Next-Generation NATO Reference Mobility Model (NG-NRMM) Final Report by NATO Exploratory Team ET-148

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Final Report of Exploratory Team, ET-148

Next Generation NATO Reference Mobility Model (NRMM) Development

EXECUTIVE SUMMARY

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 throughout the years, resulting in the most recent version, NRMM II. NRMM is traditionally used to facilitate comparisons between vehicle design candidates and to assess the mobility of existing vehicles under specific scenarios.

Although NRMM has proven to be of great practical utility to the NATO forces, when compared to modern modeling tools it exhibits several inherent limitations. It is based on empirical observations, and therefore extrapolation outside of test conditions is difficult or impossible. It is heavily dependent on in-situ soil measurements. Only two-dimensional analysis is possible; lateral vehicle dynamics are not considered. It does not account for vehicle dynamic effects, but instead only considers steady-state conditions. It is specific to wheeled/tracked vehicles. It is not easily implementable within modern vehicle dynamics simulations. It exhibits poor (or poorly understood) inter-operability and inter-scalability with other terramechanics and soil mechanics models.

Exploratory Team 148 was formed to explore the development of a Next-Generation NRMM (NG-NRMM). Theme areas were developed and teams worked on Requirements, Methodology, Tool Choices, and Input/Output needs for a NG-NRMM. Two new areas were also explored that were not part of the original NRMM: stochastics and intelligent vehicles. Based on the results of the exploration of tool choices, a benchmarking exercise was also planned to understand the capabilities of the physics-based tools available from software developers.

Through this effort, the goal is to have a mobility model with enhanced capabilities in the following areas:

- Increased flexibility to support operations by assessing the operational mobility of different deployed platforms in different areas of operation and routes
- Improved flexibility as a design and procurement support tool through enhanced fidelity and the ability to model current and emerging mobility technologies

At the conclusion of ET-148, the committee consisting of 38 persons from 13 nations, was confident that the time was right to develop an improved vehicle mobility model appropriate to the needs of the NATO nations. As laid out in this report, the requirements and methodology necessary for developing a NG-NRMM have been well specified. The follow-on activity, AVT-248, has been approved and will proceed from 2016 to 2018 to develop such a model.

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ABM	Automatic Brake Modulator
ABS	Anti-lock Braking System
AMC	Army Materiel Command
ANCF	Absolute Nodal Coordinate Formulation
AOPM	AMSAA Optimal Path Model
APC	Armored Personnel Carrier
API	Application Program Interface
ARL	Army Research Laboratory
ASME	American Society of Mechanical Engineers
AVT	Applied Vehicle Technology
AWD	All Wheel Drive
BRDF	Bidirectional Reflectance Distribution
C2	Command and Control
CAE	Computer Aided Engineering
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CGS	Coarse Grained Soil
CI	Cone Index
COTS	Commercial Off-the-Shelf
CRREL	Cold Regions Research and Engineering Laboratory
CSO	NATO Collaboration Support Office
CTIS	Central Tire Inflation System
CTS	Combinatorial Trade Study
CVT	Continuously Variable Transmission
DEM	Discrete Element Method
DEM	Digital Elevation Model
DIL	Driver in the Loop
DP	Drawbar Pull Force
DOE	Design of Experiments
DTED	Digital Terrain Elevation Data
DTM	Digital Terrain Model
DVI	Digital Visual Interface
ERDC	Engineer Research and Development Center
ESC	Electronic Stability Control
ET	Exploratory Team
FEM	Finite Element Model
FGS	Fine Grained Soil

FFT	Fast Fourier Transform
FMI	Functional Mock-up Interface
GIS	Geographical Information System
GOTS	Government Off-the-Shelf
GP	Gaussian Process
GPGPU	General Purpose Graphics Processing Unit
GUI	Graphical User Interface
GVW	Gross Vehicle Weight
HGTM	High-Resolution Ground Vehicle and Terrain Mechanics
HIL	Hardware in the Loop
HITL	Hardware in the Loop
HPC	High-Performance Computing
IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
ISTVS	International Society for Terrain-Vehicle Systems
IVT	Infinitely Variable Transmission
LIDAR	Laser Imaging Detection and Ranging
M&S	Modeling and Simulation
MBD	Multibody Dynamics
MGRS	Military Grid Reference System
MMP	Mean Maximum Pressure
MOE	Measures of Effectiveness
MOP	Measures of Performance
MSIE	Modeling & Simulation Integrating Environment
NATO	North American Treaty Organization
NG-NRMM	Next Generation NATO Reference Mobility Model
NORMMS	NATO Operational Reference Mobility Modeling Standards
NRMM	NATO Reference Mobility Model
NRMM(H)	NG-NRMM for Manned Vehicles
NRMM(I)	NG-NRMM for Intelligent Vehicles
NVH	Noise, Vibration and Harshness
OBAA	Obstacle Approach Angle
OBH	Obstacle Height
OBW	Obstacle Width
OEM	Original Equipment Manufacturer
OGC	Open Geospatial Consortium
PSD	Power Spectral Density
RCI	Rating Cone Index
RFI	Request for Information
RMS	Root Mean Square
RTG	RTO Task Group
RTO	NATO Research and Technology Organization

SAE	Society of Automotive Engineers
SIL	Software in the Loop
SLAMD	System Level Analysis Mobility Dashboard
SPH	Smoothed Particle Hydrodynamics
STO	NATO Science and Technology Organization
SRS/PVSS	Shock Response Spectra/Pseudo Velocity Shock Spectra
TAP	Technical Activity Proposal
TARDEC	Tank Automotive Research, Development and Engineering Center
TMC	Technical Management Committee
TCS	Traction Control System
UDF	Universal Disk Format
UGV	Unmanned Ground Vehicle
UMM	Urban Maneuverability Model
USCS	Unified Soil Classification System
USDA	United States Department of Agriculture
V&V	Verification and Validation
VEHDYN	Vehicle Dynamics part of NRMM code
VTI	Vehicle Terrain Interface; Vehicle Terrain Interaction
WES	Waterways Experimental Station

Chapter 1 – INTRODUCTION

1.1 BACKGROUND

The NATO Reference Mobility Model (NRMM) is the accepted international standard for modeling the mobility of ground combat and tactical vehicles. It is a simulation tool aimed at predicting the comparative capability of a vehicle to move over specified terrain. NRMM can be used for on-road and cross-country scenarios, and it can account for several parameters such as terrain type moisture content, terrain roughness, and vehicle geometry.

The model was originally developed and validated in the USA in the 1970s by the U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) in Warren, MI and the US Corps of Engineers Waterways Experimental Station (WES) in Vicksburg, MS. The Engineer Research and Development Center (ERDC) remains the code custodian and is responsible for configuration control.

NRMM has proven of great practical value to the NATO nations since its development in the 70s. Although it has been revised over the years, the basis of NRMM is 40 years old. When compared to modern modeling tools, it exhibits inherent limitations; primarily:

- It is heavily dependent on empirical observations such as in-situ soil measurements so that extrapolation outside of test conditions is difficult.
- Only two-dimensional analysis is possible.
- It does not account for vehicle dynamic effects; rather it only considers steady-state conditions for cross-country mobility.
- It is not easily implemented with modern vehicle dynamics simulations or other terramechanics models.
- It does not address uncertainty.
- It does not account for the different drivers and constraints associated with unmanned ground vehicles or alternate vehicle control strategies.

1.2 PURPOSE

Due to the recognition of the need for an updated model, a NATO Exploratory Team was proposed during the spring 2014 NATO AVT meeting in Copenhagen, Denmark by Panel Member Dr. David Gorsich, Chief Scientist of TARDEC. The scope was to investigate an efficient simulation-based next-generation NRMM. Specifically the objectives were as follows [TAP, 2014]:

- Identify scale-invariant terrain descriptions for representing topographic map data (obtained at various scales) within a suitable multi-body dynamic simulator. This will enable automated analysis of regions of interest, given heterogeneous map data products as inputs.
- Develop efficient, automated, parallelizable experimental design methods (i.e. sampling methods) for extracting metrics of interest from Monte Carlo simulations of the multi-body dynamic simulator, including mobility-related metrics and auxiliary metrics. This will yield rich statistical mobility-related outputs in a computationally efficient manner, which will allow use of modern HPC resources.
- Explore the use of compact representations of vehicle dynamics (i.e. response surface methods or other

approximation methods) within the multi-body dynamic simulator, with a goal of further reducing computational cost.

- Establish compact, user-friendly representations of output metrics that capture important dependencies. This will yield an update to classical “speed made good” or “go/no go” maps.

The Exploratory Team, as described in the Technical Activity Proposal (TAP), was approved by the AVT Panel under the designation ET-148, Next-Generation NRMM Development. The TAP for ET-148 is included in Appendix A.

1.3 ENHANCED CAPABILITIES

Through this effort, the goal is to have a mobility model with enhanced capabilities as in the examples below:

- Increased flexibility to support operations by assessing the operational mobility of different deployed platforms in different areas of operation and routes
- Improved flexibility as a design and procurement support tool through enhanced fidelity and the ability to model current and emerging mobility technologies

1.4 REFERENCES

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Chapter 2 – ORGANIZATION

2.1 ET-148 ORGANIZATION

TARDEC initiated the formation of ET-148 at the spring 2014 NATO meeting in Copenhagen, Denmark with Dr. Paramsothy Jayakumar of TARDEC as the Chairperson and the United States as the lead nation. Dr. Michael Hoenlinger of Germany was later named as the Co-Chair.

Starting in June of 2014, the group held monthly teleconferences through the end of 2015. At the first June 2014 teleconference, the membership had already grown to 26 members from 11 nations (Canada, Czech Republic, Estonia, Germany, Italy, Poland, Romania, Slovakia, Turkey, United Kingdom, and the United States). By fall of 2015, the membership had grown further to 38 members from 13 nations.

In addition to the monthly teleconferences, the group physically met three times, in Brussels, Belgium from October 13-17, 2014, in Rzeszow, Poland from April 20-24, 2015 and in Prague, Czech Republic from October 12-16, 2015. The three meetings were attended by 21 members from 9 nations, 21 members from 10 nations, and 22 members from 10 nations, respectively.

The overall project was divided into seven theme areas, each with a theme lead. All of the members of ET-148 selected one or more theme teams to join, depending on their interest and area of expertise. The seven theme areas and their leads were:

• Theme 1: Requirements	Jody Priddy/Michael Bradbury
• Theme 2: Methodology	Mike McCullough
• Theme 3: Stochastics	Karl Iagnemma, Ramon Gonzalez
• Theme 4: Intelligent Vehicle	Abhi Jain
• Theme 5: Tool Choices	Henry Hodges
• Theme 6: Input Data and Output Metrics	Brian Wojtysiak
• Theme 7: Verification and Validation	Michael Letherwood

Chapter 3 – NRMM HISTORY

Jean Dasch

3.1 HISTORY

Mobility modeling began in the US to address vehicle shortcomings recognized during World War II. Vehicle-terrain testing labs were set up with extensive test facilities at the United States Army laboratories, WES [Jones, 2011] and the TARDEC Land Locomotion Laboratory [Liston, 1965]. Following decades of research, the Army Materiel Command requested that the two Army Labs (TARDEC, WES) work together on a mobility model. The two labs in coordination with Stevens Institute of Technology issued the AMC-71 Mobility Model in 1971 [AMC '71, 1973)]. As described in the Foreword to the report on the model, "mathematical modeling allows for the evaluation of the entire vehicle system (engine, transmission, suspension, weight, geometry, inertia, winching capacity, and so on) as it interacts with soil, vegetation, slopes, ditches, mounds and other features in a synergistic fashion."

Three years of verification followed using three vehicle types at five test sites with the result that AMC-71 was considered to be correct about 70% of the time [Schreiner & Willoughby, 1976]. A refined model was issued in 1974 known as AMC-74 with improved terrain quantification and vehicle-terrain interactions. Meanwhile in 1976, NATO AC/225 Panel II, which was part of the NATO Army Armament Group (NAAG), recognized the need for standardized techniques to compare vehicle performance and the US offered to help initiate this effort [Haley et al., 1979). This was accepted by Panel II and AC 225/Working Group I (WGI) was established with membership from six countries (Canada, France, Germany, the Netherlands, the United Kingdom, and United States) and the first meeting was held at TARDEC in 1977.

US members from TARDEC, Peter Haley, and Stevens, Peter Jurkat, visited each of the six nations to ensure that they had the model running correctly on their computers. The NATO working group recommended to Panel II that a Technical Management Committee (TMC) be formed and this was done in 1978 with the same six member nations and led by Mr. Zoltan Janosi of TARDEC. They met regularly to bring participating countries up to speed on the model and to continue to update the model as needed. The model was accepted by NATO as a reference model in 1978 and was called the Initial NATO Reference Mobility Model (INRMM) and later the "Initial" was dropped leaving NRMM. It was also added to U.S. military vehicle specifications to ensure that contractors used the model to meet vehicle requirements, guaranteeing wide usage of the model [Petrick et al, 1981].

Research and development continued and the second version of the model, NRMM II, was issued in 1992 incorporating many of the changes that were made in the interim [Ahlvin and Haley, 1992]. The new algorithms were mainly due to the mobility tests conducted by WES since 1979 including the wheeled vs tracked test program (Willoughby et al, 1991) and included new equations in the area of soil traction, soil resistance, and surface slipperiness. In addition, special software was included to encompass radial tires and central tire inflation systems (CTIS).

All changes to the model had to be approved through the TMC. The TMC was disbanded in 1997, but each of the participating nations continued to advance their mobility modeling technology independently, leading to a duplication of effort. There was a need to reassemble the international community to consolidate these independent and often duplicative efforts into a collection of tools that would be considered a new version of NRMM and, subsequently to validate, standardize and maintain the resulting package as a shared NATO resource. Dr. Richard McClelland, TARDEC Director, proposed the idea to the NATO Applied Vehicle Technology (AVT) panel in the fall of 2002 [McClelland, 2002]. The NATO AVT-107 – Mobility Modelling Working Group was set up to coordinate and conduct this task. AVT-107 first met in October 2002 and concluded in 2006, with eight meetings held in the interim. The primary countries involved were Canada, France, Romania, the United Kingdom and the United States with lesser involvement by the Netherlands and Germany.

At the time of AVT-107, a Vehicle Terrain Interface (VTI) code was built in the US as a result of the Joint Army High-Resolution Ground Vehicle and Terrain Mechanics Program (HGTM) by ERDC, TARDEC and the Army Research Laboratory (ARL) [Richmond et al., 2004; Lamb et al., 2003; Reid et al., 2007]. A number of studies followed to investigate and validate the VTI code [e.g., Romano and Schultz, 2004; Parker et al., 2009]. Meanwhile, the French had developed their own code for modeling vehicle dynamics that was validated and tested, known as PROSPER, which could do all the calculations done by VEHDYN II. [Schafer and Andre, 1997] Eventually these new methodologies were not incorporated into NRMM, either due to confidentiality or commercial restrictions [Shoop, 2016]. The results from AVT-107 were presented to the AVT Panel on 6 October 2006 [AVT, 2006] and the final report was published in 2011 [Jones et al. 2011]. The committee's work and the final report are valuable in several respects in that the following areas are extensively discussed:

- A history of the development of the NRMM model from the 1960s.
- A detailed status of the model
- Identified limitations
- Communication of NRMM usage and upgrades by various nations

Despite the successes of AVT-107, many of the NRMM tool limitations were eventually not addressed. As a result, NRMM is less effectively used by the NATO nations. One significant concern is that if the current tool is not enhanced with higher fidelity and efficiency, it will leave the NATO nations with a subpar mobility tool that is neither capable of accurately differentiating competing designs nor capable of accurately predicting mobility performance of a specific design in various operational scenarios.

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Chapter 4 – NRMM OVERVIEW

Michael Bradbury

4.1 NRMM METHODOLOGY

> *NRMM ... can realistically quantify 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.* Jody Priddy, ERDC, 2014

NRMM is a modeling suite comprising obstacle crossing and ride pre-processors feeding into a main (predictions) module; the pre-processors are employed to reduce computational overhead. Each of these three models requires different parameters of terrain, vehicle and scenario (or control) data.

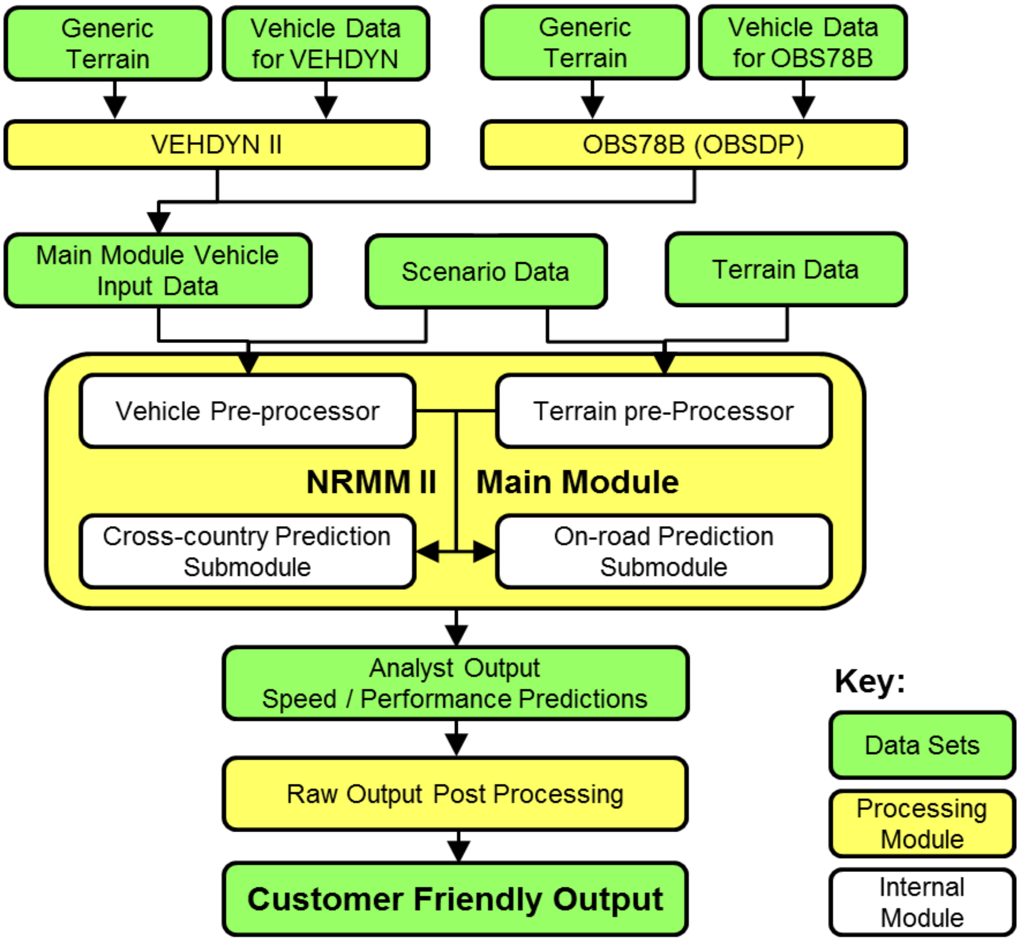


Figure 4-1. NRMM Methodology

The submodules in turn contain sub-models that each 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 newer versions, Vehdyn II and OBSDP are combined into VEHDYN 4.0 along with many other enhancements.

NRMM considers the entire vehicle underbody profile to check for obstacle interference, but only half the vehicle for speed predictions (bicycle model). In addition, only vertical acceleration is considered as a criteria for ride dynamics; the model only considers steady state speed and not acceleration or deceleration within the terrain unit. Also, the model cannot consider soil discontinuities such as rocks or the complete impact of vegetation.

4.2 PREPROCESSORS (OBSDP AND VEHDYN)

OBS78b is the obstacle crossing pre-processor for NRMM. It places a vehicle statically and sequentially along a terrain profile, and at each point it records the minimum clearance and the tractive effort required to hold the vehicle in place. 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 input data set for the main module and is used to interpolate results for the unique obstacles within the main module's terrain data.

It is a two-Dimensional model (viewed from the side) representing any given vehicle as front and rear assemblies (single or paired axles). Wheeled vehicles can also include a single assembly trailer; tracked vehicles include sprocket and idler.

However, OBSDP assumes that the tire is rigid and that the ground clearance for the under vehicle profile is fixed whereas actual vehicle suspensions allow for suspension droop and jounce and cause the under vehicle profile to change dynamically.

