provided in Figure C.7. These sample results use a 30-metre Digital Elevation Map (DEM) constructed of DTED level 2 elevation tiles and a single value of input coarse soil moisture. All interim and final results are stored as single-band GeoTIFF files.

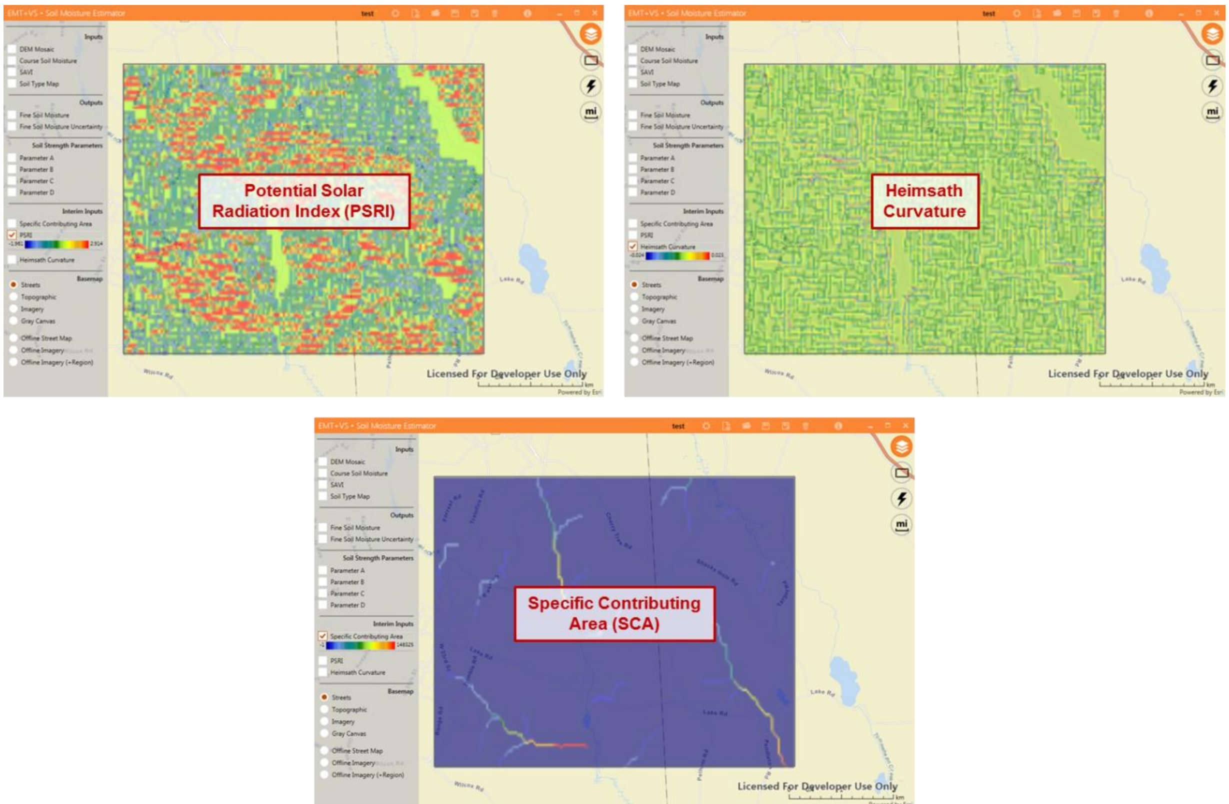

Figure C.6: Sample Intermediate EMT+VS Model Results for Fort Pickett.

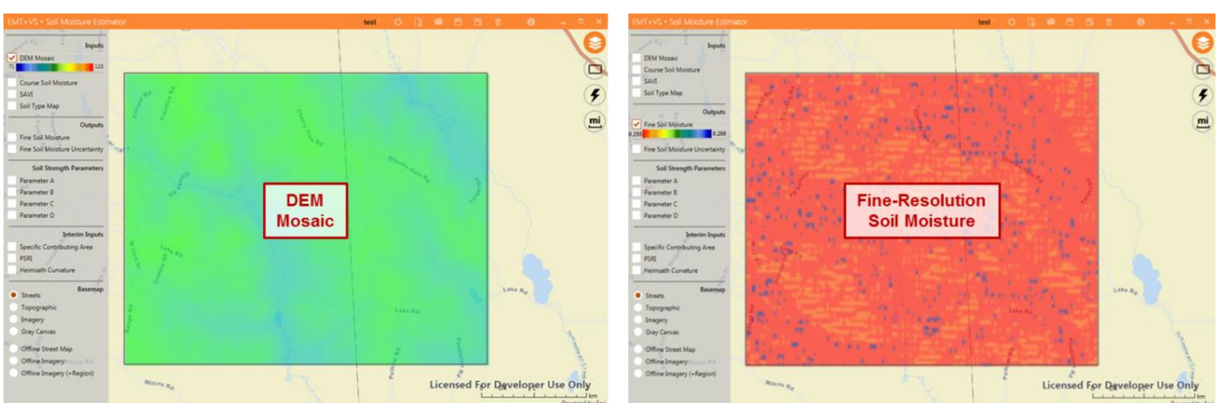

Figure C.7: Sample EMT+VS Model Outputs for Fort Pickett.

C.2. SOIL STRENGTH ESTIMATION OVERVIEW

1. At the time of this writing, a research team associated with NATO AVT-248[3] was also developing a technique for estimating both the Effective Friction Angle (φ') and Effective Cohesion (*c*') components of soil strength as a function of soil composition (type), bulk density, volumetric soil moisture content and temperature. The technique involves creating continuous functions that relate the available soil taxonomy (soil types) to unsaturated soil parameters, and then to transform those parameters to soil moisture specific values using unsaturated soil strength theory.

2. The standard and widely-used theory for soil strength is Mohr-Coulomb shear strength theory where soil shear strength (τ) is given by:

$$\tau = c + \sigma \bullet \tan(\varphi), \tag{C-1}$$

where c is the cohesion (strength component of soil strength resulting primarily from electrostatic interparticle force), σ is the total normal stress (on a plane in a soil mass) and φ is the friction angle (strength component of soil strength resulting from interparticle friction). The total normal stress (σ) is given by:

$$\sigma = \sigma' + \mu, \tag{C-2}$$

where μ is the pore water pressure (water pressure in soil pores, can be positive or negative) and σ' is the effective stress (stress felt by soil particles) – which is the item of interest here. Therefore, the relation for effective stress shear strength (τ') is:

$$\tau' = c' + \sigma' \bullet \tan(\varphi'), \tag{C-3}$$

where c' is the cohesion independent of normal stress and φ' is the effective stress friction angle. The classic concept of effective stress (σ') can be applied to an unsaturated soil framework without violating existing shear strength theory by applying unsaturated soil parameters (suction stress in unsaturated soils, σs and effective stress in unsaturated soils, σ') as follows (Lu et al., 2010):

$$\sigma^s = f(S_e, \alpha, \eta) \text{ and} \tag{C-4}$$

$$\sigma' = (\sigma - \mu_a) - \sigma^s, \tag{C-5}$$

where S_e is the effective saturation in soil (related to volumetric water content), η is the pore size spectral number, α is the inverse of air entry pressure for water saturated soil, σ is the total stress in the soil, and μ_a is the pore air pressure in soil. The soil strength estimation framework being used to guide this effort is summarized in Figure C.8.

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[3] Drs. Jeffrey Niemann, Andy Jones and Joseph Scalia of Colorado State University (CSU) along with Mssrs. Mark Cammarere and Keith Gemeinhart of Technology Service Corp (TSC).

3. If the technique is effective, the following soil strength-related parameters will also be added to the map-centric application described above: 1) suction strength in unsaturated soil (σs), 2) effective friction angle (φ’), and effective cohesion (c’).

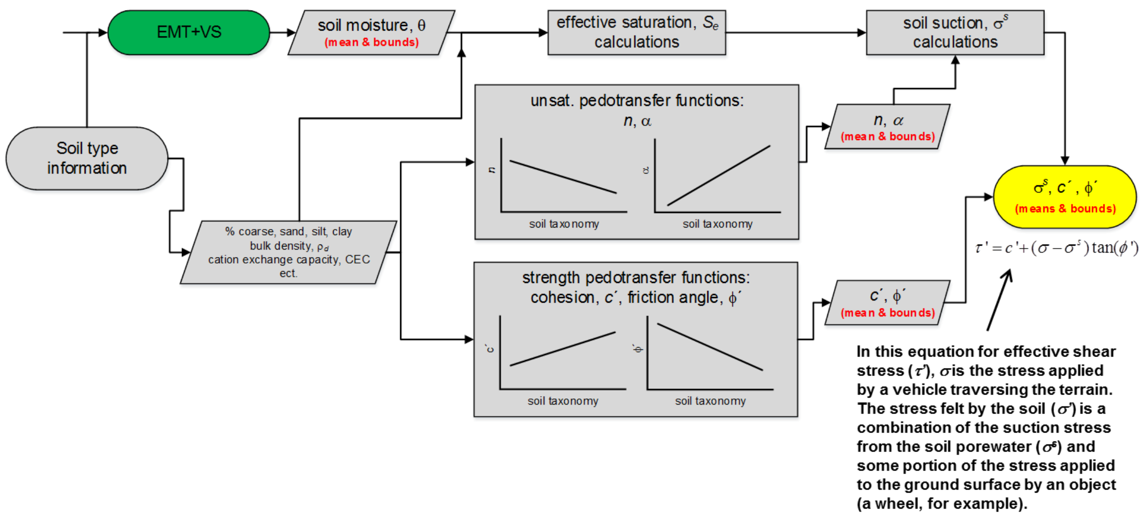

Figure C.8: Soil Strength Estimation Framework.

The work described in this appendix was performed under a U.S. Army Research Laboratory (ARL) Small Business Innovation Research (SBIR) contract for Dr. Paramsothy Jayakumar and Mr. Mike Letherwood of the U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC). Mr. Peter J. Grazaitis is the sponsor of the ARL SBIR effort.

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ANNEX D NOTIONAL NG-NRMM OUTPUT FILE FORMAT

A notional example of an ASCII output file is provided in Annex D, an Excel file available for download from NATO STO at https://www.sto.nato.int/pages/natostandards.aspx.

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ANNEX E TERRAMECHANICS DATABASE

An evolving database of Simple Terramechanics modelling parameters is provided (see Annex E) for NG-NRMM with soft terrain modelling parameters. This Annex collects available data relating to terramechanics models. The data are collected from a wide variety of sources in an EXCEL file available for download from NATO STO at https://www.sto.nato.int/pages/natostandards.aspx.

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ANNEX F NG-NRMM TRACKED VEHICLE BENCHMARK DATA

F.1. INTRODUCTION

1. Annex F presents a set of tracked vehicle model parameters compiled into a consistent data set defining a notional vehicle that is precisely representative of the vehicle from which it was derived in so far as the original sources defined it. The Annex includes data defining a tracked vehicle representing an armored personnel carrier type vehicle, described here as the “APC (Test Vehicle)”. The data are collected from various public available sources as indicated in the references. Additional arbitrary but reasonable assumptions were made to complete all additional vehicle parameters that were necessary to construct vehicle numerical models with enough resolution to predict performance on the mobility events defined in section 3.3 of the main document. The publicly available sources also give vehicle performance data for some of the defined events for Verification and Validation purposes. No additional performance tests of an actual vehicle were performed for this benchmark vehicle.

2. Nearly all the data was kindly provided by Dr. J.Y. Wong of Vehicle Systems Development Corporation (VSDC) of Toronto, ON, Canada. Since most of this material was published elsewhere, we are including the following disclaimer, suggested by Dr. Wong.

Disclaimer

The data contained in this document are from either papers published in scientific/technical journals or unpublished technical reports, which are listed as references in Section F.10. References Wong (2015); Wong et al. (2019); and Section F.2 — Tracked Vehicle Data of this document are copyrighted. It is the responsibility of the user of the data to comply with the copyright laws of appropriate jurisdictions.

While the data contained in this document were obtained with the best effort of the authors of the publications and technical reports, no expressed or implied warranties of any kind on the data, including but not limited to their accuracy and completeness, are provided.

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3. Section F.2 provides a set of tracked vehicle model parameters that were used by a VSDC computer simulation model, Nepean Tracked Vehicle Performance Model (NTVPM), to predict the performance of the APC (Test Vehicle) on deformable terrain.

4. Section F.3 provides some additional supplementary vehicle data that was not used by NTVPM, but that describes additional characteristics of the vehicle that may be useful in building 3D multibody dynamics models of the vehicle.

5. Section F.4 describes terrain parameters for three deformable terrains on which the performance of the APC (Test Vehicle) was measured in a series of field tests.

6. Section F.5 compares the measured drawbar pull-slip performance of the APC (Test Vehicle) on the three terrains described in Section F.4 with predictions of that performance that were made using NTVPM, and it quantifies the correlations there.

7. Section F.6 provides profiles for a number of non-deformable obstacles (half-rounds and trapezoidal obstacles) that may be used to evaluate the performance of tracked vehicles operating on hard surfaces. It also provides an introduction to three non-deformable random profile courses with 3-cm, 6-cm and 9-cm RMS roughness levels. No measurements were made of the performance of the APC (Test Vehicle) on these non-deformable obstacles and surfaces.

8. Sections F.7, F.8 and F.9 provide the geometries for the 3-cm, 6-cm and 9-cm RMS roughness courses, respectively.

9. Collectively, the information provided here can be used to assess the ability of an NG-NRMM simulation model to predict the performance of a tracked vehicle, the APC (Test Vehicle), on three deformable terrains and quantify the correlations there. It also provides a number of non-deformable obstacles and RMS roughness courses where the abilities of the NG-NRMM model can be assessed.

F.2. TRACKED VEHICLE DATA

This section contains the complete vehicle input data that is needed by VSDC's computer simulation model, Nepean Tracked Vehicle Performance Model (NTVPM) to simulate the performance of the APC (Test Vehicle) over a wide range of deformable terrains (Wong et al., 2019).

Table F.1: A Portion of the 2D Tracked Vehicle Input Parameters that Includes the Vehicle Type, Sprung and Unsprung Weights, Sprung Weight X- and Y-Coordinates, Initial Track Tension and Drawbar Hitch X- And Y-Coordinates, Provided to VSDC's NTVPM for the APC (Test Vehicle).

General Parameters of the Tracked Vehicle	
Vehicle type	APC (Test Vehicle)
Sprung weight (kN)	78.57
Unsprung weight (kN)	10.14
Sprung weight center of gravity x-coordinate (cm)	198.00
Sprung weight center of gravity y-coordinate (cm)	-48.10
Initial track tension (kN)	10.00
Drawbar hitch x-coordinate (cm)	427.50
Drawbar hitch y-coordinate (cm)	-12.70
NOTE: Coordinate origin is at the center of the sprocket. Positive x- and y-coordinates are to the rear and down, respectively.	

Table F.2: A Portion of the 2D Tracked Vehicle Fixed-Wheel Parameters that Includes the Radii, Wheel Center X- and Y-Coordinates, and Designation of Whether the Wheel is a Drive Sprocket, Provided to VSDC's NTVPM for the APC (Test Vehicle).

Parameters for Fixed Wheels			
Wheel Radius (cm)	X-coordinate of Wheel Center (cm)	Y- coordinate of Wheel Center (cm)	Notes
21.40	0.00	0.00	Sprocket
21.90	402.30	15.10	
NOTE: Coordinate origin is at the center of the sprocket. Positive x- and y-coordinates are to the rear and down, respectively.			

Table F.3: A Portion of the 2D Tracked Vehicle Torsion-Arm Suspension Wheel Parameters that Includes the Radii, Torsion Arm Pivot X- and Y-Coordinates, Torsion Bar Stiffness, Torsion Arm Free Position, Rebound and Jounce Limits, Torsion Arm Length, and Designation of Whether the Arm is Trailing or Not, Provided to VSDC's NTVPM for the APC (Test Vehicle).

Parameters for Torsion Arm Suspension Wheels								
	Torsion Arm Pivots			Torsion Arm Angles (+ is CW from horizontal)				Notes
Wheel Radius (cm)	X-coord. (+ is to the rear) (cm)	Y-coord. (+ is down) (cm)	Torsion Bar Stiffness (kN-m/deg)	Rebound Limit (deg)	Free Position (deg)	Jounce Limit (deg)	Torsion Arm Length (cm)	
30.50.	39.69	8.73	0.1668	50.00	30.50	30.50	30.50	T
30.50	106.36	8.73	0.1668	50.00	30.50	30.50	30.50	T
30.50	173.04	8.73	0.1668	50.00	30.50	30.50	30.50	T
30.50	239.71	8.73	0.1668	50.00	30.50	30.50	30.50	T
30.50	306.39	8.73	0.1668	50.00	30.50	30.50	30.50	T

NOTE: T = Trailing

NOTE: Coordinate origin is at the center of the sprocket. Positive x- and y-coordinates are to the rear and down, respectively.

Table F.4: A Portion of the 2D Tracked Vehicle Belly Shape and Track Link Contact Area Parameters that Includes the Belly Width and Belly X- And Y-Coordinates; and A Table Showing The Relation Between Track Link Sinkage, Incremental Track Link Contact Area, and The Proportion of Each Incremental Area that Causes External (e.g., Rubber-Terrain or Metal-Terrain) Shearing, Provided to VSDC's NTVPM For The APC (Test Vehicle).

Belly Shape Parameters	
Width: 170.0 cm	
Coordinates (cm)	
X	Y
21.4	34.3
-4.1	14.3
417.0	14.3

Track Link Contact Area Parameters			
Sinkage (cm)		Incremental Area (cm^2)	Percentage Causing External Shearing
from	to		
0.00	0.00	77.43	100.0
0.00	0.51	80.65	100.0
0.51	1.46	54.84	100.0
1.46	2.22	40.65	0.0
2.22	3.05	98.06	0.0
3.05	4.06	41.94	0.0
4.06	5.08	45.16	0.0
5.08	5.97	83.87	0.0

NOTE: Coordinate origin is at the center of the sprocket. Positive x- and y-coordinates are to the rear and down, respectively.

Table F.5: A Portion of the 2D Tracked Vehicle Track Parameters that Includes the Track Weight Per Unit Length, Track Width and Pitch, Height of the Grousers, Thickness of the Track, the Proportion of the Area for Cohesive Shearing that Causes External Shearing Instead of Rubber-Terrain Shearing, and Longitudinal Track Elasticity Parameters T_e and E_{max} that Define the Relation Between Track Tension T and Track Elongation E, provided to VSDC's NTVPM for the APC (Test Vehicle).

Track Parameters	
Weight per Unit Length (kN/m)	0.560
Width (cm)	38.0
Pitch (cm)	15.0
Height of the Grousers (cm)	4.7
Thickness (cm)	6.7
Percent External Shear Area for Cohesive Shearing (%)	41.0
Longitudinal Elasticity Const. T_e (from $T=-T_e*\ln(1-E/E_{max})$) (kN)	18.208
Longitudinal Elasticity Const. E_{max} (from $T=-T_e*\ln(1-E/E_{max})$) (%)	1.434

Table F.6: A Portion of the 2D Tracked Vehicle Output that Shows the Relationship Between Track Elongation *E* and Track Tension *T* Resulting from the Parameters T_e and E_{max} in Table F.5, And Forming Part of VSDC's NTVPM for the APC (Test Vehicle).

Track Elasticity	
Elongation (%)	Tension (kN)
0.000	0.00
0.408	4.45
0.605	8.90
0.745	13.34
0.867	17.79
0.975	22.24
1.063	26.69
1.151	31.14
1.219	35.59
1.282	40.03
1.334	44.48
1.373	48.93

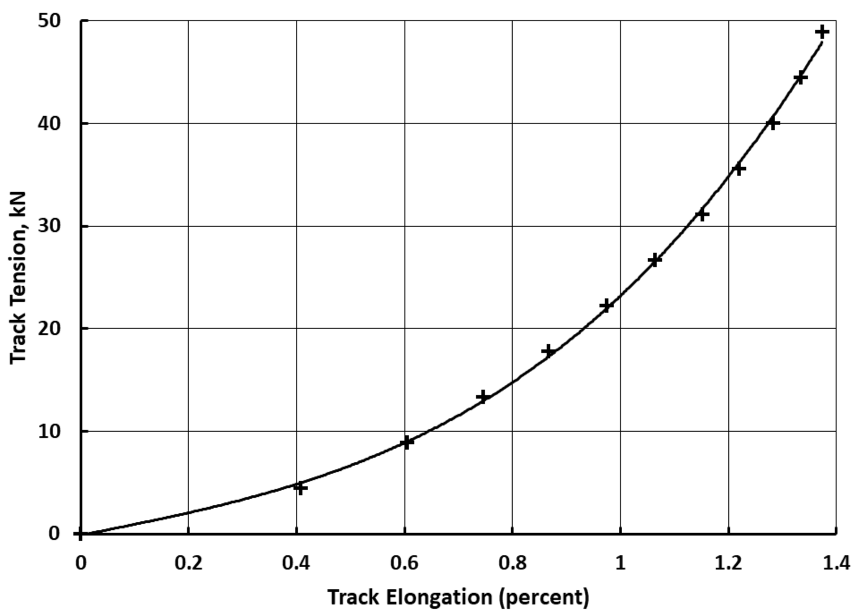

Figure F.1: A Portion of the 2D Tracked Vehicle Output that Shows the Relationship between Track Tension and Track Elongation from Table F.6. The Values in Table F.5 and Graph Shown Here Describe the Relationship Defined by the Parameters T_e and E_{max} in Table F.5, and Forming Part of VSDC's NTVPM for the APC (Test Vehicle).

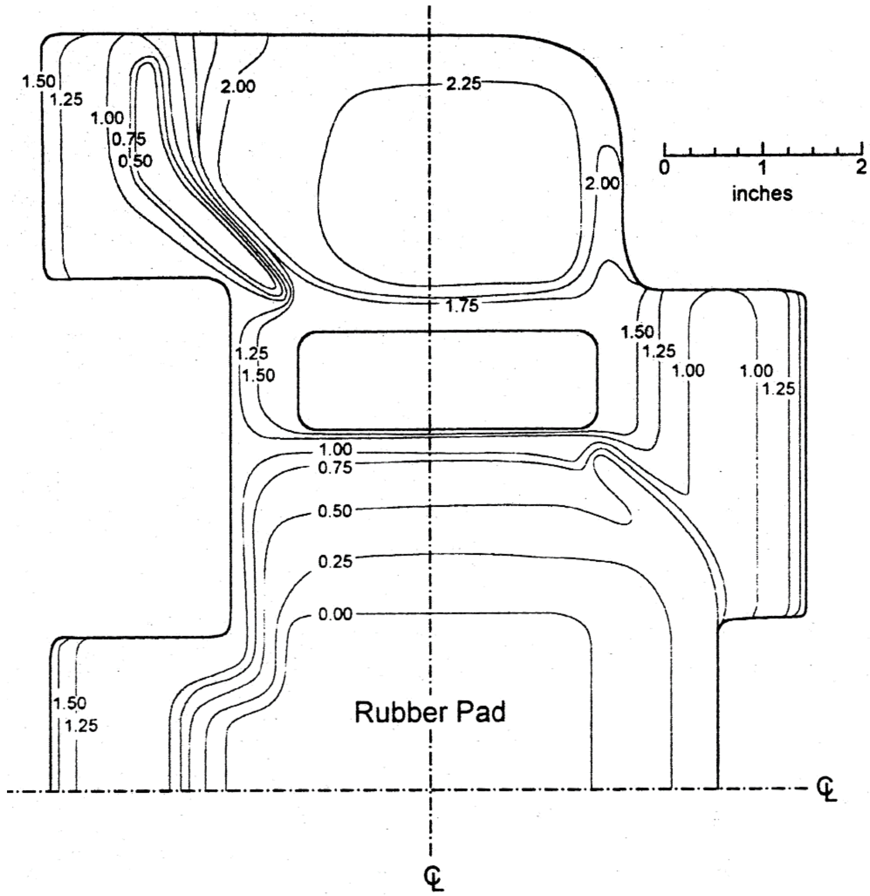

Figure F.2: Contour map of the track link with 0.25 in. contour intervals for the track link used in the simulations conducted using VSDC's NTVPM for the APC (Test Vehicle).

F.3. SUPPLEMENTARY VEHICLE DATA

This section contains input data from Conner (2017) that was not needed by VSDC's NTVPM to simulate the performance of the APC (Test Vehicle), but that was needed by NG-NRMM models in a series of tracked vehicle benchmark simulations. This supplementary data was assembled by Michael McCullough using data from Conner (2017) where possible, while making reasonable engineering judgment assumptions for the remaining input parameters that were necessary to simulate the events and responses in the benchmark.

Table F.7: General Parameters and Guidance for Modeling the APC (Test Vehicle).

General Parameters and Guidance for Modeling	
Vehicle Lateral Stance or Tread Width, center to center (in.)	85
Power at Sprockets, Total (hp)	200
Stall Torque at One Sprocket (ft-lb)	7021
Maximum Speed (mph)	40
Assume torque at low speed equals stall torque until power limited at approx. speed of (mph)	3.75
Assume power at sprockets remains constant as a function of speed for speeds beyond the low speed range for stall torque applicability.	
Baseline run should assume nothing regarding the transmission and steering systems	
Parameter sensitivity runs on steering could assume more power and regenerative systems	

Table F.8: Assumed Suspension Asymmetry for the Track Systems on the Left and Right Sides of the APC (Test Vehicle).

Assumed Suspension Asymmetry		
	Left	Right
Number of Track Shoes	63	64
Road Arm Offset Rearward Relative to Wong's Plan View (in.)	0	4

Table F.9: Assumed Single Sprocket Power Curve for the APC (Test Vehicle).

Speed, mph	0	3.75	5	10	15	20	40
Torque, ft-lb	7021	7021	5266	2633	1755	1316	658

Table F.10: Assumed Coordinates of Four Corner Points on The APC (Test Vehicle) that Should Be Checked for Bottoming on the Ground During a Vehicle Lane Change.

Lane Change Corner Points				
	Front Left	Front Right	Rear Left	Rear Right
Vertical (in.)	0	0	5.9	5.9
Horizontal (in.)	-13.5	-13.5	178.2	178.2
Lateral (in.)	53	-53	53	-53
NOTE: Coordinate reference is in line with the drive sprockets, on the vehicle centerline, and in line with the bottom near the front of the vehicle.				

