

2019 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY
SYMPOSIUM

<POWER AND MOBILITY (P&M)> TECHNICAL SESSION
AUGUST 13-15, 2019 - NOVI, MICHIGAN

THE DATA USED IN THE NEXT GENERATION
NATO REFERENCE MOBILITY MODEL
COOPERATIVE DEMONSTRATION OF TECHNOLOGY

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ABSTRACT

The Ground Vehicle Systems Center (GVSC) led a NATO Cooperative Demonstration of Technology (CDT) effort to demonstrate and validate the Next Generation NATO Reference Mobility Model (NG-NRMM). The effort was to create complex and simple terramechanics simulation models of a 12 ton wheeled vehicle traversing actual terrain and compare the results to physical tests. An overview [1] detailed research [2] and validation results [3] are described elsewhere. One aspect of the project was to make the all the data available to the research community to use for further research in off-road mobility and autonomy. All of the data/information mentioned in this paper is Distribution Statement A – Unclassified – Distribution Unlimited and can be downloaded at [ftp://ng-nrmm:thread\\$panel@nrmm.mtukrc.org](ftp://ng-nrmm:thread$panel@nrmm.mtukrc.org) for use.

Citation: Dr. Richard Gerth, Scott Bradley, Michael Letherwood, Dr. David Gorsich,

“The Data Used in the Next Generation NATO Reference Mobility Model Cooperative Demonstration of Technology”, In *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium (GVSETS)*, NDIA, Novi, MI, Aug. 13-15, 2019.

1. INTRODUCTION

The Ground Vehicle Systems Center (GVSC) led a NATO Cooperative Demonstration of Technology (CDT) effort to demonstrate and validate the Next Generation NATO Reference Mobility Model (NG-NRMM). The effort was to create complex and simple terramechanics

simulation models of a 12 ton wheeled vehicle traversing actual terrain and compare the results to physical tests. This requires collecting input data (vehicle data, scenario / test information, physical terrain & soil data), building simulation models, running the models, physically conducting the tests and collecting test result data, and comparing the simulation outputs to the physical test results. A more complete overview [1], details of the research [2] and validation results [3] are described elsewhere.

A Next Generation NATO Reference Mobility Model (NG-NRMM) is defined to be any modeling and simulation (M&S) capability that predicts land and amphibious vehicle mobility through coordinated interoperation of GIS software and multibody, physics-based vehicle dynamic M&S software. The multibody, physics-based vehicle dynamic M&S software must be capable of utilizing terramechanics to properly assess vehicle / terrain soft soil interactions, incorporate capabilities to portray autonomous control systems, and include uncertainty quantification to enable probabilistic M&S. The current version of NRMM contains a library of standard terrain locations; however, the process to build/update these terrain files can be cumbersome and time-consuming. As a result, the standard NRMM terrains have not been updated in nearly 40 years. Due to the proliferation of high resolution satellite imagery and remotely-sensed GIS terrain data, NG-NRMM must enable users to leverage these data to quickly and efficiently create new operationally-relevant terrain files. Following the generation of NG-NRMM results in the multibody, physics-based vehicle dynamic modeling and simulation software, the results must be able to be visualized cartographically. At a minimum, NG-NRMM must be capable of replicating the existing NRMM output products, specifically: Go/NoGo trafficability, Speed-Made-Good, speed limiting reason codes and single-pass / multi-pass results. In addition, newly desired output metric capabilities include generating results for: vehicle stability / handling, urban maneuverability, path modeling, fuel consumption / range estimation, and rut depths created.

In order to build prototype tools and draft requirements needed to ensure GIS software and multibody, physics-based vehicle dynamic model interoperability, it is necessary to define the process / workflow required to convert high resolution satellite imagery / remotely-sensed GIS data into NG-NRMM compliant terrain files. Figure 1

depicts the flow of data through the NG-NRMM analysis process. First GIS data is collected and aggregated into a file geodatabase using standard GIS tools and processes. The data in the file geodatabase are processed to generate the terrain properties needed by the multibody, physics-based vehicle dynamic modeling and simulation software. Once all the required properties have been populated, the file geodatabase is converted into a raster-based NG-NRMM compliant data format (“interchange” format) – either NRMM Code 11 / Map 11 or GeoTIFF. The multibody dynamic (MBD) vehicle modeling software executes vehicle runs using the NRMM Code 11 / Map 11 or GeoTIFF terrain files and generates results for each terrain unit. NG-NRMM compliant software preserves the spatial orientation of the data by linking the results (e.g. Raster Output) to the original terrain file (as shown in the Results Raster). Using GIS software, the data in the Results Raster can now be visualized to produce spatially-oriented, map products.

