The Next Generation NATO Reference Mobility Model Development

NATO-STO-AVT-248-Research Task Group
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Abstract
The NATO Reference Mobility Model (NRMM) is a simulation tool aimed at predicting the capability of a vehicle to move over specified terrain 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 '70s, and has been revised and updated through the years, resulting in the most recent version, NRMM v2.8.2b. It was originally used to facilitate comparison 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. This paper summarizes recent efforts initiated under a NATO Exploratory Team (ET) and its follow-on Research Technical Group (RTG) to upgrade this key modeling and simulation tool and the planned path forward toward implementing the recommendations of that team.

Keywords: NATO**,** NRMM, mobility model, operational planning, multibody dynamics

1. Introduction

Although NRMM has proven to be of great practical utility to the NATO forces, it has several inherent limitations, particularly when compared to modern multibody dynamic (MBD) modeling and simulation (M&S) capabilities. Many of the off-road mobility algorithms are based on empirical observations, and therefore extrapolation outside of test conditions is impossible. It is heavily dependent on in-situ soil measurements and uses one-dimensional steady state analysis of powertrain performance. Turning performance and lateral vehicle dynamics are not considered. Vehicle dynamic effects are limited to pitch plane for ride quality and all obstacle crossing models were forced to conform to an equivalent walking beam formulation for tracked vehicle suspensions systems. Due to its age and intermittent ad hoc development history and reliance on empirical performance data collected at the vehicle level, NRMM's software and data architectures do not easily support evolutionary development in terramechanics or vehicle terrain interaction (VTI) models such as the fundamental extension to 3D models that support vehicle turning mechanics and more complete mobility metrics. The means for expansion of the analysis techniques to include intelligent vehicles, custom mobility metrics, stochastic knowledge of terrain and terrain data sets for urban areas are additional pressing needs for a Next Generation NRMM (NG-NRMM).

While an effort to update NRMM was initiated in 2002 [McClelland] resulting in some specific advances summarized in a 2011 report [Jones], this effort did not lay the organizational and architectural foundations required for sustained growth and evolution of the model in a way that opens the model architecture up to multi-scale mechanics solutions, continuous future improvement, non-preferential use of commercial software capabilities and also promotes inclusion of all NATO nations preferred mobility modeling solutions. Thus in 2014, a NATO Applied Vehicle Technology (AVT) Exploratory Team 148 (ET-148) [Dasch and Jayakumar, 2016] was formed to consider the development of a truly Next-Generation NRMM (NG-NRMM). ET-148 identified seven themes with the following goals:

1) Requirements: Capture, consolidate, and summarize desired capabilities [Bradbury, 2016].

2) Methodologies: Develop a plan for deriving a ground vehicle mobility modeling and simulation (M&S) architectural specification for the NG-NRMM [McCullough, 2016].

3) Stochastics: Describe a framework for a stochastic approach for vehicle mobility prediction over large regions for integration into a NG-NRMM [Gonzalez, 2016].

4) Intelligent Vehicles: Define a NG-NRMM approach and requirements for mobility assessment for intelligent vehicles [Jain, 2016].

5) Tool choices: Identify the state of the art for NG-NRMM enabling simulation technologies as claimed by the technical community of software developers, suppliers, and user nations [Hodges, 2016].

6) Input Data and Output Metrics: To define the input/output data requirements that will inform the Next-Generation NRMM tool development/selection processes and tool recommendations for advanced mapping tools including the means for analysis of remotely sensed Geographical Information System (GIS) data [Wojtsiak, 2016].

7) Verification and Validation (V&V): Develop a plan to provide benchmarks for conducting a successful simulation tool V&V with respect to the NG-NRMM specification [Letherwood, 2016].

The NATO ET-148 committee consisted of 38 persons from 13 nations (Canada, Czech Republic, Denmark, Estonia, Germany, Italy, Poland, Romania, Slovakia, Spain, Turkey, United Kingdom, and United States) each of whom participated in the detailed research and development goals through membership on one or more of the teams formed to focus on each of the seven goals.

2. NRMM Overview

NRMM is one of the first and few enduring models that comprehensively and realistically quantifies ground vehicle mobility based on terrain accessibility and maximum attainable speeds for comparative force projection assessments of military vehicles via rational consideration of the vehicle's mission, design characteristics, and actual terrain characteristics around the globe [Priddy, 2014].

Architecturally, NRMM is a modeling suite comprised of closed form equations for a range of mobility metrics plus numerical models of obstacle crossing and ride dynamics (executed through pre-processors) combined into a main operational prediction module, as shown in Fig. 1. The obstacle and ride dynamics numerical models summarize their respective metrics in well-defined parametric performance curves, but their physics are limited to the vehicle pitch plane. These models require terrain, vehicle and environmental scenario (e.g., dry, wet, snow, sand) data at varying levels of resolution. The operational level performance over a mapped areal terrain is summarized as trafficable percent area (GO/NOGO) and speed made good on the “GO” portions of terrain. Terrain data sets characterizing particular regions of the world are part of the operational model.

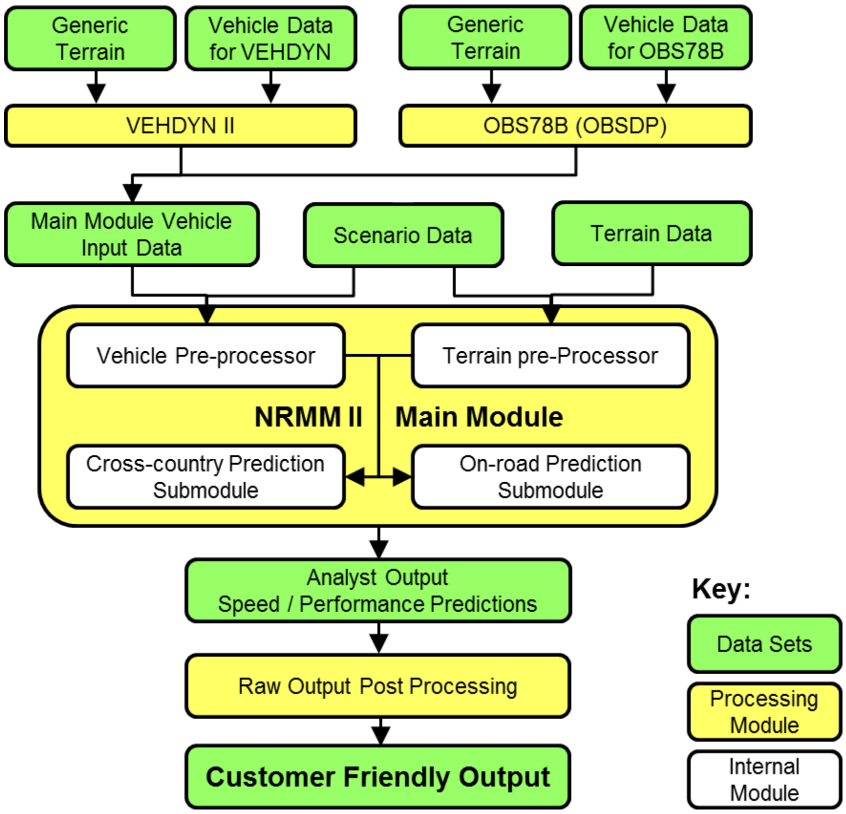


Fig. 1. *NRMM Methodology [Bradbury, 2016]*

The operational module combines and considers specific aspects of mobility performance. These include: obstacle override and avoidance, vegetation override and performance, powertrain performance, vehicle/surface interface (soils and hard surfaces), slope effects (grades and side slopes), ride dynamics, visibility, tire constraints, road curvature and braking. Note that in the latest release, version 2.8.2b, VEHDYN II and OBSDP represent differing analysis run streams for ride dynamics and obstacle crossing performance, but use the same vehicle dynamics module. The physics calculations are accomplished with the latest upgrade to the pitch plane vehicle dynamics modeling code, VEHDYN 4.3, which includes a significant list of vehicle suspension and vehicle-terrain interaction modeling enhancements [McKinley, 2014] that permit it to cover both the ride dynamics and obstacle crossing analysis run streams.