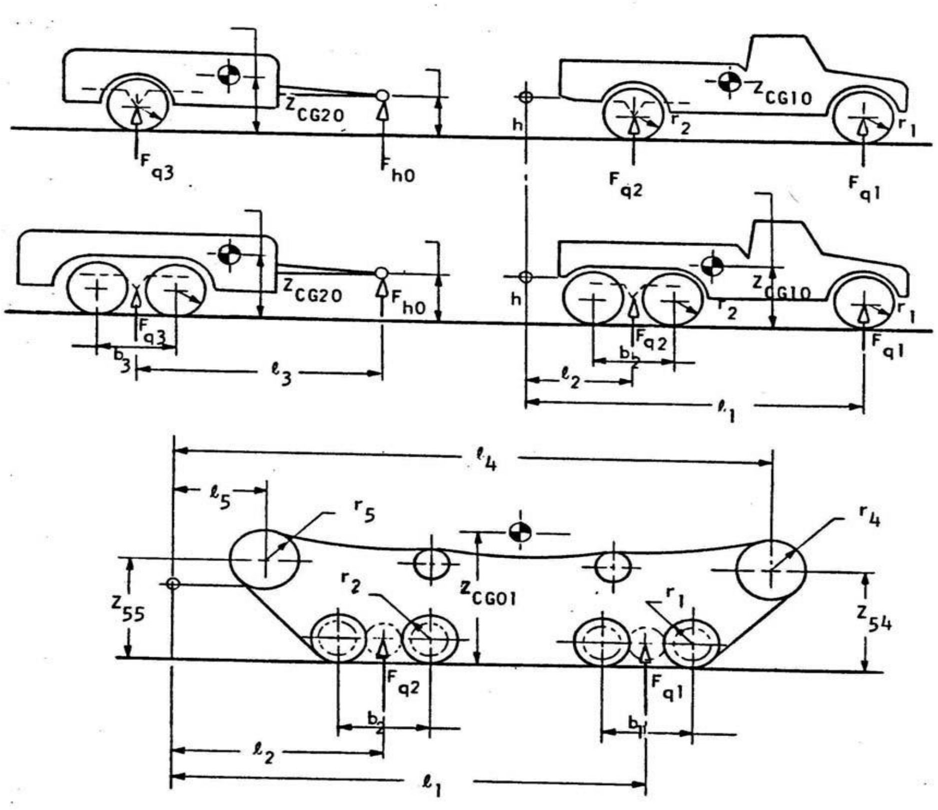


Figure 4-2. Vehicle configurations

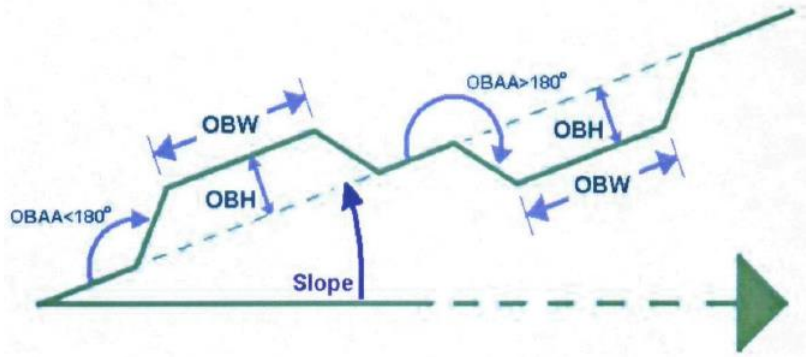


Figure 4-3. Terrain representation

The VEHDYN model was originally developed in 1974 to provide ride and shock simulation capability for general use in support of what was then the Army Mobility Model now known as NRMM. Since then it has been revised over the years and is now known as VEHDYN4.0. VEHDYN4.0 is a 2-dimensional model of a vehicle that includes improved track tension, direct user-input setting configuration, full hysteretic rotational springs in both the bogie and walking beam models and enhanced outputs.

VEHDYN is used to assess both obstacle impact (usually 2.5g vertical acceleration) and ride (usually 6 Watts absorbed power) driven speed limitations. These are used to temper platform performance by crew tolerance.

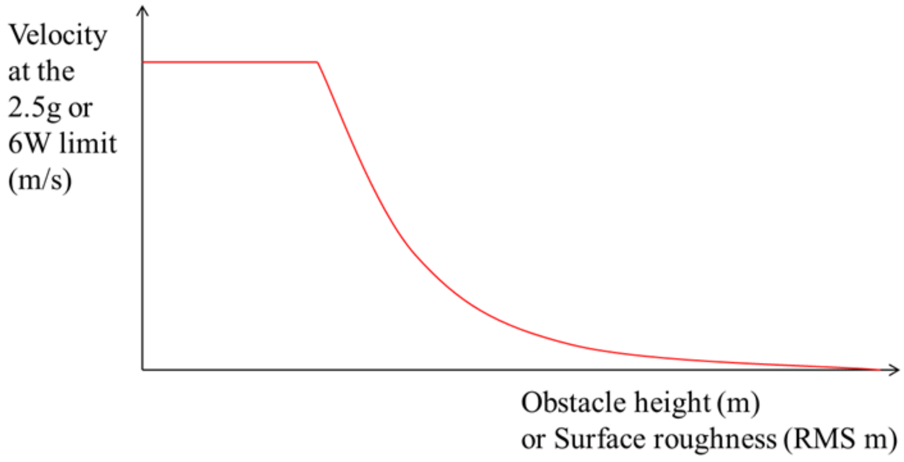


Figure 4-4. Generic VEHDYN constraint curve

4.3 INPUT REQUIREMENTS

NRMM requires a broad and detailed set of data. The data falls into four types: scenario, terrain, vehicle and operator. Some terrain information can be input in either the scenario file or the terrain file. A partial list of variables in the three main categories is given below. A fuller description is given in Chapter 11.

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

Figure 4-5. NRMM partial Scenario, Terrain and Vehicle data requirements

4.4 OUTPUT FORMATS

Predictions file: This is the backbone of the NRMM output data set. It provides the terrain patch-by-patch speed and limiting factors predictions. For each unique patch of terrain it predicts:

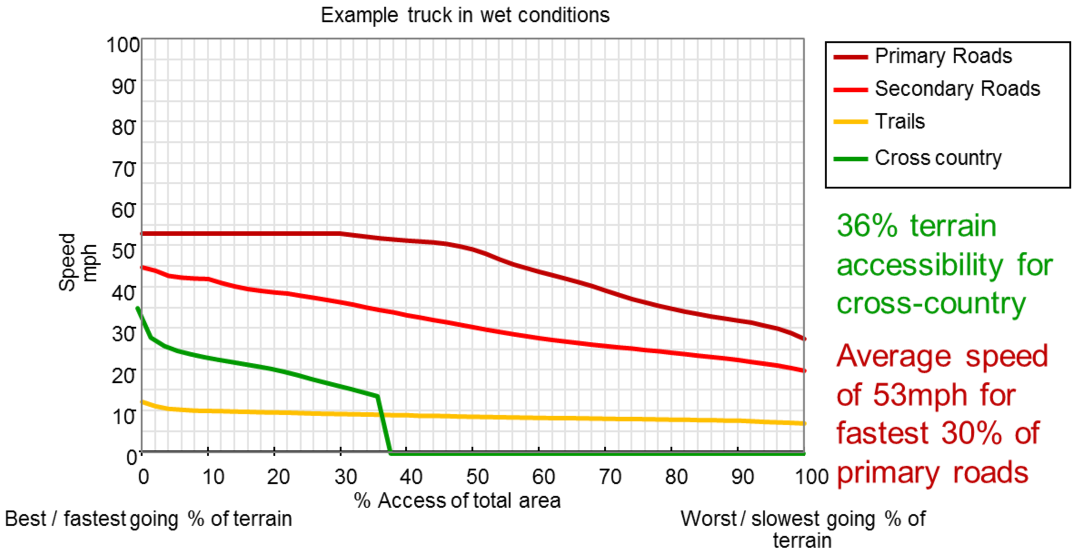
- The tire pressure/deflection setting that offers the best speed (for go terrain).
- The transmission range that offers the best speed (for go terrain).
- The OMNI speed for the patch which is a weighted average of the three directions of travel considered (up, down and across the terrain).
- A best speed prediction for each of the three directions of travel.
- A limiting reason for the no-go / go speed predicted for each of the three directions of travel.

The file also echoes the slope and size of the patch to enable filtering and post-processing of the data; for more detailed filtering and post-processing the patch number provides a common key back to the terrain data file contents.

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

Statistics file: This file contains a breakdown of the limiting reasons associated with the speed and no-go predictions by direction of travel. It also contains the speed curve data charts presented using plain ASCII characters (as a hang-over from pre-Windows days). The speed curve data is presented in both percentile and cumulative. This data is for quick reference, it is not intended for post-processing into other forms.

Cumulative speeds file: Cumulative speed curves are the standard form used in a lot of analysis reports and quoted/referenced in requirements documents.



36% terrain accessibility for cross-country

Average speed of 53mph for fastest 30% of primary roads

Figure 4-6. Example cumulative speed curves

In effect the several thousand individual predictions are put into descending order by speed and presented in speed percentiles (as calculated using a time based function). The chart can be read as the fastest terrain to the left of the horizontal axis and the slowest to the right, with any point on the curve giving the average speed for that percentage of the terrain.

Chapter 5 – THEME OVERVIEW

As stated earlier, ET-148 was organized around seven theme areas. The goal of each theme is the following:

- Theme 1, Requirements. Capture, consolidate, and summarize desired capabilities.
- Theme 2: Methodologies. Develop a plan for deriving a ground vehicle mobility modeling and simulation architectural specification for the NG-NRMM.
- Theme 3: Stochastics. Describe a framework for a stochastic approach for vehicle mobility prediction over large regions for integration into a NG-NRMM.
- Theme 4: Intelligent Vehicles. Define a NG-NRMM approach and requirements for mobility assessment for intelligent vehicles.
    - Theme 5: Tool choices. Identify critical elements for a physics-based next generation mobility model utilizing strengths and weakness criteria provided by initial "pros and cons" review of current NRMM. Identify potential solutions throughout the technical community and user nations.
- Theme 6: Input Data and Output Metrics. Define the input/output data requirements that will inform the Next-Generation NRMM tool development/selection processes.
- Theme 7: Validation and Verification. Provide a process for conducting a successful tool and software code V&V program on the NG-NRMM.

The following chapters summarize the progress made by each theme toward these goals.

Chapter 6 – THEME 1: REQUIREMENTS

Jody Priddy and Michael Bradbury

6.1 GOALS AND DELIVERABLES

Goals: Capture, consolidate, and summarize key mobility modeling capabilities desired by the team member nations.

Deliverable: Documented requirements to shape AVT recommendations.

The team members were the following:

Country	**Name**
Canada	Mayda, William
Czech Republic	Neumann, Vlastimil
UK	**Bradbury, Michael: Leader**
UK	Suttie, William
USA	Gunter, David
USA	Jayakumar, Paramsothy
USA	King, Roger
USA	Letherwood, Michael
USA	**Priddy, Jody: Leader**
USA	Shoop, Sally

6.2 INITIAL SOLICITATION OF IDEAS

During the first teleconference in June 2014, the membership was asked to respond to three questions:

- Things you like about NRMM
- Things you dislike about NRMM
- Prioritized requirements for a next-generation NRMM

Pages and pages of deliberative responses were turned in by those members of the team that were major users of the model. The complete list of responses is included in Appendix C.

The long list of responses was winnowed down and divided them into 11 categories of requirements: Output, Terrain, Vehicles, Human Factors, Modeling and Simulation (M&S) Methods, Interfacing, IT Infrastructure, Software Features, Maintainability, Expected End Users, and Distribution Approach. The items in each category are included below:

Output

- Retain NRMM-style mobility metrics and other output (e.g., off-road speed, %Nogo)
- Retain strong emphasis on comparative mobility analysis, including backwards comparability for past NRMM predictions
- Expand mission profile definitions (include deformable terrain types)
- Establish new mobility metrics (e.g., compact, user friendly, testable)
- Metrics for unmanned, robotic, perception, and sensor system performance
- Metrics of interest to all NATO partners
- Quantified uncertainty in output metrics
- Spatial considerations on mobility metrics (e.g., inaccessible “go” islands)
- Generate digital maps for use in GIS and C2 tools
- Influence of potential soil moisture/strength changes
- Performance based on simulations/predictions for developmental testing
- Powertrain performance (e.g., speed on slopes, cooling limits)
- Fuel economy and range, efficiency
- 3-D vehicle stability metrics (e.g., rollover, lane change, steering stability, split mu)
- Dynamic stability control metrics (e.g., for ABS, ESC performance)
- Steering/turning performance metrics
- Urban maneuverability metrics
- Improved terrain roughness ride quality metrics (including asymmetric terrain)
- Improved linear feature obstacle crossing performance metrics
- Swimming and fording performance, including intrinsic amphibious characteristics
- Rut depth, including multipass

Terrain

- Increased global coverage
- Updated terrain data sets
- Improved/expanded terrain definition (e.g., scale-invariant descriptions)
- Expand terrain profile definitions (e.g., specify deformable terrain features)
- Fast and facile methods for determining theater-specific terrain characteristics
- Make use of higher resolution terrain data sources (e.g., LIDAR)
- Make use of modern GIS terrain data sources
- Measurable and attainable terrain characteristics
- Comprehensive terrain features and range of characteristics
- Soil characteristics, including various strength parameters for alternative terramechanics approaches (e.g., RCI, internal friction, cohesion)
- Potential variations in soil moisture/strength
- Snow characteristics (e.g., depth)
- Freeze/thaw soil conditions
- Road characteristics

- Split mu features (e.g., gravel shoulder, road edge)
- Urban features
- Terrain roughness, including asymmetry features
- Improved roughness metrics (better than RMS, stationary, ergodic, spectrally general)
- Rocky terrain features (e.g., rocky shore in surfzone)
- 3-D linear feature obstacles (e.g., gaps, barriers)
- Library of selectable and expandable standard obstacles
- New standardized obstacle types (e.g., rubble pile, embedded hard obstacles in deformable terrain)
- 3-D water feature obstacles (e.g., streams, ponds, lakes, rivers, oceans, surfzones, ship launch)

Vehicles

- Robust comprehensive vehicle characteristics
- Attainable vehicle characteristics
- Multi-fidelity from simple to rigorous characterizations
- Modern suspensions (e.g., independent, active, semi-active)
- Modern braking systems (e.g., ABS)
- Modern powertrain systems (e.g., TCS, ESC, ABM, hybrid, electric)
- Powertrain cooling systems
- Computer controllers (e.g., ABS, TCS, ESC, ABM, active/semi-active suspensions)
- Steering systems (e.g., skid steering)
- Pneumatic tires (e.g., bias ply, radial)
- Tracks (e.g., flexible steel link, rubber band)
- Non-pneumatic wheels (e.g., rigid, airless)
- Size and weights including small/light robots to large/heavy main battle tanks
- Unmanned, robotic, perception, and sensing systems
- Undercarriage clearance geometry
- Intrinsic amphibious characteristics (e.g., buoyancy)

Human Factors

- Human tolerance limits over rough terrain (including asymmetric terrain)

M&S Methods

- Include multi-fidelity modeling options from simple to rigorous, empirical to physics based
- Improved tire/track-soil interface modeling
- 3-D tire/track models
- 3-D physics based models of deformable terrain (e.g., soil, snow)
- Include alternative terramechanics approaches
- Include physics based dynamic simulations
- 3-D MBD for vehicle dynamics, including rigid and flexible bodies
- Methods for quantifying powertrain and braking torque delivered to each traction element (e.g., wheels, tracks)
- Include dynamic simulation of powertrain and braking performance
- Driver models for simulation control
- Uncertainty quantification (e.g., Monte Carlo simulation)
- Design of experiments methods
- Include response surface methods or other approximation methods
- Chassis/undercarriage collision and resistance methods
- Methods for dynamic simulation of amphibious operations (e.g., CFD)

- Methods for sensor, perception, and autonomy system modeling

Interfacing
- Interfacing with existing GIS tools (input and output)
- Interfacing with existing 3-D MBD tools
- Driver feedback loop for speed control (e.g., controller HITL)

IT Infrastructure
- Enable use of modern HPC resources
- Maintain portability and desktop computing capability

Software Features
- Modern software
- Easy to install
- User friendly
- Modular software architecture
- Good error handling
- Runs quickly (e.g., single run in minutes or less, not hours or days)
- Enhanced user interface for inputs, outputs, and data management (e.g., GUI)
- Enhanced graphical output (e.g., graphs, charts, visuals)
- Include different versions or user modes, from "lite" to "expert"
- Include input and output compatible with common existing analysis tools (e.g., MATLAB, spreadsheets, GIS tools)
- Ability for plug-ins, add-on modules (e.g., alternate terramechanics modules, controller-logic modules)
- Provide multi-fidelity analysis options, with associated input data requirements ranging from simple/limited to robust/extensive
- Allow easy variation of select parameters for quick "what if" scenarios by non-specialists end-users (e.g., weight, power, number of axles)
- Provide clear, robust diagnostics and detail options (e.g., nogo reasons to include multiple reasons, access to intermediate and lower level results)
- Include library of terrain features that are selectable and tailorable to vehicle and mission requirements (e.g., obstacles)
- Allow terramechanics changes, alternatives, and comparisons

Maintainability
- Need formal mechanism for software maintenance

Expected End Users
- NATO community
- Non-specialists end users
- Expert end users

Distribution Approach
- Improved distribution with NATO accessibility
- Could include commercial, open source, or both
- Available and supported for use by industry
- Prefer minimal licensing/maintenance costs for use in government purposes

6.3 THE USER

When setting requirements it is also necessary to understand the needs and expectations across the stakeholder community. For the purposes of Next Generation NRMM, the User is considered to be the software operator.

Four broad categories of User have been identified as follows:

- Supervised practitioner: Someone who will require support and guidance; assistance with some aspects of data input, configuration, running the model, post-processing and/or presenting the resulting analysis to the Customer.
- Practitioner: Someone that can interpret the Customers' needs, then define and execute analysis that provides appropriate decision support without supervision or guidance. Someone that can adapt how the software is used if needed but may require advice regarding the execution or validity of that adaptation.
- Expert User: Somebody who not only is proficient in utilising the software to provide decision support but understands the science behind it and the underlying functionality. This person is a recognised authority on the subject and can truly attest as to whether the software is being used in a viable and reliable manner.
- Operational planner: This person has to operate independently, likely remotely from the core community, relying largely on re-using data (e.g. vehicle and/or terrain files) for typical, well understood analysis tasks, reaching back to core community practitioners as needed.

The initial requirements identified in this report do not discriminate between these User types. As requirements develop into formal User and System requirements documents or a technical specification they can be used to describe, qualify and differentiate functionality as needed.

6.4 KEY NEW REQUIREMENTS

The theme membership took this the requirements from Section 6.2 and further consolidated them into fewer categories. New, or enhanced, requirements have been identified across four categories:

- System: Platform types within scope.
- Modeling: Technologies and subsystems within scope.
- Analysis: Problem spaces or analysis questions within scope.
- Output: Metrics, results formats and exploitation interfaces within scope.

The final list of key new requirements for a Next-Generation NRMM model was separated into Near-Term Priorities (Threshold) and Far-Term Priorities (Objectives) as shown in Figure 6.1. Note that when an item appears in both near and far-term, it is in recognition that either ground work is needed now to enable far-term priorities or where a lesser solution is feasible as a step along the development path. Also, although a GUI and animation are not explicitly stated as Key New Requirements, they are desirable in current and future software options.

Vehicles may be manned or unmanned, in either case human control may be supplemented by varying levels of autonomy to assist or replace (for periods of time) the operator. From the perspective of mobility modeling this has implications from the terrain data definition to the modeling strategy (e.g. driver prudence/constraints). The use of the term 'autonomous vehicles' within this report is within that context. See Chapter 9 on Intelligent Vehicles for more information.

Category	Sub-category	Near-Term Priorities for NG-NRMM Threshold	Far-Term Priorities for NG-NRMM Objective
New System Capabilities	Vehicle Type	Wheeled, tracked, **autonomous**	Legged, **autonomous**
	Vehicle Scale	Conventional manned vehicles	Lighter and smaller vehicles
	Terrain Scale	**Regional, varied resolutions**	**Global, varied resolutions**
New Modeling Capabilities	Suspension Types	Passive, semi-active, active	Active
	Control Types	Driver, ABS, TCS, ESC, ABM, CTIS, **autonomy**	**Autonomy**
	Sub-systems	Steering, powertrain, **autonomy**	**Autonomy**, human cognition
	Model Features	3D Physics based models Multibody dynamic vehicle models Flexible body models Detailed tire and track models **Terrain models (e.g. Bekker-Wong)**	**Terrain models (e.g. DEM, FEM)** **Stochastic models**
New Analysis Capabilities	User Type	Analyst/Expert	Operational Planner
	Environment Types	On-road, off-road **Urban, soil, snow/ice**	**Urban**
	Powertrain Performance	Grading, turning, fuel economy	Cooling
	Amphibious Operations	Fording, swimming	
	Computations	Efficiency - fidelity trade off	High fidelity **High performance**
New Output Capabilities	Assessment Types	**Mobility performance in operational context**	
	Metric Considerations	**Verifiable mobility metrics**	

Figure 6-1. Key New Requirements for Threshold and Objective NG-NRMM. The colors indicate gap areas in Mobility Mapping (Light Blue), Environmental Modeling (Green), Intelligent Vehicle (Red), Stochastics (Purple), Computational Performance (brown) and Verification and Validation (Dark Blue).

6.5 NEXT STEPS

Theme 1 has highlighted Key New Requirements which address both capability sustainment (more accurately restoration) and growth. In essence there are two logical next steps:

Requirements documents: Turn the Key New Requirements into User and System requirements (or some other form of technical specification) with Specific, Measurable, Achievable, Relevant and Time-bound (SMART) requirements. Given it is unlikely a single solution will meets all requirements it is essential to the collaborative effort that priorities are agreed within these requirements so that collectively requirements can be traded or risk taken against them.