Table F.11: Assumed Coordinates of Four Corner Points on the Belly of the APC (Test Vehicle) that Should Be Checked tor Bottoming on the Ground During a Vehicle Obstacle Crossing.

Obstacle Crossing Corner Points				
	Front Left	Front Right	Rear Left	Rear Right
Vertical (in.)	0	0	5.6	5.6
Horizontal (in.)	-12.9	-12.9	151.3	151.3
Lateral (in.)	33.5	-33.5	33.5	-33.5
NOTE: Coordinate reference is in line with the drive sprockets, on the vehicle centerline, and in line with the bottom near the front of the vehicle.				

Table F.12: Assumed Coordinates of the Driver Position on the APC (Test Vehicle) for Use in Evaluating Ride Quality.

Driver Position for Ride Dynamics		
Vertical (in.)	20	Upward from the sprocket center
Horizontal (in.)	68.1	Aft of the sprocket center
Lateral (in.)	Unknown	Not necessary for 2D terrain profiles

Table F.13: Assumed Sprocket and Idler Stiffnesses, and Roadwheel Jounce Stops and Stiffnesses for the APC (Test Vehicle).

Stiffnesses and Jounce Stops	
Sprocket and Idler Radial Impact Stiffness (lb/in) - Assumed to be linear and governed by wheel rubber and track pad in series deflecting one in. under GVW.	20000
Roadwheel Jounce Stop Angle (deg)	30
Roadwheel Jounce Stop Stiffness (lb/in) - Radial at the roadwheel due to impact with the hull sponson plate - Assumed to be linear and governed by wheel rubber and track pad in series deflecting one in. under GVW.	20000

Table F.14: Assumed Damper Information for the APC (Test Vehicle)

Damper Assumptions and Force Curve		
Velocity, in./s	Force, lb	Notes
-50	-2000	jounce mode
-10	-2000	
0	0	
10	500	
50	500	extension mode
- Assume vertical linear dampers attached at the roadwheel center on roadwheels 1 and 5, right and left.		
- No actual data was found for damping.		
- These are fictional assumptions.		

F.4. TRACKED VEHICLE TERRAIN DATA

Terrain parameters for three terrains – LETE Sand, Petawawa Muskeg B and Petawawa Snow A – are provided here. The detailed descriptions of the terrain parameters presented herein are given in Wong et al. (2019).

F.4.1. Terrain Parameters for LETE Sand

a. Pressure-sinkage relation

Bekker's pressure-sinkage equation

$$p = (k_c / b + k_\phi)\, z^n \tag{F-1}$$

where p is normal pressure; z is sinkage; k_c, k_ϕ and n are pressure-sinkage parameters of the terrain; b is the effective radius of the track link.

b. Pressure-sinkage relation during unloading or reloading

$$p = p_u - k_u (z_u - z) \tag{F-2}$$

$$k_u = k_o + A_u z_u \tag{F-3}$$

where p is normal pressure; z is sinkage; p_u is the normal pressure from which unloading begins; z_u is the sinkage from which unloading begins; k_o and A_u are the unloading or reloading parameters of the terrain.

Table F.15: Pressure-sinkage and Repetitive Loading Parameters for LETE Sand*.

k_c kN/m^{n+1}		k_ϕ kN/m^{n+2}		n		k_o kN/m^3	A_u kN/m^4
Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Mean value
102	54	5301	775	0.793	0.012	0	503 000

*Source: Wong et al. (2019).

c. Shearing characteristics

Janosi-Hanamoto's shear stress-shear displacement relation

$$s / s_{max} = 1 - \exp(-j / K) \quad \text{(F-4)}$$

$$s_{max} = (c + p \tan \phi) \quad \text{(F-5)}$$

where s is shear stress; s_{max} is the maximum shear stress; p is normal pressure; c is the cohesion of the terrain (c_{ru} is the adhesion on the rubber-terrain interface); ϕ is the angle of internal shear resistance of the terrain (ϕ_{ru} is the angle of rubber-terrain shear resistance); j is shear displacement; K is shear deformation parameter of the terrain (K_{ru} is shear deformation parameter for rubber-terrain shearing).

Table F.16: Parameters for Internal and Rubber-Terrain Shearing for LETE Sand**.

Type of shearing	Cohesion or adhesion c or c_{ru} kPa		Angle of shear resistance ϕ or ϕ_{ru} degrees		Shear deformation parameter K or K_{ru} cm	
	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
Internal	1.36	0.09	31.56	0.38	1.60	0.61
Rubber-terrain	0.65	0.23	27.51	0.05	1.14	0.34

**Source: Wong et al. (2019).

F.4.2. Terrain parameters for Petawawa Muskeg B

a. Pressure-sinkage relation

Muskeg pressure-sinkage equation

$$p = k_m z \quad \text{(F-6)}$$

where p is normal pressure; z is sinkage; k_m is the muskeg pressure-sinkage parameter.

b. Pressure-sinkage relation during unloading or reloading

$$p = p_u - k_u (z_u - z) \quad \text{(F-7)}$$

$$k_u = k_o + A_u z_u \quad \text{(F-8)}$$

where p is normal pressure; z is sinkage; p_u is the normal pressure from which unloading begins; z_u is the sinkage from which unloading begins; k_o and A_u are unloading or reloading parameters of the terrain.

Table F.17: Pressure-sinkage Parameter k_m and Repetitive Loading Parameters for Petawawa Muskeg B, Obtained with the Surface Mat Being Cut*.

Terrain	k_m kN/m^3		k_o kN/m^3	A_u kN/m^4
	Mean value	Standard deviation	Mean value	Mean value
Petawawa Muskeg B	555	105	147	29 700

**Source:* Wong et al. (2019).

c. Shearing characteristics

Janosi-Hanamoto's shear stress-shear displacement relation

$$s / s_{max} = 1 - \exp(-j / K) \quad \text{(F-9)}$$

$$s_{max} = (c + p \tan \phi) \quad \text{(F-10)}$$

where s is shear stress; s_{max} is the maximum shear stress; p is normal pressure; c is the cohesion of the terrain; ϕ is the angle of internal shear resistance of the terrain; j is shear displacement; K is shear deformation parameter of the terrain.

Table F.18: Shear Parameters for the Peat of Petawawa Muskeg B**.

Terrain type	Type of shearing	Cohesion c kPa		Angle of shear resistance ϕ degrees		Shear deformation parameter K cm	
		Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
Peat - Muskeg B	Internal	4.14	0.01	38.11	0.35	2.79	0.68

***Source:* Wong et al. (2019).

F.4.3. Terrain parameters for Petawawa Snow A

a. Pressure-sinkage relation for each layer of a two-layer snow cover with a crust in between

$$p = p_w [- \ln (1 - z / z_w)] \quad \text{(F-11)}$$

$$p_w = k_{p1} + b\, k_{p2} \quad \text{(F-12)}$$

$$z_w = k_{z1} + k_{z2} / \mathrm{b} \quad \text{(F-13)}$$

where p is normal pressure; z is sinkage; k_{p1}, $k_{p2,}$ $k_{z1,}$ and k_{z2} are snow pressure-sinkage parameters; b is the effective radius of the track link.

b. Pressure-sinkage relation during unloading or reloading

$$p = p_u - k_u (z_u - z) \quad \text{(F-14)}$$

$$k_u = k_o + A_u z_u \quad \text{(F-15)}$$

where p is normal pressure; z is sinkage; p_u is the normal pressure from which unloading begins; z_u is the sinkage from which unloading begins; k_o and A_u are unloading or reloading parameters of the terrain.

Table F.19: Pressure-sinkage and Repetitive Loading Parameters for Petawawa Snow A*.

Terrain Parameters	Petawawa Snow A	
	Before failure of the crust	After failure of the crust
k_{p1}, kN/m^2	3.2	52.7
k_{p2}, kN/m^3	234	-48
k_{z1}, cm	0.9	14.2
k_{z2}, cm^2	39.7	67.3
L_{cr}, cm	16.7	
M_{cr}, kN	0.0402	
k_o, kN/m^3	0	
A_u, kN/m^4	109 600	

**Source:* Wong et al. (2019).
Note: L_{cr} and M_{cr} are strength parameters of the crust between the upper and lower layer of snow cover.

c. Internal shearing characteristics of snow

$$s / s_{max} = K_r \{1+ [1/ (K_r (1\text{-}1/e)) - 1] \exp (1\text{-}\, j / K_w)\} [1 - \exp (-\, j / K_w)] \quad \text{(F-16)}$$

$$s_{max} = (c + p \tan \phi) \quad \text{(F-17)}$$

where s is shear stress; s_{max} is the maximum shear stress; c is the cohesion of the terrain; ϕ is the angle of internal shear resistance of the terrain; K_r is the ratio of the residual shear stress to the maximum shear stress; K_w

represents the shear displacement where the maximum shear stress occurs; j is shear displacement.

Table F.20: Internal Shear Parameters for Petawawa Snow A**.

Terrain type	Cohesion c, kPa		Angle of shear resistance ϕ, degrees		Shear deformation parameter K_w, cm		Shear deformation parameter K_r	
	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
Petawawa Snow A	0.4	0.4	23.98	4.02	2.18	0.76	0.654	0.12

***Source:* Wong et al. (2019).

d. Rubber-snow shearing characteristics

Janosi-Hanamoto's shear stress-shear displacement relation:

$$s / s_{max} = 1 - \exp(-j / K_{ru}) \quad \text{(F-18)}$$

$$s_{max} = (c_{ru} + p \tan \phi_{ru}) \quad \text{(F-19)}$$

where s is shear stress on the rubber-terrain interface; s_{max} is the maximum shear stress on the rubber-terrain interface; p is normal pressure on the rubber-terrain interface; c_{ru} is the adhesion on the rubber-terrain interface; ϕ_{ru} is the angle of rubber-terrain shear resistance; j is shear displacement; K_{ru} is shear deformation parameter of rubber-terrain shearing.

Table F.21: Parameters for Rubber-Snow Shearing for Petawawa Snow A***.

Type of shearing	Adhesion c_{ru}, kPa		Angle of shear resistance ϕ_{ru}, degrees		Shear deformation parameter K_{ru}, cm	
	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
Rubber-Snow A	0.14	0.14	17	1.80	0.61	0.33

****Source:* Wong et al. (2019).

F.5. CORRELATIONS BETWEEN THE MEASURED AND PREDICTED PERFORMANCE OF THE APC (TEST VEHICLE) ON THREE TYPES OF TERRAIN

1. This section describes portions of an evaluation of VSDC's computer simulation model NTVPM for assessing tracked vehicle cross-country performance (Wong et al., 2019).

2. This evaluation is for the APC (Test Vehicle) described in section F.2 of this Annex, as it operates over three terrains – LETE Sand, Petawawa Muskeg B, and Petawawa Snow A. The pressure-sinkage, shear strength relationships and shear deformation relationships for the three terrains are summarized in section F.4.

3. The evaluation described here for each of the terrain types includes predictions of the drawbar pull-slip performance of the APC (Test Vehicle) made using NTVPM, and the results of field measurements that were made using a test vehicle with instrumentation to measure left and right track slip and the drawbar pull applied to the hitch of the vehicle (Wong, 2015). Each of the measured data points presented below represents at least a short period of time when the vehicle was in steady-state operation.

F.5.1. Correlations between Measured and Predicted Drawbar Pull-Slip Relationships on LETE Sand

1. The first row in Table F.22 shows that the first steady-state measurement of the drawbar pull-slip performance of the APC (Test Vehicle) operating on LETE Sand occurred with an average track slip of 1.65% and a measured drawbar pull of 17.62 kN (Wong, 2015). The same row shows that, when NTVPM was used to predict the performance of the vehicle using the mean LETE Sand terrain parameters, it predicted a drawbar pull of 13.71 kN would be achieved.

2. The remaining rows with three columns in Table F.22 show 43 additional measurements of slip and drawbar pull that were made on the APC (Test Vehicle) as the vehicle operated in steady state motion on LETE Sand under a variety of load conditions, together with the corresponding predictions of drawbar pull made by NTVPM using the mean values of terrain parameters.

3. Correlations between the measured and predicted drawbar pull-slip parameters can be evaluated using the coefficient of correlation R, the coefficient of determination R^2, the root mean square deviation *RMSD*, and the coefficient of variation *CV*, as described in Wong et al. (2019). The results of this are shown at the bottom of Table F.22. As can be seen from the table, the values of R and R^2 are 0.922 and 0.850, respectively. Thus, the correlation between the trends of the predicted drawbar pull-slip relation of the APC (Test Vehicle) by NTVPM and those of the measured data on LETE Sand can be regarded as strong. The values of *RMSD* and *CV* are 3.55 kN and 0.120, respectively.

4. Each of the steady-state measurements of the drawbar pull-slip performance of the APC (Test Vehicle) operating on LETE Sand is shown as a solid circle in Figure F.3. The drawbar pull-slip relationship that was predicted using the mean values of terrain parameters is shown as a solid line in the same Figure.

5, The predicted upper bound curve (shown with long dashes) in the Figure is the drawbar pull-slip relationship predicted by NTVPM when the mean values plus one standard deviation (SD) of the pressure-sinkage and shear strength parameters and the mean values minus one SD of the shear deformation parameter are used. The reason for using the mean values minus one SD of the shear deformation parameter for predicting the upper bound curve is that with lower values of shear deformation parameter, shear stress increases more rapidly with an increase in shear displacement, particularly at the initial part of track-terrain shearing, leading to higher tractive effort in the low/medium slip range. This is described more completely in Wong et al. (2019).

6. The lower bound curve (shown with short dashes) in the Figure is the drawbar pull-slip relationship predicted by NTVPM when the mean values minus one standard deviation (SD) of the pressure-sinkage and shear strength parameters and the mean values plus one SD of the shear deformation parameter are used.

Table F.22: Tabular Correlation between the Measured Drawbar Pull-slip Relationship of the APC (Test Vehicle) on LETE Sand, Together with that predicted by NTPVM using the Mean Values of Terrain Parameters.

Slip %	Measured drawbar pull, kN	Predicted drawbar pull with mean values of terrain parameters, kN
1.65	17.62	13.71
1.73	8.32	14.05
2.28	7.77	16.19
2.58	16.85	17.25
2.79	15.57	17.95
3.08	16.70	18.89
3.25	9.05	19.41
3.34	22.05	19.68
4.56	23.37	22.97
4.81	24.29	23.57
5.41	25.09	24.92
5.57	23.74	25.24
5.79	29.01	25.70
5.95	23.33	26.03
6.00	32.45	26.13
6.17	30.07	26.47
6.80	31.25	27.61
6.88	27.33	27.76
7.98	32.23	29.53
8.91	28.06	30.87
9.08	33.19	31.10
9.29	32.09	31.37
9.59	32.97	31.73
10.35	34.21	32.63
10.60	34.21	32.91
12.63	34.43	34.91
12.71	35.90	34.99
13.13	35.60	35.35

14.06	34.10	36.09
15.24	35.57	36.95
15.79	36.59	37.31
15.92	31.65	37.40
16.05	33.77	37.48
17.48	31.10	38.33
17.78	38.86	38.50
18.24	38.02	38.72
19.05	39.01	39.14
21.62	38.50	40.28
22.38	37.11	40.55
23.90	39.05	41.10
24.41	38.68	41.27
25.51	37.80	41.59
26.77	37.07	41.96
26.98	36.81	42.01
R = 0.922; R^2 = 0.850; $RMSD$ = 3.55 kN; CV = 0.120		

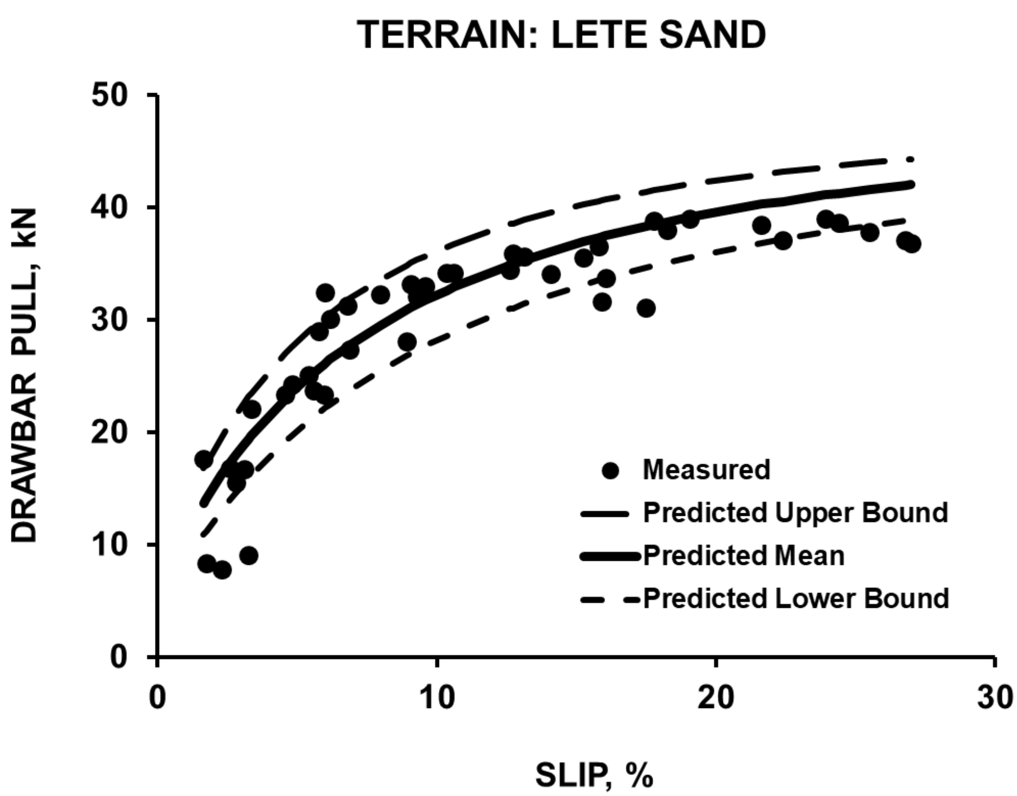

Figure F.3: Graphical Correlation between the Measured Drawbar Pull-Slip Relationship of the APC (Test Vehicle) on LETE Sand, Together with that Predicted by NTPVM.

F.5.2. Correlations Between Measured and Predicted Drawbar Pull-Slip Relationships on Petawawa Muskeg B

1. The first two columns of Table F.23 show 50 corresponding measurements of slip and drawbar pull when the APC (Tracked Vehicle) was in steady-state operation for at least a short period of time on Petawawa Muskeg B under a variety of load conditions (Wong, 2015). The third column shows the corresponding predictions of drawbar pull made by NTVPM using the mean values of the Petawawa Muskeg B terrain parameters.

2. Correlations between the measured and predicted drawbar pull-slip parameters can be evaluated using the coefficient of correlation *R*, the coefficient of determination R^2, the root mean square deviation *RMSD*, and the coefficient of variation *CV*, as described in Wong et al., 2019. As can be seen from the table, the values of *R* and R^2 are 0.903 and 0.815, respectively. Thus, the correlation between the trends of the predicted drawbar pull-slip relation of the APC (Test Vehicle) by NTVPM and those of the measured data on Petawawa Muskeg B can be regarded as strong. The values of *RMSD* and *CV* are 7.25 kN and 0.225, respectively.

3. Each of the steady-state measurements of the drawbar pull-slip performance of the APC (Test Vehicle) operating on Petawawa Muskeg B is shown as a solid circle in Figure F.4. The drawbar pull-slip relationship that was predicted using the mean values of terrain parameters is shown as a solid line in the same Figure.

4. The predicted upper bound curve (shown with long dashes) in the Figure is the drawbar pull-slip relationship predicted by NTVPM when the mean values plus one standard deviation (SD) of the pressure-sinkage and shear strength parameters and the mean values minus one SD of the shear deformation parameter are used. As noted previously, the reason for using the mean values minus one SD of the shear deformation parameter for predicting the upper bound curve is that with lower values of shear deformation parameter, shear stress increases more rapidly with an increase in shear displacement, particularly at the initial part of track-terrain shearing, leading to higher tractive effort in the low/medium slip range.

5. The lower bound curve (shown with short dashes) in the Figure is the drawbar pull-slip relationship predicted by NTVPM when the mean values minus one standard deviation (SD) of the pressure-sinkage and shear strength parameters and the mean values plus one SD of the shear deformation parameter are used.

Table F.23: Tabular Correlation between the Measured Drawbar Pull-slip Relationship of the APC (Test Vehicle) on Petawawa Muskeg B, Together with that Predicted by NTPVM using the Mean Values of Terrain Parameters.

Slip %	Measured drawbar pull, kN	Predicted drawbar pull with mean values of terrain parameters, kN
1.14	15.57	15.49
1.17	14.87	15.64
1.78	20.82	18.62
1.80	14.87	18.70
2.21	24.18	20.57
2.31	13.30	21.00
2.41	17.03	21.44
2.51	14.00	21.86
2.77	13.21	22.93
2.77	20.44	22.93
3.20	29.49	24.62
3.28	15.78	24.93
3.30	14.20	25.00
3.41	32.14	25.42
3.61	23.27	26.19
4.19	26.92	28.21
4.32	35.35	28.67
4.60	23.30	29.60
4.64	11.66	29.70
4.65	38.99	29.73
5.81	16.13	33.24
6.25	32.49	34.45
6.70	23.48	35.64
6.70	32.58	35.64
6.80	33.77	35.87
7.31	32.84	37.12
7.46	30.68	37.49
7.64	21.35	37.92
8.12	33.98	38.97
8.20	33.19	39.13
8.40	22.66	39.57
8.45	35.78	39.66
9.87	42.11	42.45
10.46	32.84	43.45
10.92	43.80	44.19
11.19	45.23	44.66
11.62	37.47	45.31
11.93	44.94	45.79

12.31	43.22	46.30
12.31	46.31	46.30
12.34	45.46	46.34
13.07	45.52	47.35
14.69	44.44	49.29
15.99	47.62	50.68
17.66	47.13	52.21
19.39	44.33	53.59
20.27	47.04	54.23
51.75	59.83	63.72
75.51	61.46	65.81
75.52	66.77	65.81
R = 0.903; R^2 = 0.815; *RMSD* = 7.25 kN; *CV* = 0.225		

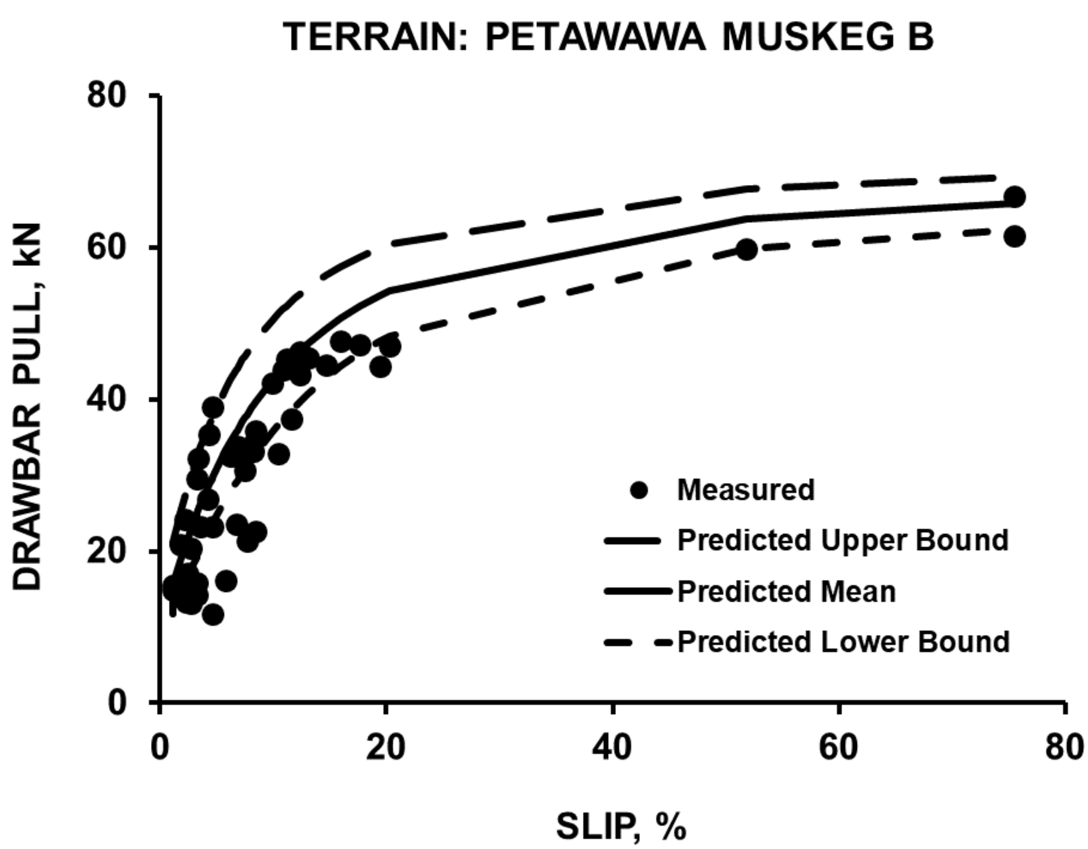

Figure F.4: Graphical Correlation between the Measured Drawbar Pull-Slip Relationship of the APC (Test Vehicle) On Petawawa Muskeg B, Together with that Predicted by NTPVM.

F.5.3. Correlations Between Measured and Predicted Drawbar Pull-Slip Relationships on Petawawa Snow A

1. The first two columns of Table F.24 show 32 corresponding measurements of slip and drawbar pull when the APC (Tracked Vehicle) was in steady-state operation for at least a short period of time on Petawawa Snow A under a variety of load conditions (Wong, 2015). The third column shows the corresponding predictions of drawbar pull made by NTVPM using the mean values of the Petawawa Snow A terrain parameters.

2. Correlations between the measured and predicted drawbar pull-slip parameters can be evaluated using the coefficient of correlation R, the coefficient of determination R^2, the root mean square deviation *RMSD*, and the coefficient of variation *CV*, as described in Wong et al. (2019). As can be seen from the table, the values of R and R^2 are 0.845 and 0.714, respectively. Thus, the correlation between the trends of the predicted drawbar pull-slip relation of the APC (Test Vehicle) by NTVPM and those of the measured data on Petawawa Snow A can be regarded as strong. The values of *RMSD* and *CV* are 2.79 kN and 0.168, respectively.

3. Each of the steady-state measurements of the drawbar pull-slip performance of the APC (Test Vehicle) operating on Petawawa Snow A is shown as a solid circle in Figure F.5. The drawbar pull-slip relationship that was predicted using the mean values of terrain parameters is shown as a solid line in the same Figure.