The ride dynamics run stream determines two separate ride quality metrics as lookup tables for the main operational module: 6 watt ride limiting speed vs terrain roughness (using random terrain profiles) and peak acceleration limiting speed vs half round obstacle size. By virtue of this well-defined mobility metric, this analysis run stream is readily substituted with results from other vehicle dynamics models and ride dynamic metrics. For example, as shown in Fig. 2, highly detailed 3D vehicle models developed in commercial MBD codes have frequently been used because they have been separately validated and/or calibrated with experimental test data [BAE Systems, 2009 and McCullough, 2000]. Other ride quality metrics such as ISO 2631 as well as those based on 3D metrics such as longitudinal and lateral acceleration have been proposed as ride limiting speed criteria and could easily be used by substitution of results tables into the higher level operational module.

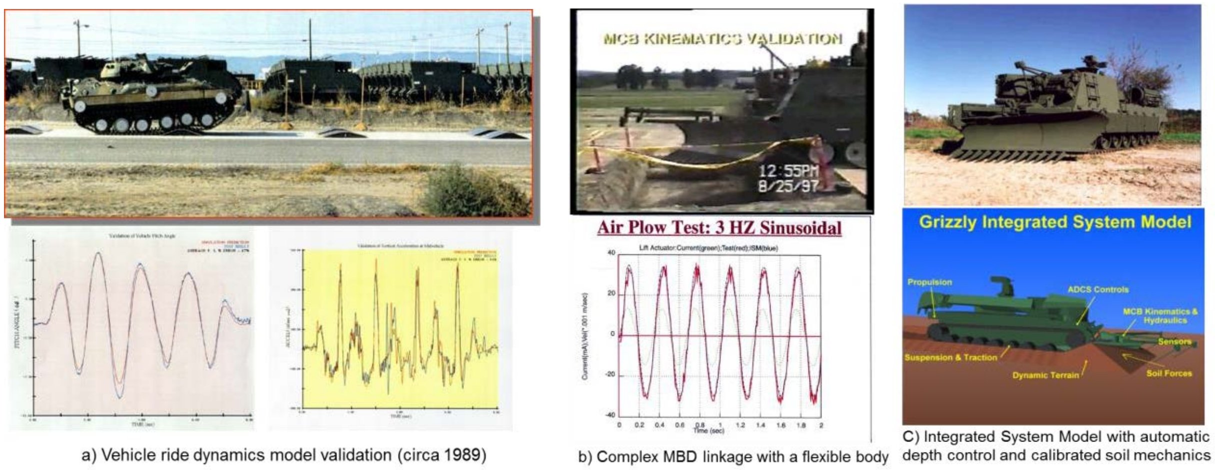


Fig. 2: *Examples of MBD model validation and calibration for off-road vehicle dynamic simulations that are already being used in NRMM by substitution of performance tables: a) ride dynamics; b) complex mechanical linkages with flexible bodies (mine plow); c) full vehicle system model of a mine plow with automatic depth control, and calibrated soil cutting [Hettiaratchi andReece, 1974], flow, bearing Wong, 1984] and drawbar pull empirical traction models, all based on a height field deformable terrain profile model[McCullough, 2000]*

This OBSDP analysis run stream presents a vehicle with a standard set of obstacle trapezoidal shapes as terrain profiles, determining the minimum clearance and the tractive effort required to overcome the obstacle, including the possibility of failure to pass. The output of the model is a lookup table, usually based on 72 standard obstacles, providing minimum clearance, maximum and average tractive effort. This lookup table forms part of the vehicle performance input data set for the main operation module and is the primary means for predicting obstacle override performance over the larger areal terrain data set of mapped obstacles distributions. Mobility failures such as high centering, gap crossing, V-ditch, near vertical step climb, and angles of approach and departure hang-ups are all approximated and predicted in this step.

2.1 INPUT DATA REQUIREMENTS

NRMM requires a broad and detailed set of input data. The data falls into three main types: scenario, terrain and vehicle. Due to ad hoc historical evolution of the models, some terrain information can be input in either the scenario file or the terrain file, but the largest part is embedded into the areal terrain file that essentially maps the features into individual terrain units (NTU), or patches. Over any patch, a fixed set of terrain parameters are considered to be uniformly defined (e.g., slope, soil type, etc). Although the NTU is the highest level of terrain data resolution for the operational module, VEHDYN 4.3 uses standardized profiles of roughness and obstacle size and shape at the geometric scale of the vehicle running gear. Additionally, for bearing and tractive strength models, soil substrates are represented across a broad range of soils and moisture content. A partial list of variables in each of the three categories is given in Table 1. For any given broad area of terrain, the on-road and off-road characteristics are modeled separately, with separate terrain data definition files.

Table 1. NRMM partial Scenario, Terrain and Vehicle data requirements [Bradbury, 2016]

Scenario data	Terrain data	Vehicle input
Snow depth and density	Surface condition, e.g. normal, slippery	General dimensions
Freeze and/or thaw depth	USCS soil type classification	Axles, bogies or track assemblies
Driver: maximum braking acceleration, braking reaction time, safety factor, recognition distance	Land use	For each powered or braked axle
Plowing depth	Wetness index	Pushbar height and force
Seasonal visibility	Soil strength: 0-6”, 6-12”, data for four ‘seasons’	Driver’s position, eyes and seat
Obstacles: height, width, length, angle, spacing	Depth to bedrock	Center of gravity
AASHO curvature safety factor	Slope	Suspension: spring and damper rates
Slope stability & traction	Surface roughness	Wheelbase and axle positions
Throttle setting	Area	Tires: section height/width, type, deflection/pressure
On & off road visibility	Obstacles: random or linear	Tracks: road wheels, sprockets/idlers, track
Surface: dry, wet, icy	Obstacles: height, width, length, angle, spacing	Drivetrain: engine, all gearboxes, torque converter
Tire deflection: highway, cross-country with/without sand/snow	Vegetation: tree stem size and spacing	Dual tires
	Visibility	Snow chains

2.2 OUTPUT DATA

The standard NRMM output data files provide results at several levels of detail. At the highest level of resolution, it provides predictions for the terrain patch-by-patch trafficability (NOGO percentage) and the maximal speed on the GO portion, as well as their limiting factors. For each unique patch of terrain it predicts:

The tire pressure/deflection setting that offers the best speed (for wheeled vehicles on GO terrain).
The transmission range that offers the best speed (for GO terrain).
The “OMNI speed” for the patch, which is a weighted average of the three directions of travel considered (up, down and across the slope occurring in the terrain patch).
A maximal speed prediction for each of the three directions of travel.
Limiting factors for each of the three directions of travel.

The data in this file is aggregated to higher level forms (e.g., terrain or mission type summaries) and can also be post-processed in more detail to understand platform performance envelopes (e.g., what limits performance for specific terrain areas or speed bands).