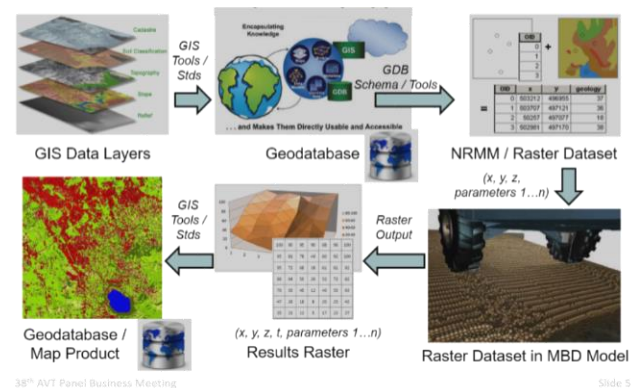


Figure 1. Flow of Data Through the NG-NRMM Analysis Process

One aspect of the project was to make the all the data available to the research community to use for further research in off-road mobility and autonomy. All of the data/information mentioned in this paper is Distribution Statement A – Unclassified – Distribution Unlimited and can be downloaded at [ftp://ng-nrmm:thread\\$panel@nrmm.mtukrc.org](ftp://ng-nrmm:thread$panel@nrmm.mtukrc.org)

for use. The data is organized according to vehicle data, terrain data, test data. This paper provides an overview of the available data, with a particular focus on the terrain data set.

2. Vehicle Data

The FED-Alpha vehicle [4] was the test vehicle for NG-NRMM demonstration efforts, because it was representative of a military vehicle with substantial off road capability. It had been subjected to extensive field testing and had utilized many commercial off-the-shelf (COTS) components. Existing McNeil Swindler Corporation (MSC) Adams multi-body dynamics and NATO Reference Mobility Model (NRMM) models had also been developed.

The FED-Alpha is made of a lightweight aluminum structure with armoring and an underbody blast shield. The vehicle features a Cummins I4 engine, a six-speed automatic transmission from Aisin and is fitted with Goodyear 335/65R22.5 G275 Fuel Max low roll resistance tires developed specifically for this vehicle. It possesses a COTS Dana central tire inflation system (CTIS) with 4 settings (E = 15 psi, SS = 25 psi, CC = 40 psi, and HY = 60 psi), a modified COTS adaptive braking system (ABS) and traction control system (TCS), and an active ride height system (Highway = 271 mm clearance, Obstacle = 341 mm clearance). The suspension is an independent unequal length A-arm SLA (short, long arm) architecture with integrated air-spring-dampers at each corner. The powertrain/driveline consists of:

- 4.5L 200 hp efficiency optimized super & turbocharged Cummins (Modified COTS)
- 24VDC Kollmorgen integrated starter-generator (Unique)
- 6-speed Aisin automatic transmission (COTS)
- Full time 4WD transfer case (COTS-HMMWV)
- Spiral bevel air-locking differentials (Modified COTS)

- Non-geared hubs (Unique)

Available vehicle data:

CAD Geometry – The 3D CAD geometry is provided in base UniGraphics' Parasolid, native UGNX9, .stl, and .stp formats. There are some .jpg images of the CAD files, and most of this data is compressed into .zip files. The CAD assembly structure is as follows:

- ITR55510_002 Master Assembly (Including all sub-assemblies)
- ITR18876_003 Electrical Systems Sub-assembly
- ITR18875_002 Suspension, Wheels, etc. Sub-assembly
- ITR18874_002 Transmission Sub-assembly
- ITR18873_004 Engine, etc. Sub-assembly
- ITR18872_003 Cooling System Sub-assembly
- ITR18871_003 Outer Body Panels, etc. Sub-assembly
- ITR18870_003 Internal Structure, Panels, etc. Sub-assembly
- ITR18869_002 Personal Equipment, Radios, etc. Sub-assembly

CAE Models – Computer simulation CAE models are provided in two formats: (1) a 3D multi body dynamics model of the full vehicle in MSC Adams, and (2) a Math Works Simulink model of the suspension damping relationship. There is an Adobe .pdf description of the damping relationship.

FED CAN Information - On-board CAN Bus information is provided in .dbc format and explained in both MS Excel and Power Point documents.

Physical Characteristics - Physical characterization data, weights, CGs, etc. for vehicle testing is provided in MS Excel, Power Point, and Adobe documents.

Subsystem Information - Subsystem Data, Steering Data, Engine Mount Information, and Raw Tire Data is provided in MS Excel, Power Point, and Adobe documents.

3. Terrain Data

The NG-NRMM CDT geospatial data set was assembled and provided by a collaboration between MTU/KRC and Great Lakes Research Center (GLRC). The terrain data is limited to a 900 acre Area of Operation (AO) at MTU/KRC's test facility. The terrain data set is divided into two categories: Geospatial Data and Soil Data.