4. The predicted upper bound curve (shown with long dashes) in the Figure is the drawbar pull-slip relationship predicted by NTVPM when the mean values plus one standard deviation (SD) of the pressure-sinkage and shear strength parameters and the mean values minus one SD of the shear deformation parameter are used. As mentioned earlier, the reason for using the mean values minus one SD of the shear deformation parameter for predicting the upper bound curve is that with lower values of shear deformation parameter, shear stress increases more rapidly with an increase in shear displacement, particularly at the initial part of track-terrain shearing, leading to higher tractive effort in the low/medium slip range.

5. The lower bound curve (shown with short dashes) in the Figure is the drawbar pull-slip relationship predicted by NTVPM when the mean values minus one standard deviation (SD) of the pressure-sinkage and shear strength parameters and the mean values plus one SD of the shear deformation parameter are used.

Table F.24: Tabular Correlation between the Measured Drawbar Pull-slip Relationship of the APC (Test Vehicle) on Petawawa Snow A, together with that Predicted by NTPVM using the Mean Values of Terrain Parameters.

Slip %	Measured drawbar pull, kN	Predicted drawbar pull with mean values of terrain parameters, kN
1.86	13.04	8.58
2.04	13.64	9.08
2.23	10.82	9.58
2.37	14.52	9.94
2.93	14.68	11.30
3.18	13.55	11.85
3.54	12.13	12.61
4.00	11.71	13.51
4.14	14.63	13.77
4.45	12.93	14.32
4.90	14.84	15.08
4.91	14.12	15.09
5.19	12.90	15.53
5.24	13.12	15.60
6.94	13.02	17.84
7.99	17.90	18.95
8.33	16.31	19.27
9.24	16.84	20.05
9.46	17.92	20.23
9.71	20.50	20.42
9.87	17.49	20.54
9.89	18.59	20.55
9.97	18.08	20.61
10.28	16.82	20.83
10.93	20.99	21.26
13.36	20.01	22.55
13.80	17.51	22.74
13.90	19.67	22.78
13.90	18.39	22.78
17.28	25.70	23.91
19.49	25.40	24.42
39.33	25.38	26.16
R = 0.845; R^2 = 0.714; $RMSD$ = 2.79 kN; CV = 0.168		

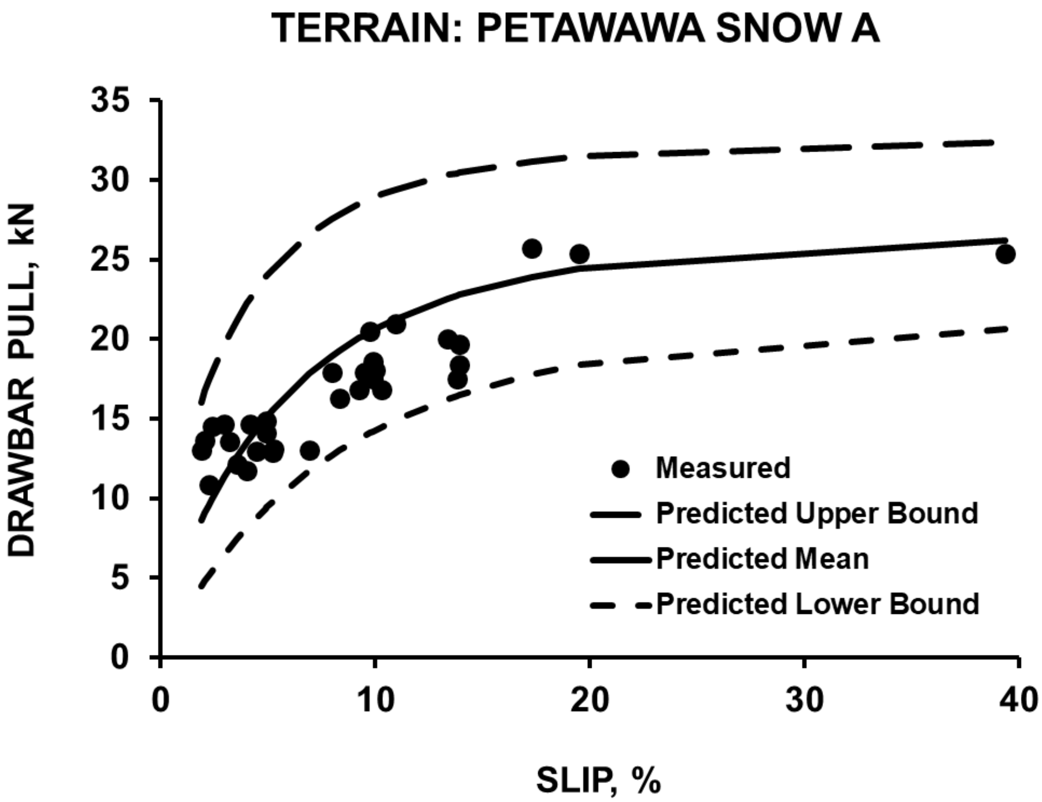

Figure F.5: Graphical Correlation between the Measured Drawbar Pull-slip Relationship of the APC (Test Vehicle) on Petawawa Snow A, together with that Predicted by NTPVM.

F.6. PROFILES OF NON-DEFORMABLE ROADS AND OBSTACLES FOR TRACKED VEHICLE PERFORMANCE EVALUATION

F.6.1. Random Terrain Ride

1. Random roughness courses like those listed below can be used to evaluate ride quality of a vehicle in physical tests, or in 2D or 3D modelling.

a. 3-cm course defined by ISO 8608 (2016) with a length of 1000 m and 0.1 m uniform elevation spacing. Data is in Section F.7.
b. 6-cm course defined by ISO 8608 (2016) with a length of 1000 m and 0.1 m uniform elevation spacing. Data is in Section F.8.
c. 9-cm course defined by ISO 8608 (2016) with a length of 1000 m and 0.1 m uniform elevation spacing. Data is in Section F.9.

F.6.2. Half-Round Obstacles

The obstacles described here can be used to evaluate ride quality of a vehicle in physical tests, or in 2D or 3D modelling.

Table F.25: Table of two Coordinate Pairs in the Horizontal and Vertical Directions describing a Flat-surface “Obstacle”.

Flat-Surface Obstacle			
Horizontal in.	Vertical in.	Horizontal in.	Vertical in.
0	0	100	0

Table F.26: Table of 13 Coordinate Pairs in the Horizontal and Vertical Directions describing the Surface of a Half-Round Obstacle with a 4-in. radius.

4 in.-Radius Half-Round Obstacle			
Horizontal in.	Vertical in.	Horizontal in.	Vertical in.
0	0	5.04	3.86
0.14	1.04	6	3.46
0.54	2	6.83	2.83
1.17	2.83	7.46	2
2	3.46	7.86	1.04
2.96	3.86	8	0
4	4		

Table F.27: Table of 13 Coordinate Pairs in the Horizontal and Vertical Directions describing the Surface of a Half-Round Obstacle with a 6-in. Radius.

6 in.-Radius Half-Round Obstacle			
Horizontal in.	Vertical in.	Horizontal in.	Vertical in.
0	0	7.55	5.8
0.2	1.55	9	5.2
0.8	3	10.24	4.24
1.76	4.24	11.2	3
3	5.2	11.8	1.55
4.45	5.8	12	0
6	6		

Table F.28: Table of 13 Coordinate Pairs in the Horizontal and Vertical Directions describing the Surface of a Half-Round Obstacle with an 8-in. Radius.

8 in.-Radius Half-Round Obstacle			
Horizontal in.	Vertical in.	Horizontal in.	Vertical in.
0	0	10.07	7.73
0.27	2.07	12	6.93
1.07	4	13.66	5.66
2.34	5.66	14.93	4
4	6.93	15.73	2.07
5.93	7.73	16	0
8	8		

Table F.29: Table of 13 Coordinate Pairs in the Horizontal and Vertical Directions describing the Surface of a Half-Round Obstacle with a 10-in. Radius.

10 in.-Radius Half-Round Obstacle			
Horizontal in.	Vertical in.	Horizontal in.	Vertical in.
0	0	12.59	9.66
0.34	2.59	15	8.66
1.34	5	17.07	7.07
2.93	7.07	18.66	5
5	8.66	19.66	2.59
7.41	9.66	20	0
10	10		

Table F.30: Table of 13 Coordinate Pairs in the Horizontal and Vertical Directions describing the Surface of a Half-Round Obstacle with a 12-in. Radius.

12 in.-Radius Half-Round Obstacle			
Horizontal in.	Vertical in.	Horizontal in.	Vertical in.
0	0	15.11	11.59
0.41	3.11	18	10.39
1.61	6	20.49	8.49
3.51	8.49	22.39	6
6	10.39	23.59	3.11
8.89	11.59	24	0
12	12		

Table F.31: Table of 13 Coordinate Pairs in the Horizontal and Vertical Directions describing the Surface of a Half-Round Obstacle with a 14-in. Radius.

14 in.-Radius Half-Round Obstacle			
Horizontal in.	Vertical in.	Horizontal in.	Vertical in.
0	0	17.62	13.52
0.48	3.62	21	12.12
1.88	7	23.9	9.9
4.1	9.9	26.12	7
7	12.12	27.52	3.52
10.38	13.52	28	0
14	14		

Table F.32: Table of 13 Coordinate Pairs in the Horizontal and Vertical Directions describing the Surface of a Half-Round Obstacle with a 16-in. radius.

16 in.-Radius Half-Round Obstacle			
Horizontal in.	Vertical in.	Horizontal in.	Vertical in.
0	0	20.14	15.45
0.55	4.14	24	13.86
2.14	8	27.31	11.31
4.69	11.31	29.86	8
8	13.86	31.45	4.14
11.86	15.45	32	0
16	16		

Table F.33: Table of 13 Coordinate Pairs in the Horizontal and Vertical Directions describing the Surface of a Half-Round Obstacle with an 18-in. Radius.

18 in.-Radius Half-Round Obstacle			
Horizontal in.	Vertical in.	Horizontal in.	Vertical in.
0	0	22.66	17.39
0.61	4.66	27	15.59
2.41	9	30.73	12.73
5.27	12.73	33.59	9
9	15.59	35.39	4.66
13.34	17.39	36	0
18	18		

F.6.3. Trapezoidal Obstacles

The 72 trapezoidal obstacles are defined in NRMM v2.8.2, and associated documentation (Haley, Jurkat and Brady, 1979).

F.7. 3-CM RANDOM PROFILE COURSE

F.8. 6-CM RANDOM PROFILE COURSE

F.9. 9-CM RANDOM PROFILE COURSE

The data for F.7, F.8, and F.9 for three Random Profile Courses are available for download from NATO STO at https://www.sto.nato.int/pages/natostandards.aspx.

F.10. REFERENCES

1. Conner, C. 2017. Armored Personnel Carrier. Available at: http://afvdb.50megs.com/usa/m113.html. updated Feb. 25, 2017.

2. Haley, P.W., Jurkat, M.P. and Brady, Jr., P.M. 1979. NATO Reference Mobility Model, Edition 1, Users Guide Volume II, Obstacle Module. US Army Tank-Automotive Research and Development Command. Technical Report 12503. October 1979.

3. ISO 8608. 2016. Mechanical Vibration – Road Surface Profiles – Reporting of Measured Data, Second Ed. 2016-11.

4. Wong, J.Y. 2015. Evaluation of the Computer-Aided Method NTVPM For Assessing Tracked Vehicle Cross-Country Performance. Final Report, Part I. Prepared by Vehicle Systems Development Corporation, Ottawa, Ontario, Canada for U.S. Army Tank-Automotive Research, Development and Engineering Center, Warren, MI 48397-5000, U.S.A.

5. Wong, J.Y., Jayakumar, P. and Preston-Thomas, J. 2019. Evaluation of the Computer Simulation Model NTVPM For Assessing Military Tracked Vehicle Cross-Country Mobility. Proceedings of the Institution of Mechanical Engineers. Vol. 233. Issue 5. 1194-1213.

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ANNEX G NG-NRMM WHEELED VEHICLE BENCHMARK DATA

G.1. WHEELED VEHICLE PLATFORM: VEHICLE DATA

1. The Wheeled Vehicle Platform (WVP) used for the benchmark is a high-mobility 4WD vehicle designed and build by Nevada Automotive Test Center (NATC). The vehicle design data as well as the reference test data are provided by NATC. The original detailed vehicle data can be found in a spreadsheet available at the Science Connect Server: https://www.sto.nato.int/pages/natostandards.aspx.

Table G.1 gives an overview of the vehicle details available in the spreadsheet.

Table G.1: Overview of Vehicle Data Available.

System	**Details**
Steering	Component CG, mass, and Inertia Steering compliance Hard points and joint descriptions
Front & Rear Suspension	Component CG, mass, and Inertia Hard points Bushing compliance Jounce and Rebound bumper stiffness Strut "spring" rate Description of strut damping behavior: Single wheel travel Parallel travel Roll stabilization
Powertrain	Component CG, mass, and Inertia Engine torque curve Parasitic loads Transmission ratios Differential ratio Hub ratio Available lock-up configurations Engine rotational inertia Engine compression braking behavior
Tires	Component CG, mass, and Inertia Load vs deflection curve Cornering and lateral stiffness Standard spec sheet characteristics Pacejka Coefficients (lateral, longitudinal, and aligning)

2. Views of the Vehicle are shown in Figures G.1, G.2, and G.3 below.

Figure G.1: Top View of Vehicle.

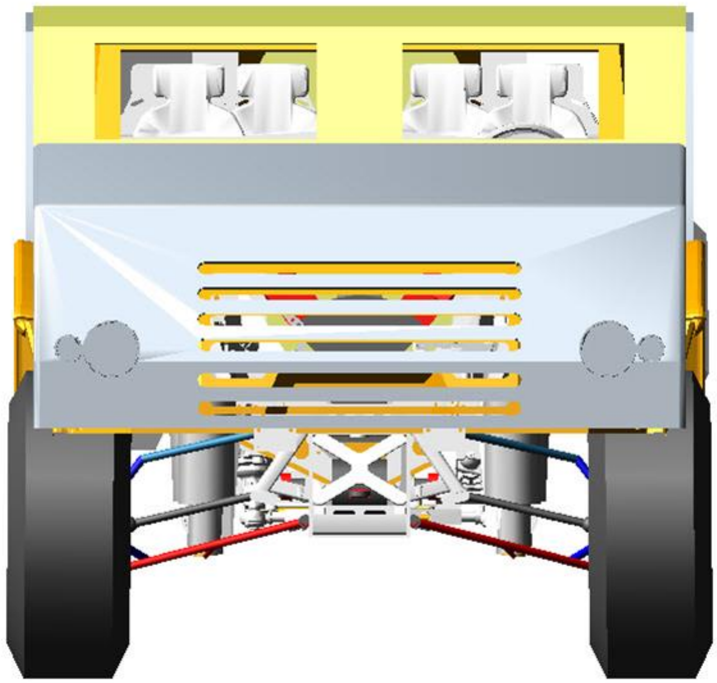


Figure G.2: Front View of Vehicle.

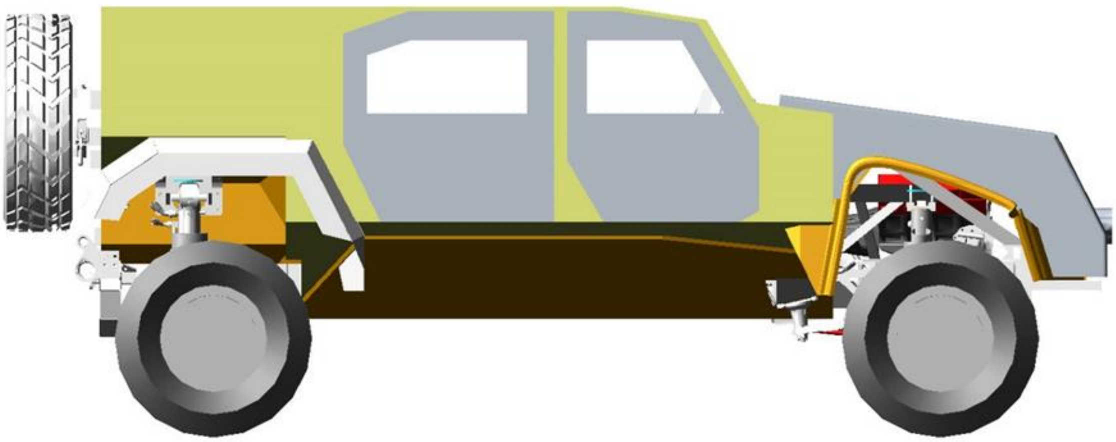


Figure G.3: Side View of Vehicle.

3. General vehicle data is shown in Table G.2.

Table G.2: General Vehicle Data.

General Data			
Wheel Base	4039	mm	
Track Width Front Axle	2066	mm	
Track Width Rear Axle	2066	mm	
Total Vehicle Length	5588	mm	
Vehicle Width	2449	mm	
Vehicle Height Including Cabin	2347	mm	
Horiz. Distance Front To Wheel Center Front	926	mm	
Horiz. Distance Rear To Wheel Center Rear	633	mm	
Vehicle Approach Angle	50	deg	
Vehicle Departure Angle	80	deg	
Fording Depth	762	mm	
Payload	2727	kg	
King Pin Inclination	8.9	deg	
Alignment Data At Static			
Camber Angle	-0.5	deg	
Toe	front = -0.9 deg rear= 0.4 deg		
Weight Distribution as Tested (fully payloaded)	**Left (lb)**	**Right (lb)**	**Total (lb)**
Front Axle	5170	5100	10270
Rear Axle	4800	4630	9430
Total	9970	9730	19700
	X	**Y**	**Z**
Estimated CG at model design position (mm)	2070	-10	495
Estimated Inertia about CG			
Roll	6.7E+09	kg-mm^2	
Pitch	2.5E+10	kg-mm^2	
Yaw	2.8E+10	kg-mm^2	

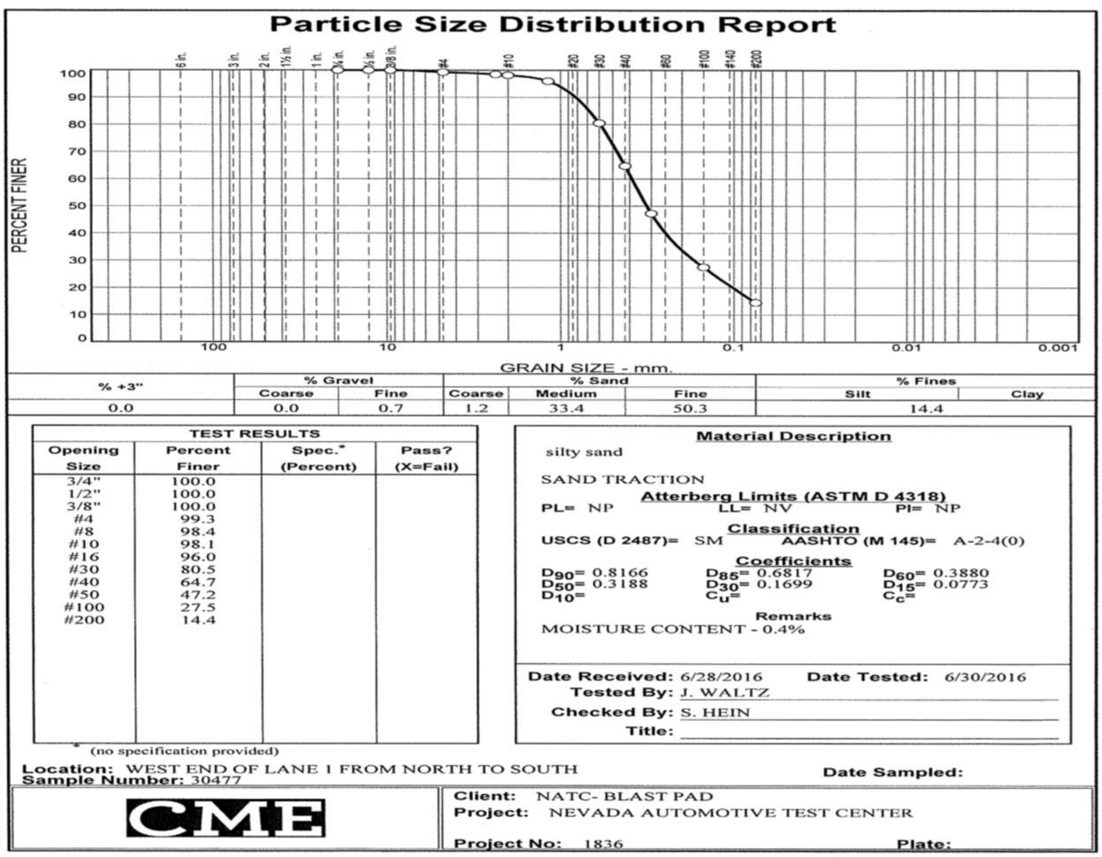
G.2. TERRAIN DATA FOR WVP TESTING

1. Tests were made on pavement, gravel and soft soil. Only one type of soft soil was used in the WVP testing. It was sand with the properties shown in Table G-3 and the particle size distribution as shown in Table G-4.

Table G.3: Properties of the Terrain Used in WVP Testing.

Property	Value	Units
Density	1650	kg/m^3
Moisture Content	1.1	%
Cohesion Strength C	1.10 x 10^3	n/m^2
Friction Angle	32	degrees
Janosi-Hanamoto shear modulus K	0.025	m

Table G.4: Particle Size Distribution of the Terrain used in WVP Testing.


Particle Size Distribution Report

% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.7	1.2	33.4	50.3	14.4	

TEST RESULTS

Opening Size	Percent Finer	Spec.* (Percent)	Pass? (X=Fail)
3/4"	100.0		
1/2"	100.0		
3/8"	100.0		
#4	99.3		
#8	98.4		
#10	98.1		
#16	96.0		
#30	80.5		
#40	64.7		
#50	47.2		
#100	27.5		
#200	14.4		

* (no specification provided)

Material Description

silty sand

SAND TRACTION

Atterberg Limits (ASTM D 4318)

PL= NP LL= NV PI= NP

Classification

USCS (D 2487)= SM AASHTO (M 145)= A-2-4(0)

Coefficients

D_{90}= 0.8166 D_{85}= 0.6817 D_{60}= 0.3880
D_{50}= 0.3188 D_{30}= 0.1699 D_{15}= 0.0773
D_{10}= C_u= C_c=

Remarks

MOISTURE CONTENT - 0.4%

Date Received: 6/28/2016 **Date Tested:** 6/30/2016
Tested By: J. WALTZ
Checked By: S. HEIN
Title:

Location: WEST END OF LANE 1 FROM NORTH TO SOUTH
Sample Number: 30477
Date Sampled:

CME

Client: NATC- BLAST PAD
Project: NEVADA AUTOMOTIVE TEST CENTER
Project No: 1836
Plate:

G.3. TEST DATA

1. The results of testing are shown in the following figures.

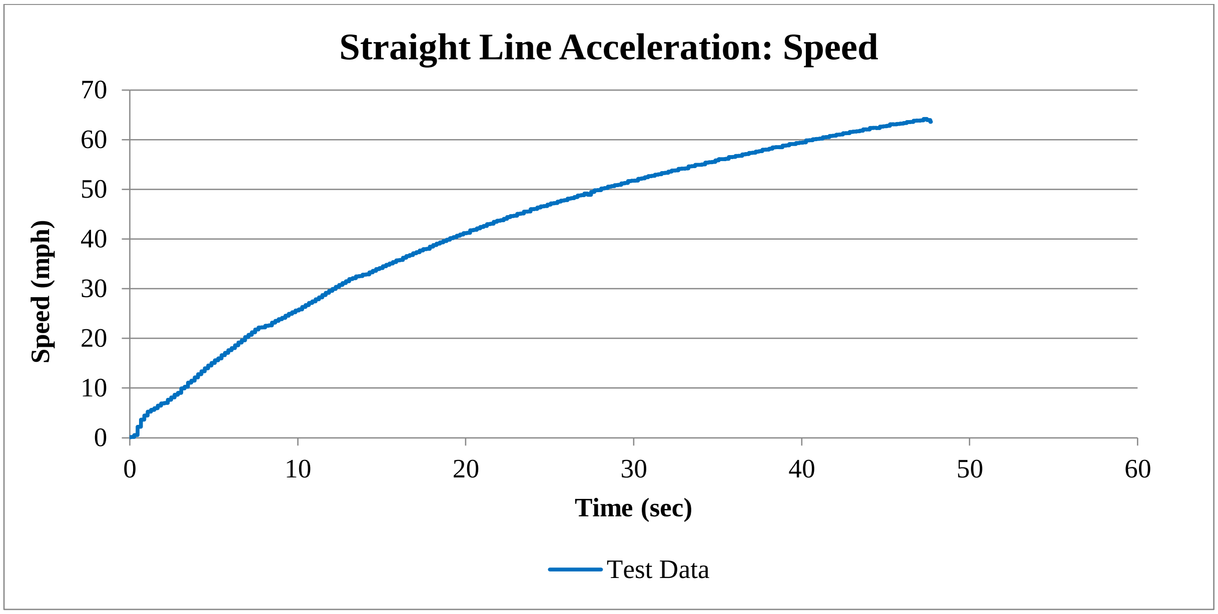


Figure G.4: Straight Line Acceleration on Paved Surface.