Requirements documents are needed to ensure the Next Generation NRMM delivers the right capability and that the community best appreciates the effort and risks therein. Detailed requirements documents will be key to securing national/international funding and support from academia/industry in addition to any commercial/contractual arrangements with suppliers.

Requirements roadmap: Generate a requirements roadmap in parallel (to refining requirements) defining the relationships and dependencies between the requirements. E.g. you cannot perform data fusion across all terrain types until you can model all terrain types.

Example:

- Current NRMM looks at on and off-road predictions in isolation.
- To provide effective decision support with a growth path to Operations, Next Generation NRMM needs to consider data and analysis fusion across the on/off roads terrain types.
- Further, at a minimum it must consider the interface with urban landscapes, if not the assimilation of. To do so, it must have an urban mobility definition or assessment capability.
- As this new capability looks at the fused terrain with greater fidelity it will need to consider directionality in context (i.e. actual as opposed maximum slope) and uncertainty (stochastics).

This is needed to allow for effective programme management and delivery for Next Generation NRMM.

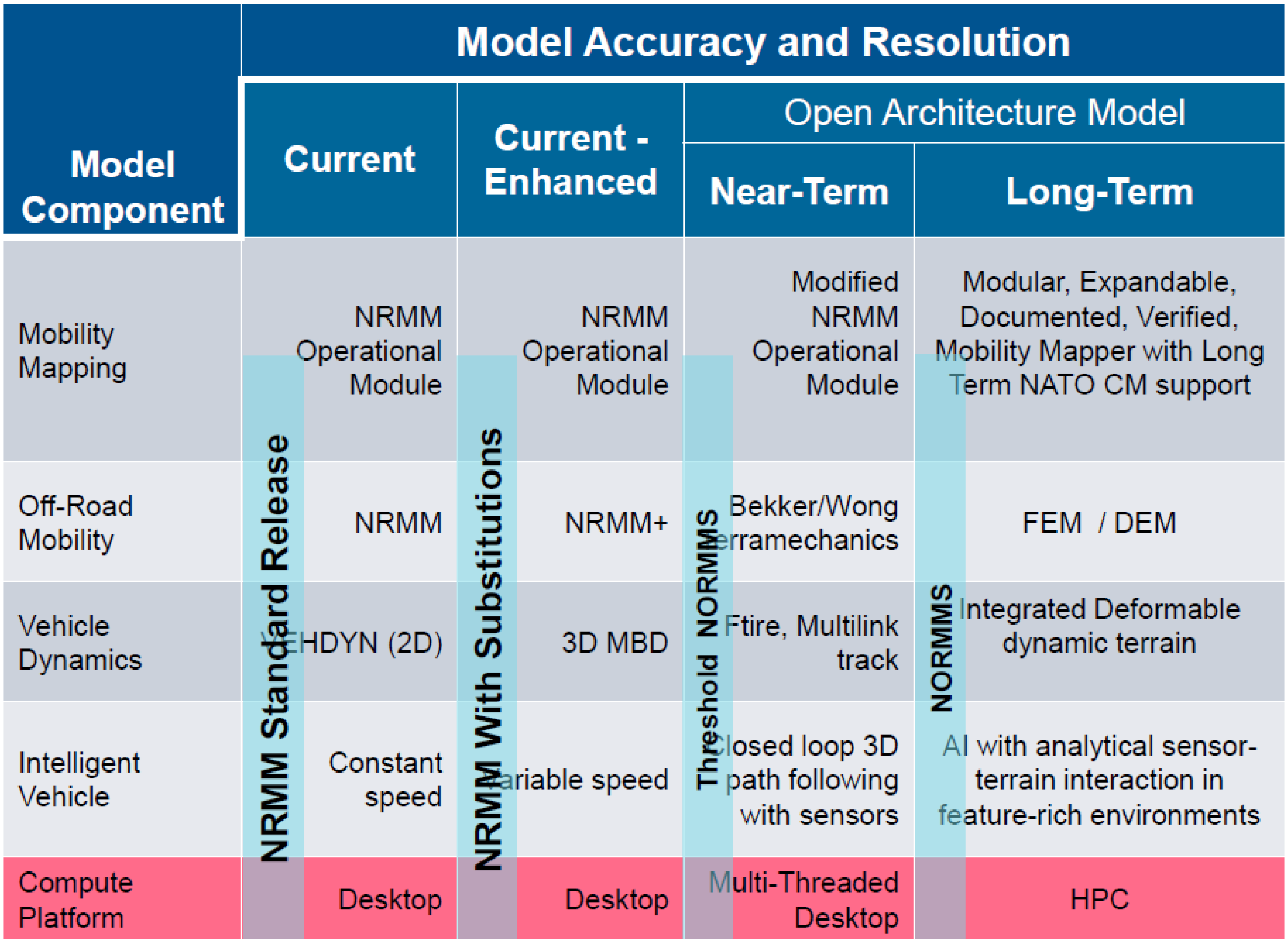
In summary, while the current level of requirements definition is sufficient for the community to progress toward improved simulation and prediction accuracy, it is insufficient for program delivery. To finalise the requirements there is a dependency on the other themes, which in turn is in practical terms dependent on currently available software solutions and their potential growth paths. The ultimate exploitation of a well-defined requirement beyond programme delivery could be the building blocks for the definition of a mobility modeling standard.

Chapter 7 – THEME 2: METHODOLOGY

Michael McCullough

7.1 GOALS AND DELIVERABLES

Through the course of the ET, a Methodology Development Vision was proposed for four different levels of model complexity. As shown in Figure 1 below, the current model, the NRMM standard release, is empirical. The Exploratory Team considered three levels of complexity for the Next-Generation NRMM as shown in the last three columns, an Enhanced Empirical Model, a Semi-Analytical and an Analytical. The decision was that the Methodology would be to develop the Open-Architecture type models with a Semi-Analytical being most possible in this time frame but with future efforts aimed toward an analytical model.



Model Component	Model Accuracy and Resolution			
	Current	Current - Enhanced	Open Architecture Model Near-Term	Open Architecture Model Long-Term
Mobility Mapping	NRMM Operational Module	NRMM Operational Module	Modified NRMM Operational Module	Modular, Expandable, Documented, Verified, Mobility Mapper with Long Term NATO CM support
Off-Road Mobility	NRMM	NRMM+	Bekker/Wong Terramechanics	FEM / DEM
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

Figure 7-1. Next-Generation NRMM Methodology Development Vision

“Open Architecture model” refers to an enduring non-preferential realization of the model that is implemented at a higher level of abstraction that will be inclusive of a variety of specific executable implementation environments, all validated legacy models and input data, while also establishing a framework for future innovation. 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. Thus, the acronym NORMMS was coined for **N**ATO **O**perational **R**eference **M**obility **M**odeling **S**tandards. The NORMMS framework was defined as 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.

The Methodology team members are shown in Figure 2. A variety of points of view were expressed and written drafts of specific proposed standards were developed by some of the team members which provide examples of specific issues and the level of detail required in the NORMMS specification statements. Appendix D contains the text of these examples. The team also developed the following high level goals:

- Develop a plan for deriving a ground vehicle mobility modeling and simulation architectural specification, or NORMMS, defining the content of the Next Generation NRMM.
- Leverage the capabilities of team members
- Address all Requirements from Theme 1
- Integrate/coordinate with methods work done by Themes 3-7

The theme members are listed below:

Country	**Name**
Canada	Wong, J.Y.
Czech Republic	Rybansky, Marian
Denmark	Balling, Ole
Germany	Gericke, Rainer
Poland	Glowka, Jakub
Poland	Wrona, Jozef
USA	Gunter, David
USA	Hodges, Henry
USA	Iagnemma, Karl
USA	Jain, Abhi
USA	Jayakumar, Paramsothy
USA	Letherwood, Michael
USA	**McCullough, Michael: Leader**
USA	Ngan, James
USA	Priddy, Jody
USA	Ward, Derek
USA	Wojtysiak, Brian

The Theme members developed a draft NORMMS specification for both the Semi-Analytical (Threshold capability) and the Analytical (Objective) Capability, starting with the high level summary given previously in Figure 7-1. The detailed requirement set forms the basis for measuring progress and completeness. Because it is impossible to predict all possible mobility metrics and these may change with every application, the open architecture is necessary to accommodate the required flexibility being expressed by the ultimate end-users. Figure 7-2 depicts schematically, and with the color scheme, the flow of input/output requirements that are expected to be typical for future applications of the NG-NRMM. This figure depicts a significant mobility mapping effort (Theme 6) that can be decoupled at the executable level from the vehicle terrain interaction (VTI) modeling perspective. 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 suggested tool set for the NG-NRMM mobility mapping component that allows mobility to be assessed at more global levels.

VTI modeling is its own focus area and 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 required to be mapped. The additional terrain data requirements and higher levels of resolution for detailed VTI simulations are one of the core research and development issues distinguishing the current NRMM from the next generations envisioned by this ET, i.e., the semi-analytical and analytical. 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, but for detailed deformable terrain models employing continuum models 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. Current state of the practice and successful use of VTI models has identified multi-body dynamics software as the primary modeling environment that is readily available, significantly validated across a practically limitless range of vehicle morphologies, and meets the goals and requirements for the integration of all of the desired capabilities identified for both threshold and objective NG-NRMM.

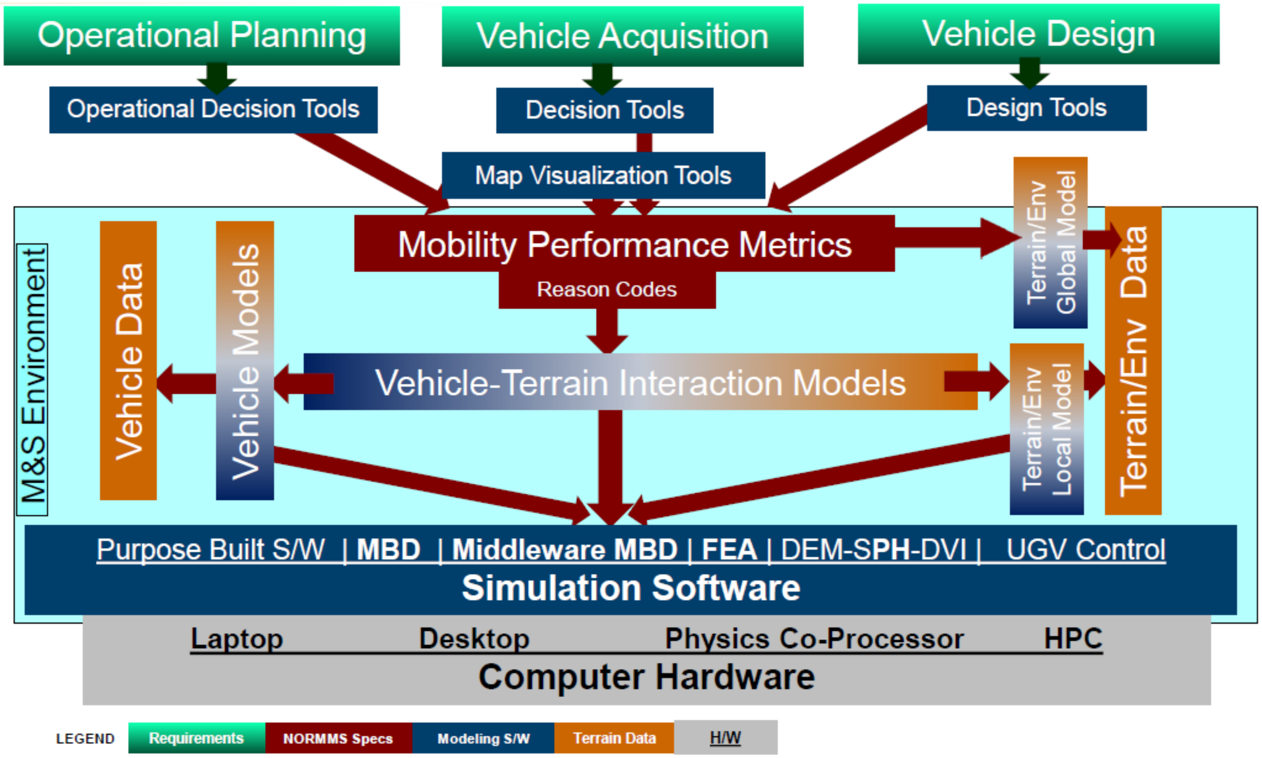


Figure 7-2: Next Generation NRMM Schematic and NORMMS Requirements Flow

The light blue box in Figure 7-2 is the M&S integrating environment (MSIE). MISE presents a unique opportunity to identify a modeling process integration tool that enables the envisioned open architecture for NG-NRMM through the implementation of executable NORMMS. The MSIE tool would enable the Research Technical Group to capture decisions about algorithms and metrics, and simultaneously implement them in a form that is ultimately executable, 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 multibody dynamics, 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 which are ultimately more enduring and directly align with, and achieve, the RTG goals for NG-NRMM. There are also commercial tools associated with Computer Aided Engineering (CAE) which share the same vision such as SimManager/SimExpert from MSC and COMET. The RTG could choose to adopt one of these as well, although they would require that financial barriers to entry/ownership be small and must demonstrate an enduring path to the future.

It should be noted in the context of the high level mobility metrics 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” are therefore considered a valuable starting list of NORMMS attributes.

7.2. DRAFT NORMMS SPECIFICATION

1. **New System Capabilities.** NG-NRMM shall be implemented in vehicle modeling environments that have system modeling capabilities supporting template based construction of a broad range of tracked, wheeled, and autonomous vehicles at the scale of conventional manned vehicles interacting with terrain data sets at the local and regional levels of resolution (threshold) with future expansion capabilities to include all vehicle morphologies, levels of autonomy, and terrain interactive capabilities extending to global data sets.
2. **New Modeling Capabilities.** The threshold NG-NRMM shall be implemented in vehicle modeling environments that have subsystem modeling capabilities to include: 3-D physics based multi-body models, inclusive of flexible bodies, passive, semi-active and active control systems (e.g. ABS, TCS, ESC, ABM, CTIS), human driver models, autonomous control, detailed powertrain models, detailed tire and track models interacting with deformable terrain models based on semi-analytical terrain response models equivalent in complexity to Bekker-Wong pressure sinkage models and Janosi type shear response models. The objective NG-NRMM shall be implemented in vehicle modeling environments that are fully inclusive of emerging advanced deformable terrain modeling methods such as DEM, SPH, and DVI as well as advanced autonomy models including human cognition and the associated terrain descriptive and interactive simulation capabilities required to support those. The objective NG-NRMM shall also include proven and accepted methods for analyzing and accounting for the primary stochastic attributes of mobility modeling.
3. **New Analysis Capabilities.** The threshold NG-NRMM shall be implemented in vehicle modeling environments that have expanded analysis tools consistent with the Figure 7-1 attributes for Environment Types, Powertrain Performance, Amphibious Operations, and Computational architectures. Objective NG-NRMM shall be implemented in modeling environments permitting automated methods of interacting with urban terrains and taking advantage of massively parallel computers and physics co-processers.
4. **New Output Capabilities**. The NG-NRMM shall implement all output data required by advanced applications of mobility data at the operational level including the ability to rapidly compute new and unusual mobility metrics that are verifiable and map enabled using GIS based visualization tools.

7.3. DETAILED NORMMS COMPLIANCE ASSESSMENT

The draft specification above is intended to form the high level framework from which a fully detailed specification can be developed that permits any interested and NATO authorized organization to develop a NG-NRMM that accomplishes the goals of this effort. In cases of existing capabilities, this exercise may simply be a process of verification of compliance to the updated expectations of NG-NRMM at the threshold or objective levels, respectively. In the immediate shorter term, the NORMMS development process can also become the broader context within which the contributions of the other themes of this ET are captured and adopted.

For the future, the draft NORMMS specification is also intended to be a living document that can be further developed to higher levels of resolution and detail as necessary to accomplish the on-going goals of the NG-NRMM development process. Early in that future process, they will provide a checklist of requirements against which proposed modeling environments can be assessed with respect to their potential to implement a NG-NRMM capability. Later, with further detailed elaboration, this can evolve into a verification and validation dashboard used to accredit a given proposed capability. Finally, if the NATO development team comes to this conclusion, it can be used as a basis for a specification of a NATO sponsored software capability that implements, in part, or in whole, a common NATO-owned and distributed NG-NRMM implementation. An example of such a progress measurement dashboard is shown in Figure 7-3 below. Development and ratification of the precise entries representing the desired attributes for a NORMMS description of the NG-NRMM is an early goal of the RTG effort.

Legend
No input
Draft proposed
Draft Vetted with SubTeam
Draft Vetted with Full Team
Released

Modules	Required attributes	Specification	Verification Statement	Verification Data	Validation Statement	Validation Data
Mobility Mapping Module						
	Portable					
	Expandable					
	Independent, published I/O specs					
	Programmable metric definitions					
	Traceable metric data dependencies					
	Supports operational planning					
	Supports acquisition					
	Supports vehicle design					
	Intelligent vehicle metrics					
	Stochastic analysis					
Physics Models Minimum List of Factors for Initial Release						
Ride dynamics (vride) limit	ISO 2631 and ISO 8608					
Tire speed limit						
Soil, slope and vegetation resistances						
Visibility						
Maneuver around obstacles						
Manuever in urban environments						
Obstacle override force						
Driver prudence						
External (scenario) limit						
Handling speed limits						
Slope operations limits						
Trafficability limits	Terramechanics with deformable soil					
Amphibious operations						
Intelligent vehicle limits						

Figure 7-3: Example Progress Measurement Dashboard for development of a NORMMS specification.

Chapter 8 – THEME 3: STOCHASTICS

Karl Iagnemma and Ramon Gonzalez

8.1 GOALS

The objective of the proposed research is to describe a framework for a stochastic approach for vehicle mobility prediction over large regions, for integration into a NG-NRMM.

The team members are shown below:

Country	**Name**
Romania	Ciobotaru, Ticusor
Spain	Gonzalez, Ramon
USA	Gunter, David
USA	Jayakumar, Paramsothy
USA	**Iagnemma, Karl: Leader**
USA	Shoop, Sally
USA	Ward, Derek

8.2 INTRODUCTION

It is well-known that before attempting a mission involving a ground vehicle in off-road conditions a reliable and comprehensive analysis of the mobility capabilities of such a vehicle is desired. This goal can be solved by means of computer simulation, where both terrain profile and vehicle-terrain interaction play a key role. Traditionally, this analysis considers nominal values for the key variables involved in the simulation. This leads to unreliable and limited results due to the uncertainty present in those variables. Key variables include those related to terrain geometry and terrain physical properties. Vehicle parameters and their dependencies should also be addressed for a full stochastics treatment, but were not considered here.

Terrain geometry information typically comes from remote sensory sources (i.e. radar technology, imagery methods, etc.). Those techniques lead to models of the terrain with uncertainty associated with the spatial position of data points. Thus, any elevation model of the terrain is corrupted by uncertainty. Digital Elevation Models (DEMs) produced by the US Geological Survey agency are a good example of this issue.

Spatial variability of physical terrain properties (e.g. soil cohesion and internal friction angle) also leads to uncertainty in vehicle-terrain interaction models. In addition, measurement methods of the soil properties are uncertain in nature.

Here, we describe a framework for a stochastic approach for vehicle mobility prediction over large regions (> 5 x 5 [Km^2]). This method could form part of a Next Generation NRMM tool. In this framework, a model of the terrain is created using geostatistical methods. The performance of a vehicle is then evaluated while considering the terrain profile and the vehicle-terrain interaction. In order to account for uncertainty, Monte Carlo simulations are performed, leading to a statistical analysis. Uncertainty in elevation is due to the new interpolated terrain model to a higher spatial resolution than the original DEM (through a geostatistical method called Ordinary Kriging). On the other hand, uncertainty in soil properties is obtained considering the variability of the parameters involved in the well-known Bekker-Wong (BW) model [Bekker, 1969; Wong, 2001].

8.3 IDENTIFICATION OF NEEDS AND CHALLENGES

After a review of the current (deterministic) NRMM [Rula and Nuttall, 1971; Haley et al., 1979] and the suggestions proposed to date to formulate a stochastic NRMM [Lessem et al., 1992; Lessem et al., 1993], the following needs and challenges have been identified:

- Previous attempts to convert NRMM from a deterministic framework to a stochastic one have failed in the core component of a stochastic procedure, that is, the origin of uncertainty. No formal mathematical reasoning about the uncertainty introduced in the simulations is given in [Lessem et al., 1992; Lessem et al., 1993; Lessem et al., 1996].
- An efficient numerical solution is highly recommended in Lessem’s works. So far, the proposed (stochastic) implementation of NRMM requires supercomputers and requires extensive time to obtain a solution.
- Development of an architecture that is flexible enough to accept a variety of information sources is required. In particular, it is desired to be able to use standard cartographical models available today, that is, digital elevation models. Worldwide maps are freely available from the US Geological Survey agency at different spatial resolutions.
- The output of the current NRMM is given in terms of a deterministic mobility map. This map shows the average cross-country speed between two points in a given region for a given vehicle. As recommended by [Lessem et al., 1992], a stochastic analysis should be given in terms of probability densities rather than the ranges in the variables.
- The current NRMM does not support autonomous mobility (this issue was pointed out in [Vong et al., 1999]). Notice that this capability is highly advisable in the Next Generation NRMM because current and future defense forces include autonomous systems.