The on-road and off-road percent NOGO as well as the cumulative maximal trafficable speed distribution curves are the standard summary form of NRMM trafficability results for a given mapped area and environmental scenario. As shown in Fig. 3, cumulative maximal speed (e.g,. historically “speed made good”) is computed by ordering the several thousand individual terrain patch predictions by speed, and computing the progressively larger cumulative areal averaged speed starting from the highest speed patch to the lowest nonzero speed terrain patch.

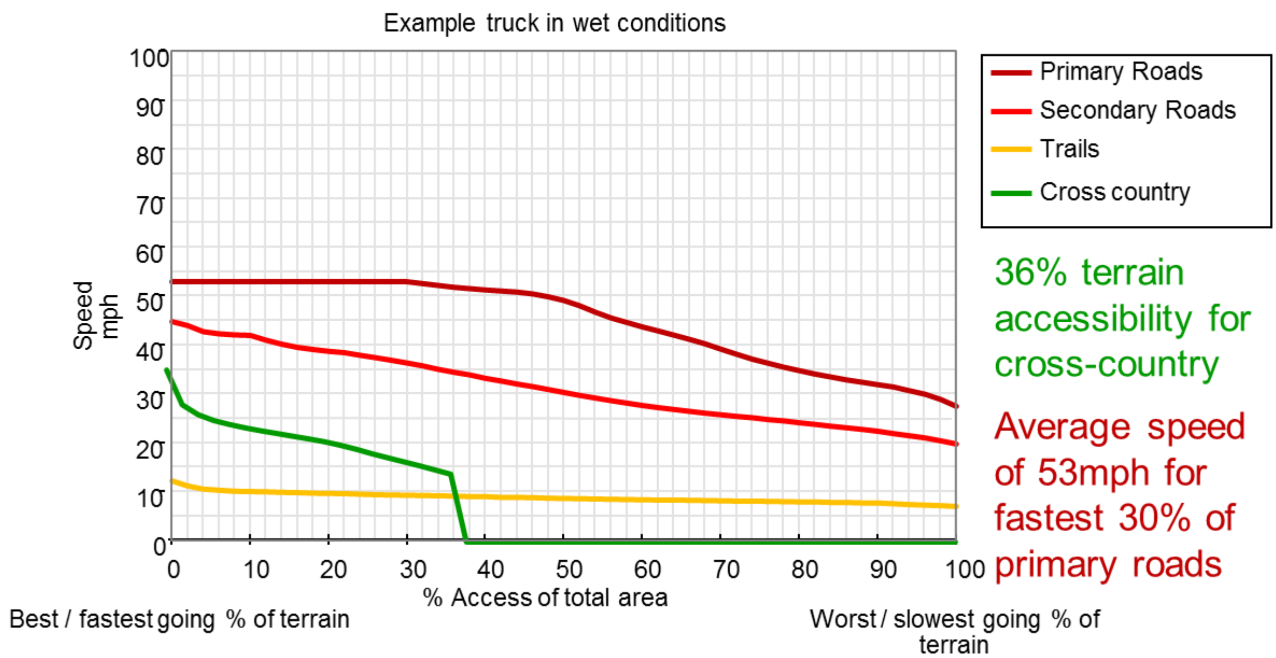


Fig. 3. Example NRMM cumulative distribution of maximal trafficable speed [Bradbury, 2016]

3. Requirements

The first step in the ET-148 team's deliberations was an exhaustive and detailed formal requirements development process to identify the mobility modeling improvement priorities of each of the team member nations. The members of the team were polled and also asked to collect from their respective constituencies, the specific shortcomings of the current NRMM, the needed future capabilities for a NG-NRMM, as well as a relative weighting of priority on those improvements. The results of this process were grouped into 11 categories of requirements: Mobility Output Metrics, Terrain Modeling, Vehicle Modeling, Human Factors in Mobility Modeling, Numerical Methods, Open Software Interfaces, Scalable to all Computing Platforms, Open Software Design, Maintainability, Expected End Users, and Distribution Approach. While recognizing the broad range of issues, the team further focused and reduced the requirements by recognizing that many of them represented issues beyond our team's charter for terrain vehicle systems modeling. Fig. 4 shows how the NG-NRMM requirements were further summarized into a time phased table that recognizes the necessity for near term (achievable now) and far term (achievable within the next 2-5 years) objectives with identified gap areas in Mobility Mapping, Environmental Effects, Intelligent Vehicles, Stochastics, Computational Performance, and M&S Verification and Validation (V&V).

Category	Sub-category	Near-Term Priorities for NG-NRMM	Far-Term Priorities for NG-NRMM
New System Capabilities	Vehicle Type	Wheeled, tracked, autonomous[3]	Legged, autonomous[3]
	Vehicle Scale	Conventional manned vehicles	Lighter and smaller vehicles
	Terrain Scale	Regional, varied resolutions[1]	Global, varied resolutions[1]
New Modeling Capabilities	Suspension Types	Passive, semi-active, active	Active
	Control Types	Driver, ABS, TCS, ESC, ABM, CTIS, autonomy[3]	Autonomy[3]
	Sub-systems	Steering, powertrain, autonomy[3]	Autonomy[3], human cognition
	Model Features	3D Physics based running gear scale deformable terrain models (e.g. Bekker/Wong, others)[2] Multibody/flexible body vehicle models Detailed tire and track models	deformable, dynamic terrain (e.g., FEM, discrete elements)[2] Stochastic models[4]
New Analysis Capabilities	User Type	Analyst/Expert	Operational Planner
	Environment Types	On-road, off-road, urban rubble, soil, snow/ice[2]	Urban (all)[2]
	Powertrain Performance	Grading, turning, fuel economy	Cooling
	Amphibious Operations	Fording, swimming	
	Computations	Computational Efficiency [5]- fidelity trade off	High fidelity and high performance [5]
New Output Capabilities	Assessment Types	Performance in operational context[6]	
	Metric Considerations	M&S Accreditable mobility metrics[6]	

Fig. 4. *Key New Requirements for Near-Term and Far-Term NG-NRMM Priorities with highlighted gap areas Mobility Mapping[1], Environmental Effects[2], Intelligent Vehicles[3], Stochastisc[4], Computational Performance[5] and M&S V&V[6].*

The overarching principles of open software architectures and open standards based mobility metrics were also broadly ratified as part of this requirement set to ensure that the NG-NRMM will be inclusive and non-preferential in the specific software tool sets that can be used for implementation.

4. Methodologies

Open architecture refers to an enduring realization of the model that is implemented at a higher level of abstraction such that the essential NG-NRMM framework definition will: 1) include all current validated legacy models and input data, 2) non-preferentially allow a variety of implementation environments, and 3) promote future innovation across all required gap areas. It was proposed and accepted that the simplest form of this higher level of abstraction is a set of mobility model standards and/or specifications that codify the NG-NRMM requirements. These proposed NATO Operational Reference Mobility Modeling Standards, or NORMMS, should establish the desired NG-NRMM framework definition. Thus the NORMMS are a ground vehicle mobility modeling and simulation architectural specification applicable to the full range of ground vehicle geometric scales that promotes standardization, integration, modular interoperability, portability, expansion, verification and validation of vehicle-terrain interaction models at multiple levels of theoretical and numerical resolution for use in vehicle design, acquisition and operational mobility planning.

As shown in Fig. 5, through the NG-NRMM requirements development process, a methodology development vision emerged. It recognized four progressively increasing levels of model complexity.