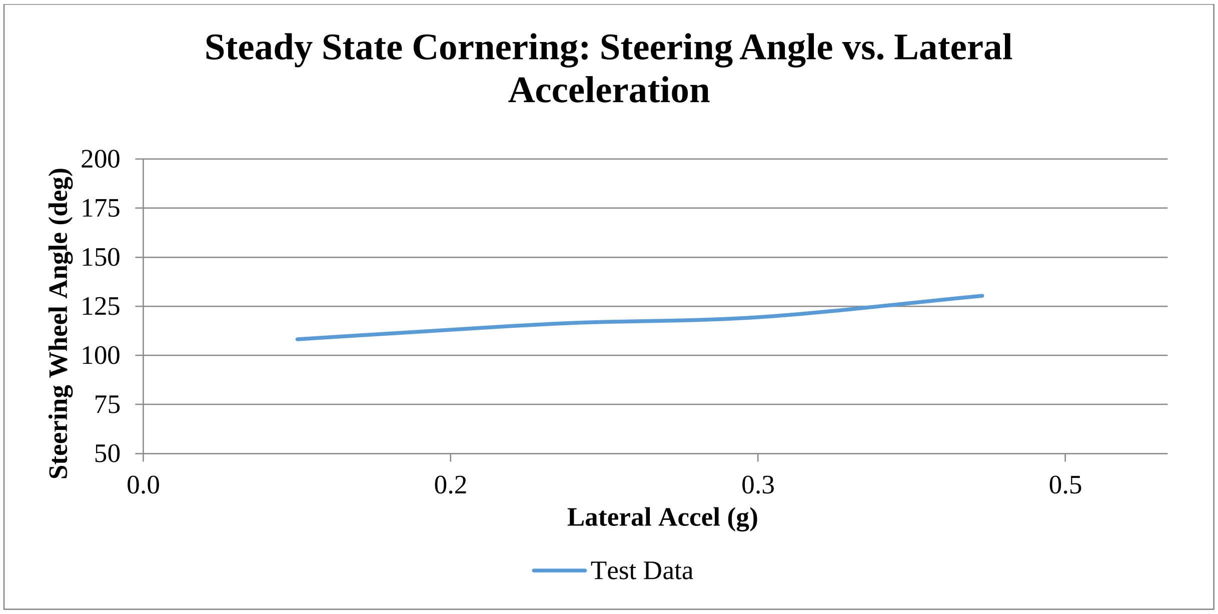
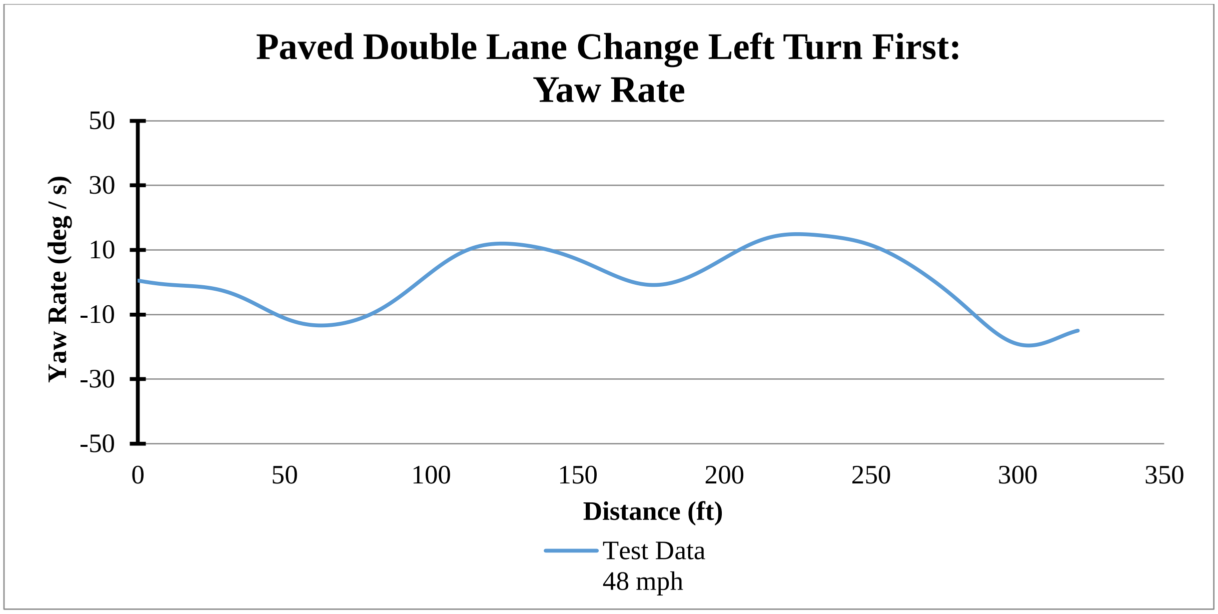


Figure G.5: Steady State Cornering on Paved Surface.



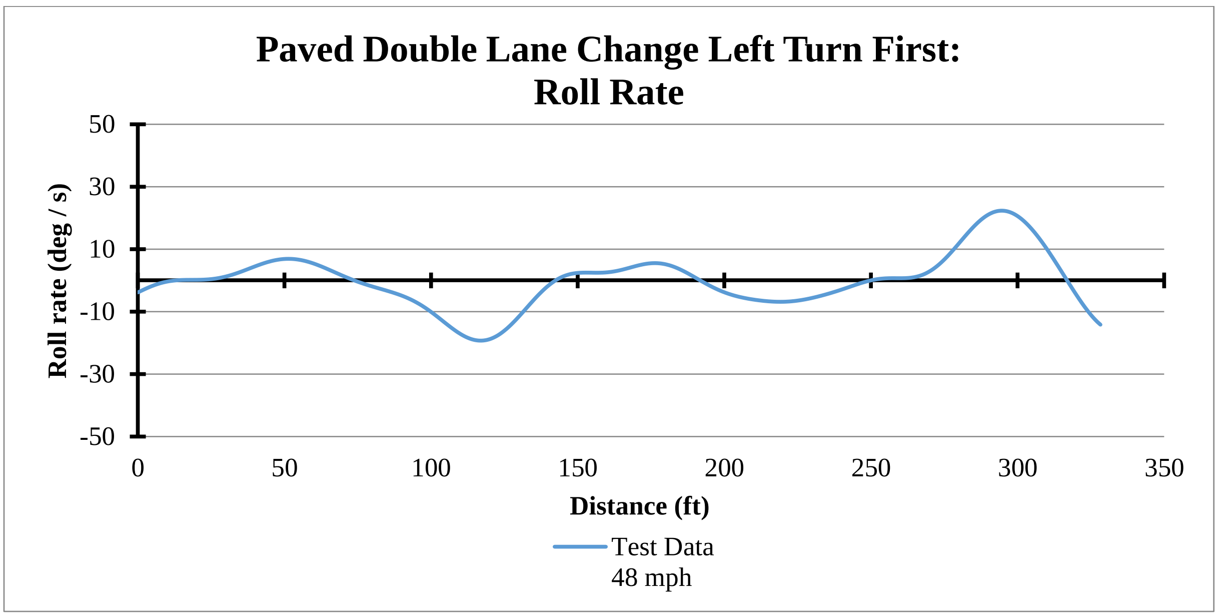


Figure G.6: Paved Double Lane Change Left Turn First, Yaw and Roll Rate.

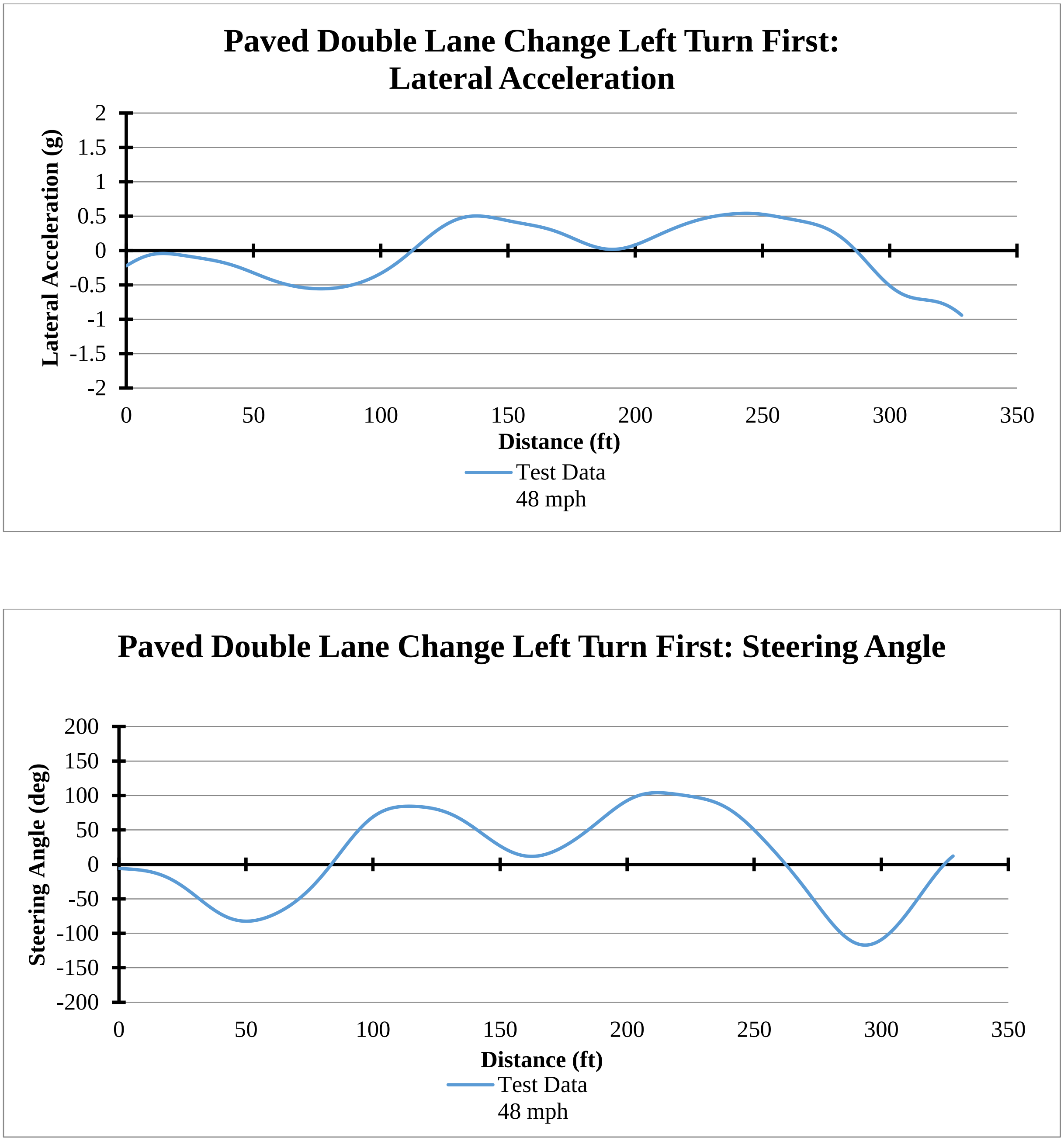
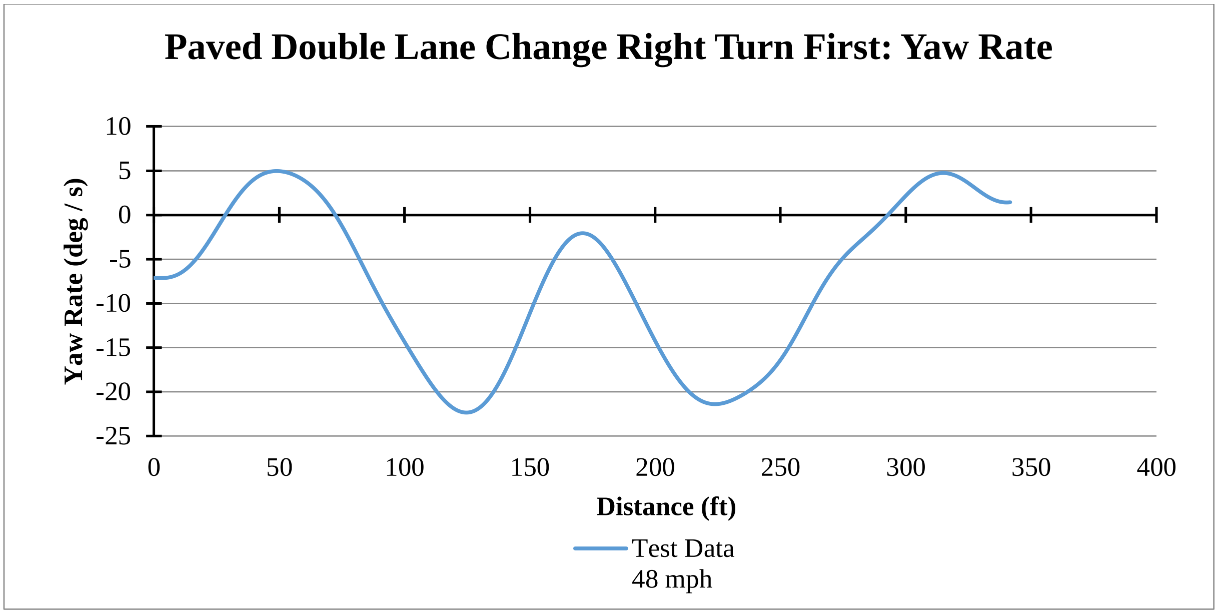


Figure G.7: Paved Double Lane Change Left Turn First, Lateral Acceleration and Steering Angle.



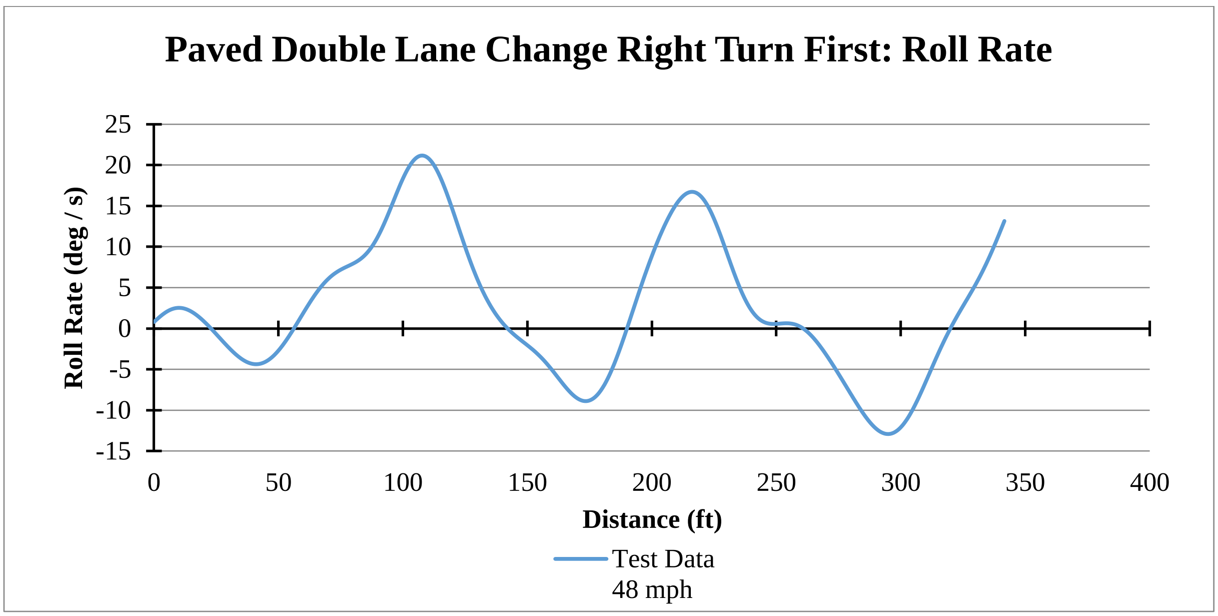
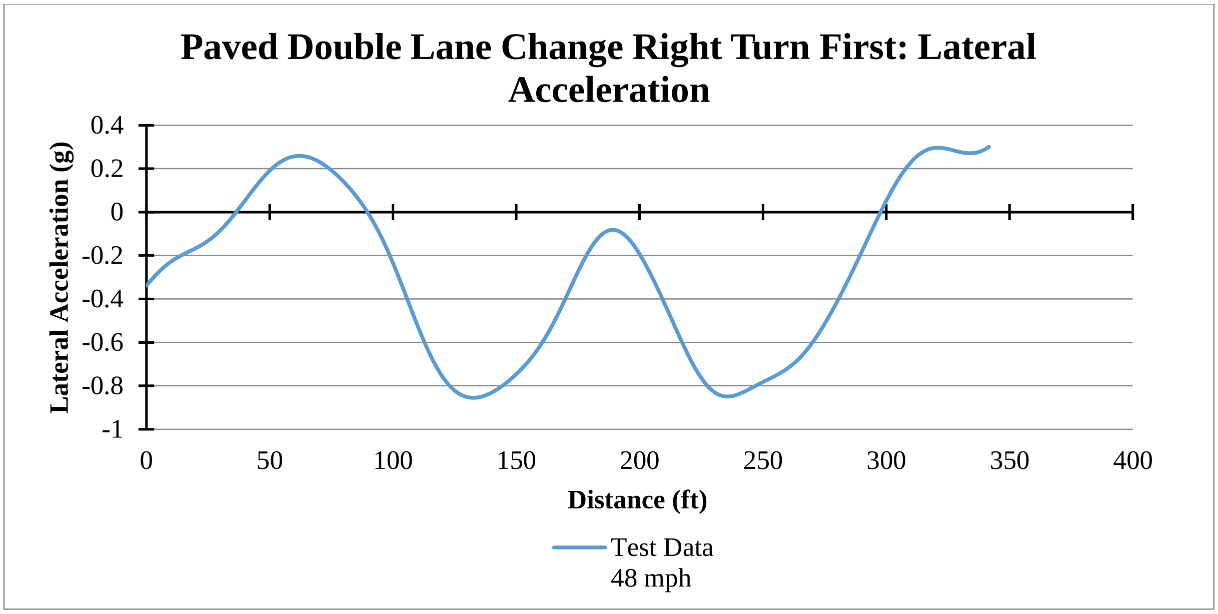


Figure G.8: Paved Double Lane Change Right Turn First, Yaw and Roll Rate.



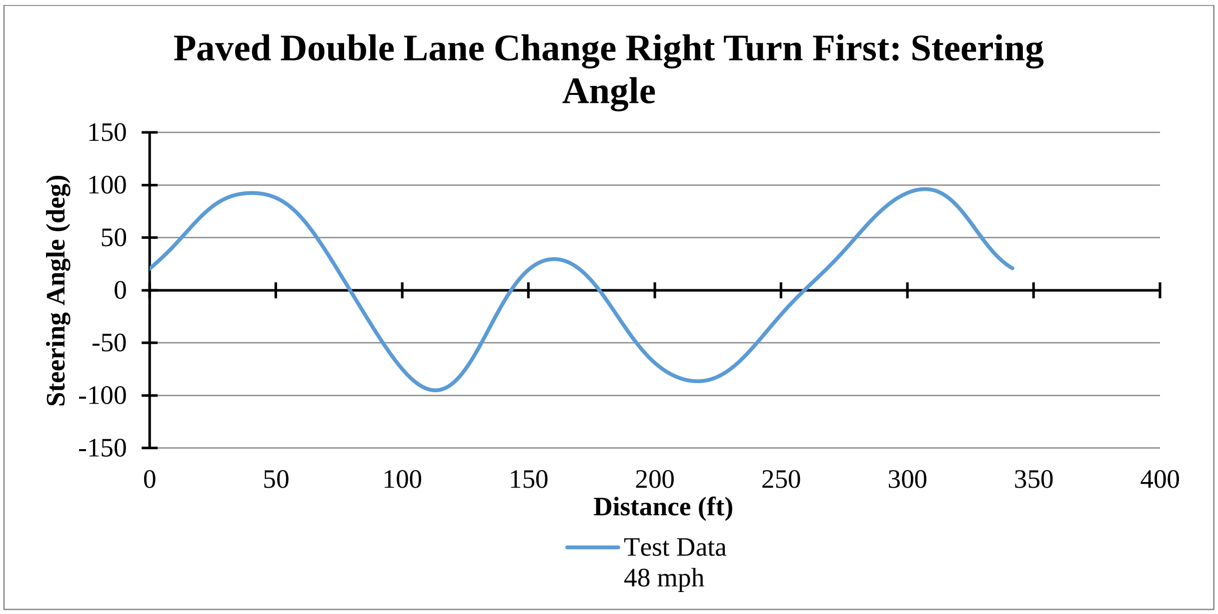
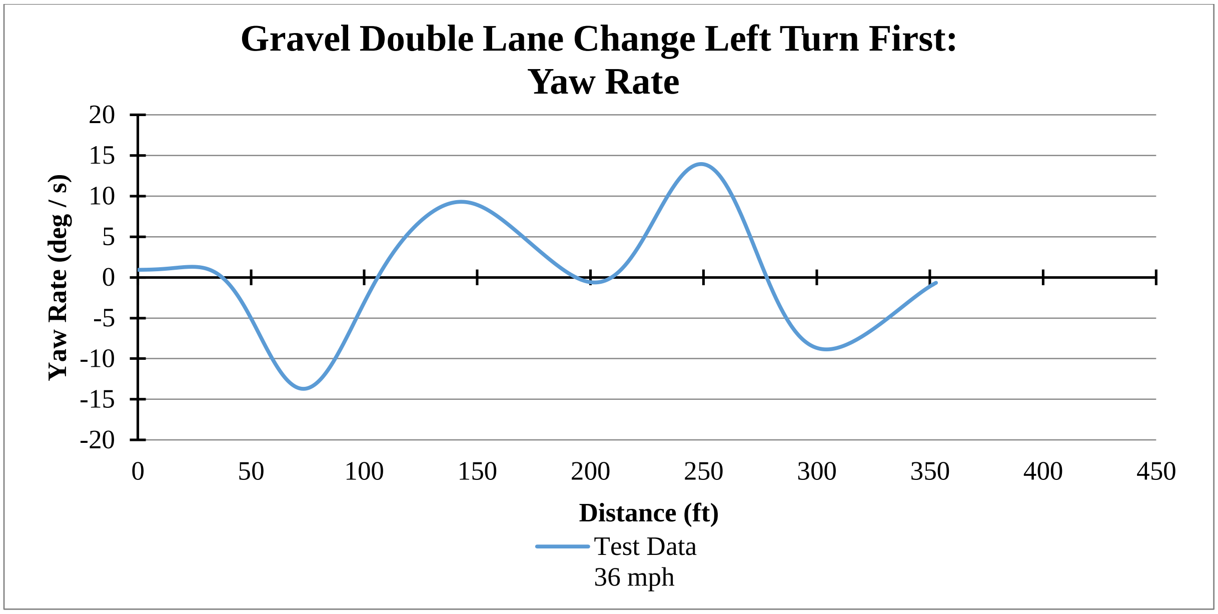


Figure G.9: Paved Double Lane Change Right Turn First, Lateral Acceleration and Steering Angle.



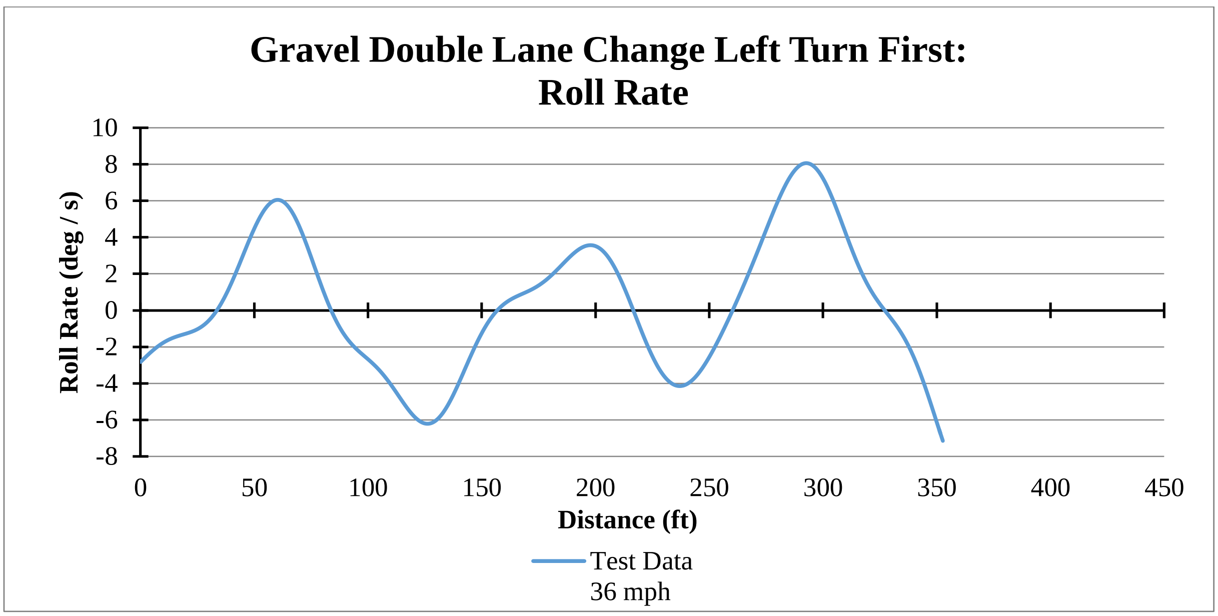
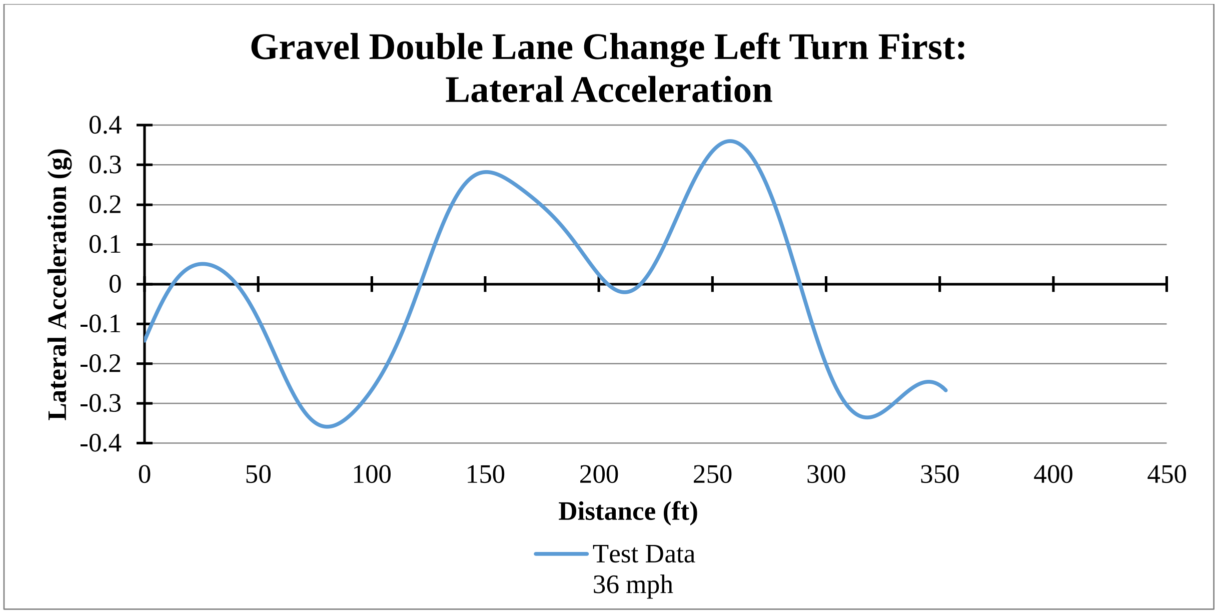


Figure G.10: Gravel Double Lane Change Left Turn First, Yaw and Roll Rate.