8.4 RELATED WORK

This section summarizes the main publications framed in the context of this work. Firstly, the state-of-the-art in the field of mobility prediction is analyzed. After that, a study of the literature related to Geostatistics is presented. Finally, a review of the previous research framed in the context of stochastic NRMM is included.

8.4.1. Mobility prediction

- Many publications cope with 3D path planning in the close vicinity of an autonomous mobile robot [Goldberg et al., 2002; Norouzi et al., 2012; Trease et al., 2011]. Those approaches are generally not appropriate for planning longer routes over large environments because they are based on sensors that perceive only the surrounding environment (e.g. stereovision, LIDAR).

- An important research effort has been made in the field of combining remote sensor and ground sensor data [Helmick et al., 2009; Stentz et al., 2002; Vandapel et al., 2006]. The solutions addressed in this report are in fact inspired by those papers.
- Mobility prediction has also been considered in terms of the vehicle-terrain interactions [Ishigami et al., 2009; Willoughby et al., 2006]. For example, in [Ishigami et al., 2009], a statistical method for mobility prediction considering uncertainty in terrain physical properties (soil cohesion and internal friction angle) is proposed.
- Uncertainty in control actions is also taken into account in the literature. For instance, in [Peynot et al., 2014], the authors define mobility prediction as the problem of estimating the likely behavior of a planetary exploration rover in response to given control actions on a given terrain.
- Some research projects focus on the reconstruction of a 3D surface from sparse data obtained from a remote sensor [Hadsell et al., 2009; Kweon and Kanade, 1992]. However, these works do not consider the second goal of this research, that is, stochastic mobility prediction.

8.4.2. Geostatistics

Geostatistics aims at providing quantitative descriptions of natural variables distributed in space-time [Chiles and Delfiner, 2012; Isaaks and Srivastava, 1989; Webster and Oliver, 2007]. Furthermore, it deals with a methodology to quantify spatial uncertainty. Next, the current applications and theoretical developments dealing with the field of geostatistics are summarized:

- The main applications deal with soil sciences: identifying chemical and physical soil properties (e.g. moisture, salinity, minerals, pH, etc.) [Basaran et al., 2011; Paul and Cressie, 2011]. Other applications include: agriculture, mining, landscape ecology (CO_2, Ozone, radiation), and manufacturing problems [Srivastava, 2013; Tardic et al., 2014; Tsui et al., 2013; Volpi et al., 2014].
- Comparison of kriging, cokriging methods, and other similar kriging-based methods is discussed in [Basaran et al., 2011; Hosseini et al., 2014; Tsui et al., 2013].
- Reducing the computation cost of kriging for large spatial datasets is addressed in [Cressie and Johannesson, 2008; Cressie and Kang, 2010].
- Creating surrogate models in order to reduce the computation burden of original physical models (i.e. dynamic kriging), see for example [Volpi et al., 2014; Zhao et al., 2011; Zhao et al., 2013].

8.4.3. NRMM

Pioneering work was developed by Lessem and others [Lessem et al., 1992; Lessem et al., 1993; Lessem et al., 1996] and constituted a significant contribution to convert NRMM from a deterministic framework to a stochastic one. In that approach, input parameters to the NRMM were randomly generated according to a given range, and after Monte Carlo simulation an output was provided in terms of the nominal, maximum and minimum speeds for a given scenario. Uncertainty was simulated by means of a fixed range for every input parameter of the NRMM. Those ranges were assigned by expert opinion. The ultimate output of Lessem's work was a deterministic GO/NOGO map based on the minimum value in the expected range of speed. That is, if that minimum value is zero (representing vehicle entrapment) that region was marked as NOGO. As remarked in [Priddy, 1995], Lessem's intent was to demonstrate the stochastic forecasting concepts rather than to reflect accurate output variability.

Another significant step in the NRMM context was addressed in [Priddy, 1995]. In that research, the authors explained different models to estimate certain parameters dealing with the vehicle-terrain interaction such as slip, motion resistance, vehicle cone index, and drawbar pull. This study concludes how well the (deterministic) NRMM performed with actual data and proposed new prediction equations to account for variability in the cross-country traction empirical relationships.

8.5 OVERALL FRAMEWORK OF PROPOSED ARCHITECTURE

8.5.1 Digital Terrain Modeling

The process of natural terrain modeling starts with a set of sparse measurements obtained using a remote sensor for a terrain region of interest (see Figure 8-2). Typically these sensors are mounted on a vehicle or on satellites. In any of those scenarios, both variable resolution (or small resolution) and irregular density of data (occlusions) are inevitable. This issue leads to non-uniformly spaced data. Therefore, a useful first step to simulating the performance of a vehicle over such terrain deals with generating a continuous surface. This point is solved by interpolating the unknown height at some uniform grid node or 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).

In the proposed framework, we are interested in methods that provide not only the elevation at areas where there is sparse or no data, but also, and most importantly, an estimate of estimation error, that is, the uncertainty associated with that new point. This is what Gaussian Process (GP) regression yields. The main drawback of a GP is that its performance is highly influenced by the kernel function chosen [Ho et al., 2011]. A particular version of a GP in the field of Geostatistics is kriging. Kriging produces an interpolation function based on a covariance or variogram model derived from the data rather than an a priori model of the interpolating function. This fact mitigates the effect of choosing a general-purpose kernel function as in GP.

Once a continuous surface is obtained, stochastic simulation of the performance of a vehicle over such terrain can be performed. However, depending on the kind of simulations and/or the computational resources a more compact mathematical model of the terrain profile may be desired. This step is mainly found in the automobile industry where simulations deal with suspension loading conditions, chassis fatigue, etc. [Chemistruck et al., 2013; Ma et al., 2013].

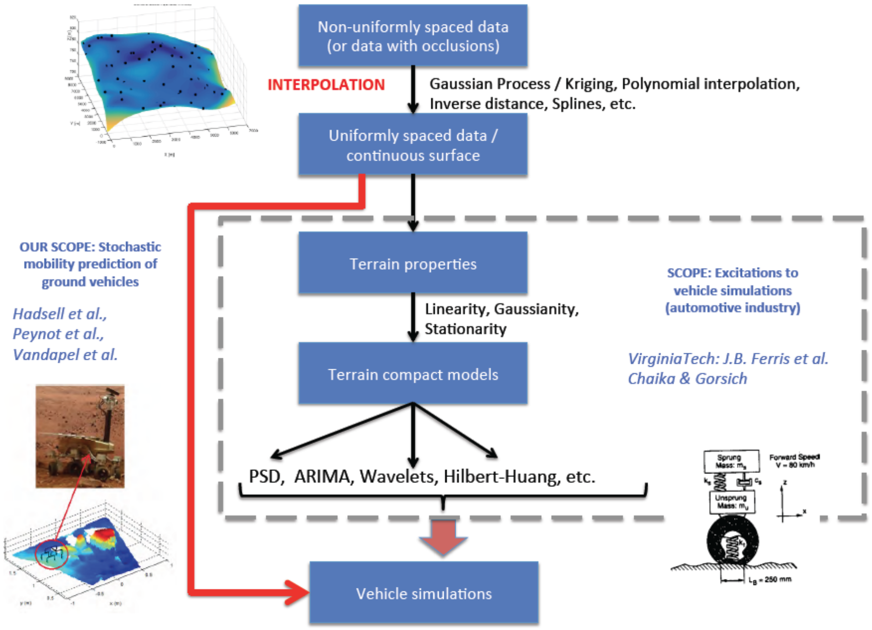


Figure 8-1. Schematic view of the different steps dealing with digital terrain modeling

8.5.2. Stochastic Mobility Prediction

Figure 8-3 shows the methodology of the proposed architecture. Initially, a DEM is obtained related to the region of interest. After that, a reduced-order representation of the DEM points is obtained via a subsampling approach. This reduced-order representation is required in order to enable an affordable computation of the variogram and kriging method. Once a set of representative points, in terms of the variogram and elevation profile, are selected, the ordinary kriging method is applied. This procedure yields a model of the terrain at a finer resolution. This model can be used for statistical simulation since each interpolated point has an uncertainty associated with it (i.e. the kriging variance). After that, two possible results can be obtained: a mobility map or a route planning result. Those two results are explained in Section 5.

The main features of this architecture are summarized as follows:

- Global path planning is considered rather than local path planning (i.e. planning in the close vicinity of the vehicle). From the decision-maker's point of view, this feature is important because it provides an ability to make movement decisions over large spatial regions.
- The main source of uncertainty comes from surface geometry (elevation) and soil properties. The first one is framed within the context of global path planning; the second one will deal with stochastic GO/NOGO maps.
- This solution does not result in a binary answer, i.e. the path is traversable or not; instead statistical data supporting each decision is given.
- An efficient solution can be obtained and has been demonstrated on a standard-performance laptop.

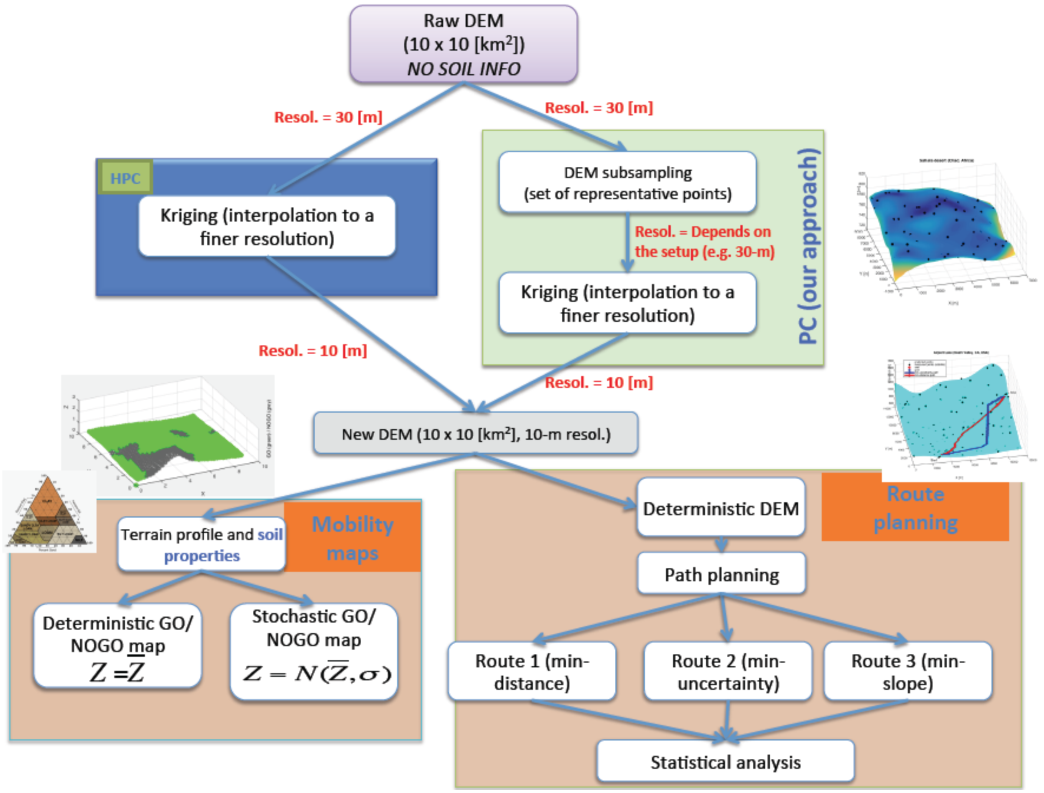


Figure 8-2. Schematic view of the steps carried out in the proposed architecture for predicting the mobility of a ground vehicle over a large region (> 5 x 5 [km^2])

8.6 POTENTIAL SOLUTIONS TO ELEMENTS OF PROPOSED ARCHITECTURE

This section introduces some potential solutions to the different elements of the proposed stochastic mobility prediction architecture. In particular, a methodology based on global path planning is formulated in order to cope with route planning in the presence of elevation uncertainty. Additionally, a novel segmentation-based algorithm is proposed to deal with the common issue of non-stationary variogram models. After that, a mobility analysis solution is described in terms of uncertainty in soil properties. A novel approach is introduced to cope with uncertainty in Bekker-Wong parameters. Then, the Bekker-Wong model is applied leading to a stochastic mobility map where decisions are made in terms of the maximum drawbar pull force that a vehicle can generate.

8.6.1. Route Planning

This element of the suggested methodology deals with analyzing the performance of a vehicle moving between two given points, a starting point and goal point, considering a model of the terrain and its associated uncertainty. The D* algorithm has been employed in order to obtain an optimal route between the starting and goal points [Stentz, 1995]. In this research, three metrics have been considered for obtaining such a route. The first metric finds the shortest route between the starting point and goal point. For that purpose, the D* cost function considers the Euclidean distance between points (in an x-y plane). Notice that in this case, uncertainty is not considered. The second route is obtained as the shortest distance between the starting and goal points but also minimizing the uncertainty. That is, the variance associated with each point is also considered in the D* cost function. Finally, the last route represents the shortest route between the starting and goal points but also minimizing the slope between points. Finally, the optimal route is given in terms of some performance indices (e.g. the shortest path, the path with the lowest uncertainty, the flattest route, etc.).

8.6.2. Segmentation-Based Local Variogram Models for Ordinary Kriging

Notice that ordinary kriging is based on the assumption of a stationary variogram. This requirement means the mean and variance of such variogram is finite and constant in the area under investigation [Fisher, 1998]. In practice, this assumption is not always ensured [Atkinson and Lloyd, 2007; Chen and Li, 2012; Lloyd and Atkinson, 1999]. This fact is especially noticeable when a global variogram intends to capture the nature of a heterogeneous region.

In other to solve the issue of non-stationarity, different approaches have been proposed in the literature. Such approaches can be grouped in the following three categories [Zhang et al., 2014]: (i) locally adaptive kriging involves predicting and modeling the local experimental variogram and using the coefficients of the locally fitted model in (the local) kriging; (ii) surface deformation aims to distort a surface such that a stationary variogram results from data in transformed space; (iii) segmentation involves dividing the region of interest into smaller segments within the variogram that can be considered stationary, thus allowing for local application of geostatistical optimal sampling design in their study.

Segmentation constitutes the most commonly used approach; see for example [Atkinson and Lloyd, 2007; Chen and Li, 2012; Lloyd and Atkinson, 1999]. Some of those references divide the region of interest by using a predefined template or rule, for example, dividing the environment into 4-subregions each time non-stationarity is found during the segmentation process [Chen and Li, 2012]. The main drawback of this approach is that it does not take advantage of the properties of the local variograms in order to increase the accuracy of the segmentation step. In contrast, in the works [Atkinson and Lloyd, 2007; Lloyd and Atkinson, 1999], a clustering segmentation algorithm is employed. The metrics on which the segmentation is based is the fractal dimension [Klinkenberg and Goodchild, 1992]. The main limitation of this method is that the fractal dimension cannot be applied when the region of interest does not fulfill Brownian properties [Kroese and Botev, 2014].

The proposed approach makes use of both the fractal dimension and elevation range as metrics in the segmentation step. This method can be applied to any type of man-made or natural terrain profile. Notice that elevation range constitutes a well-known metric in the field of Geomorphology; it has been mainly used to identify and classify terrains [Evans, 2012; Saadat et al., 2008].

8.6.3. Mobility Map Based On Soil Uncertainty

A stochastic mobility map is generated via Monte Carlo simulation. In particular, for a given soil region *n* realizations are obtained for each BW parameter according to its associated Gaussian (or other) distribution. Thus, this process leads to *n* values for the drawbar pull force (DP), obtained using a Bekker-Wong vehicle-terrain interaction model. If in a given cell the DP is higher than the vehicle can actually reach, such cell is marked as no traversable (NOGO). A cell is considered traversable when the DP of *m* runs is greater than a given threshold ($m \geq \delta$, where δ is a given confidence interval).

We note that there does not exist an exhaustive global database for all parameters of the Bekker-Wong model, for all the soil types. To be able to assign a significant value to unknown soil parameters, for each soil type a procedure based on interpolation from documented values of similar soil parameters has been implemented. In particular, the value of the parameter *x* for the soil type *i* has been obtained by solving the following equation for *M* random values for each neighboring point

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

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. The procedure followed to obtain this normal distribution is explained subsequently.

Notice that the goal of this potential solution is to represent the variability in the Bekker-Wong parameters by means of a normal distribution. A second point deals with removing the presence of outliers in those physical experiments. The decision adopted regarding the outlier removal is mainly based on our experience and it has been found after testing and comparing different metrics. Eventually, an outlier is detected when it is out of the following range

$$(\frac{median(V)}{\rho}, \rho * median(V)), \qquad (2)$$

where *median(V)* represents the median value for all the values related to a particular parameter and a soil type, ρ is an experimental parameter manually tuned in order to increase or decrease the range.

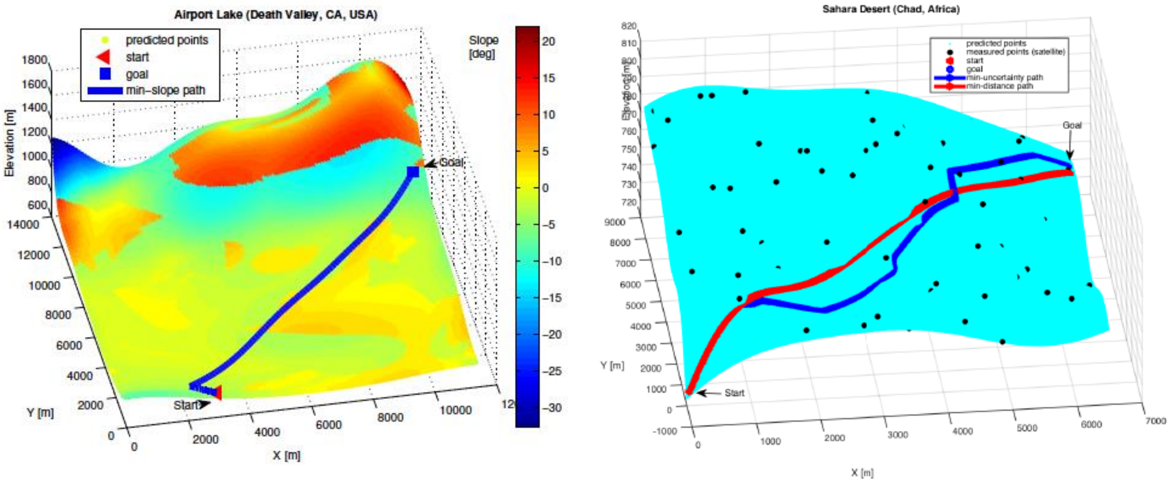
8.7. PROOF OF CONCEPT RESULTS

This section introduces some illustrative examples demonstrating the suitability of the proposed architecture. All these experiments are based on digital elevation models of real scenarios. In particular, the 7.5-Min USGS format has been considered, that is, the spatial resolution of the models is 30 meters. The code has been implemented in Matlab using the Geostatistical toolbox *mGstat* (http://mgstat.sourceforge.net).

8.7.1. Route Planning

We have demonstrated the suitability of the proposed stochastic mobility prediction approach over relatively large regions (> 5 x 5 [km^2]). Figure 8-3 shows the performance of the route planning approach over two different scenarios. Figure 8-3a displays a deterministic terrain profile illustrating the minimum slope between points (8-neighbors to each point). In this sense, a path going through a brighter region (yellow) would mean a flatter route (small variation in the elevation between one point and its neighbor). On the other hand, hazards such as high slopes are represented by blue or red color, that is, the difference in elevation between one point and its neighbors is larger than in a brighter region. Notice that positive values (red color) mean positive slopes (the vehicle would pitch up), and negative values (blue color) represent negative slopes (the vehicle would pitch down).

Figure 8-3b shows the min-distance and the min-uncertainty routes for the Sahara desert region. As expected, the shortest route (straight-line) corresponds to the min-distance line (red line). The min-uncertainty route considers the variance of the elevation (uncertainty obtained from kriging). For that reason this route passes as close as possible to the original sampled points (black dots).



(a) Min-slop route. Airport Lake (Death Valley, CA, USA)

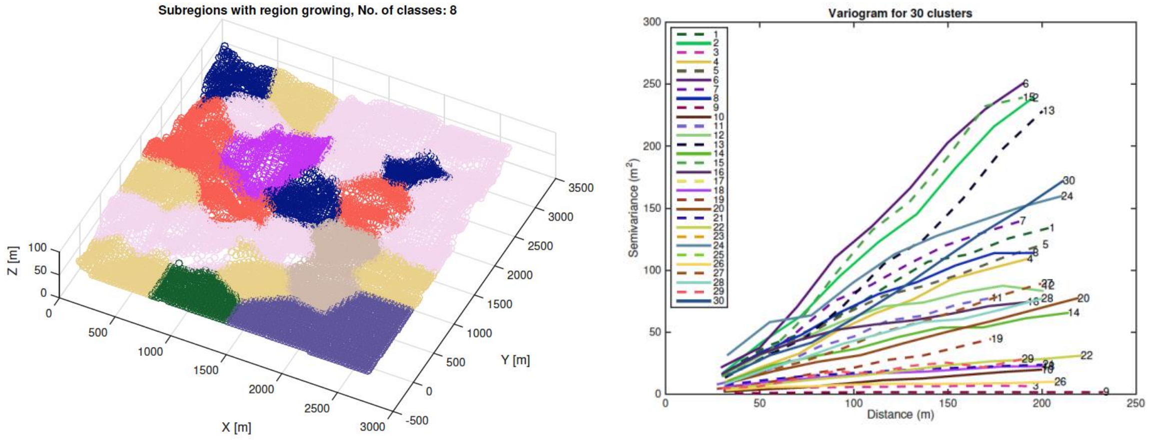
(b) Min-distance and Min-uncertainty routes. Sahara desert (Chad, Africa)

Figure 8-3. Routes obtained using the global path planner. The mesh represents the terrain model considering nominal elevations (kriging estimations).