Model Component	Model Accuracy and Resolution			
	Empirical Current	Empirical Enhanced	Open Architecture Model	
			Threshold	Objective
	NRMM Standard Release	NRMM With Substitutions	Threshold NORMMS	NORMMS
Mobility Mapping	NRMM Operational Module	NRMM Operational Module	Modified NRMM Operational Module Integrated to GIS s/w	Modular, Expandable, Documented, Verified, Mobility Mapper with Long Term NATO CM support
Off-Road Mobility	NRMM	NRMM+	Bekker/Wong, Height Field	FEM / DiscreteEM
Vehicle Dynamics	VEHDYN (2D)	3D MBD	Ftire, Multilink track	Integrated Deformable dynamic terrain
Intelligent Vehicle	Constant speed	Variable speed	Closed loop 3D path following with sensors	AI with analytical sensor-terrain interaction in feature-rich environments
Compute Platform	Desktop	Desktop	Multi-Threaded Desktop	HPC

Fig. 5*. The Next Generation- NATO Reference Mobility Model (NG-NRMM) Development Vision mapped against the enabling technologies and multi-scale, multi-disciplinary stochastic terrain data requirements, which include properties and characteristics supporting terramechanical models for vehicle-terrain interaction as well as 3D geometric scanning sensor models necessary to support intelligent vehicle models.*

The current state of NRMM as shown in column two of Fig. 5 is the NRMM standard release and is largely based on vehicle level empirical data. The next column represents current practice in which the current standard NRMM process is enhanced through substitution of performance tables using higher resolution vehicle dynamic models developed using the latest vehicle terrain interaction modeling capabilities available in commercial simulation software, thus overcoming the pitch plane limitations of VEHDYN. The next two levels are examples of near-term and far-term capabilities that address the requirements derived and presented in Fig. 4. The near-term implementation is scoped to develop a "Threshold" level of improvement that takes advantage of existing validated ground vehicle M&S (e.g., Fig. 2) and geospatial mapping software to make needed changes quickly. Long term growth is aimed at the ultimate "Objective" NG-NRMM and will spur research efforts necessary to utilize, leverage, and promote competition in the use of M&S automation methods, integration and data management environments, high performance computing, numerical algorithm development for vehicle-terrain interactions with deformable terrain, stochastic methods, intelligent vehicles, and integration with GIS data and mapping software. Most particularly for terramechanics, methods are already being developed [Wasfy, 2015; Fleischmann, 2015] that leverage the use of massively parallel computing and the associated numerical algorithms to predict vehicle performance over dynamically deformable heterogeneous terrain.

Figure 6 further visualizes the breadth of M&S methods, data scales, and output products envisioned for a true NG-NRMM capability and the challenges inherent in closing the identified M&S technology gaps.

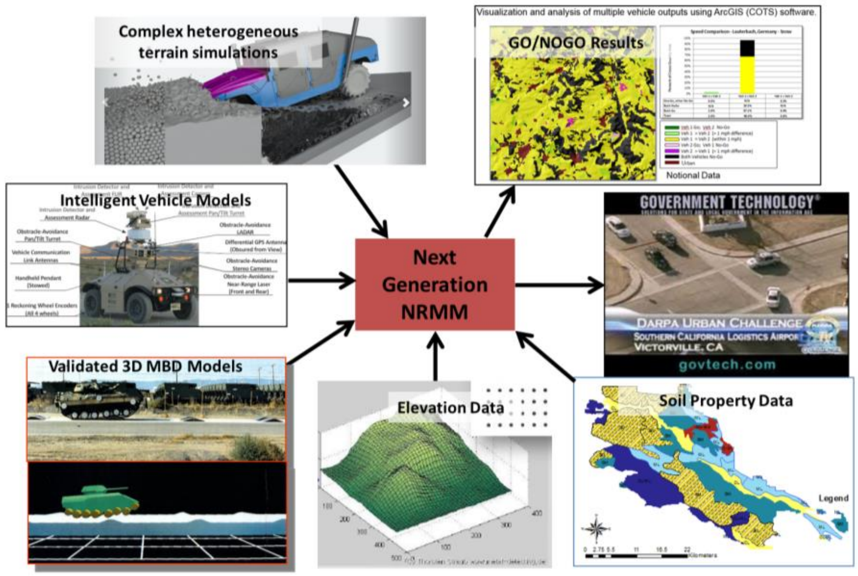


Fig. 6. *NG-NRMM will model high resolution vehicle-terrain interactions with dynamic deformable terrain leveraging broad spectrum GIS data and the latest validated terramechanical models and intelligent vehicle sensor suite models, resulting in mobility maps that display advanced mobility operations planning and effectiveness metrics for all conceivable vehicle concepts.*

Because it is impossible to predict all possible future mobility metrics, and these may change with every application, an open architecture is also necessary to accommodate the required flexibility. Figure 7 conceptually depicts, at an abstract level, the process that already occurs when advanced mobility related decision aides and/or vehicle acquisition programs request new mobility modeling capabilities. The data types and flow of requirements shown are typical for future applications of the NG-NRMM. Consistent with current practice, the mobility mapping efforts are decoupled at the executable level from the vehicle terrain interaction (VTI) modeling efforts and their data interfaces can be readily codified, templated and automated. As will be discussed and illustrated later, mobility mapping tools that allow operations and overlays with GIS and remotely sensed data are currently being used for this purpose and provide a ready tool set for the NG-NRMM mobility mapping component that allows mobility to be assessed and visualized at more global levels.

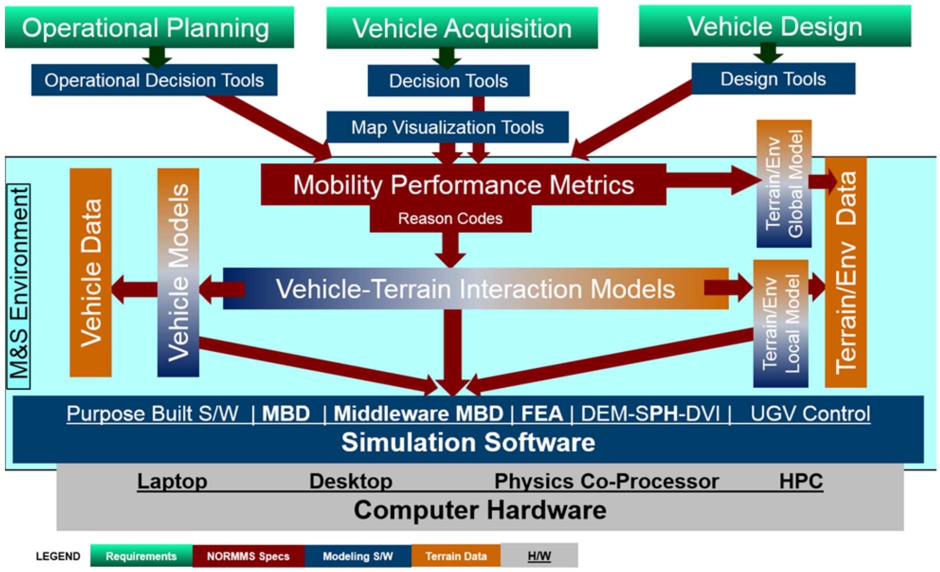


Fig. 7. *Conceptual Model of Data and Requirements Flow for NG-NRMM Applications*

VTI modeling is driven by the end-use needs of the vehicle design, acquisition and/or operational mobility planning communities. These driving requirements are frequently requested as map-enabled mobility metrics, but just as often are summary level performance metrics reduced to averages across specific regions of terrain and scenario combinations, and are therefore not always required to be mapped. The additional terrain data requirements and higher levels of resolution for detailed VTI simulations are the core terramechanical research and development issue distinguishing the current NRMM from the next generation. This additional and higher resolution terrain data is used in the local mobility models. On the lower end of the chart, the computer aided engineering software and computer hardware spectrums are currently decoupled at the executable level because the general purpose vehicle modeling codes are ported to all hardware platforms. For detailed deformable terrain models employing continuum models and/or discrete element model approximations of heterogeneous soil substrates that take advantage of physics co-processers, or general purpose graphics processing units (GPGPUs), there will be a tighter coupling between the software and hardware. The current state of the practice and successful use of VTI models has identified MBD software as the primary vehicle modeling environment within which the various advanced VTI simulation methods can be readily integrated. And, MBD codes are readily available, significantly validated across a practically limitless range of vehicle morphologies, physics, and control topologies.