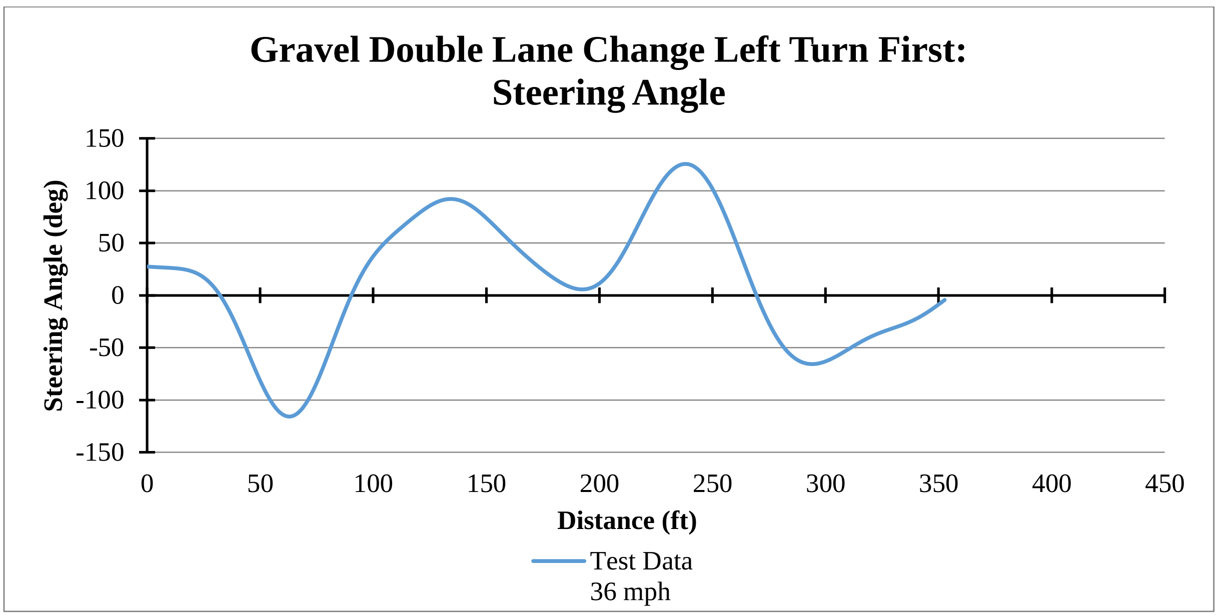
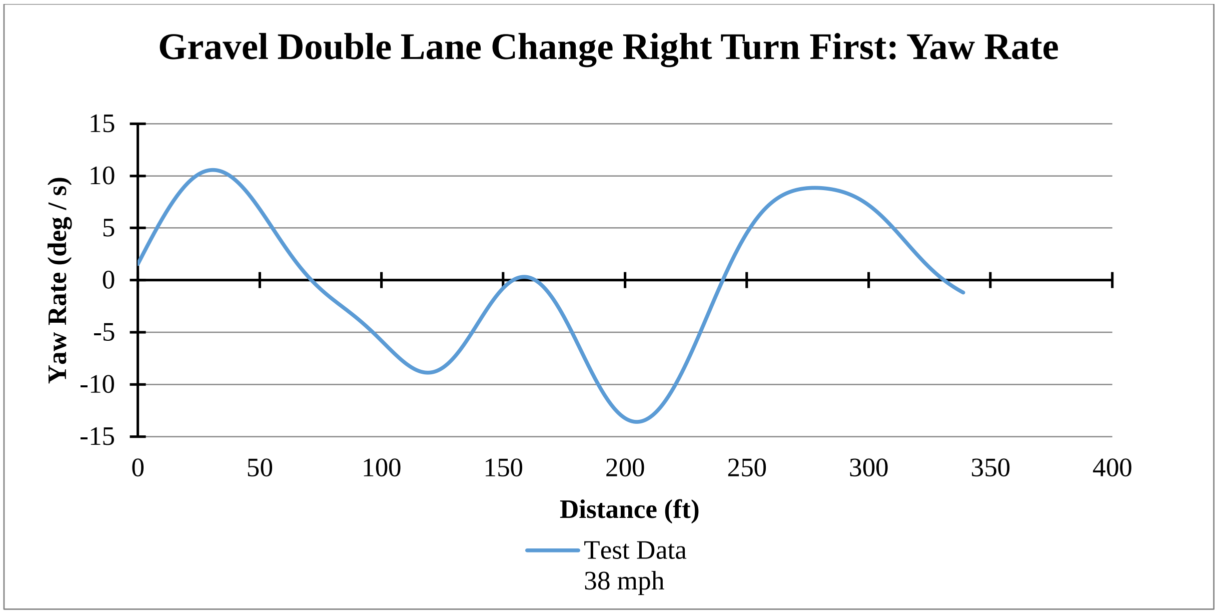


Figure G.11: Gravel Double Lane Change Left Turn First, Lateral Acceleration and Steering Angle.



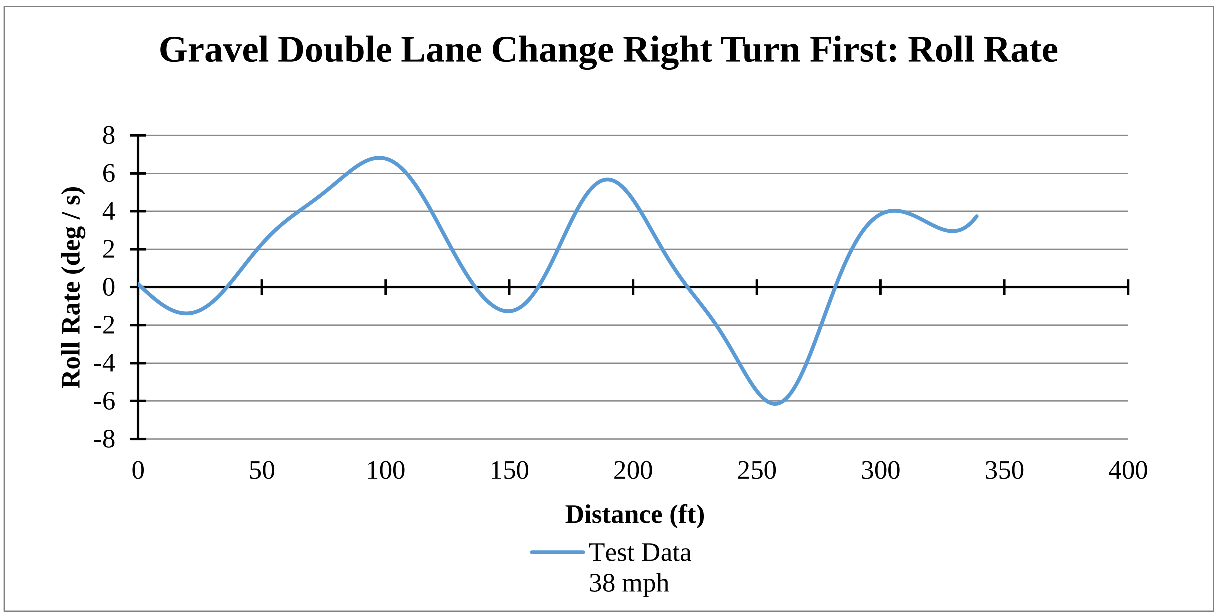
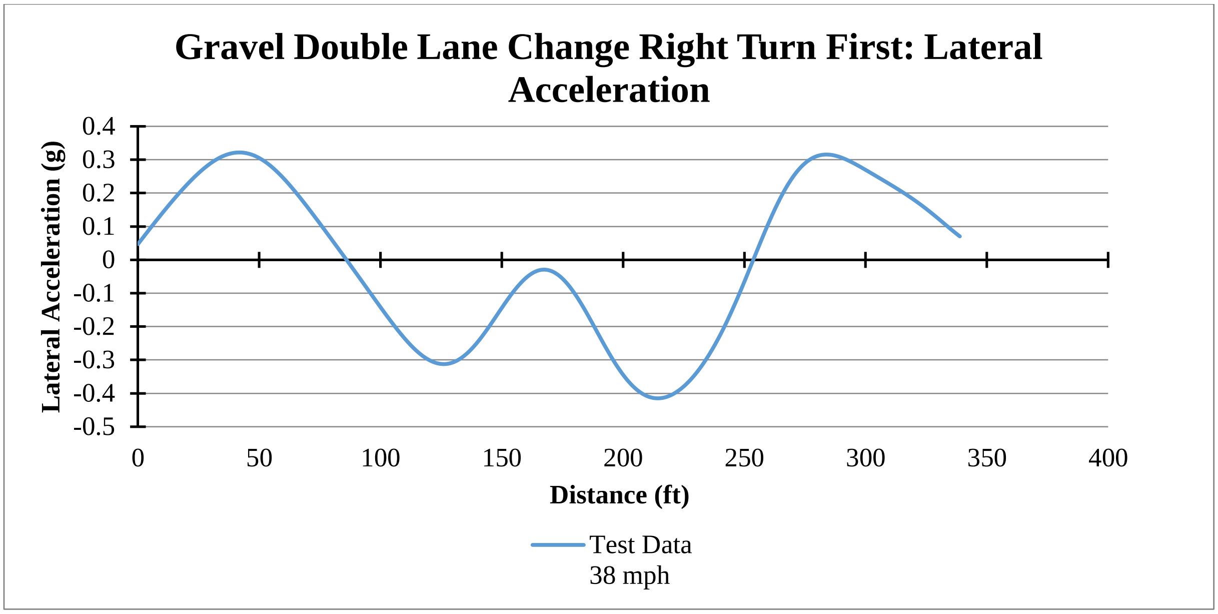


Figure G.12: Gravel Double Lane Change Right Turn First, Yaw and Roll Rate.



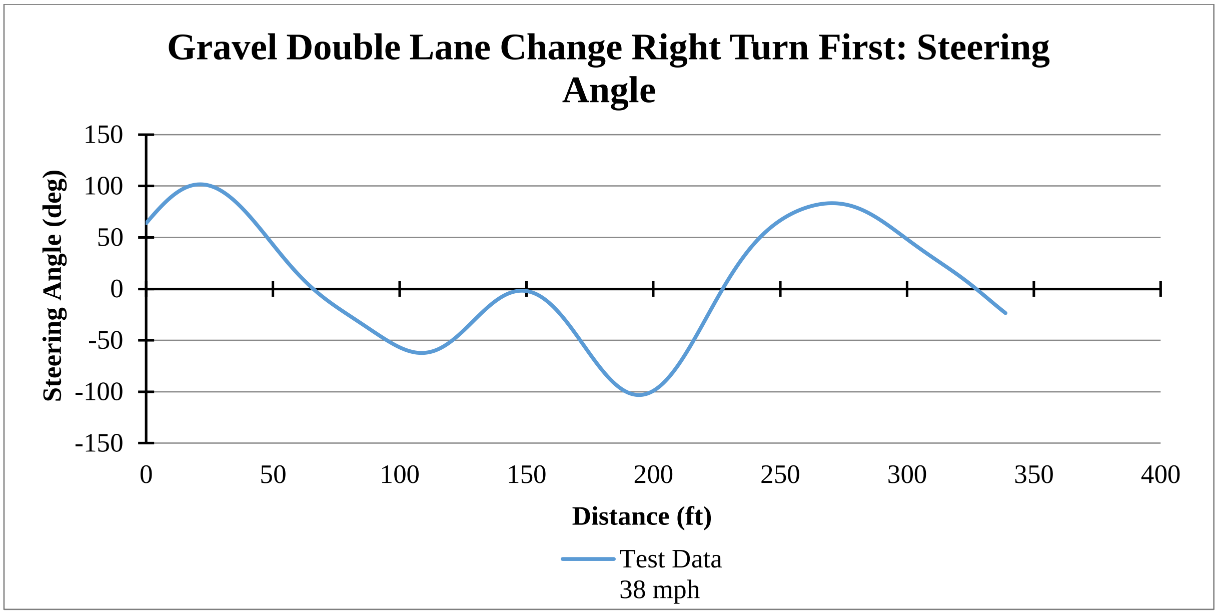
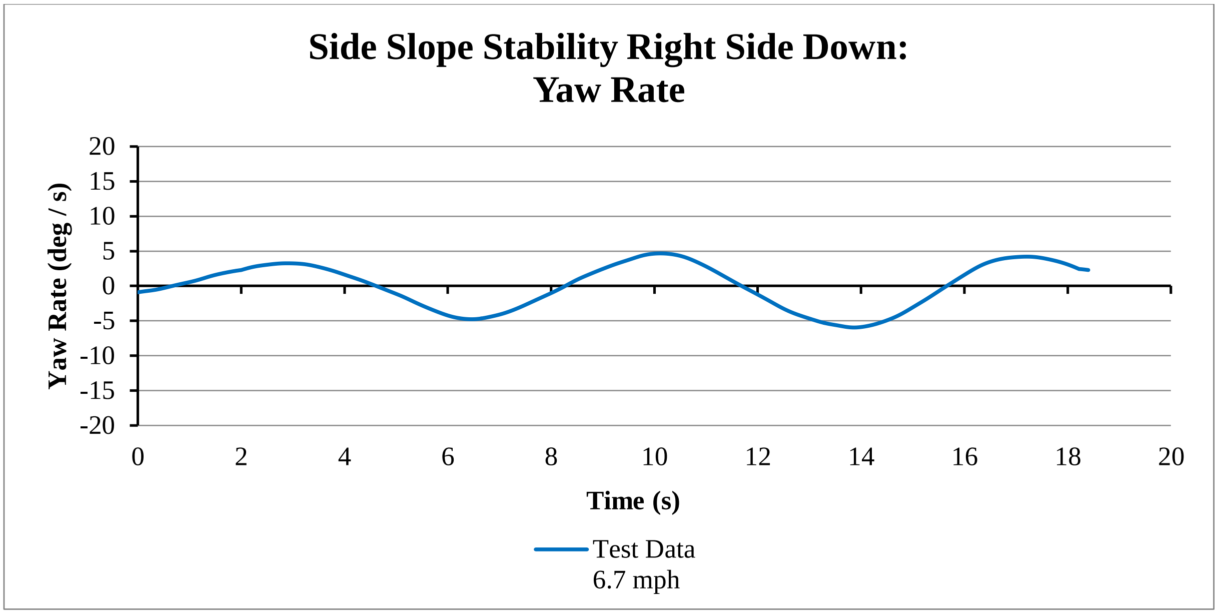


Figure G.13: Gravel Double Lane Change Right Turn First, Lateral Acceleration and Steering Angle.



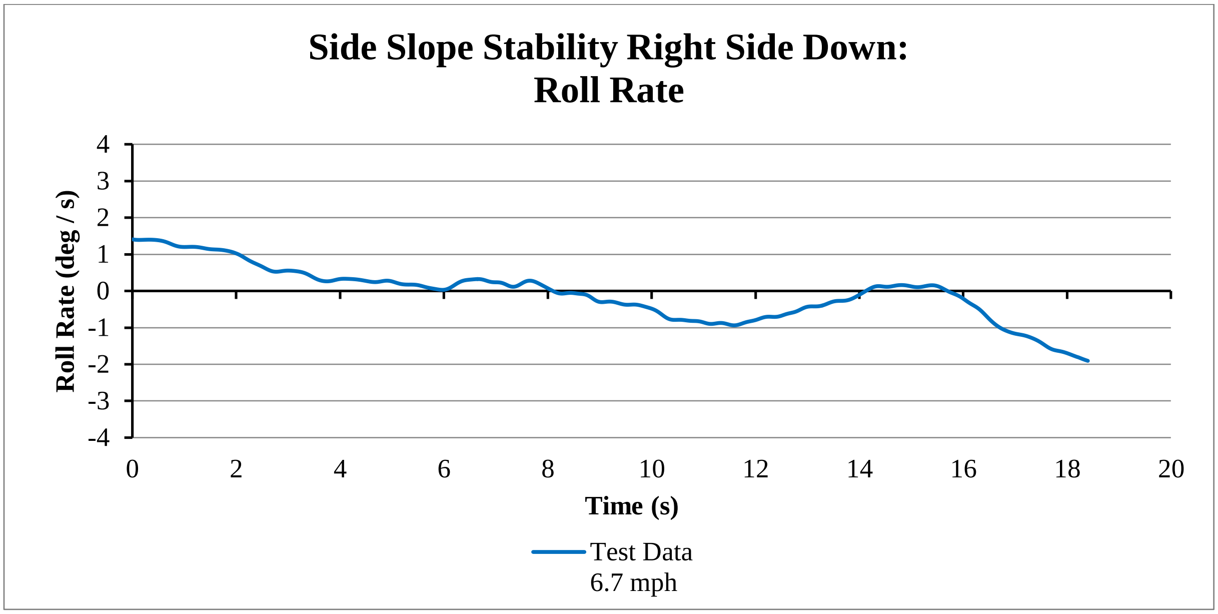
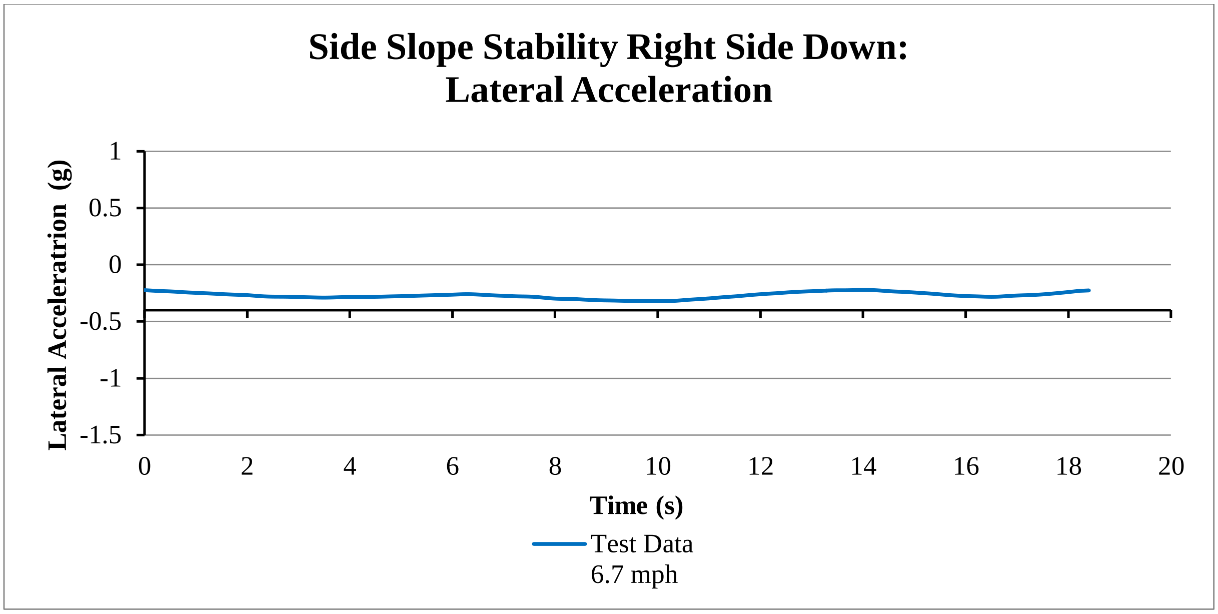


Figure G.14: Side Slope Stability Right Side Down, Yaw and Roll Rate on Compacted Soil (Non-deformable).



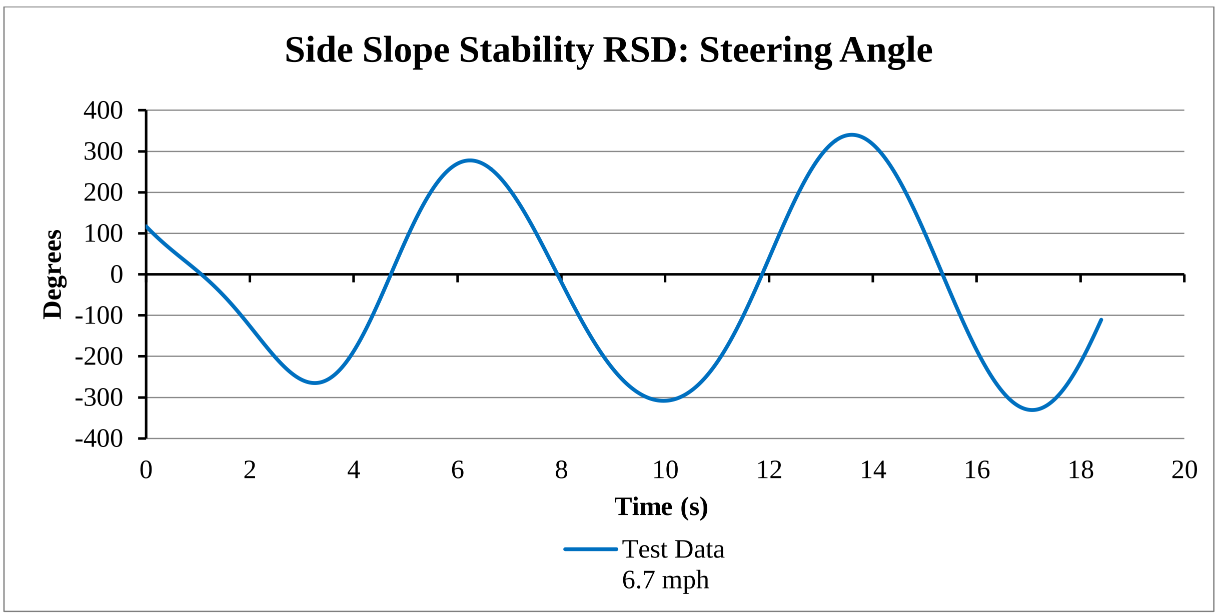
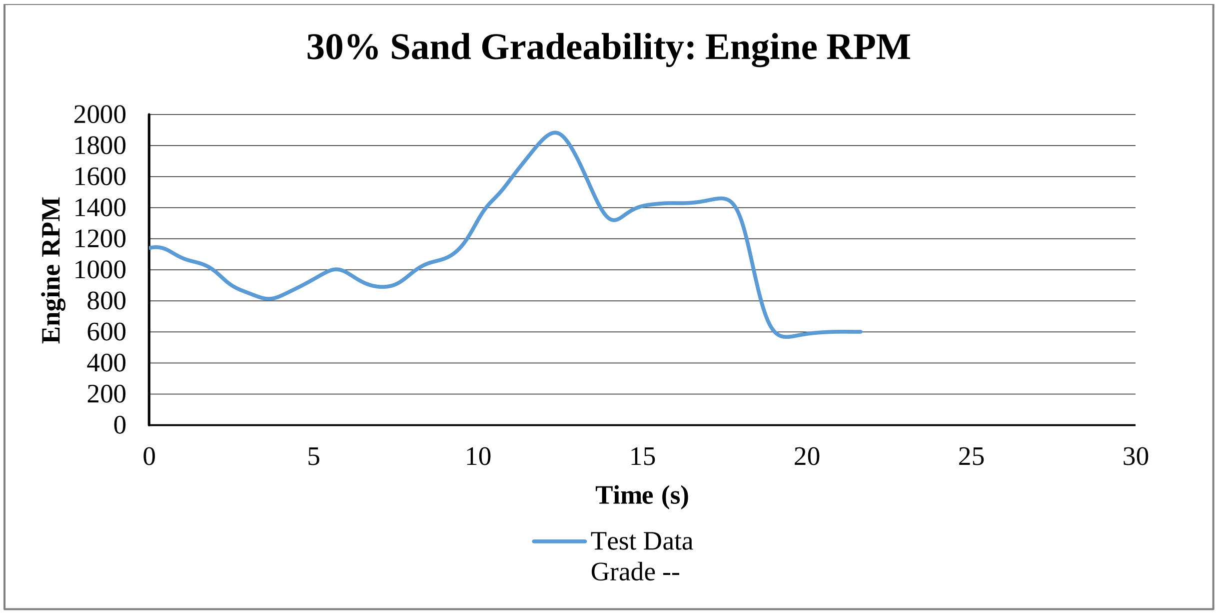


Figure G.15: Side Slope Stability Right Side Down, Lateral Acceleration and Steering Angle on Compacted Soil (Non-deformable).



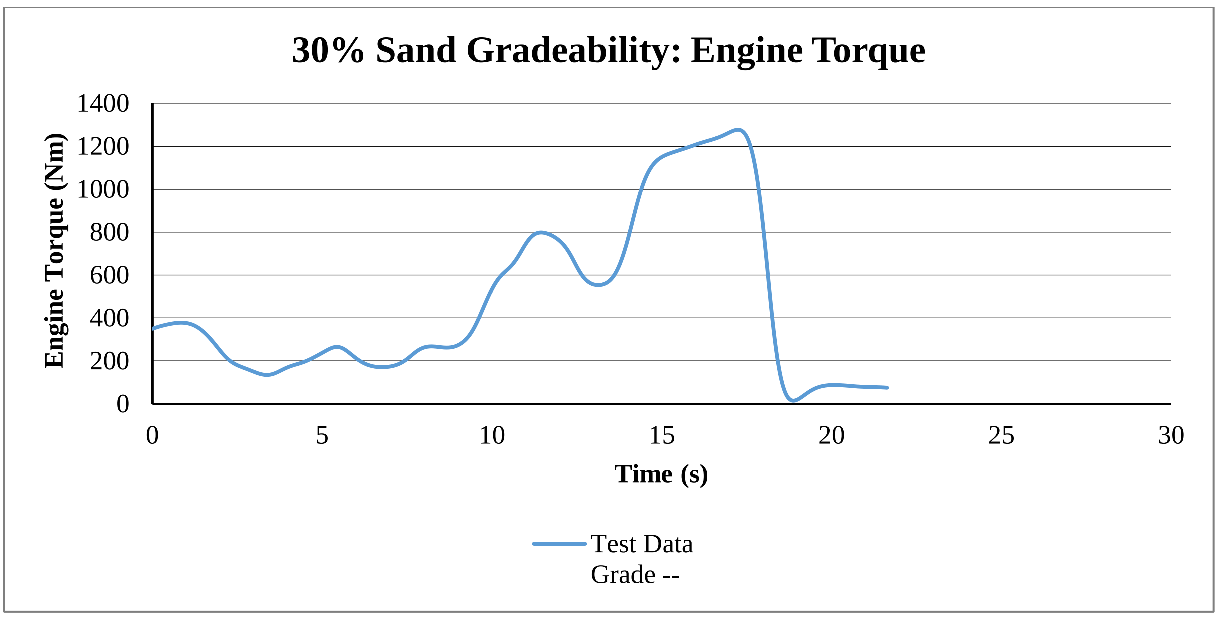


Figure G.16: Sand Gradeability.