8.7.2. Segmentation-Based Local Variogram Models For Ordinary kriging

The main goals regarding this work are to increase kriging accuracy and reduce computation time. The suitability of the proposed method has been demonstrated with heterogeneous scenarios, i.e. scenarios that include natural Brownian-like terrain profiles, natural non-Brownian-like terrain profiles, and scenarios combining natural and man-made regions. In all those cases, the standard deviation of the kriging variance is smaller when the local variograms are considered instead of the global variogram, resulting in smaller uncertainty in the new interpolated points. Furthermore, computation time has been reduced in the proposed approach. For instance, for a given region, the computation time following the traditional approach (i.e. computing a global variogram over the entire environment of interest) is approximately 1 hour on COTS laptop; considering local regions and local variograms, the computation time for the same environment is less than 2 minutes.

Figure 8-4a shows the result obtained after applying the segmentation-based approach to an environment composed of natural and man-made regions, Hyannis Village (Barnstable, MA, USA). Figure 8-4b shows the variograms of the original 30 local regions.



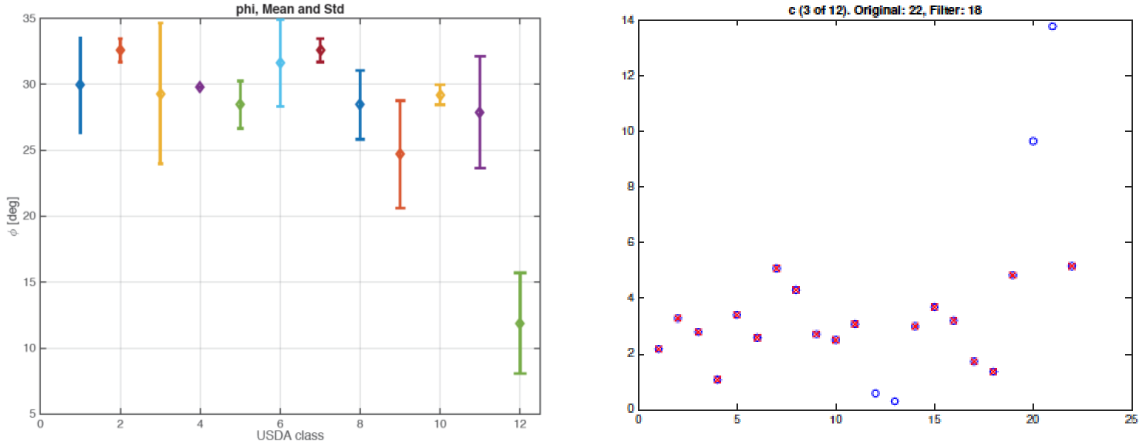
(a) Regions after applying the segmentation based on the fractal dimension and elevation range

(b) Local variograms for all the regions before merging those regions with similar features

Figure 8-4. Hyannis Village (Barnstable, MA, USA).

8.7.3. Mobility Map Based On Soil Uncertainty

As previously explained, a novel methodology has been proposed in order to represent each parameter in the Bekker-Wong model for each soil type in the USDA soil system according to a Gaussian distribution. Figure 8-5a shows an example of such Gaussian distribution, in this case, the internal friction angle for the 12 soil types in the USDA classification system. 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 Figure 8-5b. 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.

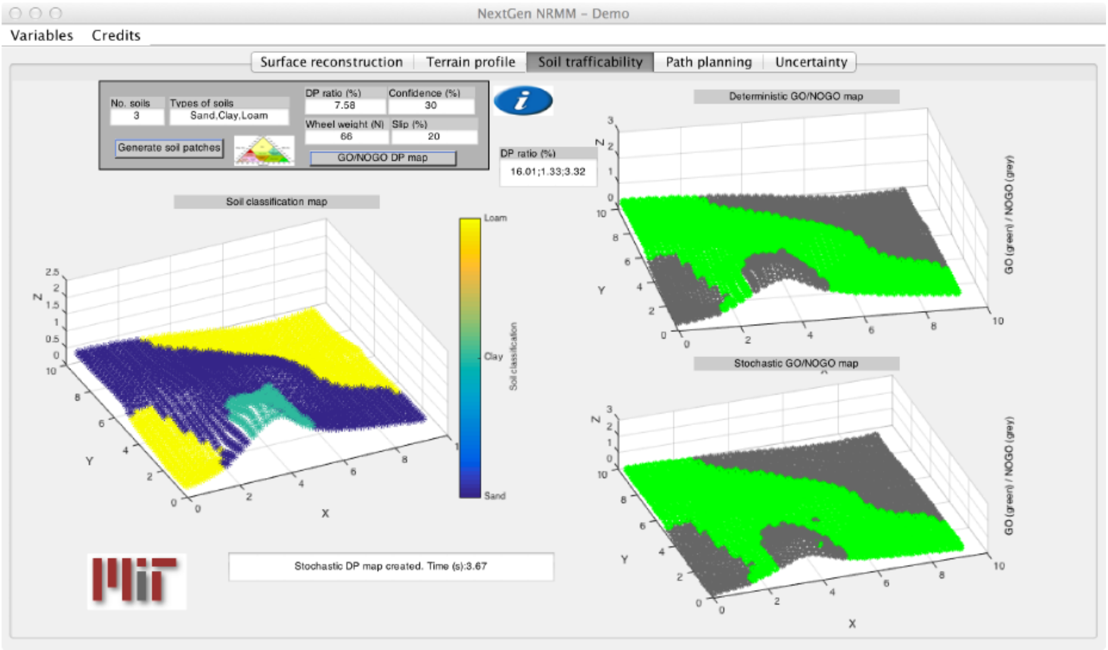


(a) Internal friction angle

(b) Cohesion, sandy loam

Figure 8-5. Variability in Bekker-Wong parameters and filter designed to remove outliers

On the other hand, Figure 8-6 shows a Matlab GUI implemented in order to perform interactive simulations regarding soil trafficability. In this case, a random surface is generated and three soil types are assigned to three different regions. Then, a mobility map is obtained according to the maximum drawbar pull force introduced by the user.



No. soils: 3

Types of soils: Sand,Clay,Loam

DP ratio (%): 7.58

Confidence (%): 30

Wheel weight (N): 66

Slip (%): 20

DP ratio (%): 16.01;1.33;3.32

Stochastic DP map created. Time (s):3.67

Figure 8-6. Matlab GUI implemented in order to perform stochastic mobility analysis

8.8. RECOMMENDATIONS AND OPEN QUESTIONS

Based on this study, the following recommendations are made:

- Any extension of NRMM in terms of stochastic mobility prediction should allow for consideration of uncertainty in elevation as well as in soil physical properties. Notice that uncertainty in elevation is in fact present in any DEM (uniform continuous model derived from sparse data), and uncertainty in terrain properties is also expected due to the physical variability of natural terrain.
- As evidenced in this work, computation time constitutes a key factor that must be considered in the development of the new NRMM. In this sense, any new proposal should focus on efficient algorithms. Notice that avoiding this recommendation may lead to practically infeasible solutions.
- It is desirable from a stochastics perspective to base vehicle-terrain interaction on the Bekker-Wong model, as these models are compatible with numerous multi-body dynamic simulation codes. Other well-known solutions such as Cone Index (CI) do not have this property.

After an analysis of the state of the art and the work performed in the framework of this effort, the following concerns are still open to debate:

- Soil moisture constitutes an essential climate variable that deals with the level of water diffused as vapor or condensed in soil. Even though it seems that soil moisture "implicitly" appears in Bekker-Wong parameters, there is a lack of experimental data relating soil moisture to those parameters for all the soil types appearing in the USDA soil classification system. A possible solution to this problem would require performing experiments with the bevameter technique under different soil moisture levels and finding some kind of relationship between Bekker-Wong parameters and the level of water on such soils.
- There is not a clear answer to what is the most appropriate spatial resolution in order to perform a reliable stochastic mobility prediction analysis. It is not known whether any detailed study on this issue has been performed. It appears that spatial resolution of data for 3D terrain models should be dependent on the size of the vehicle, the variability of the terrain, and on the nature of any natural or man-made obstacles that the vehicle must negotiate.

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Chapter 9 – THEME 4: INTELLIGENT VEHICLES

Abhinandan Jain

9.1 GOALS AND DELIVERABLES

The Goals of Theme 4 are to define a Next-Gen NRMM approach and requirements for mobility assessment for intelligent vehicles. For the purposes of this discussion, an intelligent vehicle is assumed to be one without a human driver onboard, and operated with a combination of on-board intelligence, remote operators and shared-control resources. The vehicle itself may have onboard passengers, and may be operated singly or as part of a group of vehicles. Within this section, we adopt the following acronyms to distinguish between the Next-Gen NRMM for manned and intelligent (unmanned) vehicles:

- **NRMM(H)** – Next-Gen NRMM for manned vehicles, i.e. vehicles with onboard human driver
- **NRMM(I)** – Next-Gen NRMM for intelligent vehicles (w/o onboard human driver)

Historically, the focus of NRMM has been on manned vehicles alone, and hence has been synonymous with NRMM(H). However, with the rapid emergence of intelligent vehicle capabilities, the need for NRMM(I) has become evident, and we seek here to define ideas and approaches that are pertinent to its development. While it is expected that NRMM(I) will leverage and benefit from NRMM(H) development, we focus here specifically on NRMM(I) since the development of NRMM(H) is covered in considerable detail in the rest of this document.

Some of the questions and topics addressed are as follows:

- Define intelligent vehicle classes and mobility types
- Define range of operational environments
- What characteristics of intelligent vehicles are pertinent to NRMM?
- What is common and different from manned vehicle NRMM?
- What NRMM output products are appropriate for intelligent vehicles?
- What approaches can we use to make performance metrics quantitative?
- Identify methods specific to intelligent vehicles
- Identify tool needs for intelligent vehicles
- Identify current capabilities and gaps

The members of Theme 4 are the following:

Country	**Name**
Canada	Mayda, William
Poland	Wrona, Joseph
Poland	Glowka, Jakub
USA	Gunter, David
USA	Iagnemma, Karl
USA	**Jain, Abhinandan, Leader**
USA	Jayakumar, Paramsothy
USA	Letherwood, Michael
USA	Ward, Derek

9.2 WHAT IS DIFFERENT ABOUT INTELLIGENT VEHICLES?

Before plunging into NRMM(I) capability development, and how it relates to the NRMM(H) capability, we begin by reviewing the characteristics of intelligent vehicles that distinguish them from manned vehicles. The areas of differentiation include (a) the types of vehicle mobility; (b) variations in their environment of operation; and (c) their control.

9.2.1 Variety of Mobility Types

Traditionally NRMM has focused on large wheeled and tracked vehicles with manned drivers. The family of intelligent vehicles include unmanned versions of these vehicles as well as others such as (see Figure 9-1):

- **Large wheeled/tracked vehicles:** These are unmanned versions of the traditional large wheeled/tracked vehicles. These may be operated individually or be part of a mixed convoy of manned and unmanned vehicles.
- **Small robots:** A number of portable, small wheeled/tracked vehicles, e.g., Talons, Pacbots, are already in active use in operational settings and are emerging as an important new class of vehicles.
- **Legged robots:** While wheeled and tracked vehicles are the dominant class of mobile vehicles, they can operate only over smooth or moderately rough terrains. Legged vehicles (eg. Big Dog) are being developed for rough terrain environments.
- **Bipedal Humanoids:** Humanoid robots (eg. Petman, Atlas) are another area of development where the limbs can be used as support legs as well as for manipulation tasks.
- **Emerging technologies:** There are ongoing technological developments involving non-traditional platforms such as climbing/insect robots, as well as ones involving coordinated mobility and manipulation. Moreover vehicles can be operated as part of multi-vehicle convoys, cooperating vehicles and robots, loosely coupled swarms etc. Multi-modal mobility such as for amphibious/ground operation or involving limbed/wheel platforms are also relevant for NRMM(I).

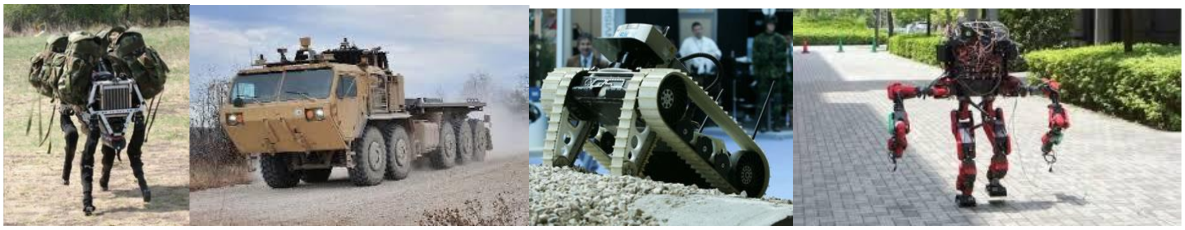

Figure 9-1: Example of a variety of ground vehicle platforms.

9.2.2 Operational Environments

Intelligent vehicles can operate in the following environments (see Figure 9-2):

- **On-road, urban:** Operation over roads, while following traffic rules (e.g., lane-following, lane-change, traffic signals, speed limits, over passes, tunnels etc.). Maneuvering in the presence of other traffic as well as pedestrians.
- **Off-road:** Operation in off-road areas under a variety of terrain types and vegetation; unstructured, uncertain conditions with hazards and impassable areas.
- **Building interiors:** Operation within building interiors or other structures, and navigating doors, stairs, hallways, railings etc.

Figure 9-2: Ground vehicles operating in off-road, urban and indoor environments.

9.2.3 Control Options

In general, the operation of a vehicle can be viewed as involving

1. Onboard human driver
2. Onboard autopilot/intelligence
3. Remote human driver
4. Remote autopilot/intelligence

While option (1) is the focus of NRMM(H), options 2-4 characterize intelligent vehicle control and operation as described in the examples below (see Figure 9-3):

- Intelligent vehicles have no onboard human driver, but can be operating with other human driven vehicles or in convoys with other UGVs.
- They typically have remote operators and resources. Control modes can include low-level teleoperation, to shared control, to full autonomy. Closed loop control can be impacted by bandwidth and latency limitations over the communication link.
- A key characteristic of intelligent vehicles is the presence of an onboard sensor suite and use of onboard software and algorithms for
    - Sensor fusion, localization, state estimation, handling of noise/drop outs, obstacle detection, situational awareness, map building
    - Locomotion, obstacle avoidance, slippage detection, model predict motion control algorithms
    - Legged - self balancing, foot placement, walking gaits, manipulation etc.
    - Executive for real-time coordination and control, shared control interface
    - Planning/executive layer for deliberative long term motion and path planning, vehicle fault diagnosis/recovery

Figure 9-3: Vehicle intelligence involves multiple on-board sensors, autonomy algorithms, and interaction with remote operators and resources.

The performance of an intelligent vehicle can be inferior (due to less sophisticated sensing, decision/planning and control) as well as superior (due to no fatigue or distractions, faster processing of information, more sensors) in comparison with the performance of a manned vehicle. For a broad overview of the growing presence and importance of onboard autonomy – and the challenges they represent across DoD applications please see references [Defense Science Board, 2012; Air Force Research Laboratory, 2013; Office of Technology Intelligence, 2015].

9.2.4 Vehicle Intelligence Challenges

The characterization of the performance of intelligent vehicles required for NRMM(I) presents several additional challenges over performance characterization for manned vehicles. Some of these are:

- **Vehicle intelligence is an amorphous concept:** There is no standard or settled definition for onboard intelligence. There is significant variance in intelligence architectures as well as capabilities – even for the same vehicle hardware platform. Performance assessment methods have to handle such variability
- **Lack of performance metrics for autonomous systems:** While quantitative performance metrics are essential for NRMM, such metrics are seriously lacking in the vehicle intelligence area. On the one hand the difficulty is in defining metrics that span performance over the large space of operational conditions and environments, and on the other is the paucity of analytical techniques for the characterization of the performance of rule based modules. As a result, metrics often are based on empirical measurements over a small sample set.
- **Vehicle intelligence is a rapidly evolving area:** Vehicle intelligence technology is rapidly evolving – on both the hardware and software fronts. It is essential that the techniques developed for NRMM(I) be able to scale and handle performance assessment from such new and emerging intelligent vehicle capabilities, or else risk rapid obsolescence. While “one of” solutions for NRMM(I) may be expedient they may not be useful over time.
- **Vehicle intelligence is not all or nothing:** Often vehicle “intelligence” and “autonomy” are viewed as on or off capabilities. This is rarely the case in reality. The more typical situation is that of *sliding autonomy*. That is, onboard intelligence modules typically provide a broad range of modes and options to select between different levels of autonomy, where selective features can be disabled or degraded as needed. An important consequence of this is that the primary goal of an NRMM(I) capability is not so much to provide GO/NOGO guidance for vehicle intelligence, and instead is to provide guidance on the level of autonomy to use for the best performance and risk outcome for the

mission at hand.

- **Performance evaluation is significantly more complex:** One of the challenges with developing performance measurement techniques for vehicle intelligence is the high dimensional state space associated with the intelligence algorithms together with the large dimensionality of representations for unstructured/uncertain environments. Such large dimensional combinatorics is difficult and impractical to handle using standard techniques.
- **Coupling between vehicle dynamics and intelligence is poorly understood:** By and large, the intelligence development focuses on the sensing, kinematic and geometric characteristics of the vehicle. While this may be appropriate for quasi-static or slowly moving vehicles, such approaches are inadequate for vehicles moving at even moderate speed where the vehicle dynamics plays an important role in its performance. Significant interaction between the vehicle dynamics and vehicle intelligence communities is essential for the development of autonomy capabilities for dynamic vehicles as well as the performance assessment capabilities needed for NRMM(I).
- **Leveraging classical NRMM(H) for human driven vehicles is desirable:** There is parallel development of the next generation NRMM(H) capability for manned vehicles that ideally NRMM(I) should be able to leverage. This requires a good understanding of the coupling between the NRMM(H) and NRMM(I) capabilities to avoid duplication, as well as to influence the development of NRMM(H) so that it includes interfaces and supports performance data products required by NRMM(I).
- **Off-line as well as in-the-field NRMM usage needs:** Use during operations requires the timely generation of performance assessment results. This imposes additional speed requirements on NRMM(I) usage.

9.2.5 Does Vehicle Dynamics Impact Intelligence Performance?

As mentioned earlier, the coupling between **vehicle dynamics** and vehicle **intelligence performance** is poorly understood and often not seriously considered during intelligence design, development and evaluation. In fact there is a strong connection between them. Some examples of the coupling between vehicle dynamics and the performance of the onboard intelligence are:

- While the effect of ride roughness and vibration on drivers is not relevant for UGVs (unless there are onboard passengers), ride roughness and vibration can degrade sensor performance. The impact can lead to dropouts and increase in sensing error. Degraded sensor performance directly impacts key intelligence functions such as obstacle detection and detection of traffic, pedestrians and road signals that onboard intelligence depends on.
- Vehicle speed can also effects the performance and update rates of onboard sensors used by the onboard intelligence. Moreover, higher vehicle speed can reduce the time windows available for the onboard algorithms (such as obstacle detection and avoidance) to complete their computations which adversely impact their robustness and performance.
- The dynamic behavior of vehicles is affected by vehicle/terrain interaction that results in vehicle slippage. Vehicle slippage can introduce errors in the autonomy software’s estimate of the vehicles state. Accurate knowledge of the vehicle state is critical information used by the other autonomy algorithms such as for situational awareness and motion planning, and slippage derived errors can significantly degrade the performance of the autonomy algorithms. In addition, when slippage is high (eg. on slopes) proper traction control needs to be taken into account for reducing slippage for the accurate control of the vehicle’s motion.
- The suspension and dynamic properties of vehicles define their stability and rollover limits. These limits need to be taken into account by onboard motion planning algorithms for the vehicle during nominal

driving, lane change maneuvers and obstacle avoidance especially when driving at modest to high speeds in order to ensure and safe and stable performance.

- Latencies in control action can have a significant impact on vehicle dynamics. This can be an important consideration since the vehicle control loop for intelligent vehicles can involve sensor hardware, sensor data processing, state estimation, motion planning algorithms as well as communication and data exchange with remote operators which can all contribute to significant, and variable latency in the control action.