The light blue box in Fig. 7 is the M&S integrating environment (MSIE). MSIE presents a unique opportunity to identify a modeling process and configuration management integration tool that enables the envisioned open architecture for NG-NRMM through the implementation of executable NORMMS. The MSIE tool would enable the RTG and its successor organizations, to capture decisions about algorithms and metrics, and implement them in a form that is executable, or at least implementable, portable, enduring, and promotes easy collaboration and distribution of the standard algorithms with non-preferential interfaces to the simulation codes and GIS tools that are already seen as essential components of NG-NRMM. A key requirement of the MSIE is the ability to construct customizable templates that support integration of the wide variety of MBD, multiphysics, and GIS tools that have become indigenous to the various organizations and countries with stakeholder interest in the Next Generation-NRMM. By way of example, a potential candidate for this MSIE might be the Windows/DOS command environment combined with EXCEL and Visual Basic or Visual Studio. However, there may be more modern tools such as Python [Wojtysiak, 2014] which are ultimately more enduring and directly align with, and achieve, the RTG goals for NG-NRMM. There are already many commercial tools associated with Computer Aided Engineering (CAE) which share the same vision [NAFEMS, 2015]. The RTG could choose to adopt one of these as well, although this would require that financial barriers to entry/ownership be small and must demonstrate an enduring path to the future.

It should also be noted in the context of the high level mobility metrics tool, that the current version of the NRMM Operational Module provides a valuable starting point. It is written in FORTRAN and can be adopted in parts or even translated into the new MSIE environment language. This is considered a valuable first step for the RTG after a decision on the MSIE is made. Based on this observation, the current NRMM mobility "reason codes" and standard terrain input and output data file formats are therefore considered a valuable starting list of NORMMS attributes as evidenced by the significant extended use of NRMM in mobility operational planning and support tools discussed in Sections 8 and [Wojtysiak, 2014] and Section 9.

5. Stochastics

Various efforts to account for differing types of uncertainty in NRMM have been performed in the past [Lessem, et al, 1992,1993, 1996; Priddy, 1995]. Stochastic natural terrain modeling leverages, in part, the significant body of research and methods from geostatistics which is always characterized by a set of sparse measurements obtained for a terrain region of interest. The methods apply to terrain elevation as well as physical properties such as those which might eventually be correlated to soil strength. Sensors are mounted on ground or air vehicles, satellites and in some cases fixed monitoring stations. Variable resolution and irregular density of data (occlusions) are inevitable, leading to non-uniformly spaced data. Therefore, a useful first step to simulating the performance of a vehicle over such terrain is generating a continuous surface. There are many known interpolation methods; see Detweiler and Ferris {2010] for a review of four of the most popular ones (mean, median, inverse distance to a power, and ordinary kriging).

Kriging is a Gaussian Process (GP) regression method that produces an interpolation function based on a covariance or variogram model derived from the data rather than any a priori model of the interpolating function. Thus the interpolated data reflect a broader averaging process and also include an estimate of the uncertainty. To satisfy stationarity conditions in the local variograms to achieve higher accuracy over a broad range of geographies, Gonzalez et al. [2016] also found it necessary to augment this method with a localized segmentation process that combines use of the fractal dimension with elevation range as decision metrics in the segmentation step. As shown in Fig. 8, once a continuous surface is obtained, stochastic simulations of the performance of a vehicle over such terrain can be performed, and the simulations can be embedded in highly iterative processes typical of current advanced uses for NRMM in Operational Planning and acquisition.

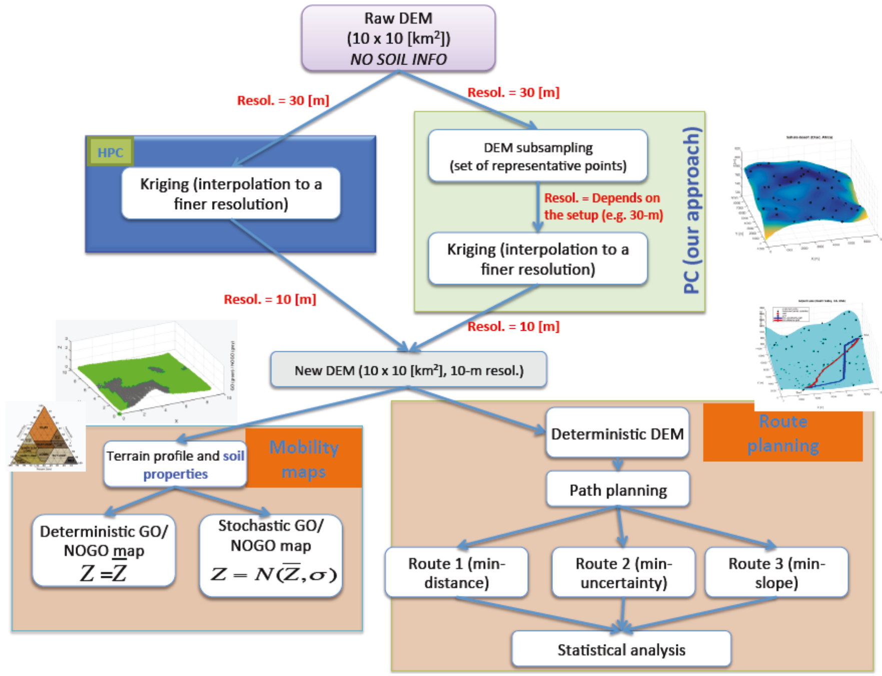


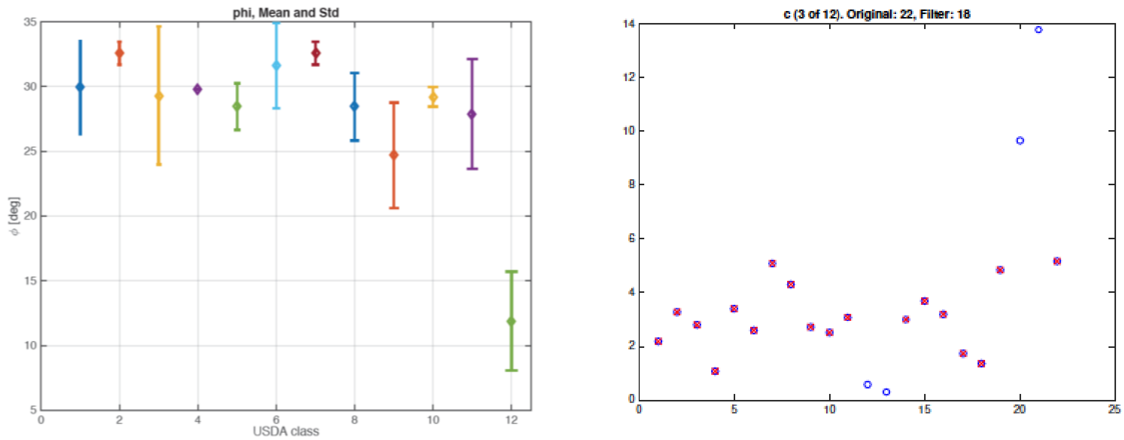
***Fig. 8**. Schematic view of the steps carried out in the proposed architecture for predicting the mobility of a ground vehicle over a large region (> 5 x 5 [km2]) [Gonzales, et al., 2016]]*