3.1. Geospatial Data

The Geospatial data is broken down as follows:

- Aerial Images, High Res Topology: AO, OLE's SPECIAL MAP, Mobility Traverse Sections, Cleaned TINs (Triangular Irregular Networks)
- Map11 & Geotiffs: Mobility Traverse (NRMM) JPEGs, Jpegs 180614, Legacy NRMM Map with Aspect
- Terrestrial Scan Info: Side Slope, Half Rounds, AO, Sand Grade, RMS Lanes, V Ditch

The Geospatial Data represents several sets of terrain data that exists at MTU/KRC's test facility and is spatially located to a specific geographic location on the earth. This geographical reference data is provided in several formats depending upon the type of information. The topology information is provided in the following formats:

- TINs – Essentially a Mesh of triangles in .xml format
- GeoTiff (Georeferenced Tagged Image File) – A special raster data format used for geographic data transfer. Jpegs are provided to view the content of the GeoTiff files
- STEP (STandard for the Exchange of Product) Model Data
- MAP11 – NRMM files in .ter, .prj, and .asc ASCII readable formats
- Aerial images in .jpg format

3.1.1 Aerial Images and High Resolution Topology

Geospatial data is referenced to a specific location on earth, and represents the earth's shape and description at that location. CDT geospatial data was collected from the physical environment used

for modeling the interaction of a vehicle moving across the terrain within an AO. This data was organized into several thematic layers including: Elevation, Slope Grade, Slope Aspect, Soil Classification, Soil Moisture, Bulk Density, Depth to Bedrock, Soil Strength (Cone Index), Road Type, Land Cover, Vegetation Size, Vegetation Density, Recognition Distance, and Obstacles.

Readily available pre-existing data sources were identified and procured from publicly accessible websites and included elevation data and land cover data from the United States Geologic Survey (USGS) and soil attribute data from the United States Department of Agriculture (USDA). Elevation data from the USGS managed National Elevation Dataset (NED) has a resolution of $\frac{1}{3}$ arc second (approximately 8 meters at KRC) and accuracy of +/- 2 meters at the AO. It is produced from diverse source datasets and is continually updated, but had not been updated recently in this project's AO. Land Cover data from the USGS managed National Land Cover Dataset (NLCD) has a resolution of 30 Meters and accuracy of +/- 10m and classifies land cover into 16 broad categories over the AO. Soil attribute data from the USDA Soil Survey Geographic Database (SSURGO) has a varying resolution, with most information being collected at a map scale of 1:12,000. Numerous soil attributes are described and linked to soil map unit polygons that can be overlaid with other thematic layers. While there were several USDA soil types described over the AO, this project required the use of Universal Soil Classification System (USCS) soil type codes. There were only two unique USCS codes described in the AO: Sand and Peat. The database also did not capture the varied composition of the test courses and structures within the AO.

Overall, none of these pre-existing sources had the level of precision, accuracy, or timeliness necessary to support complex terramechanics modeling. These data layers were considered

coarse resolution and were used to fill in gaps outside of the areas to be modeled. Additional data collection was necessary to produce higher resolution datasets.

In order to produce data layers suitable for use in complex terramechanics models, high-resolution geospatial data was collected using remote sensing and direct sensing techniques. Multi-season, aerial imagery was collected, and individual images were stitched together into a mosaic of images and georeferenced to their correct location on earth using GIS software and the 2015 USDA National Aerial Imagery Program (NAIP) Aerial Imagery as a reference layer. Additionally, three inch resolution aerial photography was collected and georeferenced. This collection of aerial imagery (Figure 2) was used to create several high-resolution layers including land cover, surface type, road type, surface water depth, vegetation stem size, vegetation density, and recognition distance.



Figure 2. High Resolution Images of the MTU/KRC Test Course.

High-resolution elevation data was collected at sub-centimeter accuracy through manual elevation mapping using Terrestrial Lidar Scanning techniques. 3D Point clouds were created at individual stations along the 5 km path used for the mobility traverse evaluation and other areas of the test course. The majority of all scans were recorded with the range set to 120 m / 270 m mode which has a range accuracy of 1.2 mm +10 ppm recording 1 million points per second. Figure 3 shows a Terrestrial Scanning Tri-Pod and Point Cloud example.

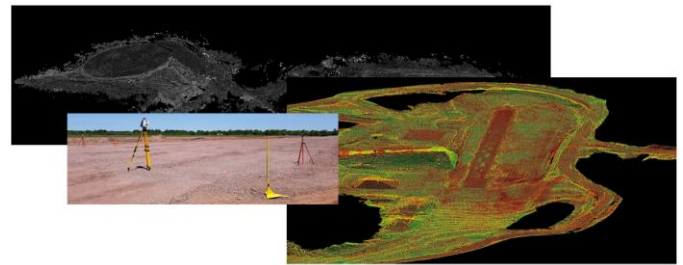


Figure 3. Terrestrial Scanning Tri-Pod and Point Cloud
Example of the MTU/KRC Test Course

Due to the small AO, complex vegetation mixture, and numerous distinct test course features, manual image classification techniques were used. Polygons were drawn around each distinct area of land cover and classified into 1 of 6 general land cover categories including: evergreen forest, mixed forest, grass, grass with scrub, bare ground, and open water. Additionally, forested areas were subdivided into areas of differing stem diameters and stem spacing and classified as large, medium, and small diameters and high, medium, and low densities. Land cover classifications were translated to match the NRMM MAP11 schema land cover classification codes. Several direct-sensing techniques, including Terrestrial Lidar Scanning, Cone Penetrometer testing, and manual soil sampling and classification, were used to create additional high-resolution layers for elevation, slope, aspect, cone index, and custom soil type. Bevameter readings were collected for each custom soil type and stored as attributes that could be linked to custom soil type map polygons (See Soil Section). These data layers were combined to create a high resolution soil map (Figure 4).