9.3 QUANTITATIVE FRAMEWORK FOR ASSESSING VEHICLE INTELLIGENCE

The inputs for the traditional NRMM(H) consist of models and data for the vehicle platform and the terrain environment the vehicle is to operate in. NRMM(H) processes these together with the mission scenario requirements and constraints to generate GO/NOGO maps for the vehicle, and estimates of the attainable vehicle speeds to help guide the vehicle operation. In this context, the change for NRMM(I) is in the form of additional inputs to the process consisting of models for the on-board and off-board shared intelligence resources (see Figure 9-4).

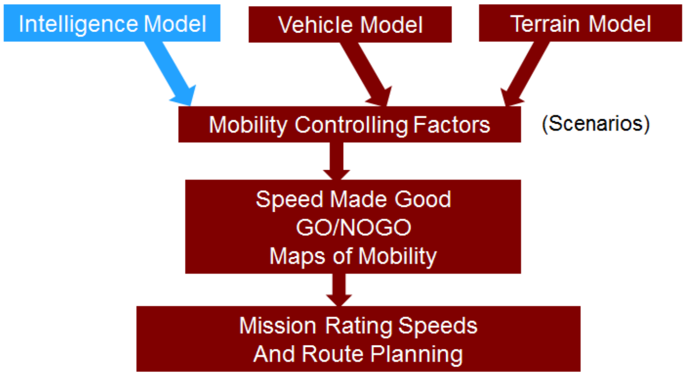

Figure 9-4: NRRM(I) introduces models for vehicle intelligence that need to be included in the prediction of vehicle performance.

A key requirement for the NRMM(I) outputs are quantitative metrics that provide actionable guidance for the safe and optimal operation of the vehicle to meet the mission scenario objectives. Some of the existing efforts to develop quantitative assessments of semi-autonomous ground vehicle performance are described in references [Haueisen, 2004; Baylot, 2005; Richmond, 2009]. Given the uncertainty in the model inputs to the NRMM process, it is necessary that the performance predictions generated by NRMM(I) be accompanied with risk assessment that reflect the confidence in meeting the projected performance. Operationally, the plan for vehicle mobility will have to take into account not only that the vehicle can meet the desired objectives, but also that the risks are below the threshold acceptable for the mission.

9.3.1 Intelligence Levels

Virtually all intelligent systems are designed to support multiple **levels of intelligence** that can be selectively enabled during operations. This is also referred to as sliding autonomy. For instance an intelligent vehicle may support manual operation, or operation with just the onboard obstacle detection turned on, or with both obstacle detection and obstacle avoidance enabled, or at an even higher level with autonomous path planning and navigation to goal enabled. These options describe operational modes with increasing levels of onboard autonomy. The purpose of these multiple autonomy level options is to allow the use of the intelligence mode that best meets the dual objectives of exceeding performance needs while keeping risk below acceptable thresholds for a given task and environment. As an example, it is possible that in environments with dense clutter, the vehicle may be operated with only hazard detection mode on, with autonomous obstacle avoidance being enabled only when operating in less cluttered situations. Similarly the remote human operator may choose to manually joystick control a vehicle in tight situations, or manually supervise lane change maneuvers on busy roads. Even human drivers only use cruise control on highways and not on city streets where the need for reactive control is higher. Given this context, the need for NRMM(I) is to generate data products that can assist the remote operator in choosing the vehicle intelligence level to best meet mission objectives from scenario to scenario.

Figure 5 below depicts an example scenario illustrating the use of NRMM(I). In this example, the mission performance objectives consist of traverse time, accuracy with which the path is followed, and requirements on the stability of the vehicle. For each of these performance objectives, there are assumed to be minimum performance requirements, as well as maximum acceptable risk levels. The vehicle intelligence is assumed to support three modes, namely (A) pure manual control by the remote operator with no feedback; (B) manual control by the operator with feedback of vehicle sensor data to the operator; and (C) shared control where the vehicle does local hazard avoidance while the operator designates waypoints for the vehicle to follow. The operator needs to make a decision on which intelligence mode to choose to meet the multiple mission objective while keeping the risk at acceptable levels. NRMM(I) generates data products that assist the operator in choosing the best overall intelligence level to meet the scenario objectives.

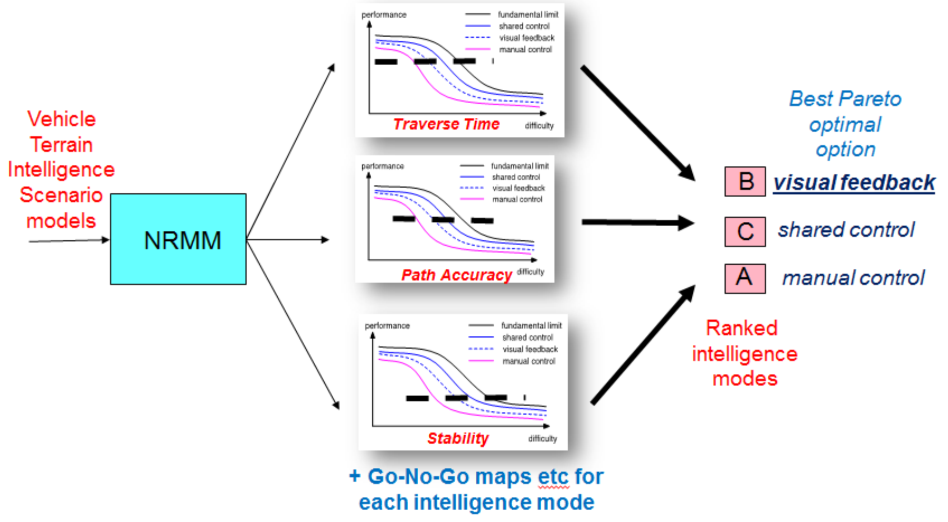

Figure 9-5: Example of the operational use of NRMM(I) to generate performance/risk predicts for multiple autonomy levels to allow operator to select the optimal level for carrying out the task.

Conceptually, one way of addressing this would be for NRMM(I) to generate performance/risk curves for each of the mission objectives for each of the available intelligence modes. Given that there are multiple objectives, it is likely that different intelligence mode options are best suited for the different objectives. Ideally, the ranking of the best intelligence modes for each objective is generated by the NRMM(I) and made available to the operator. Based on this information, the operator can make the final choice on the intelligence mode to choose to best meet the overall mission objectives. Just to complete the discussion, note that the above decision flow also applies to the manned vehicle NRMM(H) case – except that the multiple intelligence mode options need to be replaced with the single onboard driver option.

In general, the various vehicle intelligence levels can be hierarchical, or reflect a combination of discrete and continuous settings within the intelligence modules. While vehicle safety is often given a higher priority over performance, the paradigm described above makes the safety and performance objectives explicit, and allows the operators to make operational choices that best meet the mission objectives.

Thus it is essential that NRMM(I) be able to generate reliable quantitative performance/risk predicts for available intelligence modes to support the operational decision making described above. Such a capability does not currently exist for intelligent vehicles, and requires sustained research and development effort to develop. Without attempting to guess or preempt the eventual outcomes from such an R&D effort, we now embark on a potential approach to further our thinking on the required solutions. A key consideration for any viable NRMM(I) solution is the fluid and rapidly evolving nature of vehicle intelligence. The performance of component intelligence algorithms can be changed at very little cost compared to the costs involved in changing vehicle hardware. Thus the desired NRMM(I) solution needs to be able to accommodate such variability in generating predicts. “One of” NRMM(I) solutions that are brittle to such changes are vulnerable to becoming obsolete even before they begin to see use.

With this in mind, we explore a **skills** based strategy for vehicle intelligence that may provide an avenue for the scalability required of NRMM(I). From the Oxford dictionary, *“intelligence is the ability to acquire and apply knowledge and skills”*. Based on this, we propose the operational definition that intelligent vehicles are characterized by their *skills* in executing vehicle mobility tasks in a variety of environments. As illustrated in the Figure 9-6 below, our notion of a skill is rooted in the systems and control ideas of modules that implement a function that processes inputs to generate desired outputs, and consume resources in the process. It is important to emphasize that a skill is not a software/algorithm attribute, but can also include hardware resources for computing, sensing, communication etc. Thus an autonomous obstacle detection skill consists of sensor hardware for situational awareness, computers and memory to run classification algorithms to detect obstacles.

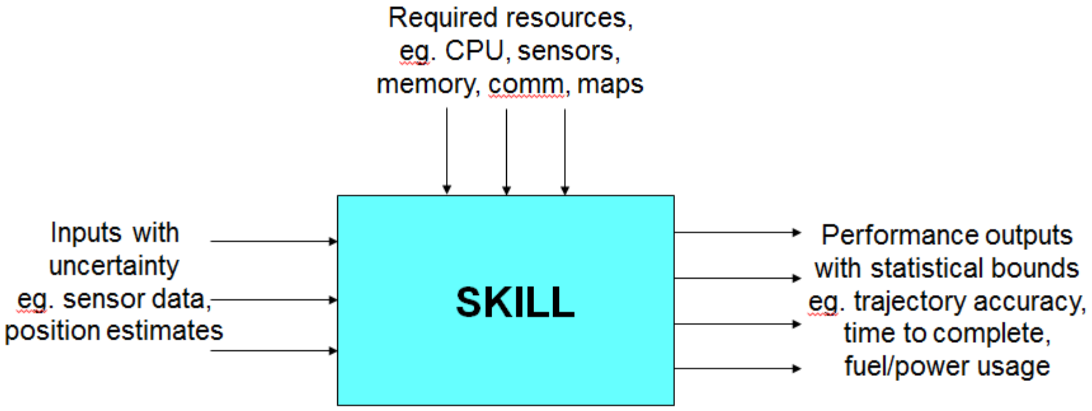

Figure 9-6: A systems based representation of a performance/risk model for a typical component skill illustrating its inputs, outputs and resource needs.

In the following section we provide some examples to illustrate the notion of skills for intelligent vehicles.

9.3.2 Examples of Intelligent Vehicle Skills

Some examples of capabilities that are pertinent to vehicle intelligence (and we refer to as *skills*) are listed below:

- Is the vehicle capable of detecting slippage? This ability means different things for wheeled versus legged vehicles. Is the vehicle capable of compensating for slippage?
- Can the vehicle detect “instability” - vehicle rollover for wheeled, loss of balance for legged platforms?
- Does the vehicle have situational awareness? Under what conditions - day/night, clear sky/cloudy/rain?
- Can the vehicle detect hazards, moving pedestrians & other vehicles, traffic lights, curbs etc.?
- Can the vehicle execute lane change maneuvers?
- Can the vehicle follow traffic rules?
- Can the vehicle do onboard path planning/replanning?
- Can the vehicle generate optimal options for path to follow/foot placement?
- Can the vehicle carry out coordinated motion across multiple articulation degrees of freedom (eg. for manipulation, legged vehicle)
- Can the vehicle coordinate mobility with manipulation?
- Can the vehicle auto-balance, self-right/recover for legged systems?
- Can the vehicle monitor its own health and detect anomalies? Can it autonomously enter a “call home” safe mode when in trouble?
- Can the vehicle learn from its own current or past success/failure performance?

Many skills are hierarchical, i.e. higher level skill depends on lower level skills. Assisted driving features such as roll over stabilization, distance following that are increasingly available are examples of component skills in the intelligence scale. As illustrated in Figure 9-7, the autonomous obstacle avoidance skill depends on other component skills.

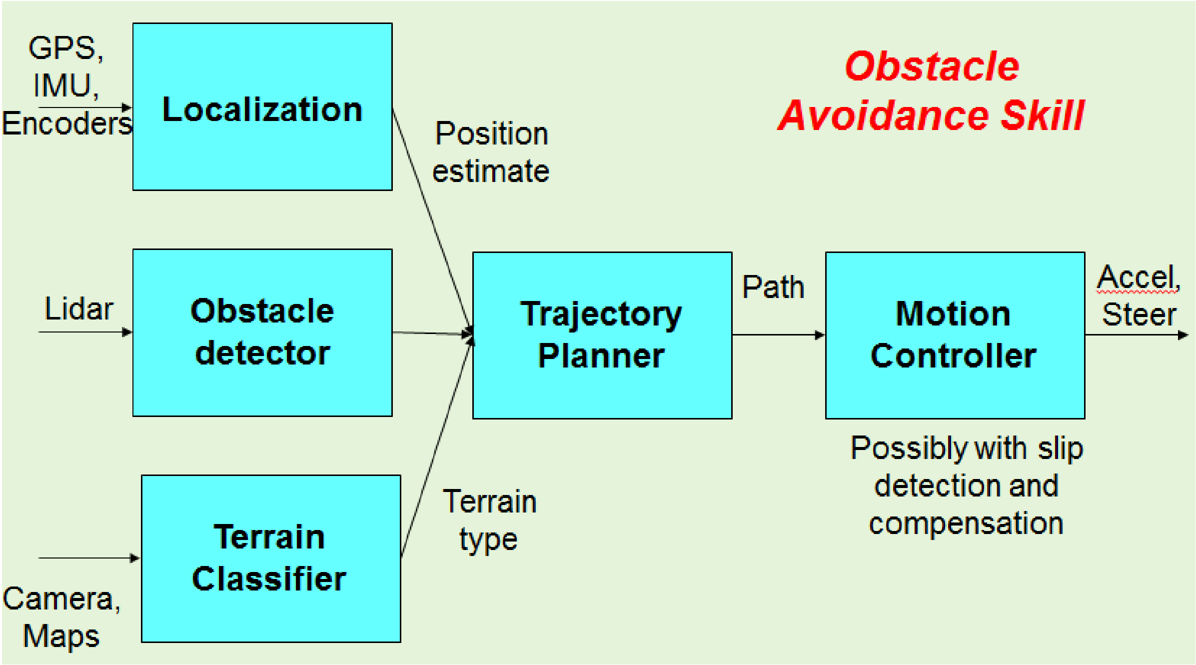

Figure 9-7: Illustration of the hierarchical nature of skills using the obstacle avoidance skill example.

The autonomous obstacle avoidance skill of an intelligent vehicle in this example depends hierarchically on the following component skills:

- The obstacle detection skill that processes the lidar's sensed data to generate a map of hazards in the path of the vehicle.
- The localization skill that uses onboard IMU and encoder sensors to generate real-time estimates of the vehicle's position and attitude.
- The terrain classifier skill uses onboard maps together with sensed camera imagery to determine the type of terrain ahead of the vehicle.
- The trajectory planner skill uses the current estimate of the vehicle's position and attitude together with the hazard map and the type of terrain ahead to plan a trajectory that takes the vehicle towards its goal while avoiding obstacles. The planned trajectory needs to take into account the characteristics (steering, dynamics, and speed) of the vehicle platform.
- The vehicle motion controller skill controls the steering and acceleration of the vehicle to follow the trajectory planned by the trajectory planner.

It is evident from this example that the overall performance/risk characteristics of the obstacle avoidance skill depends directly on the performance/risk characteristics of the underlying skills. Thus the quality of the IMU sensor affects the quality of the vehicle state estimate, while the lidar quality impacts the ability to resolve hazards. The sophistication of the trajectory planning algorithm will be reflected in the quality of the computed trajectories. The motion control performance depends on the number of wheels that are steerable, as well as the vehicle dynamics.

9.3.3 Skills Based Approach

The skill based paradigm allows us to decompose the behavior of an intelligent vehicle into a hierarchy of component skills, where the performance of each skill is limited to a specific scope – and thus making it amenable to quantitative characterization of its performance/risk behavior. Other benefits of the skill-based approach are:

- Metrics on skills can be used as a foundation for developing quantitative metrics on intelligence performance.
- Mapping from skill metrics to higher level skill metrics though not trivial is possible and may also be more computationally tractable.
- Skills can be used to support assessment of multiple intelligence modes that represent different combinations of skills.
- This component skills approach allows expanding metrics to new types of intelligence modules as they are developed.
- Understanding the sensitivity of task level performance on component skill performance can provide guidance on skill areas needing performance and risk improvements.
- The skills based paradigm allows us to focus on input/output behavior and be less dependent on specifics of their implementation and specific algorithms.
- Skills based description of intelligence can also help develop standards for intelligence capabilities within the community.

9.3.4 Skill Performance/Risk Characterization

- Associated with each skill are levels of **performance and risk** that depend on
  - vehicle/terrain dynamics - terrain difficulty (soil characteristics, roughness, hazards, slopes)
  - availability of sensor data (affected by lighting, fog, texture, vegetation, GPS availability, etc.)
  - mission scenario constraints & needs (e.g., time to complete, power, comm. bandwidth, a-priori knowledge of terrain, hostile or friendly terrain)
  - robustness to uncertain and unstructured environments, anomalies and violated assumptions (e.g.. lack of texture)
- Metrics reflect uncertainties in inputs, outputs and performance
- Shared control interactions that adjust skill level for optimal performance and risk

9.4 NRMM(I) PRODUCTS

NRMM(I) Goals: The NRMM(I) goals are in principle the same as for traditional NRMM, i.e. to generate performance/risk predicts to support assessments for vehicle design and operation.

Intelligence is an additional layer over a traditional human driven vehicle. One of the questions that arises is the role of the NRMM(H) capability for manned vehicles in addressing the mobility assessment requirements for unmanned intelligent vehicles.

- The traditional NRMM(H) vehicle/terrain interaction (VTI) based methods are based on the assumption that the vehicle control is being carried out by an expert human driver.

- Under the assumption that the intelligent, unmanned vehicle will always under-perform the manned vehicle with an expert driver, the GO/NOGO and speed predicts from NRMM(H) can be used as bounding, best case predicts for the performance of the intelligent vehicle. Under this assumption, the no-go regions of operation predicted by NRMM(H) also apply for intelligent vehicles as well.
- The above under-performance assumption however is not universal – because in certain situations the intelligent vehicle may have superior performance since onboard intelligence can have more sensors, carry out better sensor fusion, have faster response, not suffer from fatigue and be less prone to sensory overload and distractions.

NRMM(I) Products: During operations, the NRMM(I) products need to assist in selecting specific skills and intelligence modes that will best meet the performance and risk for the task objectives.

- GO/NOGO traversability maps & speed-to-go are products generated by NRMM(H) for manned vehicles
- For intelligent vehicles, there will be a palette of available skill level options, and for each level NRRM(I) needs to generate GO/NOGO map, speed-to-go, performance metric predicts (e.g., time to complete, fuel/energy, comm bandwidth, external resources) and risk for the combination of vehicle, terrain and mission scenarios (see Figure 9-8).

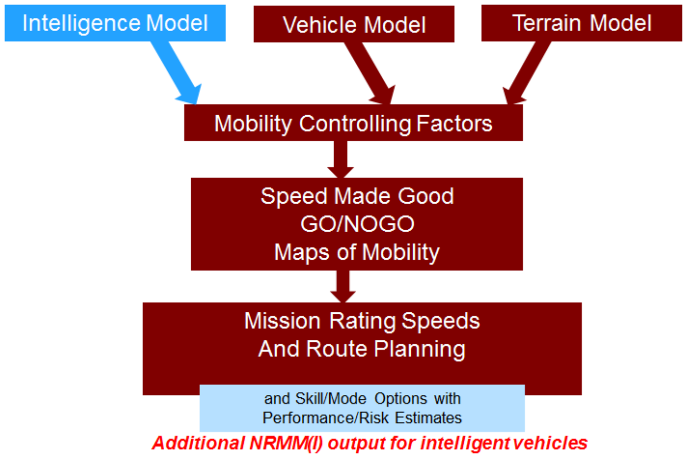

Figure 9-8: The expected output from NRMM(I) consists of performance/risk estimates for the available skill/mode vehicle mobility options.

9.4.1 Leveraging NRMM(H)

- For wheeled/tracked vehicles NRMM(H) mostly sets the performance ceiling
    - One exception is drive comfort which may not be a factor for intelligent vehicles - unless passengers are present.
    - However, drive roughness can impact sensor and intelligence performance so it cannot be ignored
- NRMM(H) may allow operator to decide whether intelligence is even an option
- Are there additional outputs or other requirements on NRMM(H) that can be important for NRMM(I)?

- For example, outputs that are pertinent to sensors – vibration levels, occlusions
- Terrain classification to include terrain properties (e.g. adequate texture) that are important for robust sensor performance
- Power consumption
- Others?

9.5 NRMM(I) PERFORMANCE MODELS

NRMM(I) needs methods and models that can quantitatively predict skill and system level performance and risk from vehicle, terrain & mission specifications. A significant challenge is the large dimensional state space of the onboard autonomy software and the resulting computational complexity for exploring and characterizing performance. We describe below two approaches at opposite ends of the performance modeling options.

9.5.1 Black box/top down performance modeling

The black box option does not use knowledge of vehicle intelligence design or implementation. The focus is on characterizing the observable input/output behavior of the system. The black box approach has been pursued by the recent **DARPA autonomy grand challenge competition's** for

- off road driving
- urban driving
- humanoid robotics

The DARPA challenges designed specific test ranges and tasks to evaluate the system level performance of intelligent vehicles and robots, without attempting to influence or evaluate the implementation of the systems. The key to the effectiveness of the black box approach is the design of a test suite that can adequately characterize the performance of the system. A real life example of the black box approach is a driving license test, where the focus is not on the how, and instead on the evaluation of the licensee's skill under a variety of conditions (e.g., test facility, obstacle course, stress tests). The scores obtained on these tests are used to assess the competency and skill level of the driver. Such black box techniques are also used for acceptance testing of a new vehicle.