Using geostatistically described terrain, stochastic mobility maps can be generated via Monte Carlo simulation. For example, for a given terrain map region **n** realizations are obtained for each soil strength parameter according to its associated Gaussian (or other) distribution, leading to **n** values of the drawbar pull force (DP) and motions resistance (MR), obtained using a VTI model. In a given terrain patch the MR will exceed the DP (i.e. a NOGO) in a statistically distributed way. A cell is considered traversable when the DP is in excess of MR for **m** runs at a given statistical threshold (i.e., **m** ≥ δ**n**, where δ is a given confidence interval).

Because terrain sensing and characterization data do not include soil parameters directly involved in mechanical strength models such as internal friction angle and cohesion, there is also a need to link soil types and moisture content with these mechanical strength parameters. Therefore Gonzalez et al. [2016] developed an interpolation procedure from documented values of correlating soil parameters for the 12 USDA soil types. In particular, the interpolation method determines the value of the parameter *X* for the soil type *i* by solving the following equation for *M* random values for each neighboring point

$$X_i = \frac{\sum_{j=1,j!=i}^{M} w_j R_j}{M * \sum_{j=1,j!=i}^{M} w_j}, \quad \bar{x}_i = mean(X_i), \sigma(x_i) = std(X_i), \qquad (1)$$

where w is given as the inverse of the distance between the centroids of the cells in the USDA triangle [USDA, 1987]. The value R comes from generating M random values within the normal distribution associated to each soil type for this parameter. An example of the data used to obtain this normal distribution for the 12 soil types in the USDA soil system is shown Fig. 9a. Soil parameter data was collected from a variety of published sources in the open literature. It bears mentioning that in order to avoid a misrepresentation of the Gaussian distribution a filter was designed in order to remove outliers from the calculation. An example of such filter is shown in Fig. 9b. In particular, all the measurements associated to the cohesion of sandy loam are plotted, but only those regions within a certain range (solid circles) are used for determining the Gaussian distribution.



(a) Internal friction angle

(b) Cohesion, sandy loam

Fig. 9. *Source data for a statistical model correlating soil strength parameters to USDA soil type. [Gonzales, et al., 2016]*

6. Intelligent Vehicles

The emergence of intelligent ground vehicles and their dependence upon quantitative analysis of mobility has infused terrain vehicle systems modeling with a new relevance and broader scope than ever before. At an M&S architectural level, vehicle intelligence (VI) can be viewed as a broader more intensive form of automatic control system such as anti-lock brakes, traction control, and controlled suspension systems. Mobility metrics and analysis for robotics and VI is therefore a very active and prolific research area and therefore becomes an essential element of a NG-NRMM from two application perspectives:

1) inclusion of robotics and VI in mobility metrics and assessments for operational planning, acquisition, and design; and
2) embedding NG-NRMM models and metrics into robots and VI algorithms because they are standards for mobility assessment and decision making (see Fig. 10)

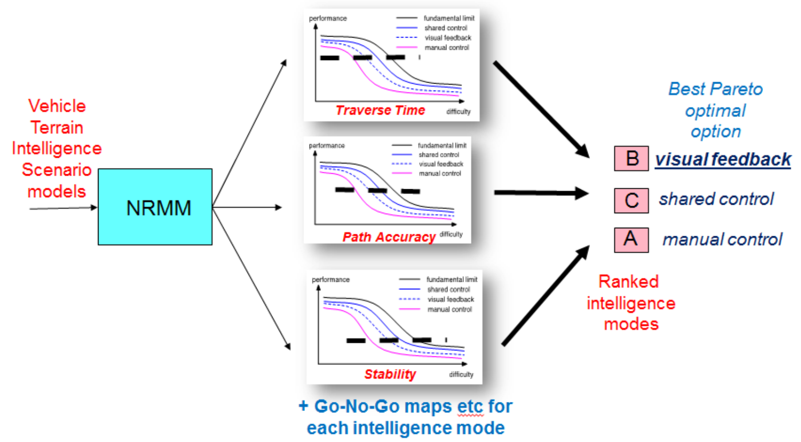


***Fig. 10**. Example of the operational use of NRMM to generate performance/risk for multiple autonomy levels to allow operator to select the optimal level for carrying out the task.[Jain, 2016]*

Numerous examples of these applications already exist [Haueisen, 2004; Office of Technical Intelligence, 2015; Richmond et al.,, 2009]. Therefore the NG-NRMM development process must include and embrace VI in mobility modelling as a foundational architectural goal. Expanding upon the previous requirements and methodology discussions, with a particular focus on VI considerations, the NG-NRMM must:

1. include every conceivable ground vehicle physical morphology (Fig. 11)
2. broaden the definition of terrain to include urban and building interior environments
3. make allowance for multiple levels of model resolution to support computational burden tradeoffs
4. embrace stochastic modeling and database development necessary to support VI algorithms
5. recognize a hierarchical and skills based sliding scale of VI, autonomy, and control
6. develop applicable VI related mobility metrics for M&S V&V and accreditation

***Fig 11.** Examples of a variety of VI controlled ground vehicle platforms[Jain, 2016].*

The NG-NRMM development team plans to leverage the significant parallel multi-disciplinary efforts already directed toward quantifying and standardizing robotic and VI mobility descriptions [Jain, 2015]. The team recognized that the unique near term tasks that must be accomplished as next steps involve the capture and codifying of practical mobility metrics as well as M&S and MSIE methods from the VI community. Based on the results of the ET-148 study, a set of expanded mobility metrics are being proposed and developed for NG-NRMM that include the unique adaptation of standard mobility metrics to assess the effectiveness of the VI and control features of intelligent vehicles. Preliminary 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: as 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.

7. Tool Choices

Due to the limitations of classic NRMM to meet evolving needs, various tools and methods have been developed across the NATO nation countries as well as within the military vehicle industry and adjacent and supporting industries, most particularly ground vehicle M&S researchers and software developers. The NATO ET-148 team recognized this and therefore established a major theme for investigating these more advanced and varied tool sets to determine how well they address the NG-NRMM requirements and reflect the vision of the NG-NRMM and NORMMS framework.

The first step was to develop a series of criteria and levels of importance for the evaluation to meet the goals for the Next Generation- NRMM effort [Hodges, 2015]. Since capability often conflicts with cost, and speed of analysis conflicts with accuracy, Measures of Effectiveness (MOE) and Measures of Performance (MOP) were established and weighted utilizing a Combinatorial Trade Study Process (see Table 2).

Table 2. M&S Industry Request for Information (Survey) MOE and MOP Weighting [Hodges,2016].