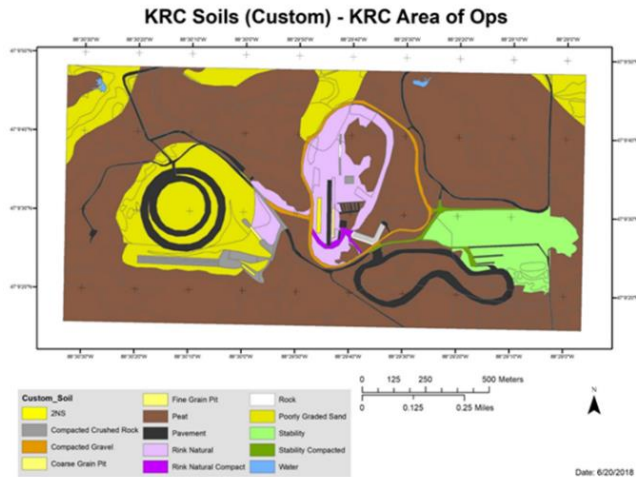


Figure 4. Custom Soil Distribution for the KRC Test Course

3.1.2 MAP 11 and GeoTiffs

Output datasets intended for use in modeling environments must adhere to a data schema that defines attribute names, attribute value types, data value domains and ranges, and standard default and null values. To facilitate this, a template geodatabase was created and configured to meet the existing NRMM Map11 Data Schema. Attributes and polygons from all thematic data layers were combined into a single combined data layer. This combined data layer includes attributes from all the input data layers and polygon geometries representing areas of homogeneous attributes. Processing scripts were used to map some discrete attribute values to multiple other attribute fields in the MAP11 schema and used by the NRMM Model. Land cover values were used to determine multiple monthly recognition distance values as well as surface cover type values. Cone Index measurements were used to determine scenario representative cone index values. After all layers were combined and attributes transformed and filled, geometry boundaries were cleaned using geodatabase topology tools in ArcGIS Desktop. Very similar feature boundaries were made coincident to remove small ‘sliver’ polygons, and features were dissolved to create polygons of homogenous attributes, reducing the number of

total polygons. Several output and interchange formats were requested to enable data transfer to modeling environments and use in complex terramechanics models and legacy NRMM models. The NRMM MAP11 format is the newest format for the NRMM model. Attributes from the combined layer were exported using custom built tools to convert polygons into raster format and then into an ASCII file grid of terrain units, with an associated terrain unit attribute table. The NRMM MAP90 format is a legacy format for the NRMM model and the same tools used to export to MAP11 format were used to export to the MAP90 format. However, column headers needed to be manually edited in the MAP90 attribute table to work properly with legacy NRMM models.

Each individual Geodatabase attribute was also exported in GeoTIFF format, which is a raster format similar to a photograph, but with an attribute value in each pixel instead of a color in each pixel. This format is commonly used to visualize attribute values such as elevation, slope, aspect and soil type and high-resolution elevation data was output in TIN and Mesh format. High Resolution elevation data could not be retained in NRMM MAP formats without leading to a file too large to use and, similarly, GeoTiff Files of high-resolution elevation data became too large to use. TIN or Mesh formats allowed for high resolution elevation data with manageable file sizes which allowed the entire area to be modeled, but still proved too large for most models to use, so TINs and Meshes were generated for subsections of the course to reduce file sizes to usable levels. All geospatial thematic data layers, such as land use and soil types, are available for download in GeoTiff and geodatabase format, as well as very high resolution elevation data are available for download in 3D mesh and TIN format for the entire AO as well as subsections of the area. Geospatial data was exported in MAP90 format and used to produce speed-made-good prediction files using the legacy NRMM modeling environment. The ASCII file grid of

terrain units was converted to a map layer and linked to the attributes of the associated output prediction files using the Terrain Unit ID (NTU) attribute. Thematic maps of speed-made-good and reason-codes were produced and used for data quality testing (Figure 5).

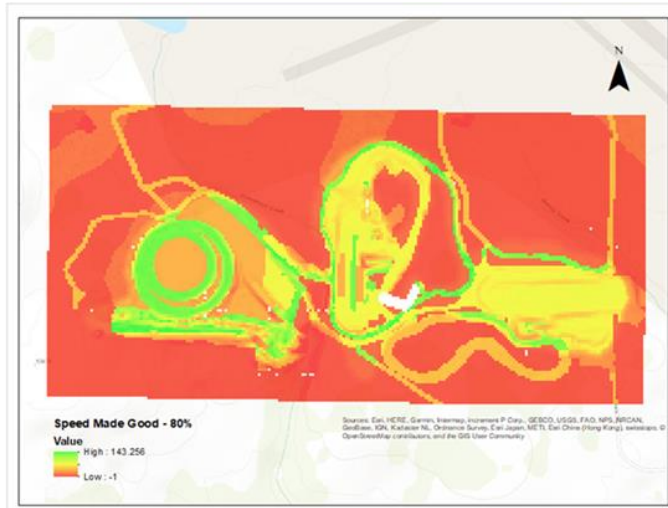


Figure 5. Sample Speed Made Good Map of the MTU/KRC Test Course

3.2. Soil Data

Soil Data represents information that quantifies the strength of the types of soil found at MTU/KRC's test facility. Two types of data are provided; data collected from laboratory tests on soil samples and data collected from In Situ (field) tests collected at various test facility locations. All of the soil data is provided in MS Excel format with some assorted MS Power Point and Adobe ".pdf" files describing the collection procedures. Additionally, some .jpg images are provided to aid in describing the data.