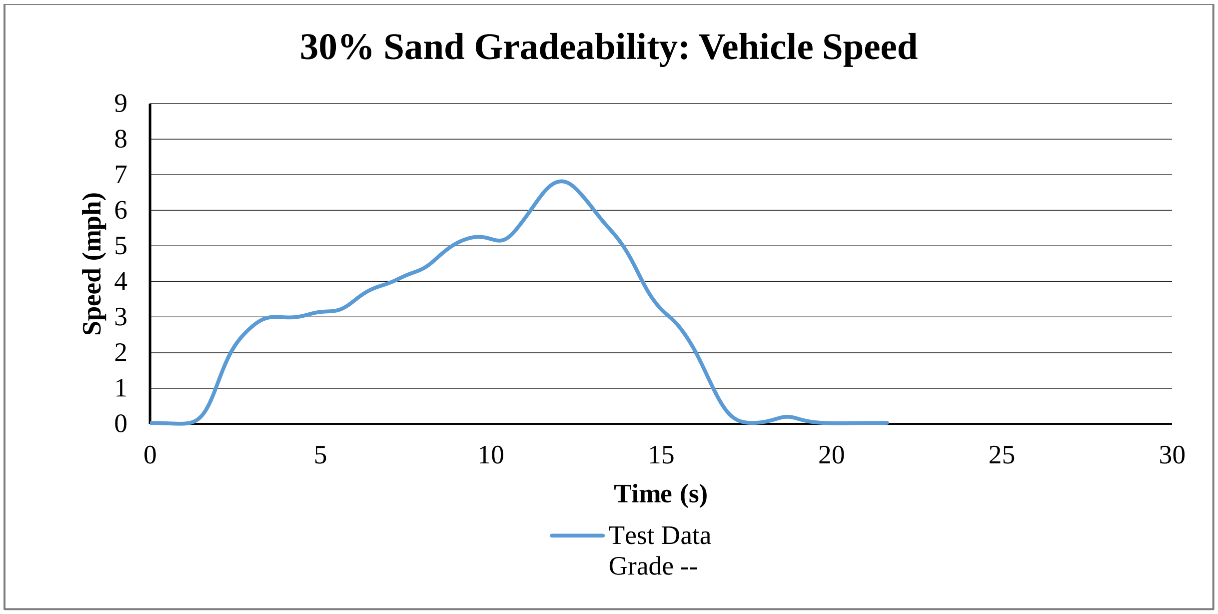


Figure G.17: Sand Gradeability.

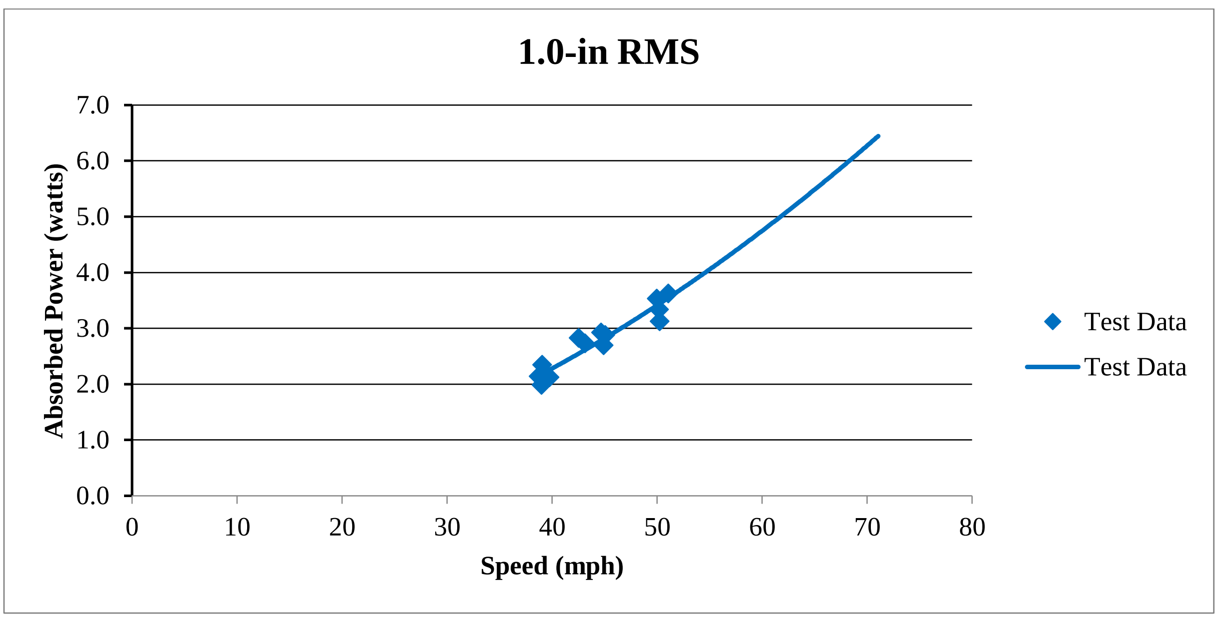
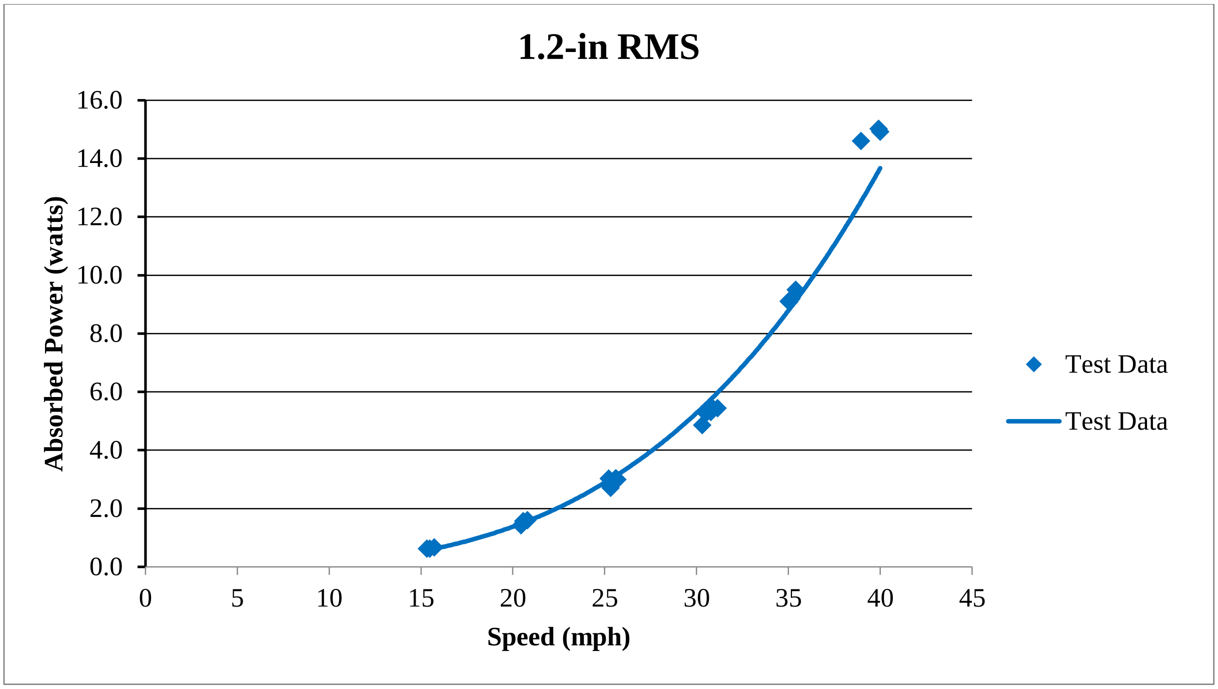


Figure G.18: Ride Quality at 1.0-in RMS on Compacted Soil (Non-deformable).



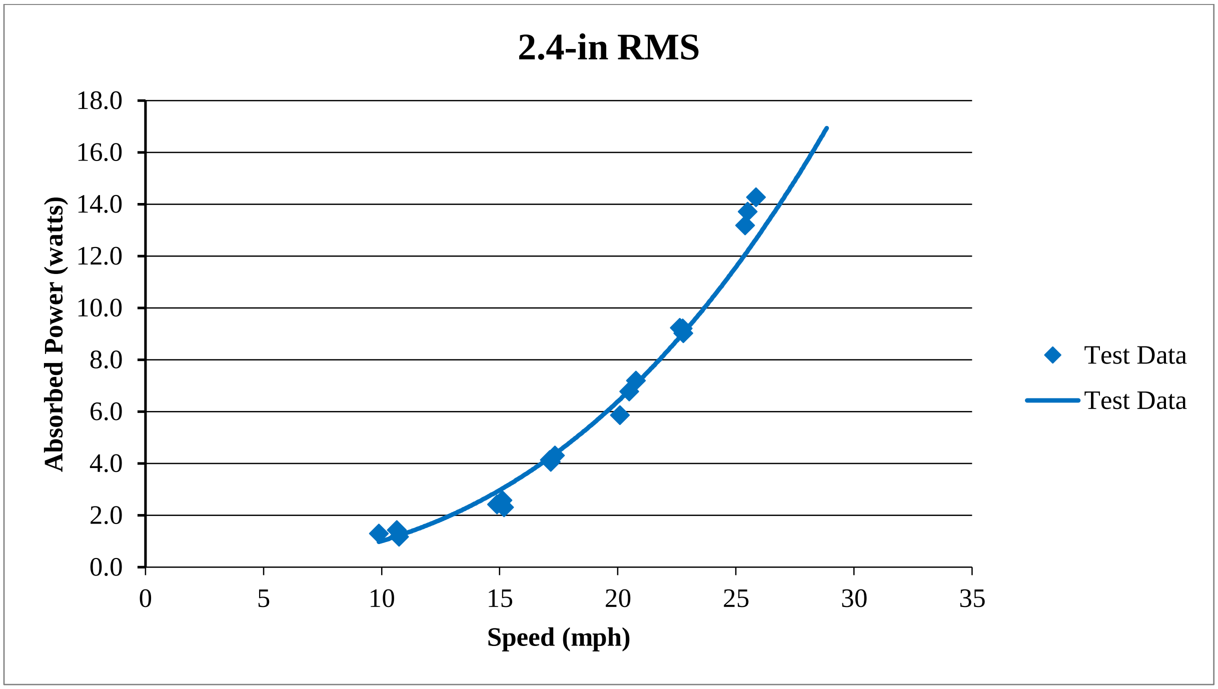


Figure G.19: Ride Quality at 1.2- and 2.4-in RMS on Compacted Soil (Non-deformable).

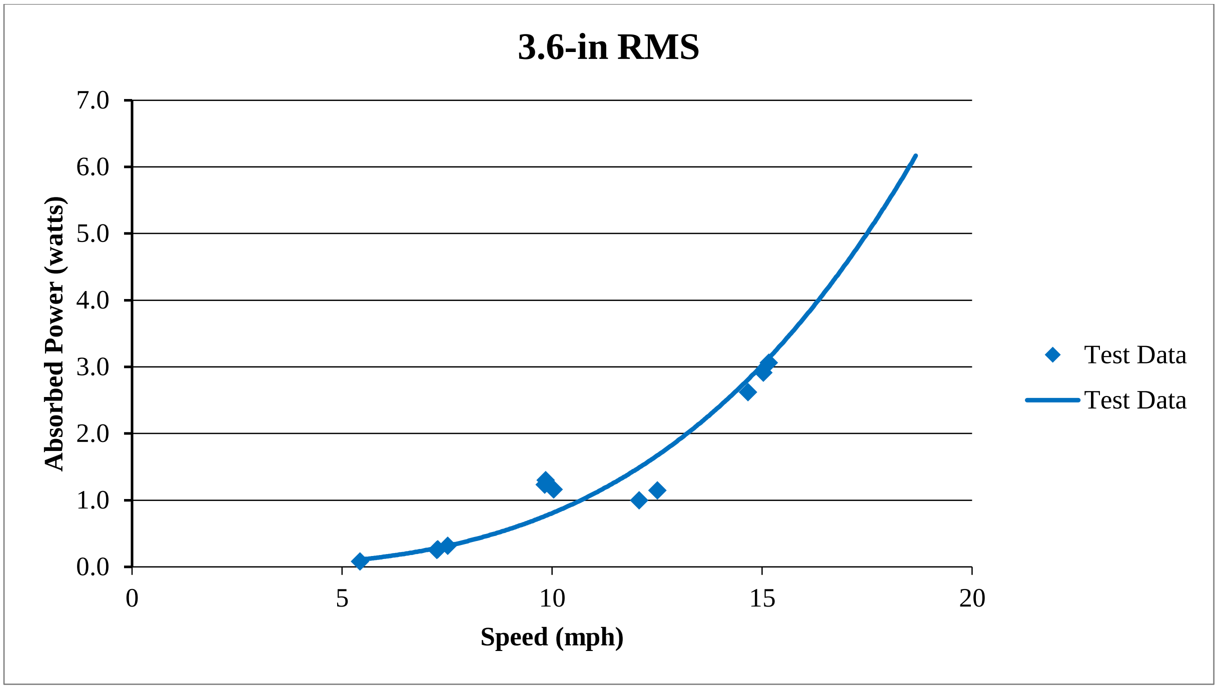


Figure G.19: Ride Quality at 3.6-in RMS on Compacted Soil (Non-deformable).

ANNEX H COOPERATIVE DEMONSTRATION OF TECHNOLOGY (CDT) DATA

The data from the CDT are available for download from NATO STO at https://www.sto.nato.int/pages/natostandards.aspx. This includes the vehicle data (Annex H1), the terrain data (Annex H2), and the test data (Annex H3).

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ANNEX I ENVISIONED FIELD USE OF AVAILABLE MOBILITY ANALYSIS TOOLS BY MILITARY PLANNERS

I.1. INTRODUCTION

1. This Annex provides a description of how an operational unit would use a successfully implemented NG-NRMM in mission planning to generate mobility corridors from which to support development of a Scheme of Maneuver or movement routes for operational forces.

2. To accomplish that task, this section uses an operational vignette technique to define a notional but operationally relevant area of operations and illustrates how area reconnaissance and GeoIntelligence products would be compiled and processed in NG-NRMM, developing mobility prediction products in relation to specific vehicles of the unit user. The planning staff would frame the area of operations, avenues of interest, then enter vehicle configurations as reflected in unit Table of Equipment to predict vehicle trafficability and Speed-Made-Good within mobility corridors, or alternatively along specific routes. This vignette Annex is created to illustrate its utility for operational planning.

I.1.1. The Problem that Field Use of NG-NRMM Seeks to Solve

1. Military staffs planning to conduct mounted maneuver operations frequently lack real time tools and information to support maneuver planning during the Intelligence Preparation of the Battlefield (IPB) process. Current planning can be based on information gathered days or weeks prior to the operation, failing to reflect changes due to recent environmental or operational events. Military engineer units, responsible for conducting engineer reconnaissance, are often under-manned, and today have limited or inaccurate field tools and insufficient time to perform trafficability analysis. This project seeks to resolve that problem by combining digital terrain databases augmented with remote sensing products to generate a high-fidelity, trafficability assessment based on known mobility parameters of the deployed tactical and combat vehicles. This allows the military engineers and unit commanders to plan maneuver corridors to an acceptable confidence level.

2. As NATO forces conduct missions over a wide variety of terrains, an updated NG-NRMM can substantially improve situational awareness and better focus reconnaissance assets to determine terrain trafficability and provide information to the individual unit for feasible and/or best terrain path to achieve mission completion. By equipping the planning staff with NG-NRMM combined with improved remote reconnaissance sensing platforms, military planning staffs would have the ability to generate/update local digital Modified Combined Obstacle Overlays (MCOO) with improved fidelity in trafficability (Go, Slow-Go, or No-Go) projections. By continuing to use the MCOO methodology, but with

improved databases and analytical tools, planners could reduce the time associated with the deliberate staff planning activity to provide high-fidelity localized products.

I.2. TECHNICAL CONCEPT

Recognizing NG-NRMM as a vehicle mobility prediction computational database integrated with terrain data from higher level sources (MAP-11, FACC+ format, GeoTIFF, other), develop a tool for military planners to support reconnaissance on mobility corridors and route alternatives for mounted formations. Where additional reconnaissance is warranted, manned reconnaissance or remote sensors will be deployed to tailor the geospatial core database with surface and terrain condition data. The computational tool then solves for feasible trafficable corridors and routes based on vehicle performance data stored in the computational database. The vision is to provide staffs conducting maneuver and route reconnaissance planning with data informed analysis in lieu of manual, qualitative mobility estimation.

I.3. NG-NRMM OPERATIONAL CONCEPT OF EMPLOYMENT

I.3.1. NG-NRMM in Support of the IPB Process

1. This section describes how an operational unit would use NG-NRMM in the IPB process to generate mobility corridors from which to support development of a Scheme of Maneuver or movement routes for operational forces.

2. Key Definitions

a. Intelligence Preparation of the Battlefield:

(1) The IPB process <u>combines intelligence on the battlefield environment</u> and threat doctrine to determine how the Opposing Forces will complete their mission and how the 'Blue Forces' will accomplish ours.

(2) An early step in the process is analyzing the battlefield within the assigned Area of Operations (AO). During this activity, the analysts determine what information, products, and support will be required to complete the IPB.

(3) Key inputs to NG-NRMM during this process will be provided by the planning staff as they gain <u>information on the terrain, hydrography and weather</u> to support mobility predictions.

b. Mobility Corridor:

(1) An area where a military force will find some route or combination of routes to be passible, due to the characteristics of the terrain and surface structures and vegetation. Given the Area of Responsibility (AOR) the mobility corridor provides the most promising avenue to maneuver, therefore it is relatively free of obstacles and No-Go areas.

(2) Mobility corridors are combined to develop avenues of approach / axis of advance.

(a) Regimental avenues of approach / axis of advance have battalion mobility corridors no more than 6 kilometres apart.
(b) Battalion avenues of approach / axis of advance have company mobility corridors no more than 2 kilometres apart.
(c) Company avenues of approach / axis of advance are at least 500 metres wide.

3. The IPB process when used by military forces is centered on METT-T (Mission, Enemy, Terrain, Time, Troops). The assigned Area of Operations is based on the factors of METT-T and must be of sufficient size to allow completion of the assigned mission. Commanders at each level are normally assigned areas of operations, and attack objectives at a distance commensurate with their unit capabilities.

4. The IPB process evaluates the Area of Operations and mission to develop a Scheme of Maneuver to accomplish the assigned mission. Figure I.1 below provides an outline of the key elements which will be considered as input to NG-NRMM field use. These inputs include:

a. Unit and Mission (which compels timelines, distances, vehicle configurations)
b. Area of Operations (describes geographical area and its limits)
c. Environmental Conditions (climatological, meteorological, tidal)
d. Ground Reconnaissance (in-situ updates collected prior to operation)

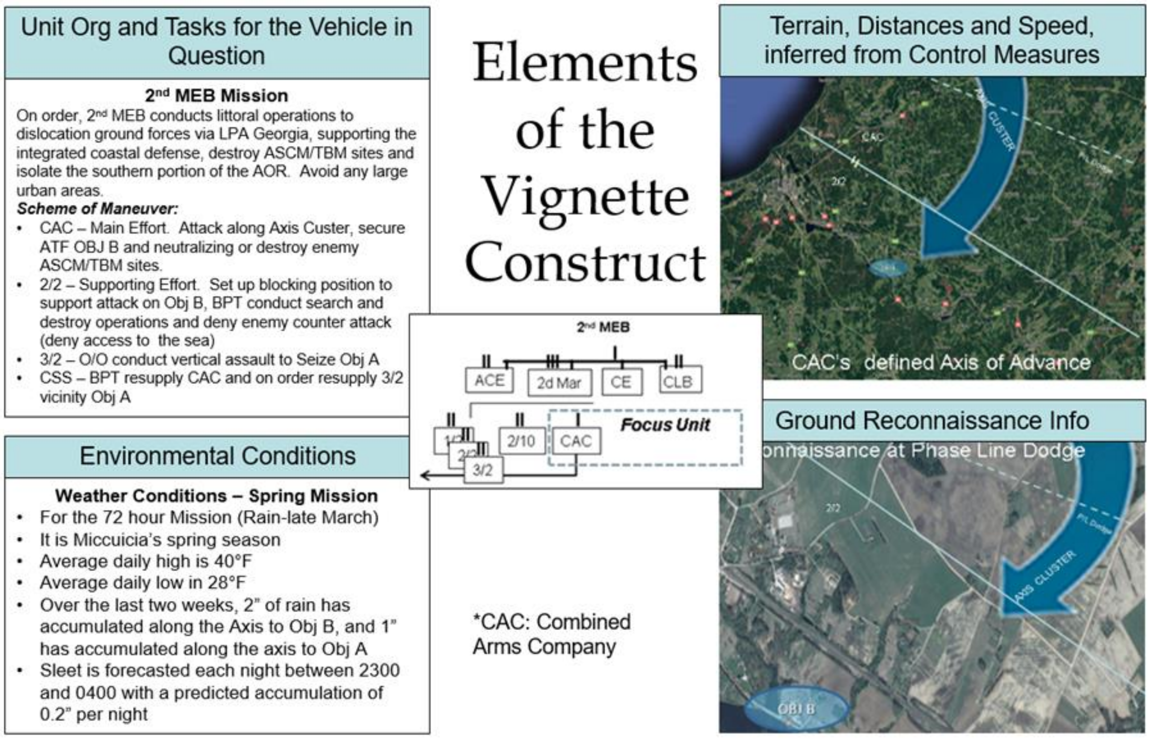

Figure I.1: Elements of Operational Planning.

5. The IPB process evaluates terrain and weather in a combined function. Terrain analysis reduces the uncertainties regarding the effects of terrain on operations. The intelligence staff receives support from a direct support engineer terrain team or detachment. The terrain team performs a technical evaluation of the topographic considerations of relief and drainage, vegetation, hydrology, and the cultural and political aspects of the region. Their products support the analysis of the military aspects of terrain performed by the intelligence staff:

a. Observation and Fields of Fire
b. Cover and Concealment
c. Obstacles (man-made and natural)
d. Key Terrain
e. Ground Avenues of Approach and Mobility Corridors
f. Air Avenues of Approach

6. Military planners currently start with relief maps to plan for potential movement. Starting with where they are (Assembly Area or Attack Position) and where they want to go (Objective), they evaluate:

a. Elevation
b. Obstacles (natural or man-made obstacles)
c. Bridges, highways and railroads
d. Vegetation
e. Soils trafficability

7. The end-state is mobility corridors that provide a potential Axis of Advance, Avenues of Attack or Routes, each of which infer a different level of control over movement. The graphic product of the composite of the topographical considerations is the Modified Combined Obstacles Overlay.

8. <u>Employment: Understanding the Terrain – Pulling from the Geospatial Database</u>
During the IPB process, the operational unit will use the geospatial database, comprised of tailored products that combine or integrate matrixed values for elevation, location, surface slope, vegetation, surface roughness, infrastructure, soil characteristics, hydrology, and climatology information. Those products would be queried to project scalable overlays utilized at different unit levels.

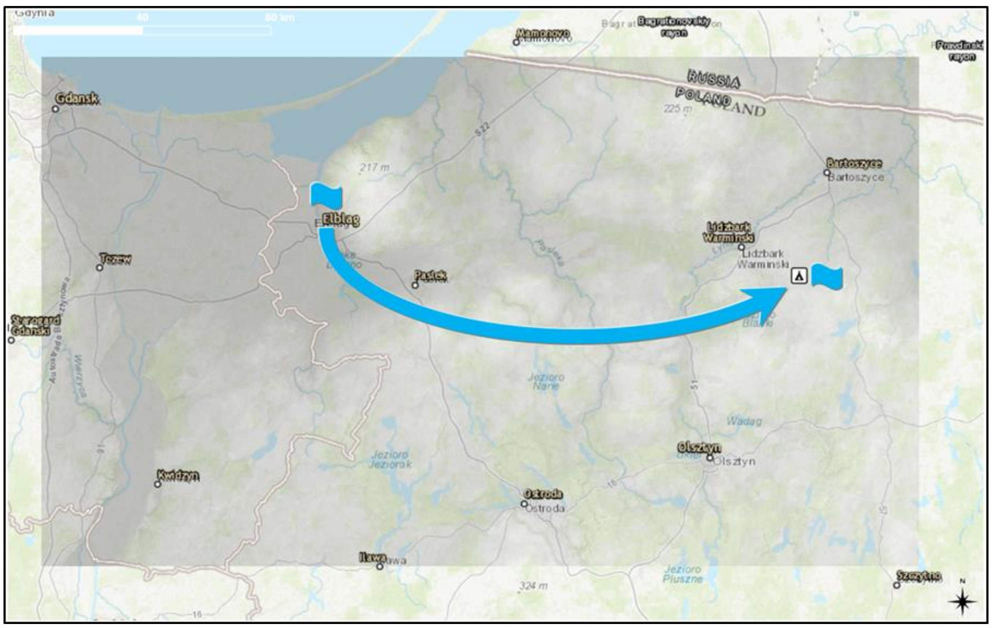

Figure I.2: Define Geospatial Area.

9. The terrain is analyzed in terms of its military aspects which includes, for mobility purposes: obstacles, key terrain, and avenues of approach. These are analyzed in light of the mission, the Unit and equipment (of interest to us, the vehicles to be used for maneuver).

- **Define Route**
- **Quantify Attributes**
  - Soil Type
  - Terrain Type
  - Foliage
  - Gap Crossings
    - Ravines
    - Drainage Ditches
    - Irrigation Ditches
    - Seasonal Run-Off
- **Combine Attributes For Mission Scenario Trafficability Calculations**

Figure I.3: Example of Preliminary Terrain Analysis Informing a "Scheme of Maneuver."