MOE	*MOP*	**MOE Weight**	**MOP Composite Weight**
Accuracy / Robustness	**Physics based**	37.50%	16.67%
	Validation through measurement		12.50%
	Supports time and frequency domain analysis		8.33%
Flexibility	**Template based**	37.50%	8.33%
	Wheeled or tracked vehicles		20.83%
	Automotive Subsystems		8.33%
Cost, Maintenance, and Run Time	**License**	12.50%	5.56%
	Run Time		2.78%
	Training		4.17%
NATO Specific Applications	**Supports unique terrain or mission definition**	12.50%	6.94%
	Worldwide tool availability to approved sources		2.78%
	Worldwide tool support		2.78%

100.00%

To properly gage the level of capability for each potential solution, five levels of satisfaction were established: unacceptable, below threshold, threshold, above threshold, and objective. For the various levels, a score of zero (0), 0.5, 0.7, 0.77, and 0.85 was applied, respectively. Based on this set of criteria, a request for information (RFI) survey document was sent out to 27 organizations with the understanding that the responses would be reviewed and evaluated accordingly. Fourteen organizations responded and 12 were eventually scored as sufficiently responsive to warrant a meaningful result. Detailed definitions of the MOPs and MOEs were developed to support the most objective assessment.

This trade study concluded that currently available tools exist which can fill most of the NG-NRMM needs. Many of the solutions met above threshold or objective levels in the given criteria of Accuracy, Flexibility, Cost, and NATO specific applications. The scores reflect the fact that three of the twelve organizations consider off-road vehicles as central to their business and/or research focus. However, several organizations have a closely adjacent research and development focus. Thus there is a significant potential for additional university and industrial contributors and participants in the future NG-NRMM developments. Thus by setting NORMMS and M&S benchmark standards for NG-NRMM it is possible to motivate, leverage and establish several competing M&S software sources as a first step toward a near-term solution for the open architecture NG-NRMM.

The detailed scores also revealed that accuracy for vehicle system performance is the biggest shortfall of the current NRMM when compared to other M&S sources. Validated physics-based methods are a recognized improvement over the current empirical methods for simulating vehicle and suspension designs. Likewise the study also revealed that there is an industry wide shortfall with tire dynamics and soft soil behaviour. Through the NG-NRMM process this can be addressed with new methods including the emergence of dynamic deformable terrain contact models.

8. Input Data and Output Metrics

Based on their deep experience with advanced applications of NRMM, the Input Data and Output Metrics team developed detailed decompositions of current and extended NRMM application data requirements and collected them into several check lists. The team also produced a valuable set of recommendations for NG-NRMM capabilities and interfaces that contributed significantly to the open architecture methodology and NORMMS framework previously discussed. The teams more specific input and output data recommendations focus on the mobility mapping tools and include:

1) Publish Next-Generation NRMM Data Interoperability Standards to ensure NRMM outputs maintain linkages to spatially oriented data to facilitate visualization using COTS GIS tools. The Open Geospatial Consortium (OGC) data standards are one example.
2) Improve methodologies to transform high resolution satellite imagery / remotely-sensed GIS data into accurate NRMM terrain representations.
3) Map the Input Data Requirements / Output Products to the varying model resolutions and user experience levels envisioned for NG-NRMM
4) Produce a complete and systematic decomposition of the current NRMM Operational modules algorithms and models as a starting point toward a draft input/output component of the NORMMS and an open architected NG-NRMM Operational module.

As concluded by the Methodology team and illustrated in Fig. 7, the detailed mobility metric requirements and application drivers for the NG-NRMM come from those users currently supporting Operational Planning and Acquisition processes such as the United States Army Materiel Systems Analysis Activity (**AMSAA**) users. Users there have developed the following capabilities to enhance and augment the classic standard release NRMM [Wojtysiak, 2014] :

The System Level Analysis Mobility Dashboard (SLAMD) – a Python-based NRMM wrapper that improves the end-user experience, integrates the various NRMM modules (ObsMod, VehDyn, etc.) into one user interface, reduces vehicle file development time with improved error handling capabilities, improves data post-processing capabilities, etc.

The AMSAA Urban Maneuverability Model (UMM) – a custom-built ESRI ArcGIS / Python tool that can be used to address vehicle urban maneuverability analysis capability gaps. (See Fig. 12).

The AMSAA Optimal Path Model (AOPM) – a custom-built ESRI ArcGIS tool that incorporates NRMM on-road and off-road speed and trafficability predictions to plot the optimal path between geospatially-oriented point locations

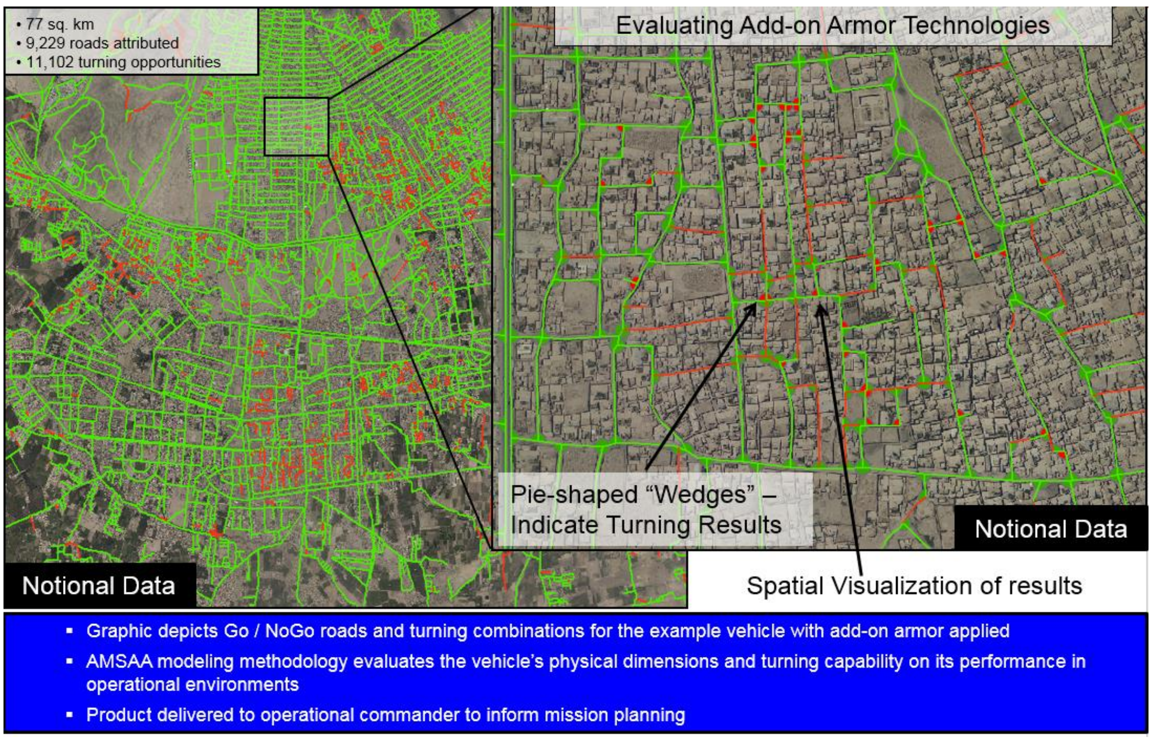


***Fig. 12**. Notional Urban Maneuverability Analysis Product – Evaluating Maneuverability Degradation Associated with Add-On Armor [Wojtysiak, 2016]*

These codes represent early prototypes instances of NG-NRMM and the environments and tools used to develop them are examples (e.g. Python) of the open sourced MSIE identified in the Methodologies section earlier.