The soil data was broken down as follows:

- Laboratory Soil Results - General Information, Triaxial, Sieve and Hydrometer Combined, Proctor, Organic Content, Direct Shear, Stability, RinkNatural, FinePit, CoarsePit, 2NS, Compressibility

- In Situ Soil Results (Field Tests), Soil Types and Location, Friction Data, Bevameter Specifics, Cone Traces, Raw Bevameter Data, Bevameter Results, Field Measurement Results

In addition to the shape of the earth's surface, there was also a need to collect soil data; information that describes the composition of the surface layer. Like elevation, soil data is available from public sources and is acquired for the overall area, but it must be processed to fit the exact area of interest and match the target schema. General soil data was first obtained from the SSURGO database which is an aggregation of state-level soil surveys over the entire United States. This soil database is a multi-level relational database that includes a spatial component as a set of map units. To process this dataset, the SSURGO data was extracted from flat files to the government-provided database schema and matched to map unit keys. Then the map units were matched to the desired attributes, in this case the soil type and bulk density, and exported to an intermediate dataset. This intermediate dataset was then created by clipping to the correct area of interest, and the field names converted to match the NG-NRMM schema and was then merged into the geodatabase. But, like the elevation data, the SSURGO data was not detailed enough. The MTU/KRC's test areas are active research areas and the surface composition changes for the different portions of the test course. Readily available soil survey data from the NRCS was also not sufficiently precise or current enough for use and only provided two general soil classifications; Sand and Peat. To improve this, pavement and water were manually added to the source dataset and manual on-the-ground soil sampling was conducted to further classify the test course soils into 14 different categories which were manually mapped and digitized as a thematic map of custom soil types.

The soil collection and analysis plan for the CDT was designed with the intent to fully describe the

soils that would be tested to ensure accurate modeling results so both laboratory and in-situ soils measurements would be included. Standard laboratory tests are well specified and engineering properties are documented in ASTM specifications. However, there was a need for field measurements during testing to supply input data to the models for predicting test results. A laboratory soil analysis determined the grain size, specific gravity, Proctor compaction, Atterberg limits, direct shear, and triaxial shear. Terramechanics provides the data for the soil's exponent of deformation (n), cohesive modulus of deformation (Kc), frictional modulus of deformation (Kphi), soil cohesion (c), soil internal friction angle (phi), and soil shear deformation modulus (K) as well as a lookup table synchronized to the land use or soil type. A list of "standard" tests were conducted and measurements were made on the soils that were deemed to describe the AO on test courses and five (5) different soil regimes are present within AO as follows:

Fine Grained Pit - The fine grained soil is natural to the test course and was sieved through a 1/8" mesh to remove any coarse particles and is classified in the USCS as ML. It is a cohesive soil, a sandy silt of low plasticity, and was chosen since it is highly moisture susceptible and 6% moisture is very stable whereas 18% moisture has essentially no strength and is highly susceptible to freeze thaw immobility.

Coarse Grained Pit - The Coarse Grained Pit actually contains a medium sand and is classified as SP/SM by USCS which is "poorly graded" silty sand. This means that the grains are for the most part the same size and this soil was chosen because it has very consistent grain size and very rounded and it is essentially beach sand that has been rounded by glacial water. This soil gets easier to traverse when it is wet as compared to dry.

2NS Sand – Variable Hill Climb - This sand is also characterized as SP. It is a poorly graded medium sand, but contains a fraction that is closer to coarse sand as compare to the coarse pit. The sand particles are also more angular than the coarse

pit resulting in a different mobility scenario and, in general, a little stiffer and slightly easier to traverse and exhibits better mobility wet than dry.

Rink Natural Soil - The area around the "RinkNatural" contains a soil type that is classified as SM, or silty sand. It contains a fraction of gravel sized particles, has some cohesion, and is very stable when it is dry and gets weaker when it gets wet and is susceptible to freeze thaw.

Stability Soil - The area known as "Stability" contains a soil type that is classified as SW/SM, or well graded silty sand. This means that it contains fractions of clay through medium sand in gradual amounts. It has more fine sized particles including clay than the rink natural and contains a fraction of gravel sized particles and cobbles. This soil has some cohesion and is very stable when it is dry and gets much weaker when it gets wet and is highly susceptible to freeze thaw.