- **Pros:** The black box approach avoids the expensive process of understanding the system design and implementation and focuses on the direct evaluation of the system performance.
- **Cons:** The success of the black box approach depends on how well one is able to generalize the observed performance from a limited number of test conditions to real-life performance in the field. Considerable care is required in the design of the depth and breadth of the tests to provide adequate coverage and stress testing of the system. A major issue with the black box approach is that when the performance is found to fall short in an area, the limited visibility into the internal design makes it difficult to identify sub-areas or components that need to be improved to overcome the performance gap.

9.5.2 White box/bottom up performance modeling

At the other end of the spectrum, the white box approach relies on a detailed knowledge and understanding of the intelligence layer architecture and design to assess the performance of the system. Such white box techniques are also a key aspect of system engineering processes that rely on understanding of sub-system performance and their cross-coupling to carry out design trade-offs and improve overall system level performance and risk. A couple of examples of such cross-coupling for intelligent vehicles include:

- Sensor selection and placement on a vehicle. Requirements include using camera baselines for adequate resolution, desired depth of field, coverage, low noise characteristics, low-light performance, redundancy, power/CPU/data throughput needs etc. The choices made have a direct impact on a vehicle's situational awareness and hence its performance
- Implementation of onboard motion control capability involves trade-offs between state update rates (e.g. via expensive visual odometry techniques) and localization accuracy. Trade choices have a direct bearing on safe vehicle speed and robustness, which in turn affect system performance and risk.

The white box approach decomposes the performance and risk assessment task into smaller performance and risk assessment task for the component modules. For instance, the vehicle performance depends on the performance of the sensor suite in terms of coverage, sensor errors, update rates, robustness under range of conditions. Another example is the impact that the quality of state estimation layer as measured by its accuracy, robustness of sensor fusion etc. under range of conditions has on higher level performance. An understanding of the dependence of the higher level performance and risk sensitivity on those of its components can provide a clear understanding on the coupling between component and higher system level performance and risk.

- **Pros:** The white box approach provides detailed understanding of performance sensitivity needed for design changes and options selection during operations. Moreover, the decomposition into component layers can help make the evaluation problem computationally tractable
- **Cons:** Assessment requires detailed understanding of internal design, and assessments are specific to the intelligence architecture

In their purest form, the dual white box and black box approaches represent opposite ends of approaches for system performance assessment. They differ in the level of abstraction used for representing the system. In practice, we should expect a **gray box** approach to be pursued where the level of abstraction is somewhere in between the extremes of the white and black box approaches. The idea is to strike a balance between exploiting knowledge of the intelligence structure and the complexity of characterizing the inter-dependency between the system and component system performance. Indeed, the skills based paradigm provides a way to adjust the level of abstraction by choosing the granularity of decomposition used for the skills hierarchy.

9.6 NRMM(I) METHODS, TOOLS, BENCHMARKING

The development of NRMM(I) will require the advancement of modeling and simulation capabilities, and methods, tools and benchmarking techniques for vehicle performance and risk assessment.

9.6.1 M&S Architecture Needs

The NRMM(H) approach has in the past largely relied on empirical models, and is transitioning to a blend of modeling and simulation (M&S) techniques that rely on physics-based and semi-analytical computational models. The new capabilities are expected to be cost-effective, computationally tractable, and easier to generalize and be adaptable to new vehicle and scenario needs.

In principle, NRMM(I) should be able to build upon the new NRMM(H) M&S capabilities. The types of models that would be needed in such an intelligent vehicle M&S capability would include models and modules for:

- Vehicle dynamics
- Sensors
- Intelligent system algorithms
- Environment
- Human cognition (for remote operator)

While we can expect to leverage mature capabilities in the vehicle dynamics area from NRMM(H), the other areas are new ones needed for NRMM(I). At the minimum, development and test efforts are needed to develop a suite of validated high-fidelity models in the new areas for NRMM(I) to build upon. Among the challenges in developing such a foundational capability are:

- Validation of model performance under the variety of unstructured and uncertain operational conditions for intelligent vehicle operation
- Integration of models from multiple domains to work together, and validation of the integrated model performance
- The large footprint and computational demands of the models

Once such a modeling capability exists, in theory we can exercise it over a parameter set representing the scenario uncertainty to generate predicts for the system performance and risk. For intelligent systems such a parameter set can be expected to be large for unstructured and uncertain operational environments, with large computational cost for each run. So, while such a suite of foundational models is essential, the routine use of such a kitchen sink simulation with high-fidelity validated models all the time will be computationally prohibitive and impractical. In practice, research and development for advancing M&S architectures is required for

- Agile M&S architectures that allow the integration of models from multiple domains, as well as swapping them out due to changes in intelligence sensors, algorithms, logic and parameters
- M&S architectures that allow the swapping out and/or idealization of scaffolding models in order to focus on characterization of the closed-loop performance, robustness and sensitivities of specific sub-systems. Note that such stubbing out will effect both hardware and their corresponding software algorithms. For instance, idealizing the performance of the localization algorithm may require the replacing of the combination of camera sensor models as well as machine vision algorithms with an idealized virtual sensor that provides similar outputs.
- M&S architectures that allow the use of models at different fidelity levels. Such a capability can be used to trade off model fidelity for reduced computational cost. Thus for instance it may be advantageous to use fast GPU hardware and algorithms for vision sensor modeling instead of the more accurate but computationally demanding ray tracing techniques when appropriate. Or one may choose to work with idealized pin-hole camera models instead of higher-fidelity camera models that handle non-idealities such as non-square pixels, radial distortion etc. However, such choices cannot be made in isolation since machine vision algorithms rely on camera calibration parameters, and will not perform as expected if the hardware simulation is changed independently. The M&S architecture needs to allow the ability to make fidelity trades without compromising the consistency and integrity of the simulation. An important consideration is to avoid over interpretation of the results when using lower-fidelity models since the range of applicability of the results is narrower.

Moreover, even with the existence of a foundation of validated high-fidelity models for intelligent vehicles, their use for kitchen-sink M&S on a routine basis is impractical on a routine basis due to the large computational resources needed. We need instead a process and model flow such as illustrated in Figure 9-9.

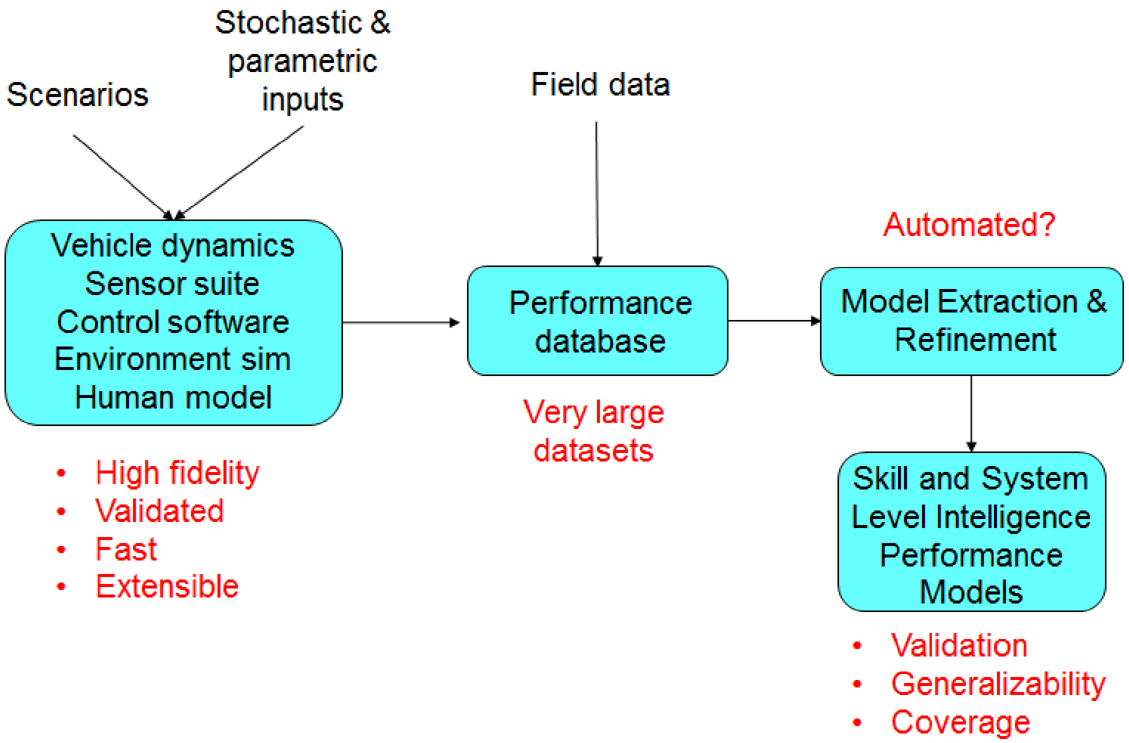

Figure 9-9: The model pipeline spanning high-fidelity vehicle mobility models to operational vehicle performance models needed by NRMM(I).

This figure uses as a starting point a high-fidelity intelligent vehicle M&S capability as described above that is capable of simulating desired scenarios over a suite of uncertain parameters characterizing the environment and operation. Such a capability is expected to be computationally demanding. The blocks on the right describe a pipeline for extracting simpler performance/risk models that while less accurate are also significantly less computationally demanding. This pipeline assumes that the high-fidelity M&S can be run offline on high performance computing platforms to simulate intelligent vehicles over a large scenario envelop. The results of these simulations would be archived in a large performance database. The database data can also be used to store data collected from intelligent vehicles during field operations. The next block describes algorithms and methods that process the simulation and field data to extract simpler surrogate models. While computationally simpler, these surrogate models will be of lower fidelity and with a narrower range of applicability. Since the data sets are large, this process would be an ideal candidate for automation. The last block consists of a repository for surrogate models that can be used to predict intelligent vehicles performance over a variety conditions. A key requirement on the surrogate model repository will be the extent of coverage of the expected use cases, because the individual models are expected to have narrower applicability. Gaps in coverage or encountered weaknesses are expected to be fed back to the first block to trigger additional high-fidelity M&S runs and expansion of the performance database.

Such a model pipeline architecture will be capable of meeting the varied and evolving capabilities of intelligent vehicles. Moreover, an important advantage is that the surrogate models will be based on a foundation of high-fidelity models. Currently, the component capabilities across the entire pipeline are not available. At best, we can currently find component capabilities that are domain specific that would need to adapted and integrated together into such a pipeline.

9.6.2 NRMM(I) Methods

Some of the new methods needed for development of NRMM(I) are listed below:

- **Skill decomposition and skills taxonomy for classes of intelligence vehicles:** The skill-based performance/risk assessment approach requires the decomposition of higher level skills into component skills. Techniques are needed to systematically define a taxonomy and a decomposition process. Clearly the skill set will depend on the type of vehicle, environment and its use and will vary across wheeled, tracked, in-traffic, off-road, indoors, legged platforms etc.
- **Component skill performance/risk modeling:** Given a skill decomposition, we need methods to quantitatively assess their performance/risk under a variety of conditions. These techniques can be combination of
    - Analytical techniques
    - Simulation, Monte Carlo & empirical methods
    - White/black/gray box performance assessment methods
- **Task level performance/risk models based on component skill models:** Given performance/risk models for component skills, we need methods to combine these to predict integrated, higher level performance and risk. Again, these may consist of
    - Analytical techniques
    - Simulation, Monte Carlo & empirical methods
- **Multiple levels of NRMM(I):** We need methods to develop different levels of NRMM(I) for use off-line for detailed and accurate analyses, as well as ones that can work under more restrictive computing and time line constraints. Example options include:
    - Off line, highest fidelity models (HPC, cloud resources)
    - Workstation NRMM(I) for analyst and remote operator use
    - Rapid response NRMM(I) models for operational field use
- **Vehicle dynamics and autonomy performance coupling:** One of the current gaps between the vehicle dynamics and autonomy communities is the lack of systematic understanding of the coupling between the two areas. These are central to NRMM(I), and as such we need to improve the understanding of the relationship between them. This can help
    - improve combined NRMM(H) and NRMM(I) coupling & capabilities
    - improve intelligent vehicle and control design
- **Vehicle dynamics models:** While the dynamics modeling of wheeled and tracked vehicles has been a major research area, gaps remain for modeling vehicle dynamics over soft-soil, wet conditions etc. While NRMM(H) is expected to invest in meeting these gaps, intelligent vehicles can include non-traditional vehicles (e.g. legged, indoor) for which validated dynamics models remain sparse. Moreover there are also opportunities for leveraging new multibody techniques (e.g,. recursive methods, parallel techniques) for improving computational speed and accuracy that are not yet main stream for the vehicle dynamics community but are widely used within the robotics community. There also remain open questions about the applicability of accepted vehicle terrain interaction techniques that have historically been developed for large vehicles to the smaller platforms used for intelligent vehicles. The development of validated and computationally tractable models for

intelligent vehicle dynamics simulations is a critical need for NRMM(I).

- **Intelligent vehicle modeling and simulation architectures:** Conventional modeling and simulation of vehicles has largely focused on capturing the correct physics of the vehicle and vehicle/terrain interaction and the M&S architecture designs reflect this emphasis in the available COTS and non-COTS toolkits. While fidelity remains an important factor for intelligent vehicles, additional important factors for intelligent vehicle M&S architectures are the ability to:
    - include new types of models (e.g. sensors)
    - integrate models and autonomy algorithms from across multiple domains
    - support for stubbing out peripheral sub-systems in order to focus performance analysis on selected sub-systems
    - use models at different levels of fidelity for non-critical areas to improve computational performance
    - use HPC simulations for large throughput
- **Extracting performance/risk models:** Given the large dimension of the state space for intelligent vehicles, it is computationally impractical to rely entirely on high-fidelity simulations for all NRMM(I) performance/risk assessments. Methods to extract computationally tractable models from available performance data will go towards making NRMM(I) practical in the field or when there are time constraints. There is little by way of success stories to build upon on this front, though deep learning and other machine learning technologies are highly relevant - especially for automating the process. Another important factor is for the models to be easily extensible and adaptable to changes in intelligent vehicles and scenarios or as additional field data becomes available.
- **Man/machine interaction models:** For the foreseeable future we expect to see shared-control techniques to be used for intelligent vehicles with a remote operator in the loop managing the level of autonomy on the remote vehicle and the operator console. Thus modeling the intelligent vehicle effectively requires models for the remote operator’s behavior and interaction with the vehicle. This requires the development of human cognition and human-machine interaction models that can be used for NRMM(I) for intelligent vehicles.
- **Relevant technologies:** Methods from other technical areas that may be of use for NRMM(I) modeling include:
    - Uncertainty quantification: The uncertainty quantification area focuses on methods for quantifying uncertainties in model outputs and their propagation through other models. These methods are very relevant to similar needs for the quantification and propagation of performance and risk through the skills hierarchy.
    - Autonomy validation technologies: While there is extensive investment in the development of autonomy technologies, the area of autonomy validation remains in a relatively nascent stage. However autonomy validation deals with the same challenges of assessing performance and risk for high-dimensional autonomous systems as NRMM(I) and there is strong potential for carryover of techniques across these areas.
    - System engineering methods: An important aspect of system engineering is the need for assessing the impact of and the sensitivity of overall system performance to sub-system performance in order to carry out system level trades. For intelligent vehicles, there is a similar parallel within the hierarchy of skills, where it is desirable to understand the sensitivity of the performance/risk of a skill to the performance/risk changes of its component skills.
- **Alternatives to skill based paradigm:** While we have devoted attention here to a skills based approach for characterizing the performance and risk of intelligent vehicles, there are potentially other approaches which may be relevant and offer advantages to the NRMM(I) development that should be investigated.

9.6.3 NRMM(I) Tool

In contrast with NRMM(H) which has many decades of development and a suite of capable tools to build upon, NRMM(I) is in its infancy, with a lot of ground to cover in methods and architecture development that can provide the ground work for the development of a tool suite for NRMM(I). Some of the potential tools of relevance to NRMM(I) at this stage are:

- Closed loop dynamics simulations with sensors, intelligence algorithms and scenarios
    - Current M&S technologies and tools provide a good foundation on HPC and clouds for off-line, large state space exploration
- Simulation options for workstation and field use are quite limited
    - Current options are mostly fragmented across autonomy and vehicle dynamics domains
    - Need computationally tractable tools for intelligence scenarios with adequate dynamics fidelity
    - Flexible simulation tool architectures for isolating subsystems to assess performance
- Machine learning tools and techniques

9.6.4 NRMM(I) Benchmarking

As discussed earlier, the white-box and black-box approaches can be regarded as opposite extremes for testing approaches used to evaluate the performance of a system, while we expect that in practice NRMM(I) will use a grey box approach that lies somewhere in the middle. Benchmarking and test areas needing development for NRMM(I) include:

- For the top-down, black-box approach, effective performance assessment is dependent entirely on the test sets and scenarios used to measure performance and risk. As such, the benchmark testbed suite needs to include tests and scenarios of sufficient quality, depth and breadth to extract information that provides sufficient coverage and insight into the system performance, and in a way that performance predicts can be derived for real-life scenarios that fall outside the test suite. A challenge here is to meet these benchmarking objectives without a large and burdensome test suite that is expensive and impractical to exercise. Another important consideration for the benchmark suite is its ability to adapt and be extensible to changes to the intelligent vehicle and its usage. Brittle and highly specialized testbeds will quickly become obsolete due to variability of intelligent vehicles. The benchmark test suite will need to include a combination of nominal, as well as (possibly unrealistic) stress tests to help tease out the knees in system performance.
- The bottoms-up, white-box approach for performance assessment depends upon a detailed understanding of the design and implementation of the intelligent vehicle hardware and software. The benchmarking and test needs for this approach are:

    - Benchmark skills test suite to assess and validate component skill, and sub-system performance and risk
    - Benchmark task-level test suite to assess and validate task performance models
    - Benchmark and test suites to measure the sensitivity of a sub-system's performance to changes in the performance of its component sub-systems throughout the system hierarchy.
    - Once again, the benchmarking methods and test suites developed here need to be able to

accommodate changes to the intelligent vehicle software and hardware.

Since intelligent vehicles are expected to operate in unstructured and uncertain environments, the above methods will need to be used within a stochastic testing framework to generate performance and risk envelopes. Techniques from design of experiments and other sampling techniques will be invaluable for keeping the test suite manageable. An important side benefit of the development of such benchmark and test suites is that this might help standardize vendor/provider designs, interfaces and architectures, which can have a significant impact on the variability that the testing framework needs to be able to accommodate. Such a development may also allow requirements to be placed on vendors to provide skill models for their hardware/software during the procurement process.

9.7 SUMMARY

We summarize below key ideas pertaining to the development of NRMM(I) for intelligent vehicles:

- Intelligent vehicles still remain new – though rapidly evolving – technology, and NRMM(I) has to be able to adapt and grow with it
- We have outlined a skills based framework for characterizing vehicle intelligence and its many modes
- This can form the basis for quantitative performance/risk metrics that are essential for NRMM(I) – and allow scaling to new classes of intelligent vehicles
- Beyond GO/NOGO like data products, NRMM(I) needs to provide assistance for selecting intelligence mode best suited for managing scenario performance/risk during operations
- NRMM(I) can, and should be designed to build upon NRMM(H) capabilities
- Proposed NRMM(I) roadmap is currently aspirational, and significant methodology challenges need to be addressed in developing a quantitative approach
    - Maturity level is low, so high priority to develop capabilities since intelligent vehicles are already being deployed
    - Long road ahead to achieve NRMM(H) like capability and maturity
    - A concrete plan needs to be developed to prioritize, scope and make progress in the near and longer term

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Chapter 10 – THEME 5: TOOL CHOICES

Henry Hodges

10.1 GOALS AND DELIVERABLES

The Goals of Theme 5 are the following:

- Identify critical elements for physics-based Next Generation mobility model utilizing strengths and weakness criteria provided by initial "pros and cons" review of current NATO Reference Mobility Model.
- Integrate/coordinate tool choice evaluation with other themes within the overall effort, particularly Requirements and Methodology.
- Identify potential solutions throughout the technical community and user nations.
- Provide a robust review process utilizing approved Request for Information (RFI) and Combinatorial Trade Study (CTS) processes.

This summary report identifies the ability of current and projected future physics-based simulation environments to provide accurate and timely results which can be used to support vehicle system development, acquisition, prediction of vehicle performance in an adverse operational environment, and force projection metrics in the areas of accuracy, speed, supportability, validation, sustainment, and cost; and the ability of physics-based simulation tools to address the current capabilities and limitations of the existing NRMM tool set.

The theme members are shown below:

Country	Name
Germany	Gericke, Rainer
Germany	Hoenlinger, Michael
Turkey	Akalin, Ozgen
USA	Gunter, David
USA	**Hodges, Henry: Leader**
USA	Jain, Abhinandan (Abhi)
USA	Jayakumar, Paramsothy
USA	McDonald, Eric
USA	Shoop, Sally
USA	Ward, Derek

10.2 TOOL CHOICE DESCRIPTIONS

In summary there are two basic approaches to the prediction of vehicle performance over complex and mobility challenging terrain. There are simulation and prediction tools which are based on historically measured performance of complete vehicles and various components. The relationships developed using these field and laboratory measurements to generate algorithms are generally referred to as empirical. Then there are simulation tools which are "physics-based" and these generally take all of the various terrain and vehicle component and system parameters and then utilize either energy management or equations of motion to predict the performance of a vehicle system. There are also solutions which combine both empirical and physics-based analysis, utilizing empirical or look-up tables to represent certain elements of the vehicle terrain interaction and then relying on the physics-based tools to determine mobility, performance, stability, and other vehicle system parameters. Within this study, all potential solutions were considered.