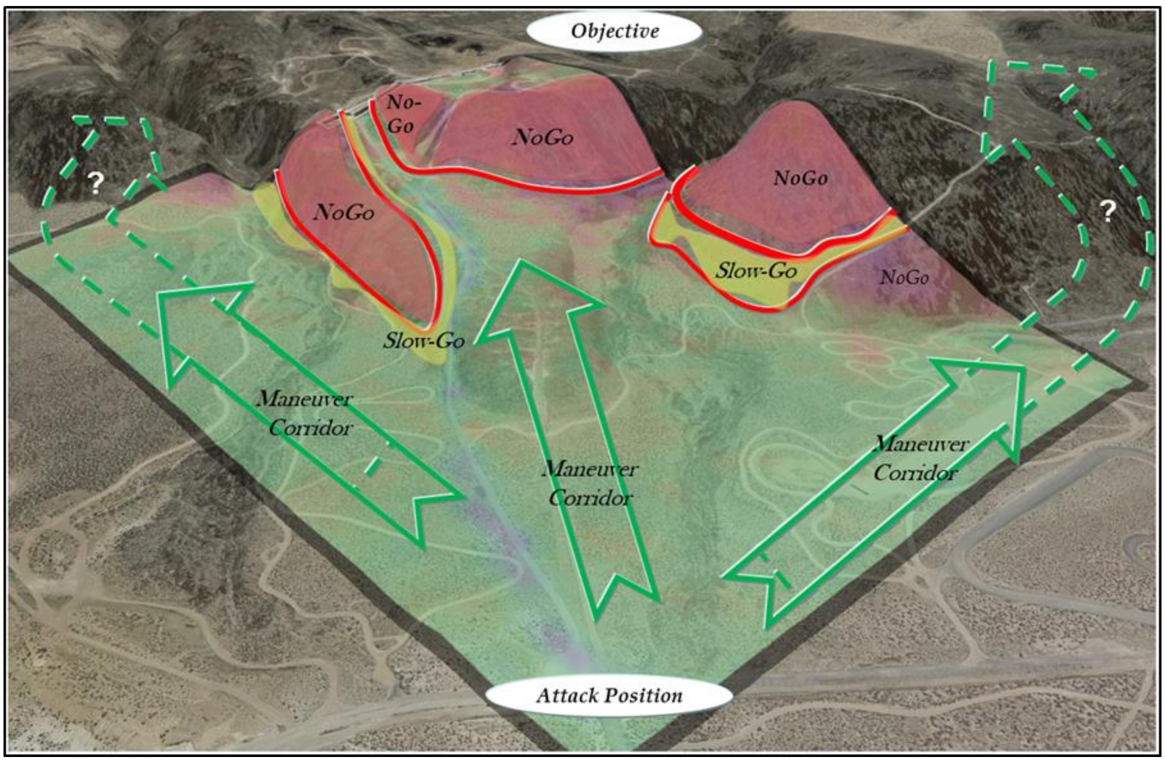

Figure I.4: Mobility Corridor Starting Point – Elevation Analysis.

10. To determine an avenue of approach the staff first determines where the force wants to get to (immediate and subsequent Objectives). Then, based upon all the

previous terrain analysis, you determine how the terrain will allow the force to maneuver to these objectives.

11. Current staffs often have very limited resources to determine trafficability. NG-NRMM, properly developed, will provide a significant enhancement for planning staffs.
Properly developed, it could also support NATO units in defense, to aid in the effort to determine enemy avenues of approach to show how the threat may maneuver into the friendly force's defense sector.

12. As analysis continues, detailed analysis of each type of feature will be compiled to develop a full understanding of the environment influencing the unit’s ability to maneuver.

I.3.2. Working Products

1. Traditional MCOO starts with a basic elevation layer, often in the form of a contour map. This is combined with known infrastructure and obstacles such as forest land, waterways, bridges/tunnels, and enemy positions.

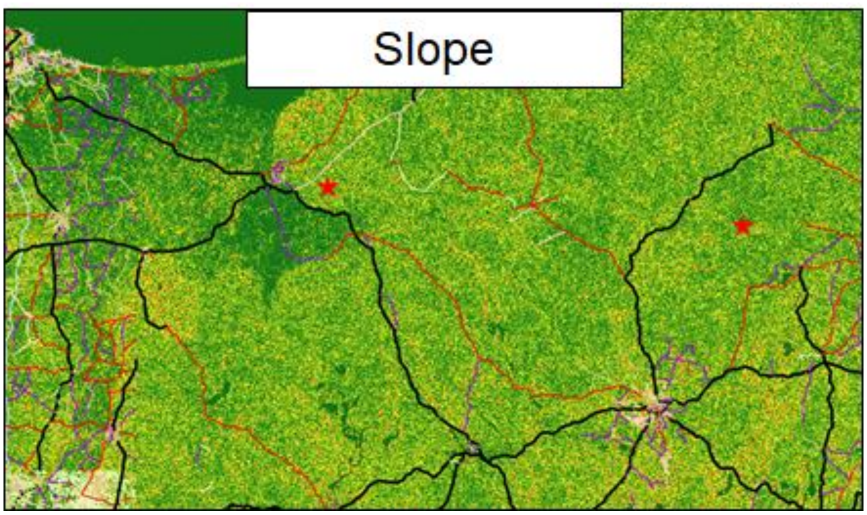

Figure I.5: Elevation and Slope.

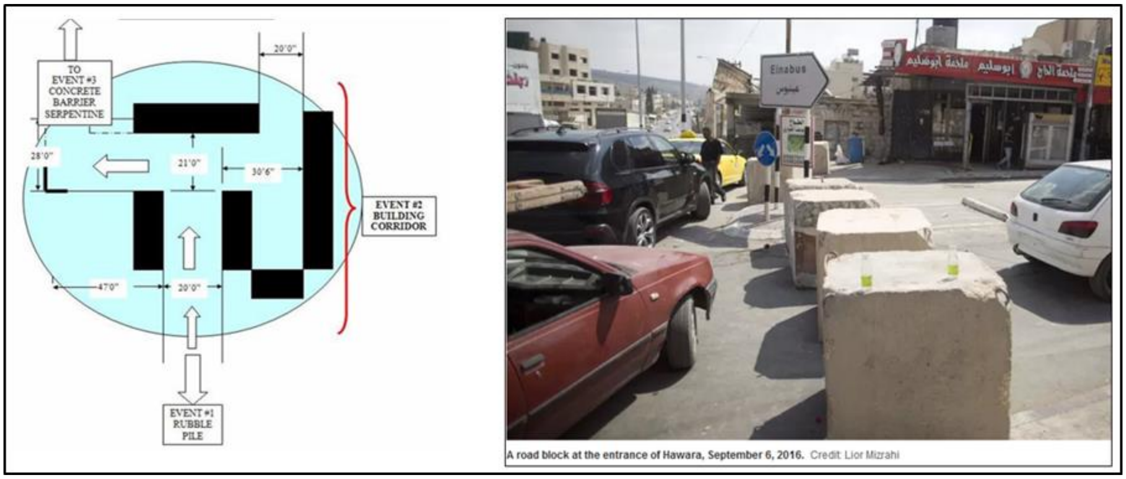

Figure I.6: Obstacle / Infrastructure Restrictions.

- **Restrictions and shoulders would be appropriate data fields for inclusion in a fielded NG-NRMM**
- **Surface roughness and friction coefficients are logical inclusions in NG-NRMM modeling as they impact speed made good and as the Field User will be compelled to consider these restrictions.**

Figure I.7: Highway and Road Characteristics.

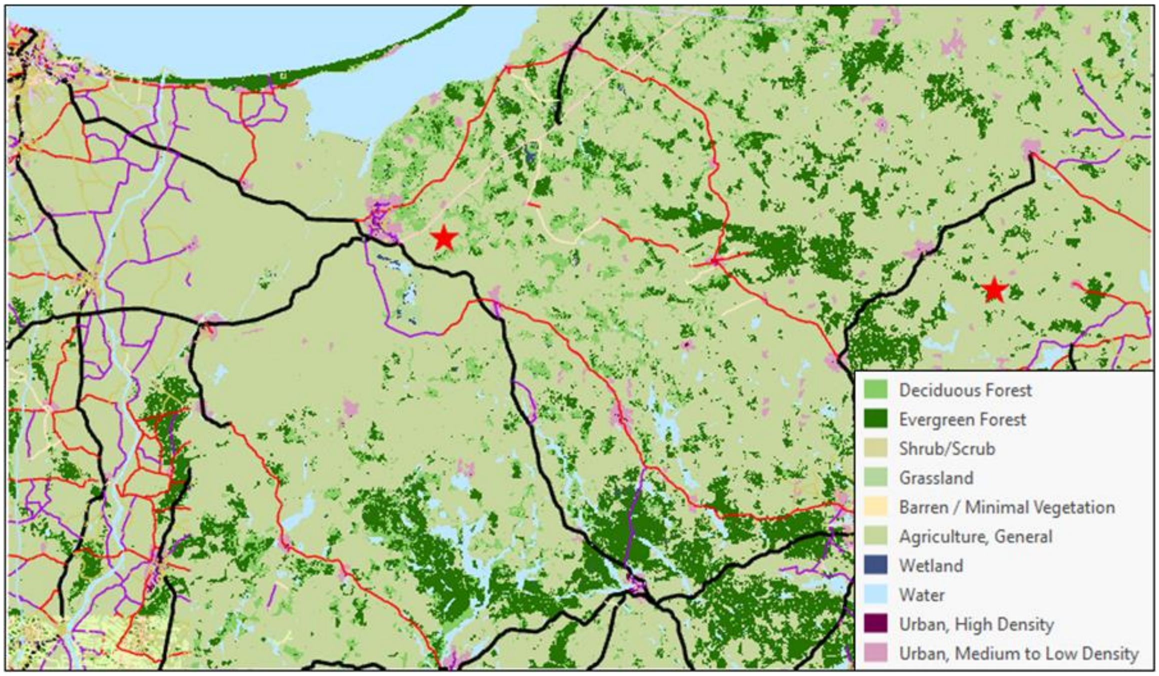

Figure I.8: General Vegetation, Cover.

- **Except for vegetative root structure, does not require terramechanics level modeling. Appropriate data fields which could be included in NG-NRMM as the Field User will be compelled vegetation impact on mobility.**

Foliage encroachment to routes is a consideration for secondary roads/trails.

Figure I.9: Specific Vegetation, Impediments.

2. NG-NRMM has the potential to offer much more information to the mission planner. Adding soil type with information about recent weather conditions could allow inference of soil strength, and thus trafficability for vehicles with known capabilities.

Figure I.10: General Conditions of Soils Trafficability.

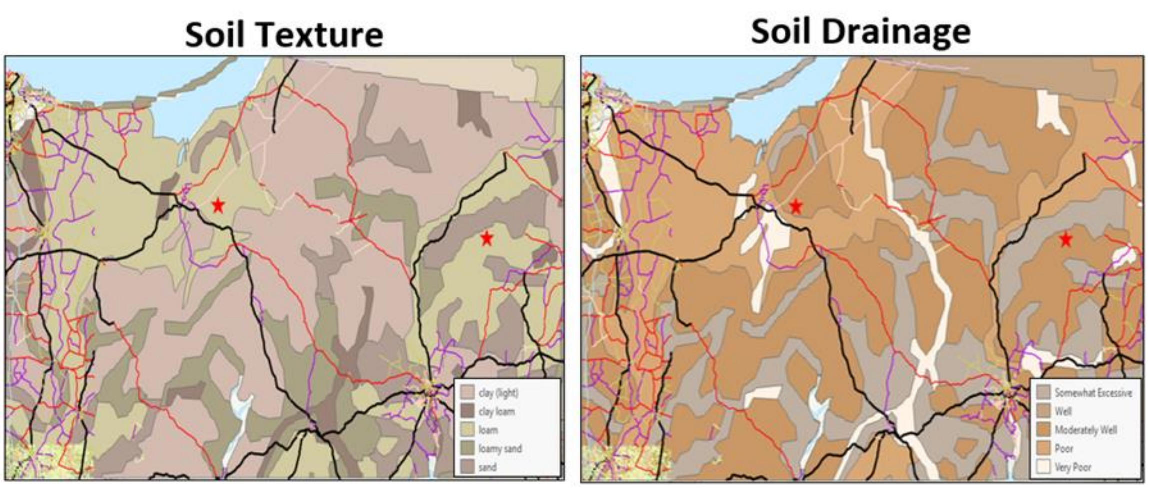

Figure I.11: Soils Classification Information (from the Geospatial Database).

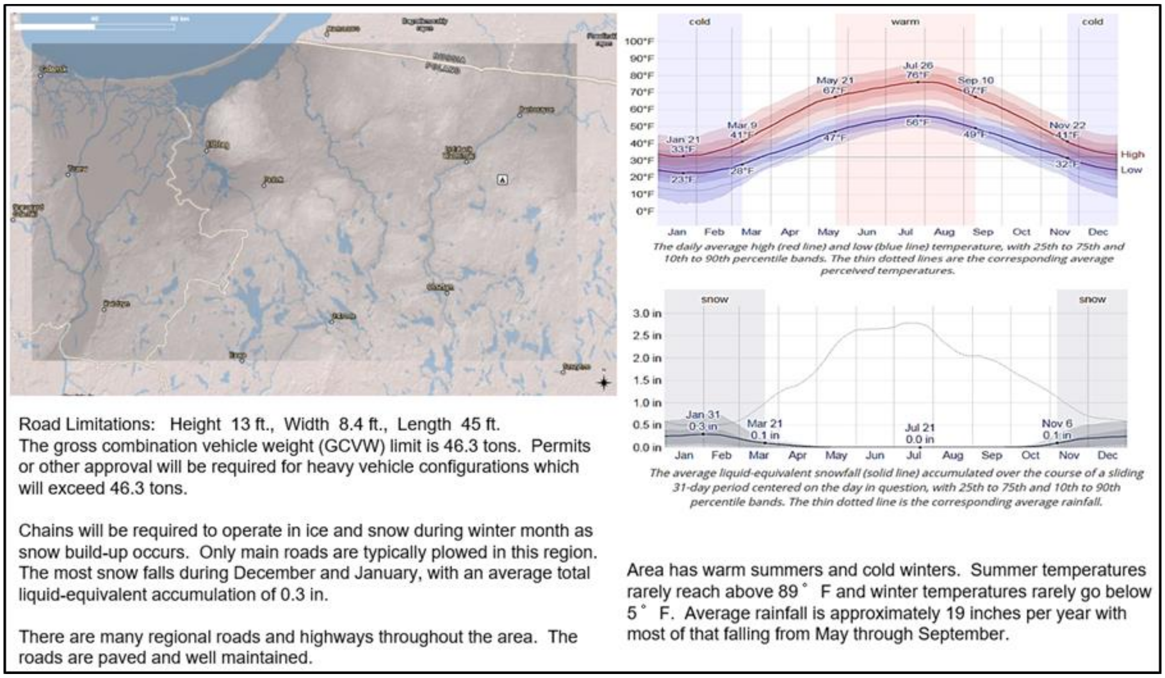

Figure I.12: Weather and Climate.

3. Areas requiring more detailed information and reconnaissance will be identified. A unit dispatched to conduct the reconnaissance could use manned assets or remotely sensed data to provide local inputs, e.g., tailoring the weather and other collected reconnaissance at the Battalion level, as part of the planning process to identify vehicles of the planned maneuver formation to conduct mobility predictions.

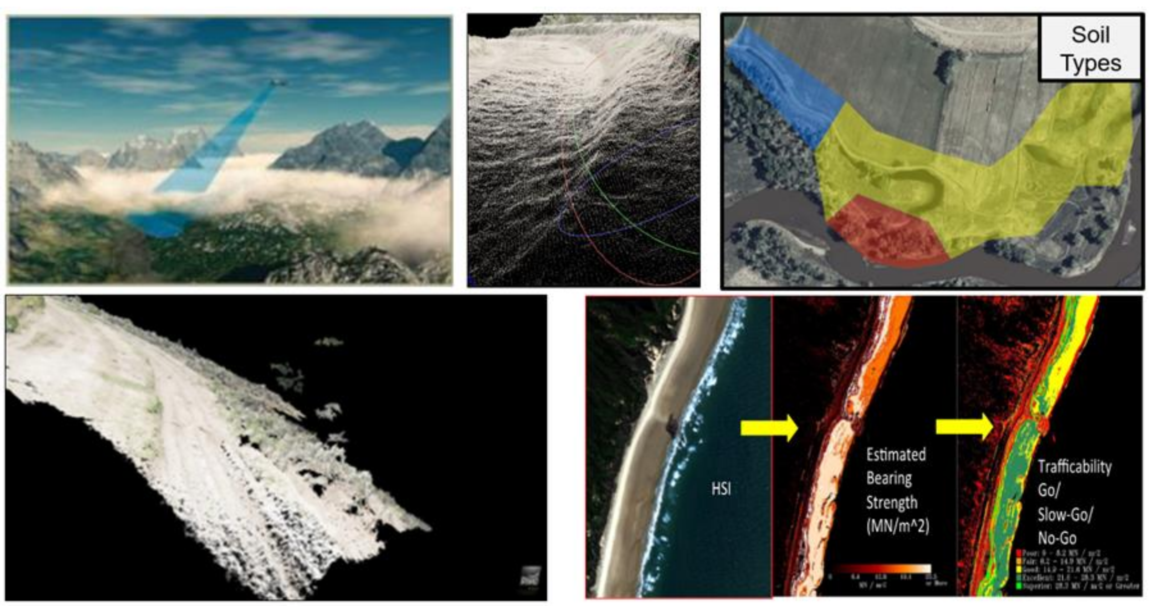

Figure I.13: Local Reconnaissance Products.

4. As a fuller understanding of surface and soil characteristics is populated, initial calculations of the soil/mechanical interface are developed to learn both where information is sufficient or irrelevant to the operation and where more information is needed.

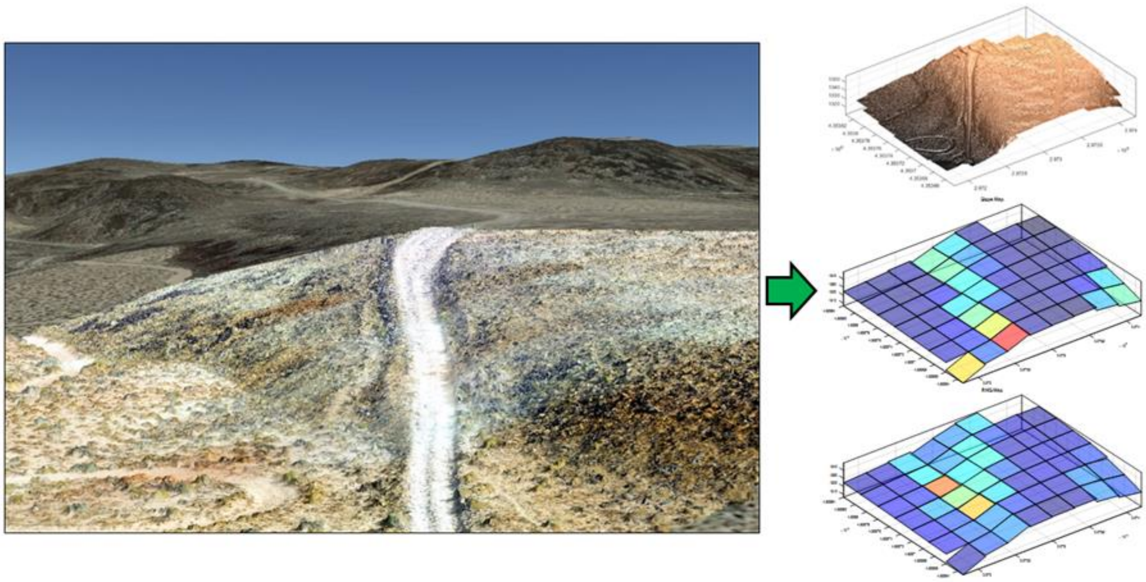

Figure I.14: Translating Local Reconnaissance Products to NG-NRMM Inputs.

5. The vehicle database will be comprised of specific vehicle characteristics, validated 3-D MBD simulations, optimized vehicle configuration options (CTIS, traction control, optimized drivetrain, optimized ride height, optimized transmission and engine configuration, etc.) related to mobility. These vehicle models, when processed through the maneuver computational algorithms with the related calculation from the geospatial characteristics of the candidate route, will provide trafficability estimates (GO/NOGO, single-pass or multi-pass), projected speed, and constraining factors affecting the route. The vehicle database would include values for tractive effort, geo-technical data for the soil conditions, gradeability, ride quality, center of gravity, clearance and physical dimensions.

6. Using the vehicle database, and updated information on surface / soil conditions, predictive vehicle performance modelling would be run in succession to generate mobility and trafficability products of use to the military planners. These products will tend to be organized as products on non-deformable surfaces and deformable surfaces, as the dominant physical attributes of the soil / vehicle interface differ between these two surface types.

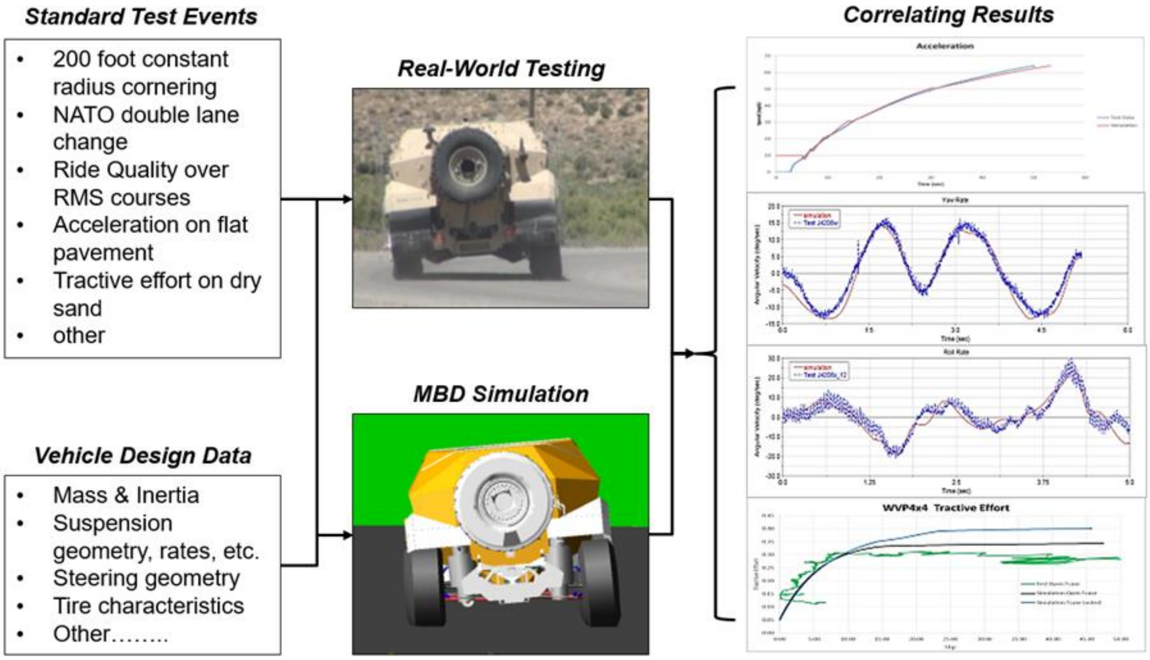

Figure I.15: Modeling on Non-Deformable Surfaces.

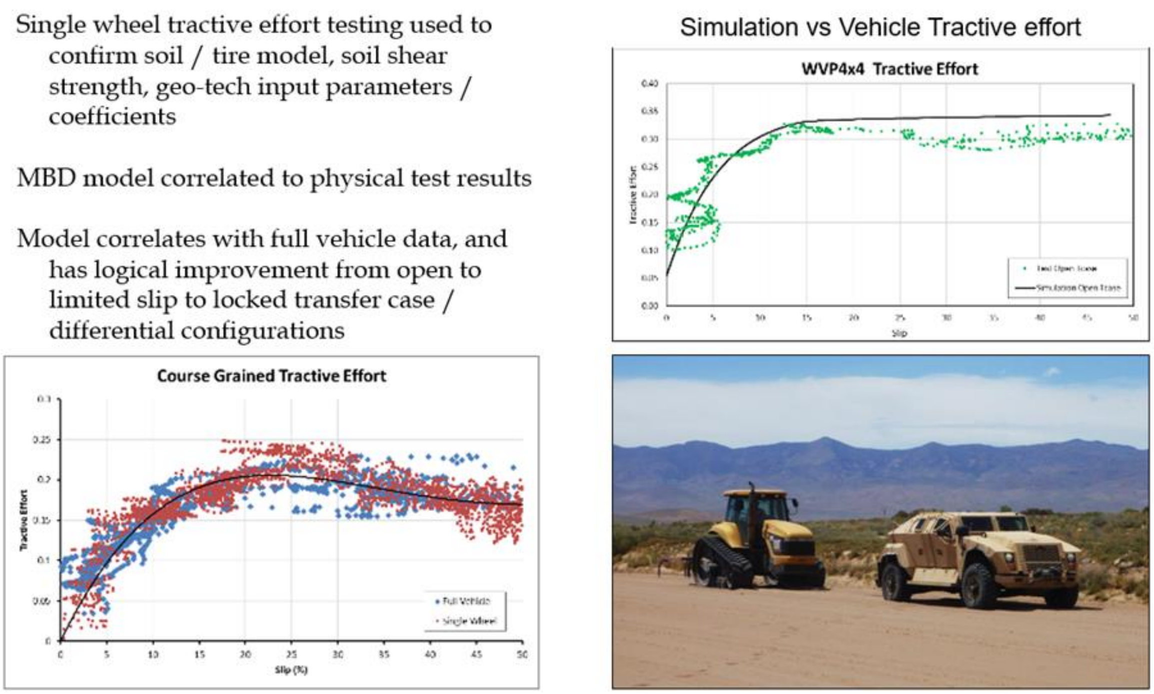

Figure I.16: Modeling on Deformable Surfaces.

7. As in any planning endeavor, in order to provide relevant information within an allowable timeline, military planners must strike a balance between depth of analysis (leading to higher fidelity) and time. Below is a typical notional timeline for a military staff

deployed on an operation. The purpose in showing this timeline is to provide NG-NRMM developers a framework for processing time.