The laboratory data collection tests consisted of:

- Visual – ASTM D2488
- Moisture Content @ Sample Collection ASTM D2216
- Grain Size Analysis: Sieve – ASTM D6913 & Hydrometer - ASTM D7928
- Atterberg Limits – ASTM D4318
- ASTM USCS Classification
- Specific Gravity – ASTM D854 and Relative Density ASTM D4254 and D4253
- MaxVoid ratio (MinDensity) ASTM D4254
- MinVoid ratio (Max Density) ASTM D4253
- Standard Proctor – ASTM D698
- Total Organics – ASTM D2974
- Direct Shear – ASTM D3080
- Triaxial Test (drained) – ASTM D7181
- Compressibility in Pressure Cell-ASTM D7181

Large samples were obtained from each of the five (5) different soil areas and taken to the soils laboratory. The laboratory analyses were performed independently of vehicle testing to blanket the extremes of moisture content and density.

Table 3. Bekker-Wong Soil Strength Measurements Collected for the CDT Tests

Date	Test Set	Location	Test Performed	P _{max} (kPa)	n	K _c (kN/m ²)	K _φ (kN/m ²)	A ₀ (kN/m ²)	K ₀ (kN/m ²)	Grouser	Rubber Ring
6/2/2018	Test Set 1	Variable Hill Climb	Variable Hill Climb	825	0.40	8.8	100.8	905.13	13176.28	n _{max} (kPa)	C (kPa)
6/2/2018	Test Set 2	Variable Hill Climb	Variable Hill Climb	825	0.62	7.6	39.2	905.13	13176.28	φ _{max} (deg)	φ _{max} (deg)
6/5/2018	Test Set 9	Fine grain soil pit (dry)	Drumbar Pull - Dry	825	1.49	-26.6	646.6	91870	1746425	n _{max} (kPa)	C (kPa)
6/5/2018	Test Set 10	Fine grain soil pit (dry)	Drumbar Pull - Dry	825	1.82	73.7	-716.0	91870	1746425	φ _{max} (deg)	φ _{max} (deg)
6/5/2018	Test Set 11	Fine grain soil pit (dry)	Drumbar Pull - Dry	825	1.82	73.7	-716.0	91870	1746425	n _{max} (kPa)	C (kPa)
6/5/2018	Test Set 12	Coarse Pit	Drumbar Pull	825	0.46	6.1	174.1	NO DATA	NO DATA	n _{max} (kPa)	C (kPa)
6/5/2018	Test Set 13	Coarse Pit	Drumbar Pull	825	0.61	4.8	144.8	120421	2009790	φ _{max} (deg)	φ _{max} (deg)
6/5/2018	Test Set 14	Coarse Pit	Drumbar Pull	825	0.81	7.3	46.2	120421	2009790	n _{max} (kPa)	C (kPa)
6/5/2018	Test Set 17	Fine grain soil pit (wet)	Drumbar Pull - Wet	825	3.57	-0.1	3.5	-49417	1954322	φ _{max} (deg)	φ _{max} (deg)
6/5/2018	Test Set 18	Fine grain soil pit (wet)	Drumbar Pull - Wet	825	2.97	0.2	-11.5	-49417	1954322	n _{max} (kPa)	C (kPa)
6/5/2018	Test Set 19	Fine grain soil pit (wet)	Drumbar Pull - Wet	825	2.97	0.2	-11.5	-49417	1954322	φ _{max} (deg)	φ _{max} (deg)
6/7/2018	Test Set 24	Variable Hill Climb	Traverse	825	0.50	8.8	81.6	?	?	n _{max} (kPa)	C (kPa)
6/7/2018	Test Set 25	Variable Hill Climb	Traverse	825	0.59	-1.8	218.1	?	?	φ _{max} (deg)	φ _{max} (deg)
6/7/2018	Test Set 26	Variable Hill Climb	Traverse	825	0.81	14.9	-70.7	?	?	n _{max} (kPa)	C (kPa)
6/7/2018	Test Set 27	Coarse Pit	Traverse	825	0.84	1.3	142.4	?	?	φ _{max} (deg)	φ _{max} (deg)
6/7/2018	Test Set 28	Fine grain soil pit	Traverse	825	3.03	0.0	5.0	?	?	n _{max} (kPa)	C (kPa)
6/7/2018	Test Set 29	Fine grain soil pit	Traverse	825	4.01	-0.1	5.0	?	?	φ _{max} (deg)	φ _{max} (deg)
6/7/2018	Test Set 30a	Ice Risk	Traverse	825	1.69	8.2	94.2	?	?	n _{max} (kPa)	C (kPa)
6/7/2018	Test Set 31	Ice Risk North	Traverse	825	1.75	234.8	-2993.7	?	?	φ _{max} (deg)	φ _{max} (deg)
6/7/2018	Test Set 32	Stability	Traverse	825	2.98	10.1	6.2	?	?	n _{max} (kPa)	C (kPa)
6/7/2018	Test Set 33	Stability (Saturated+)	Traverse	825	2.15	-20.7	627.6	?	?	φ _{max} (deg)	φ _{max} (deg)

Table 2. Additional Measurements Collected at the Bekker-Wong Measurement Sites and the Corresponding Strength Values Obtained from Laboratory Tests for that Soil