9. Verification and Validation (V&V)

A standards based open architected NG-NRMM development approach requires early and continuous engagement with the M&S and GIS software industry and research communities and also implies that there will also be a basis for M&S tool V&V. Therefore subsequent to the Tool Choice RFI and trade study, the study participants (i.e., commercial software vendors and university researchers) were invited to make open forum presentations to the larger team and also receive feedback regarding the alignment of their capabilities with NG-NRMM aspirations. To collect the opinions of the larger ET membership regarding the readiness and state of the art relative to NG-NRMM goals, a score sheet with a reduced and focused set of attributes was developed. These attributes now form the genesis of the NORMMS that can be used as the broadest metric for the evaluating status of compliance for any proposed capability:

<u>Geospatial Data Analysis and Mapping:</u> Terrain modeling and visualization in compliance to GIS standards; Able to handle

urban terrain data; Supports sensor-terrain interaction modeling; Mobility metrics mapping tools

Computational Physics of Vehicle Terrain Interaction; Model any vehicle morphology; Full range of ground vehicle geometric scales; VTI models at multiple levels of theoretical and numerical resolution; Full coupling capability with latest dynamic deformable soil modeling methods; Full coupling with power train models; Full coupling with embedded control systems including robotic, VI and human cognition; Full coupling with flexible bodies; Amphibious operations modeling; Useful for vehicle design

M&S Integrating Environment: Interfaces to broad range of tools from GIS, visualization, to computational physics; Tools for automation and standardization**;** Parallelization and HPC compatibility**;** Tools for modeling, data managing and performing stochastic M&S;**;** Modular interoperability (ability to plug and play subsystems)**;** Portable to most common computing environments**;** Distributable/available to NATO designated stake holders**;** Enduring and supported (not likely to become easily obsolete)**;** Expansion capability (no financial, legal, technical, or architectural limits or constraints to mobility research and development)

M&S Verification and Validation Basis**:** Verification and validation benchmarks exist and distributable; Verification basis is sound for benchmarks provided; Validation basis is sound for benchmarks provided; V&V benchmarks address NG-NRMM requirements

To drive the process into the implementation stage, a set of specific new NG-NRMM mobility metrics as wells as distributable vehicle model data sets supporting their use in a practical application must also be developed as NG-NRMM V&V Benchmarks. Vehicle data sets for both tracked and wheeled vehicles are necessary. Current distributable data set has been found to establish a tracked vehicle benchmark (shown in Fig. 13) and the committee is searching for a wheeled vehicle example.

Fig. 13. *The vehicle data for the specific vehicle used by Wong, et al [1984], plus data from other public domain sources, forms the basis for the initial NG-NRMM tracked vehicle benchmark.*

The selected initial new mobility metrics are:

1. Steady State Cornering and Steering Performance (pavement and soft soil)
2. Double Lane Change with Autonomy (pavement and gravel)
3. Side Slope Mobility (pavement and soft soil)
4. Grade climbing (pavement and soft soil)
5. Ride and Shock Quality (standard NRMM definitions initially)
6. Obstacle Performance (standard NRMM definitions initially)
7. Off-road Trafficability

Benchmark detailed definitions use current NRMM definitions, AVTP, ISO, or SAE standards and only augment or develop new metric definitions where necessary. It is expected that parallel efforts underway in the test community will address evolutions of many of these metrics such as the use of ISO 2631 for ride quality, and detailed test methods will be replicated in simulations. Some detailed procedures have been derived and provided where none currently exist. Consistent with principles of open source development, participants are encouraged to provide suggestions for improvement. The vehicle model data sets should include both a wheeled and tracked vehicle and it is envisioned that they are only the first of many that will cover the breadth of the NG-NRMM requirements.

To develop an objective basis for expressing any given M&S tool's credibility and maturity, a progressive scale of V&V achievement is required. This scale should build off of ET opinions and deliberations on V&V, the US Army's definitions found in DA Pamphlet 5-11 [2014], and the maturity scales from the M&S and software industries [Oberkampf et al., 2007; Meintjes, 2015; Paulk et al., 1993]. Accordingly, the team has developed the following draft M&S V&V maturity scale:

Level 1. DEMONSTRATION: Vendor demonstration
Level 2. VERIFICATION: Independent user demonstration and correlation to vendor results
Level 3A. PARAMETER SENSITIVITY VERIFICATION: Verification that performance change with a change in system parameter such as GVW or terrain deformability is consistent with theory and physics principles.
Level 3B. CROSS CODE VERIFICATION: Cross verification with another accepted mobility simulation code, or accepted physics principles
Level 4. CALIBRATION: Calibration to a real vehicle test data set
Level 5. VALIDATION: Blind correlation to a real vehicle test data set
Level 6. PARAMETER VARIATION VALIDATION: Blind correlation to a real vehicle test data set with a change in system parameter(s).

10. Conclusion

At the conclusion of the NATO ET-148 committee deliberations it was unanimously agreed, and approved by the AVT Panel, that a follow-on Research Task Group (RTG) be formed to immediately begin implementing the recommendations for the development of an improved vehicle mobility model appropriate to the current and future needs of the NATO nations for operational planning, acquisition and vehicle design. This paper has summarized the identified requirements, enabling technologies and development framework for the M&S methods recommended for a NG-NRMM. The development framework has informed the organization of the subsequent NATO Research Task Group (RTG-248), leading to six research thrust areas along with their respective goals:

1) GIS-Terrain and Mobility Mapping: Identify a GIS-based mapping tool that implements and integrates existing valid mobility metrics (%NOGO and Speed Made Good) in an open architected environment.

2) Simple Terramechanics: Identify most promising existing terramechanics methods supporting minimum near-term ET-148 NG-NRMM requirements and provides possible means of correlating the requisite terrain characteristics to remotely sensed GIS data.

3) Complex Terramechanics: Establish a vision for the long term terramechanics approaches that overcome the limitations of existing models.

4) Intelligent Vehicle Mobility: Identify unique mobility metrics and M&S methods necessary for predictions supporting mobility assessments of intelligent vehicles over a sliding scale of data and control system resolutions.

5) Uncertainty Treatment: Identify the practical steps required to embed stochastic characteristics of vehicle and terrain data to extend and refine the current deterministic mobility metrics.

6) Verification & Validation (V&V): Implement near-term vehicle-terrain interaction benchmarks for verification of candidate NG-NRMM M&S software solutions and lay the groundwork for long term validation data through cooperative development with test-standards committees.

Through this committee and the M&S benchmarking effort already underway, delegates of the 13 NATO nations involved in this effort expect to make rapid progress toward the genesis of a set of standards and M&S use cases that represent a consensus solution for a NG-NRMM that is expected to codify and standardize mobility metrics in a modular open architecture. Thus the NG-NRMM will likely be implemented in a variety of M&S tools and environments, all of which conform to standards, and thus will leverage the latest modeling, simulation and visualization tools whilst also recognizing the value in a sliding scale of model resolution that is inclusive of the broad range of legacy methods and data.

Nomenclature

X	A selected stochastic soil property	[psi, deg, etc]
w	Radial distance in USDA triangle from	
R	Random number	
i	Sample number	
$\bar{x}$	Mean value of stochastic property	[psi, deg, etc]
σ	Standard deviation of stochastic property	[psi, deg, etc]

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