8. Temporally, in order to provide products on the timeline necessary to support mission planning in a Division or Brigade staff, one would allocate the following times:

a. **Higher Headquarters provides Warning Order and Area of Operations, normally 24 hours in advance of Mission Order.** The NG-NRMM user frames the terrain to be analyzed in the model by pulling and isolating the geospatial data fields for this region.

b**.** **Staff identifies candidate mobility corridors in AOR, over a roughly 2- to 6-hour period.** During this time the NG-NRMM users set up unit vehicle inputs and select broad mobility corridors, limiting the data needed for modelling.

c. **Staff identifies and directs local reconnaissance needs in key areas over a roughly 6 to 18 hour period.** After initial review of the AOA and potential mobility corridors, the NG-NRMM user has the opportunity to identify omission or outdated fields in the database that warrant either updates or more detailed/definitive values. This is where the 'art' of this process will apply, and updating the data through local reconnaissance takes and investment in time and resources, and the military staff may have neither the time nor resources to collect all the data / information the NG-NRMM user would like to have to achieve high fidelity in the model runs.

9. Since the geospatial data is generally persistent in duration (probably consistent for months) and the vehicle database is persistent in duration (probably consistent for the life of the vehicle in a specific configuration), it is here, as the opportunity to supplement the database with updates and higher fidelity that the NG-NRMM user must be restrained in requesting all desired data. He must remember that the military staff generally considers "perfect to be the enemy of good enough." The military staff is used to dealing with ambiguity and risk, so a moderately accurate product delivered on the staff's timeline is infinitely more valuable than a very accurate product delivered after the military operations order/plan is completed.

10. Any request for additional information through local reconnaissance should be generated within an hour or two. Once assigned a Commander's Critical Information Requirement (CCIR) or other information need, the reconnaissance unit usually has between 6-24 hours to generate a response. The longer they have, the better the chance they can fulfill it.

a. **Input reconnaissance information to NG-NRMM, nominally within 2 hrs of receipt.** The NG-NRMM user inputs information updates that have been provided by the reconnaissance team; normally these will be consolidated by the Intelligence Officer and distributed to staff members requesting the information.

b. **Use NG-NRMM interface and database to provide products for staff use: 2 hr.** Once the local reconnaissance products are received, the NG-NRMM user begins his Final run of NG-NRMM calculations. This activity is similar to that accomplished by other members of the military staff, as target lists, logistical plan, resupply and maintenance planning are all finalized prior to start of mission. It is at this point, that the NG-NRMM user can appreciate the advantage of organizing his inputs and accomplishing any preliminary runs of mobility predictions. If he has done a number of preliminary runs with gross data, once he has his final inputs, updating the predictions should ideally be achievable within an hour, then adjustments for final presentation in a form the consumer (Operations Officer and subordinate unit commanders) can understand consume the second hour.

c. **Updates from NG-NRMM briefed to unit conducting mission 2 hr prior to start** With the final predictions in hand there will still be context considerations that the NG-NRMM user will need to be armed with to brief the Operations Officer and unit commanders. The primary example of this consideration is confidence level of the predictions. Since the average military staff member is neither a mathematician nor student of statistics, expressions of confidence in the accuracy of the prediction will most likely be staff specific. The user interface for NG-NRMM may be well served to have a subroutine to express confidence level as a statistical expression, as an expression of risk in presenting inaccurate results or other means.

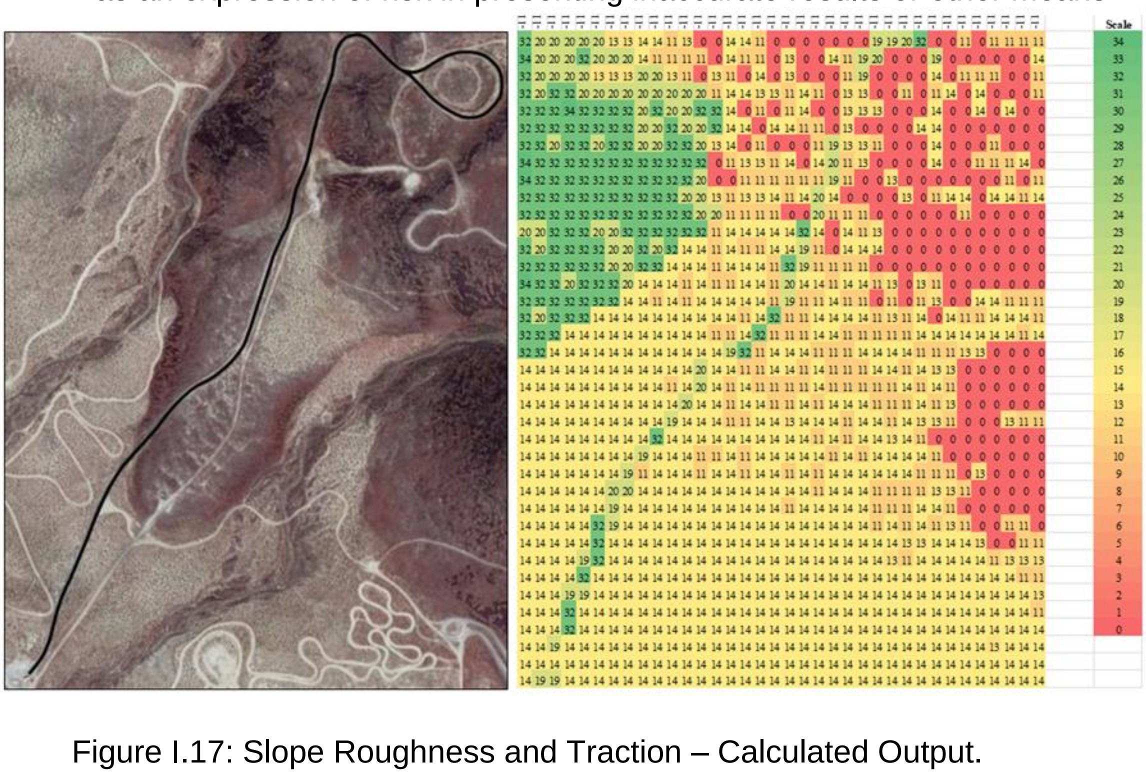

Figure I.17: Slope Roughness and Traction – Calculated Output.

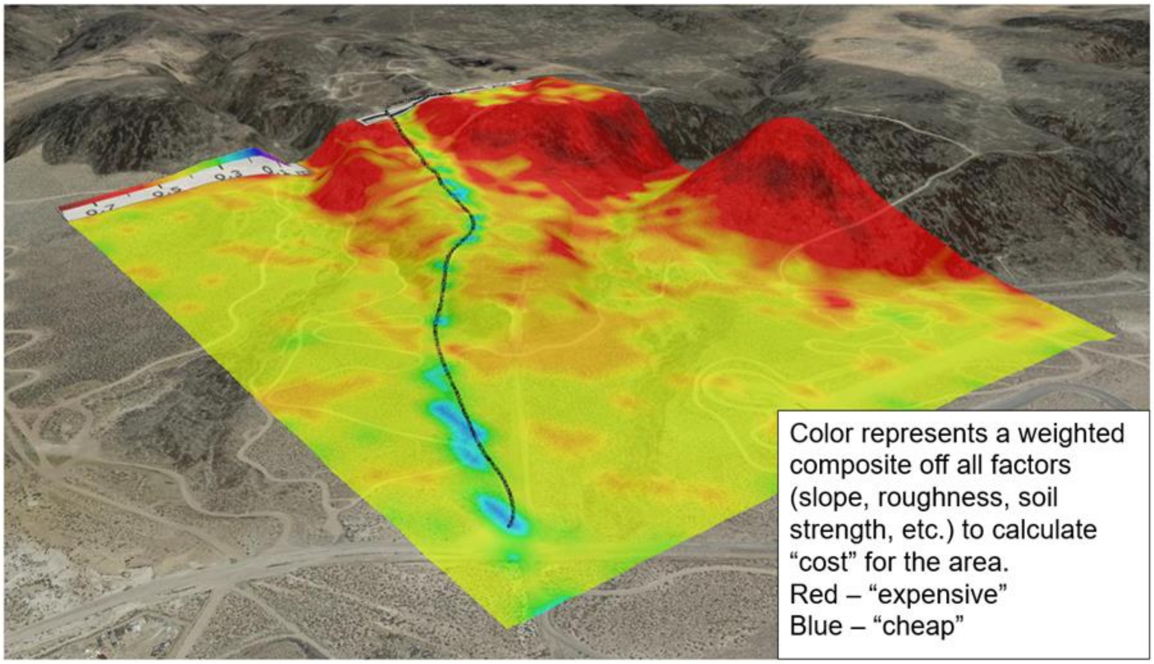

Figure I.18: Slope, Roughness, Power, Resistance, Traction – Calculated Output.

I.4. OPERATIONAL VIGNETTE (EXAMPLE EMPLOYMENT PRODUCTS)

1. To this point, we've described an implementation of NG-NRMM designed to support the needs of a military staff. We've described in very general terms how the military staff conducts terrain appreciation and maneuver planning. (At this point, we'll remind the reader that military staff planning process is complex enough that it is the subject of year-long schools for field grade officers, so it would not even be accurate to call this Annex a survey of military staff planning, it simply provides a framework for orienting NG-NRMM developers to understand some very basic demands of mobility planning).

2. With that said, we'll move on to one very specific example of what an NG-NRMM product might look like.

I.4.1. Example of Staff Issue Presented to Mobility Analyst

1. In the example below, during the staff planning process, the Logistics Officer asked the NG-NRMM user to conduct analysis on which of the two types of available trucks in the unit was a better selection to move 30 tons of supplies from the port of Gdansk to several field re-supply points located within 60 miles of the port, but located in a rural area accessible by secondary roads most of the way, but most located off road in obscured resupply points for security purposes.

2. Three operationally relevant questions were asked by the Logistics Officer

a. Can both vehicle types deliver logistics to all forward sites?
b. What is the time it will take each type of truck to deliver 30 tons of supplies to the farthest resupply site in this terrain?
c. What is the more efficient type of truck to deliver 30 tons, measured in payload-ton miles per gallon?

3. While these would not be the only questions generated by the staff, these specific questions should be answerable with specific "run set-ups" of vehicle vs terrain, and generated in parallel with other specific questions from the staff which will result in other modelling "run set-ups." (For example, what are the available mobility corridors to maneuver a Stryker Company from Assembly Area X to Objective Y?)

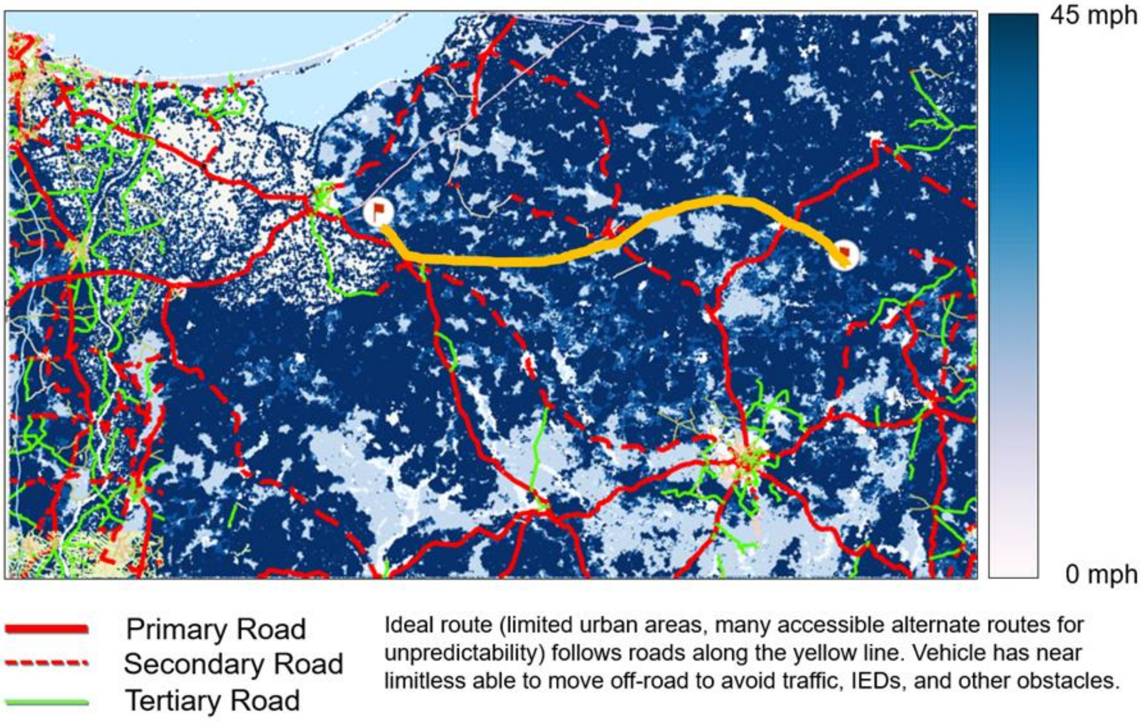

Figure I.19: "Least Cost" Route, Truck Type 1.

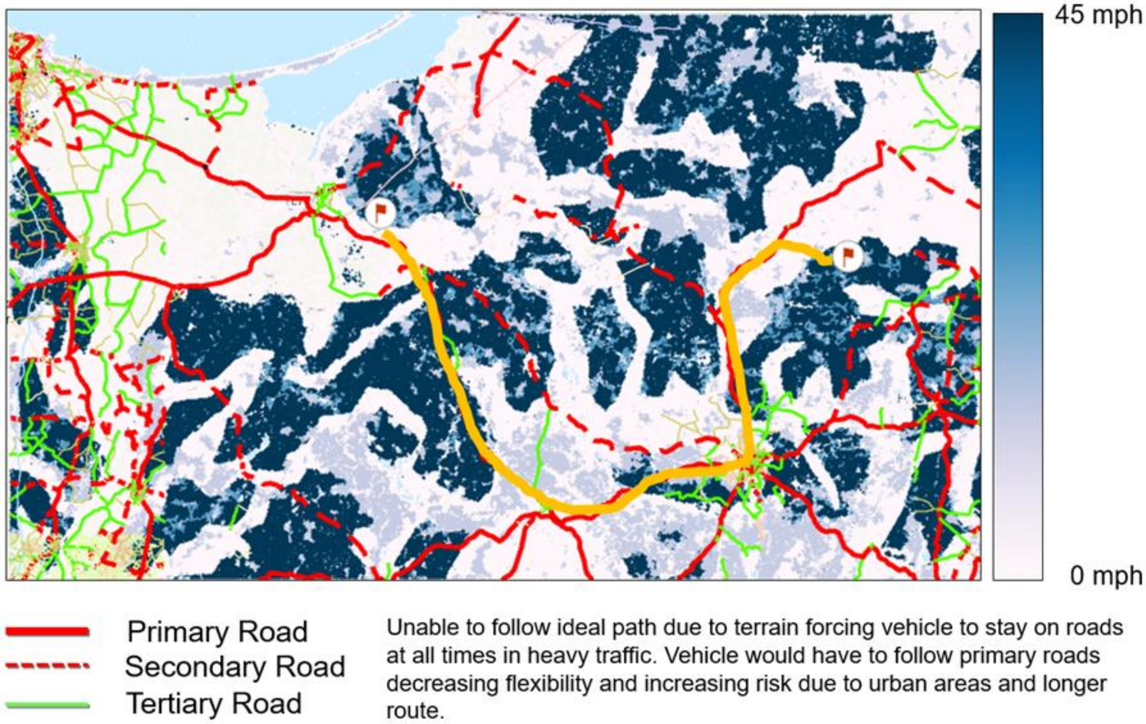

Figure I.20: “Least Cost” Route, Truck Type 2.

Table I.1: Tabulated Results.

Unit Forward Supt Delivery Metrics	Metric	Truck 1	Truck 2
Calculated VCI	VCI	27	49
Time to Deliver 30 tons to Forward Site	Hrs	2.5	4.3
Payload Ton-mile / gal**	PTMPG	34.5	24.5

**PTMPG = Vehicle mpg X cargo payload

I.5. SUMMARY

4. In this Annex, we have described:

a. How an operational unit would use NG-NRMM in the IPB process to generate mobility corridors from which to support development of a Scheme of Maneuver or movement routes for operational forces.

b. How NG-NRMM enables translation of that route to engineering values of sufficient specificity to enable predictive terramechanics modelling to satisfy the needs of military planners using the tool in the field.

c. Example predicted vehicle performance over a specific route, using the physics-based modelling principle we advocate for NG-NRMM.

d. Operationally relevant metrics (speed, time, efficiency) that we assert will be of use to the military planning staff as they use the NG-NRMM tool.

ANNEX J AVT-327 MOBILITY MEASUREMENT AND ANALYSIS SURVEY

J.1. INTRODUCTION

1. Military staffs planning to conduct mounted maneuver operations frequently lack real-time tools and information to support maneuver planning during the Intelligence Preparation of the Battlefield (IPB) process. Current planning can be based on information gathered days or weeks prior, and therefore may not accurately reflect the available maneuver corridors due to changes in environmental, threat, or other recent events. Military engineer units conducting engineer reconnaissance are often under-manned and have limited field tools that cannot accurately inform mobility maneuver decisions. Further, with the projected increased speed of engagement there is often insufficient time to perform necessary trafficability analysis to optimize mobility maneuver corridor planning. The advent of improved accuracy of remote sensing, unmanned aerial and ground systems, and advanced mapping technology now make available near real-time information for terrain and other dominant conditions within the battle space. This technology, coupled with the ability to accurately predict vehicle performance in that complex environment, enables mission planners to establish maneuver corridors with greater accuracy than the traditional review of paper topographic maps. The ability to define tactical and combat vehicle performance in dynamic engineering terms also has improved. Therefore, advanced engineering data and associated analysis tools can provide operational planners more accurate predictions of vehicle mobility, speed and performance within the varying conditions found in the battle space.

2. This survey seeks to help inform the NATO community of the current employment of historic measurement and analysis tools and the potential future application of the more capable solutions. The effort seeks to deploy these available tools in a standardized format available and deployable throughout the NATO operational community. This survey also seeks to address the potential for establishing a more standard approach for terrain and vehicle information, which is critical to the accurate determination of vehicle mobility during NATO-wide, year-round operations. This will enable a substantially improved understanding among the NATO community of interoperability between force elements and therefore improve overall combat effectiveness. Among the variety of digital terrain database options available, data may not include parameters critical to estimating how vehicles may be able to maneuver, particularly during more extreme climatic events (heavy rain, snow, etc.). Currently, data from different sources may be incompatible, thereby limiting communication, delaying decisions and adversely impacting interoperability. Further, the methods used to determine the capability of a vehicle system may vary among operational elements. This current effort seeks to provide a better understanding of the status of the tools and methods used by each organization. Based on that information, criteria can be developed to better enable the interoperability of existing tools or inform the decision to adopt common tools. Further, this effort will help establish information on best available practices based on the level of accuracy of terrain and vehicle data available to the NATO community and to individual force elements. This

survey and the participation in this initial survey represent the first step while the longer vision goal is to provide operational units with the best tools to determine a range of potential “best available” mobility maneuver corridors. This goal will be accomplished by augmenting digital terrain databases with remote sensing products to generate a higher fidelity trafficability assessment based on known mobility parameters of the deployed tactical and combat vehicles.

3. As NATO forces conduct missions over a wide variety of terrains, this approach through the use of updated tools such as a Next-Generation NATO Reference Mobility Model (NG-NRMM) with the associated NATO Standardization Recommendation can improve situational awareness substantially. These tools will allow better focus reconnaissance assets to determine terrain trafficability and provide information to the individual unit for feasible and best mobility maneuver corridor options to achieve mission completion. By equipping the planning staff with these tools, combined with improved remote reconnaissance sensing platforms, military planning staffs would have the ability to generate and update local digital tools such as Modified Combined Obstacle Overlays (MCOO) with improved fidelity in trafficability (Go, Slow-Go, or No-Go) projections.

4. To provide an open source reference for this effort, notional vignettes have been developed to better define the impact of the range of potential sources for terrain, environment and vehicle data. Please refer to the Vignette for Survey document for more information.

5. As National Defence Ministries and NATO develop common data repositories for the multiple battlefield purposes, NG-NRMM tools should be structured to enable use of scalable fidelities and accuracies in those data fields. The logic behind this is to develop the tool so it can resolve large-scale predictions with low quality data while also having the capacity to scale to high fidelity predictions when a small, high-resolution data set is available.

J.2. CURRENT DATA COLLECTION AND MODELING TOOLS

In an effort to establish a basic point of departure, it is instructive to identify the types of devices that are used to quantify the approach used, as identified below.

J.2.1. Terrain Data

Do you obtain measurements of terrain conditions prior to a training maneuver?	Yes	No

What devices or approach do you typically utilize?		
Cone Penetrometer	Yes	No
Precursor vehicle	Yes	No
Experience with deployed vehicles in similar conditions or operational events	Yes	No
Are there other devices which you utilize regularly? Please list below as appropriate.	Yes	No

Do you have access to any predictive tools for the terrain?	Yes	No
These tools may have been developed originally for agricultural or forestry or erosion control purposes, but are used to inform decisions on how to prepare for planting, how well the soil may retain moisture, how best to manage the soil and vehicles while harvesting, etc. If such agricultural or water management tools are available please indicate some of the specifics below.		

Do you currently employ remote sensing systems to aid in the analysis of terrain conditions? If yes, please provide details below.	Yes	No

J.2.2. Vehicle Terrain Interaction

Do you have access to tools that combine information for vehicles and terrain, which provides analysis of the performance of the vehicle and/or the soil?	Yes	No
For example, agricultural tools that are available may support prediction of the recommended maximum number of passes of a tractor in a certain type of field before conditions occur that will reduce the potential crop yield (e.g., excessive soil compaction). If such tools are available please provide a list below.		

Several levels of analysis have been used historically to estimate the ability of the unit to maneuver through a certain area. Each of these approaches has strengths and limitations.

Simplified Analysis – Do you estimate the various elements of the terrain that create resistance to motion (soil strength, sinkage, slope, obstacles) and then estimate, based on vehicle capabilities, the potential for success? If yes, please provide details below.	Yes	No
Do you use this information to inform decisions on operations such as selecting tire pressure or recommending certain gear and drive train selections (e.g., locked differential operation)?	Yes	No

Empirical Analysis – This is the type of tool that uses measured vehicle data generally obtained over the terrain conditions of greatest interest. This information and the associated analysis come from extensive testing and data gathering, which is combined in a manner to estimate vehicle mobility and performance. Do you use available tools such as the NATO Reference Mobility Model or other methods that consider prior knowledge of the performance of a given vehicle over a given terrain at a particular time of year? If yes, please provide details below.	Yes	No

Simplified Terramechanics – Do you apply lessons learned from agricultural or mining or operational analysis that include a mathematical representation of the strength of the soil and a similar, physics-based, mathematical representation of the vehicle? If yes, please provide details below.	Yes	No

Discrete Element Modeling – Do you use advanced computational analysis of the interaction of the soil and the vehicle that incorporates details of the particles and moisture and vegetation of the terrain and includes detailed analysis of the tire or track to soil interaction? If yes, please provide details below.	Yes	No

Vehicle as a Sensor – Do you apply near real time determination of the environmental conditions and automatically identify best path for the vehicle based on data gathered and provided by the vehicle system or by associated vehicles? If yes, please provide details below.	Yes	No

Do you utilize more advanced, commercially available dynamics analysis tools, which typically are identified by their commercial names including DADS, ADAMS, CARSIM, TRUCKSIM, CHRONO, etc.? If yes, please provide details below.	Yes	No

Do you utilize proprietary in-house software? If yes, please provide details below.	Yes	No

Do you use this information to inform decisions on operations such as selecting tire pressure or recommending certain gear and drive train selections (e.g., locked differential operation? If yes, please provide details below.	Yes	No

Do you deploy the tool in the field? If yes, please provide details below.	Yes	No
Is the analysis completed well in advance of the operation using available engineering resources? If yes, please provide details below.	Yes	No

J.3. REQUIRED RESULTS

1. What are the most important outputs from a model or simulation? Rank the following from not important (1) to essential (5).

	Not Important				Essential
MODEL OUTPUTS	**1**	**2**	**3**	**4**	**5**
GO/NOGO for single vehicle					
GO/NOGO for multiple vehicles					
Speed across terrain					
Time to a given destination					
Confidence levels					
Handling					
Ride quality as it impacts the operator, weapons systems or payload					
Ability to negotiate a particular slope (longitudinal or side slope)					
Ability to negotiate a specific obstacle (downed timber, urban rubble, irrigation ditch, etc.)					
Other (please describe)					

2. In the tables below, please rank the following vehicle and terrain systems/subsystems on a scale of 1 to 5, with regard to desired output from a mobility simulation. One (1) represents that the item is not important at all, possibly not even included in the model. Five (5) is the highest importance and a measurement that you would consider to be essential in your analysis of the capability of the vehicle and its interaction with the terrain. Your emphasis on the various elements will help NATO AVT-327 determine where necessary focus should be placed on the definitions of the various elements along with the accuracy required for the input data to ensure an appropriate outcome to achieve the intended accuracy in the prediction.

	Not Important				Essential
VEHICLE DATA	**1**	**2**	**3**	**4**	**5**
Tire Analysis					
Importance of proper tire selection for the vehicle					
Importance of a range of operational tire pressures as a function of terrain conditions					
Ability to operate the vehicle at reduced tire pressures to gain mobility					
Ability to incorporate a run-flat system with the tire and measure the effect of the run-flat					
When considering the tire as a component of the overall vehicle how do you consider the following parameters?					
Weight					
Spring rate					
Damping					
Contact area / lug geometry					
Pacejka coefficients					
Other? Please describe.					
Suspension Analysis					
Weight of the suspension and axle system					
Total wheel travel					
Ability to adjust suspension performance for the condition (e.g., off-road operation versus on-road stability)					
Adjustable ride height suspension and the impact on mobility					
On-road stability and the use of anti-roll bars					
Other? Please describe.					

	Not Important				Essential
VEHICLE DATA	**1**	**2**	**3**	**4**	**5**
Chassis Analysis					
Impact of the total weight of the vehicle system					
Overall geometry including angle of approach, departure and break-over angle					
Other? Please describe.					

	Not Important				Essential
TERRAIN DATA	**1**	**2**	**3**	**4**	**5**
Elevation / Slope					
Terrain Roughness					
Soil Type					
General type (USDA / USGS*)					
Seasonal effects (e.g., moisture, winter)					
Terramechanics parameters					
Soil sinkage					
Soil shear strength					
Land Cover / Usage					
Road Network					
Building material					
Road width / number of lanes					
Geometry (curves / banks)					
Hydrography (streams / rivers)					
Aerial Photography					
Obstacles					
Geometry					
Density					
Forest Characteristics					
Stem size					
Stem spacing					
Climate Effects					

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