Date	Test Set	Location	Test Performed	Soil (USCS)	Cone Index		Moisture Grav. %	Bulk Density (Dry Kg/m ³)	Direct Shear		Triaxial	
					(10-15 cm)	(15-30 cm)			C (kPa)	φ _{max} (deg)	C (kPa)	φ _{max} (deg)
6/2/2018	Test Set 1	Variable Hill Climb	Variable Hill Climb	2N5 Sand - SP	82	---	2.0	1325	158.6	0	33.8	5.5
6/2/2018	Test Set 2	Variable Hill Climb	Variable Hill Climb	2N5 Sand - SP	99	---	2.8	1443	158.6	0	33.8	5.5
6/5/2018	Test Set 9	Fine grain soil pit (dry)	Drumbar Pull - Dry	Fine Grain Pit - ML	127	320+	9.3	1517	158.6	0	33.8	4.5
6/5/2018	Test Set 10	Fine grain soil pit (dry)	Drumbar Pull - Dry	Fine Grain Pit - ML	161	320+	8.6	1525	158.6	0	33.8	4.5
6/5/2018	Test Set 11	Fine grain soil pit (dry)	Drumbar Pull - Dry	Fine Grain Pit - ML	---	---	---	---	158.6	0	33.8	4.5
6/5/2018	Test Set 12	Coarse Pit	Drumbar Pull	Coarse Pit - SP/SM	60	258	2.5	1541	158.6	0	33.8	3.5
6/5/2018	Test Set 13	Coarse Pit	Drumbar Pull	Coarse Pit - SP/SM	85	300+	2.4	1610	158.6	0	33.8	3.5
6/5/2018	Test Set 14	Coarse Pit	Drumbar Pull	Coarse Pit - SP/SM	118	320+	7.3	1708	158.6	0	33.8	3.5
6/5/2018	Test Set 17	Fine grain soil pit (wet)	Drumbar Pull - Wet	Fine Grain Pit - ML	7	213	14.4	1562	158.6	0	33.8	4.5
6/5/2018	Test Set 18	Fine grain soil pit (wet)	Drumbar Pull - Wet	Fine Grain Pit - ML	---	---	---	---	158.6	0	33.8	4.5
6/5/2018	Test Set 24	Variable Hill Climb	Traverse	2N5 Sand - SP	99	189	3.0	1661	158.6	0	33.8	5.5
6/7/2018	Test Set 25	Variable Hill Climb	Traverse	2N5 Sand - SP	---	---	---	---	158.6	0	33.8	5.5
6/7/2018	Test Set 26	Coarse Pit	Traverse	Coarse Pit - SP/SM	89	299	2.3	1605	158.6	0	33.8	3.5
6/7/2018	Test Set 27	Coarse Pit	Traverse	Coarse Pit - SP/SM	---	---	---	---	158.6	0	33.8	3.5
6/7/2018	Test Set 28	Fine grain soil pit	Traverse	Fine Grain Pit - ML	15	253	10.3	1490	158.6	0	33.8	4.5
6/7/2018	Test Set 29	Fine grain soil pit	Traverse	Fine Grain Pit - ML	32	316	9.1	1490	158.6	0	33.8	4.5
6/7/2018	Test Set 30	Ice Risk	Traverse	Rink Natural (Compact) - SM	320+	320+	4.8	1914	158.6	0	33.8	8.3
6/7/2018	Test Set 31	Ice Risk North	Traverse	Rink Natural (Grass) - SM	177	247	14.1	1571	158.6	0	33.8	8.3
6/7/2018	Test Set 32	Stability	Traverse	Stability - SN/SM	199	308	10.6	1554	158.6	0	33.8	12.1
6/7/2018	Test Set 33	Stability (Saturated+)	Traverse	Stability [Sat] - SN/SM	200	320+	---	---	158.6	0	33.8	12.1

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In addition to the in-depth laboratory analysis, several different in-situ measurements were made in an attempt to bracket the specific properties needed in the models. These included methods that are commonly used in construction and mobility research as well as the development of a state-of-the-art Bevameter to predict Bekker-Wong parameters of the soils. The list of in-situ measurements were as follows:

- Visual
- Cone Penetrometer
- Rating Cone Index
- CLEGG Hammer
- Standard Moisture Content (moisture samples dried in a soils oven)
- Sand Cone Density
- Nuclear Density
- Moisture content from Nuclear Densometer
- Plate Sinkage (Bevameter)
- Shear annulus (Bevameter)

In situ measurements were made when mobility tests were performed, and the measurement schedule depended on the test and weather. The Bevameter was the most time consuming, since it was limited to 10 full data sets in different locations per day. For each mobility test, 3 sets of plate sinkages and shears, Nuclear Densities and moistures, CLEGGs (on hard soils), and moisture tins were completed within the area being tested (Table 1). For each Bevameter reading a continuous cone penetrometer trace was collected. Cone penetrometer readings were made 5-10 times per test area per day. In some instances measurements were made between test days to look at the effects of varying moisture content for days when soil measurements were not conducted.

Table 1. Inventory of In Situ Soil Strength Measurements Collected

Soil Type	Nuc Density	Nuc Moisture	Moisture Tin	Cone Penetrometer	Clegg	Cone Trace	B/W
2NS Sand	5	5	5	20	4	10	10
Coarse Pit	6	6	6	29	5	6	6
Rink Natural	5	5	4	20	2	4	4
Stability	6	6	6	36	3	4	4
Fine Pit	11	11	8	45	14	9	9
Crushed Rock	3	3	0	0	4	----	----
Gravel	1	1	2	3	5	----	----
Total	37	37	31	153	37	33	33

The raw Bevameter data was analyzed using the methods outlined in [5]. Table(s) 2 and 3 contain an overview of the strength parameters derived for the major soils data groups measured during vehicle testing for CDT.

4. Test Plan and Data

Table 1 lists the CDT tests that were conducted and the corresponding outputs that were collected. Vehicle behavior data is categorized by “paved” and “off road” maneuvers and these two categories are further sub divided into the individual test types conducted. A majority of the test types have a summary report in MS Power Point format and some test types have additional summaries contained in MS Excel spreadsheet format. Most of the raw vehicle data is provided in Matlab’s open sourced “.mat” format contained in sub directories in each test type directories. The raw “.mat” files are based on structure arrays for each data channel that contain both ordinate and abscissa headers, units, and values. A channel map is provided on the website in MS Excel spreadsheet format with instructions appended to ease use of the structured arrays. The complete test plan can be found in [5].

Table 1. Summary of tests performed and corresponding outputs recorded.

Test Name	Soil	Simulation Outputs
Straight Line Acceleration (TOP 2-2-602)	Pavement	Position, speed, acceleration histories

Test Name	Soil	Simulation Outputs
Wall to Wall Turn Circle Radius	Pavement	max diameter of tightest circle position, speed, clockwise and ccw
Steady state cornering (30 m radius) (SAE J2181)	Pavement	Understeer/oversteer characteristics, steering angle, max. speed, lateral accel
NATO Double lane change (AVTP 03-160 W)	Gravel	Speed, path, steering angle, lateral acceleration, yaw rate, roll angle
Side slope with obstacle avoidance steer	Hard-packed crushed mine rock	Side slope, speed, pass/fail
60% Longitudinal grade	Coarse grain sand	Speed, grade, pass/fail
0 to 30% Longitudinal grade	Coarse grain sand	Max grade at set speed, pass/fail
4, 8, 10, 12 inch half-round	Pavement	Speed at 2.5g vert acc at driver's seat
18 and 24 inch vertical step	Concrete	Go/no-go and identify any interference
V-ditch	Concrete	Go/no-go and identify any interference
Drawbar Pull Fine Grain Organic/Silty Sand Coarse Grain Sand	Sand Dry and Wet Dry and Wet	Drawbar pull vs. slip
Asymmetric 1, 2, 3 inch RMS	Hard-packed crushed mine rock	6-Watt absorbed power speed
Symmetric 1/2/3/4/4.8 inch RMS	Hard-packed crushed mine rock	6-Watt absorbed power speed

5. Conclusions

This paper has outlined the data available from the Next Generation NATO Reference Mobility Model effort. Future publications will provide more detail on computations, error values, and the Uncertainty Quantification analysis conducted. In addition, information regarding test procedures, data, and instrumentation, MTU/KRC's "Detailed Test Plan for the Automotive Performance and Mobility Evaluation of the TARDEC Fuel Efficiency Demonstrator Concept A (FED-A) Vehicle" [5]. The CDT Final Report [3] as well as all raw test performance data, vehicle data, terrain and soil

data, CDT event information, and promotional videos can be found at the following location: [ftp://ng-nrmm:thread\\$panel@nrmm.mtukrc.org](ftp://ng-nrmm:thread$panel@nrmm.mtukrc.org)

The entire site is currently set to read-only access and all information and media located on the sites is Distribution A - Unlimited Access so it can be used and distributed freely.

This data represents a valuable asset to the mobility research community, particularly as it relates to military relevant, off-road mobility research. This complete data set represents a base line from which the performance of advanced mobility and autonomous vehicle technology could be evaluated.

1. REFERENCES

- [1] Dr. Richard Gerth, Scott Bradley, Michael Letherwood, Dr. David Gorsich, "An Overview of the Next-Generation NATO Reference Mobility Model (NG-NRMM) Cooperative Demonstration of Technology (CDT)", In Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium (GVSETS), NDIA, Novi, MI, Aug. 13-15, 2019.
- [2] STO Technical Report "AVT-248 Next Generation NATO Reference Mobility Model (NG-NRMM) Development"
- [3] STO Technical Report, "CDT-308 Cooperative Demonstration of Technology Next Generation NATO Reference Mobility Model (NG-NRMM)"
- [4] Ricardo Defense, "FED Data.xls" 2017
- [5] Gwaltney, G., Bradley, S., "Detailed Test Plan for Automotive Performance and Mobility Evaluation of the TARDEC Fuel Efficiency Demonstrator Concept A (FED-A) Vehicle", Michigan Technological University, Keweenaw Research Center, 2018
- [6] "Terramechanics and Off-road Vehicle Engineering" by J.Y. Wong (2nd Edition, 2010)