10.2.1 Questions to be Addressed

1. Do adequate physics-based modeling and simulation tools exist either in the public domain or provided by industry which can be used to accurately represent the key mobility elements which affect ground vehicles and are those tools currently affordable and implementable?

2. What are the key benefits of using physics-based modeling tools over empirical tools to the three end users (operational planners, acquisition officers, vehicle designers)?

3. How will the NATO or other user-specific mission profile events be described and provided to the simulation environment?

4. What are the most important capabilities of the existing NRMM tool set and what are the greatest limitations, and how do the various simulation solutions improve upon the existing tool set?

10.2.2 Framework

The initial focus for development of potential replacement tools was to establish a framework through which the mobility analysis tools could continue to be updated and new technological improvements could be added. To that end, the following framework statement was developed.

> 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 operational mobility planning, vehicle acquisition, and vehicle design.

10.2.3 Notional Mobility Software Tool Criteria

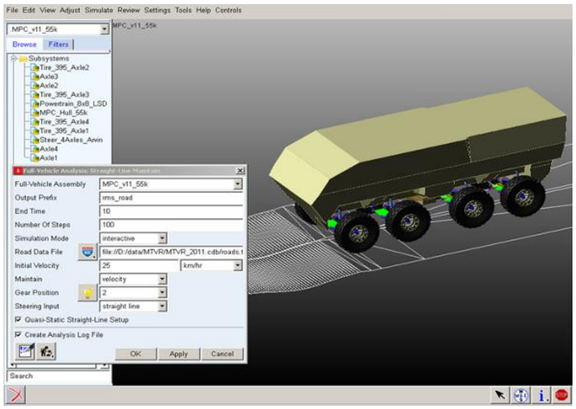
In determining the potential capabilities for the future tools, the following were considered to be important and therefore were used to help guide the development of the request for information and the evaluation criteria for the various potential solutions.

- Can be used to accurately determine minimum ground vehicle mobility performance over representative world-wide mission profile conditions
- Tool has sufficient accuracy to support pre-hardware engineering decisions and incorporates the latest technology
- Can be used to rank order designs or vehicle systems

  - i.e., Solution A is superior to solution B (down-select)
  - Current Government needs may require greater fidelity than historic comparisons
  - Accurate prediction of absolute values necessary for hardware selection and determination of mission success
- Can be used to establish critical design parameters during development
  - Ground contact pressure, power to weight, tractive effort, ride quality, maneuverability, etc.
- Can be updated to include new events that reflect current mobility challenges (Afghanistan versus Southeast Asia versus Fulda Gap).

10.2.4 Desired Software Capabilities

- Minimum Criteria/Constraints:
  - Fully 3-D, multibody dynamics (MBD) including contact forces
  - Model wheeled, tracked, and legged vehicles (wheeled and tracked vehicles are the priority)
  - Include electronic control systems to accurately represent suspension and drive train hardware which optimize mobility and performance(software/hardware in the loop)
  - Advanced powertrain models allowing fuel economy assessments
  - Rigid and deformable bodies and terrain
  - Includes driver in the loop model
  - Template based (defined as the ability to create subsystems for a given vehicle where components can be easily modified to reflect changes in technology and then apply those components directly to established model without the need to build a new vehicle system model)
    - Includes all parts, forces, constraints, outputs
    - Can be used on multiple models
    - Insures standard modeling practices
    - Templates include communicators to automatically connect and exchange data with other vehicle subsystems
    - Template contains the subsystem topology
    - By changing the appropriate data such as mass properties, hard points, spring and damper data, etc., the same template can be used on a wide range of vehicles
  - Validation possible in both time and frequency domain as well as ability to run design of experiments (DOE) iterations to identify dominant parameters and “corners” in performance
  - Provides accurate (in terms of elements which impact mobility) representations of terrain and mobility events
  - Allows terrain to be updated based on environmental or mission requirement changes
  - Provides “deformable” terrain elements
- Allow “Layman” user to run simulations
  - Almost any code can be used by an “expert” but availability of experts limits ability of the solution to be more widely used as intended.
  - Implementing GUI, tools and processes for layman use is a significant task (Figure 10-1).



Full-Vehicle Assembly: MPC_v11_55k
Output Prefix: rms_road
End Time: 10
Number Of Steps: 100
Simulation Mode: interactive
Road Data File: file://D:/data/MTVR/MTVR_2011.cdb/roads.t
Initial Velocity: 25 km/hr
Maintain: velocity
Gear Position: 2
Steering Input: straight line
☑ Quasi-Static Straight-Line Setup
☑ Create Analysis Log File

Figure 10-1. Graphical User Interface (GUI Example. Intent is to allow a non-expert user to run simulations. Note: the dialog box contains vehicle specific fields for setting up and running a full vehicle simulation. Underlying framework is desirable to be template-based.

10.2.5 Vehicle Terrain Interaction

One of the key elements for success of any future simulation will be the ability to quantify the interaction between the vehicle and the terrain over which it travels. As such, models for the tire or track terrain interaction which can address all combinations of soil type and moisture content with a broad range of compactions will be critical to future success. In the case of the tire system, accurate representation of tire spring and damping, cornering stiffness and compliance under free rolling and torque applied conditions will be essential. These models will address sinkage, dynamic tire deformation, lug engagement, dynamic slip/ sinkage relationships, tractive force slip, lateral force slip, and multi-pass effects. The tire surface models should address discontinuities within the surface material and accurately predict the interactive force slip and terrain deformation relationship. The tools should support validation in both the complex field and controlled laboratory environment. The more severe off-road military environment presents some unique challenges including:

- Military off-road tires with aspect ratio approaching 1 are highly nonlinear and uniquely built to meet the severe off-road duty cycle.
- On-road tire models have to be substantially tuned and adjusted to accommodate deformable soil conditions. Therefore simulations which may work with uniform conditions found during traditional on-road maneuvers may be substantially less successful in the analysis of off-road events.
- Inclusion of finite element models of the tires may initially be necessary to accurately represent the tire soil interaction. These detailed models may be replaced by other representative solutions to aid in the simulation speed to insure that the simulation tool can quickly compare the performance of vehicles or estimate mobility in real time field situations.
- Because uniform ground contact pressure is often the key to successful mobility, the ability of the simulation to accurately quantify these parameters may be critical to accurate mobility prediction. Available tools have demonstrated this ability, however, the integration of these tools into a full vehicle simulation may be a significant challenge and therefore must be evaluated through this process.
- Unique simulation tools are required to address the interaction between tracked vehicle systems and the terrain. Local high stress and shear conditions at the track grouser to soil or terrain element have

to be considered. Due to requirements for this type of analysis, the number of specialized tools may prove to be more limiting. Further consideration will have to be given to a combination of physics-based and empirically based solutions to successfully quantify tracked vehicle to terrain interaction.

- Tracked vehicle turning in soft soil represents a particularly challenging simulation condition. Physical testing has demonstrated that local contact pressure at the road wheel to track element can significantly influence the mobility of the system. Therefore, to be successful, the fidelity of the simulation will have to be verified given the established goals of this effort.

10.2.6 Potential Sources

Within this theme effort, a range of potential solution sources have been considered. Each potential source has different strengths and weakness and for each potential source, the capability of the solution has to be quantified.

The following range of sources was considered.

- Government
- Commercial
- Open source
- Modular (representing a combination of various tools and sources)

The following primary criteria were considered most important in the evaluation given the established constraints.

- Accuracy
- Sustainability/Flexibility
- Template-based
- Cost (acquisition, implementation, and support)

10.2.7 Scoring Protocol

Although members of the committee and representatives of other countries were queried, no Government-based simulation code other than the existing modifications to NRMM were identified. It was noted by representatives of Canada, Germany, and other countries that other solutions had been explored and implemented due to the known limitations of the current release for NRMM. However, no organization indicated that there was a tool which existed that would meet all of the goals established by the committee. All representatives indicated that they were currently utilizing a mix of commercial, in-house developed, modified NRMM, and other tools. Each organization indicated that improvements to the available methodologies was required to more accurately predict vehicle performance in the modern operational environment. If was further recognized that funding for continued development of these tools which would meet all the objectives for next generation NRMM had been limited. Long term funding to sustain Government-based solutions was generally identified as a limitation in the current more austere conditions. Further although each country identified internal structure to support analysis, this analysis was focused specifically on the country's own vehicles and requirements and not generally available for broader implementation. As such no specific "off the shelf" Government solution was identified.

Potential open source codes were discussed. Although there was awareness of multiple tools, their ability to properly function to meet the goals of the next generation NRMM was generally unknown. Stability of such codes was generally identified as a potential limitation.

All organizations identified the use of some versions of commercially available tools to quantify and predict vehicle performance. The availability of commercial three dimensional (3-D) physics-based tools was fully recognized along with the significant investment to improve those tools made by vehicle manufacturers worldwide. When combined with the current autonomous vehicle development this investment was estimated to be in the billions of dollars. However, there was no clear dominant tool which could support vehicle dynamics as well as soft soil operation.

Based on the fact that no clear solution or combination of solutions could be identified, the decision was made to send out requests for information (RFI) to recommended and otherwise known participants. Recommendations and identification of tools already in use by various Government organizations served to help determine the range of organizations that were sent the RFI. The intent of the effort was to identify whether any robust solutions existed or if a complete development effort was required and hence significant funding would have to be established in support of the development of the next generation mobility tool.

The committee then worked to develop a set of criteria and appropriate questions to determine the capability of existing tools from a variety of Government, commercial, and university sources. 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. Capability often conflicts with cost, and speed of analysis conflicts with accuracy. To that end, the Measures of Effectiveness (MOE) and Measures of Performance (MOP) were established and then weighted utilizing the Combinatorial Trade Study Process. The results of that weighting are presented below. As can be seen from the table, the accuracy and flexibility of the simulation tools were identified as the most important aspects while cost and the ability to update and run unique NATO events were less important.

Table 10-1 MOE and MOP Weighting.

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. Based on this set of criteria, the RFI document was sent out with the understanding that the responses would be reviewed and evaluated accordingly. For the various levels a score of zero (0), 0.5, 0.7, 0.77, and 0.85 was applied, respectively. For each category, should the response be deemed to meet threshold or an acceptable level of capability, then a score of 0.7 was applied. If the response was deemed unacceptable then a score of zero (0) was applied.

Table 10-2. Accuracy/Robustness Satisfaction Levels

	ACCURACY / ROBUSTNESS WEIGHTED 37.50%				
	Unacceptable	Below Threshold	Threshold	Above Threshold	Objective
Physics Based **16.67%**	1) Fails to incorporate force & moment relationships in a physics-based dynamic format 2) Unable to represent vehicle motion in three dimensions over time	Incorporates basic inertial properties only. Unable to represent system in all three dimensions simultaneously. Functions on non-deformable surfaces only. Is only able to manage traditional tire or track to surface interface. Cannot address exterior vehicle to obstacle (tree, step, etc.) contact.	Physics-based simulation, but is limited: 1) only rigid body model (no dynamically deformable bodies or surfaces) 2) has representation of three dimensional performance over terrain which can be initially represented as non-deformable but for which the terrain parameters, (motion resistance, shear strength, etc.) can be represented in a look-up table which can then be applied to the performance calculations of the vehicle.	Simulation can accurately represent varying levels of sinkage, surface coefficient, etc. but considers the terrain to be homogeneous within a contact element.	Captures interaction of all components, subsystems, & systems & their interaction with the environment based on equations of motions, force & moments, temperature, pressure, acceleration, etc. Allows system to achieve point contact with the environment & predicts the results of the interaction of the component, subsystems & systems with the environment.

	ACCURACY / ROBUSTNESS WEIGHTED 37.50%				
	Unacceptable	Below Threshold	Threshold	Above Threshold	Objective
Validation Through Measurement **12.50%**	No ability to directly compare either through time history or motion the results of the simulation with the results of test	Rudimentary ability to correlate simulation results with test results. Evaluation remains three dimensional but only basic inertial or center of gravity motion can be correlated. Limited force vector comparison is possible	Ability to track basic suspension and powertrain relationships. Identifies motion of suspension over non-deformable terrain elements. Can determine acceleration and force at various points within the vehicle system and those results can be correlated to measured test events through time history comparison. Provides vehicle system gross motion output. Includes all steering and powertrain functions but does not address rapidly changing component responses including limited slip differentials, semi active suspension, etc.	Capable of addressing adaptive, semi-active, and fully active suspensions. Able to include digital backbone and integration with control algorithms. Supports vehicle sensing and adjustment to terrain and is able to directly compare simulation results with measured results over complex terrain events	Simulation includes deformable terrain elements, provides prediction of full vehicle system terrain interaction including dynamic sinkage for various soils

	ACCURACY / ROBUSTNESS WEIGHTED 37.50%				
	Unacceptable	Below Threshold	Threshold	Above Threshold	Objective
Supports Time & Frequency Domain Analysis **8.33%**	No capability to generate time history data. Model is steady state only, thus only an average speed or pass/fail answer is given.	Generates limited time history data (i.e., vehicle average speed, but no information on subsystems)	Generates thorough time history data and movie files of complete system & components. Provides time history representation over multiple terrain discontinuities. Provides time history for control algorithms and application to multiple components within the vehicle system. Manages algorithm input updates at the rate of 10 times per second of real time providing closed loop control updates at 10 Hz resolved	Offers frequency domain analysis of all time history data.	Offers further post-processing like SRS/PVSS, durability stress/strain life, etc. Can support flexible body analysis, can manage the frequency response through the suspension to allow analysis of unique dynamics including resonance and traction hop, etc.

Table 10-3. Flexibility Satisfaction Levels

	FLEXIBILITY WEIGHTED 37.50%				
	Unacceptable	Below Threshold	Threshold	Above Threshold	Objective
Template Based **8.33%**	Only general vehicle characteristics are used (GVW, power look-up table, gross tire dimensions, track length/width)	Systems can be modeled separately, but the program depends on low-level coding or text file inputs	Large systems can be modeled in a plug-and-play fashion	Limited subsystems / components can be modeled in a plug-and-play fashion	Objective criteria – provides component, subsystem, and system models which can be interconnected by simply imbedding the component into the system model and having the model automatically solve the performance over any event and provide an immediate comparison of the difference in performance between the two events
Wheeled or Tracked Vehicles **20.83%**	Does not have the capability to model a track/wheel off-road. On-road dynamics only	Only a crude tire / super-element track model is available	A detailed tire / track model is available, but customization is limited. Tire pressure, sidewall strength, lug pattern, track design, etc. is limited	Detailed off-road tire model (fidelity similar to FEM). Track model includes physical design for pins, shoes, bushings, etc.	Detailed off-road tire model (fidelity similar to FEM). Track model includes physical design for pins, shoes, bushings, etc.

	FLEXIBILITY WEIGHTED 37.50%				
	Unacceptable	Below Threshold	Threshold	Above Threshold	Objective
Automotive Subsystems **8.33%**	Unable to create a template or plug-and-play approach which allows integration of traditional powertrain and suspension components	Provides ability to integrate subsystems but not components. Allows plug-and-play with subsystems. Provides limited correlation with similar hardware in other applications (i.e., commercial vocational suspensions with geometric modifications to provide wheel travel suitable for severe off-road conditions)	Provides integration of all automotive subsystems and components to include all rotating, linear, and non-linear systems. Allows plug and play for validated components and provides connectivity through established hardware and firmware interface points. Provides basic constant control algorithms (shift profile, adaptive suspension, central tire inflation system control for differentials, abs, traction control, stability control, electronically controlled braking subsystems etc.). Supports basic co-simulation structure	Supports limited autonomous representation - (collision avoidance, lane following input, etc.) includes intelligent vehicle systems, closed loop, and open loop interactive control throughout the vehicle system, expands Functional Mock-up Interface (FMI) capability	Supports full autonomous operation based on terrain and vehicle sensor inputs, includes all drive types from traditional fuel fired to full electric drive trains, provides full drive by wire utilizing gig Ethernet digital backbone representation, provides real time updates to control algorithms based on sensor inputs, fully integratable through FMI, manages all flexible body interfaces, manages all non-linear component to subsystem to system interfaces

Table 10-4 Cost, Maintenance, and Run Time Satisfaction Levels

	COST, MAINTANENCE, AND RUN TIME 12.50%				
	Unacceptable	Below Threshold	Threshold	Above Threshold	Objective
License **5.56%**	Proprietary code, no potential to extend capabilities without Vendor's involvement	Expandable code but only through the purchase of modules/add-ons, but can be had for a lower price	Open source code Moderate cost (less than $5000 per seat fee).	Open source code, non-restrictive usage structure (install on unlimited machines) extensive user groups and support, deployed to more than 5,000 users, regular international user group meetings, broad application beyond automotive utilizing physics-based analysis	Open source: strong user support, long term support based on university or application, long term funding, planned updates, models can be exported into any environment. Vendor supported, significant market penetration, integration with multiple platforms and multiple software codes, no-cost single user license for simulation-based acquisition.
Run-Time **2.78%**	Can't run in parallel, does not work on Windows and Linux	Runs in parallel with increased core capability, works on at least Windows based systems or Linux systems	Can run in parallel with up to 16 cores, works on Linux and Windows based computers	Can run in parallel with unlimited cores, works on Linux and Windows based systems	Can conduct real-time calculations, while running an unlimited number of cores and works with Linux and Windows based computers

	COST, MAINTANENCE, AND RUN TIME 12.50%				
	Unacceptable	Below Threshold	Threshold	Above Threshold	Objective
Training **4.17%**	No training available. Limited and inexperienced user base. No technical manuals or published case studies.	Web-based support and tutorials at additional cost, infrequent user group meetings, limited market penetration, limited consultant support	Full web-based tutorials and support. Troubleshooting hotline, regional offices, yearly conferences, and specialized training offered, extended consultant base, university support. Provide basic novice applications but requires greater expertise to run successfully	Full web-based tutorials and support. Troubleshooting hotline, regional offices, yearly conferences, and specialized training offered, extended consultant base, university support, Government support provide full expert development environment. Provides user groups interaction allowing implementation of latest expert applications	Extensive training and support. Wide and experienced user base with active group meetings and wealth of published documents. Detailed User’s Manuals are required. Video tutorials, tools embedded in university environment and included in advanced degree programs, conferences and well established user groups, modular development with outreach to other disciplines. Fully interactive with established mechanical engineering, autonomous system, structural engineering, etc. Novice and expert development capability

Table 10-5. NATO Specific Applications Satisfaction Levels

	NATO SPECIFIC APPLICATIONS 12.50%				
	Unacceptable	Below Threshold	Threshold	Above Threshold	Objective
Supports Unique Terrain or Mission Definition **6.94%**	Variable terrain is not possible - simulation can handle only homogenous surface.	Terrain is defined as a 2-D road. Terrain is not considered deformable. Effects of climate not considered.	Terrain is 3-D, but not customizable. Limited soft-soil effect available (e.g., homogeneous soft soil, but not variable)	3-D customizable terrain that supports heterogeneous soil conditions is possible, but must be explicitly defined. Cannot be integrated with climate conditions. Outside data can be imported.	3-D customizable terrain that supports heterogeneous soil conditions. Outside data can be imported. Surface conditions can be altered depending on climate conditions.
Worldwide Tool Availability to Approved Sources **2.78%**	Poor deployment, limited user base, single university or venue only, no user groups	Specialized deployment, applicable to unique requirements and analysis, deployed for specific markets such as oil field, unique military, deployed to support single vehicle sets (i.e., captive to a single manufacturer such as CAT or Renault or Mercedes, etc.) Captive to a specific government agency	Unique NATO events firewalled and isolated from other analysis within the simulation environment as may be required. Tool supports regular updates as may be designed by NATO for new events. Updates deployed within 30 days after validation.	Improved update deployment timing	Immediate updates for NATO events as developed. Regular updates for NATO identified terrain and mobility criteria. Support to NATO established proving ground and other validation test events. Environmental updates possible as identified

	NATO SPECIFIC APPLICATIONS 12.50%				
	Unacceptable	Below Threshold	Threshold	Above Threshold	Objective
World Wide Tool Support **2.78%**	Little or no support. Single country footprint of sponsor.	Support is available only through e-mail or telephone. No established user groups.	Support provided in all NATO countries	Support provided to all NATO countries, user groups established through primary technical societies including ASME, ISO, SAE, Imech, etc. Deployed to multiple commercial and government agencies, extended consultant base, integrated with terrain mapping user groups	Supporting entity has a global presence with representation in all NATO countries and worldwide, deployed across multiple disciplines, worldwide on-site support, agreements in place with multiple specialty software solutions, demonstrated integration and problem solving

10.3 REQUEST FOR INFORMATION (RFI)

The purpose of the Request for Information is to determine the availability of such tools and to establish a sustainable simulation environment which has the flexibility to incorporate new simulation solutions as they are developed. It is further noted that continuing and new research development are necessary in specific technology areas. As such a "template" based simulation environment is envisioned under the following charter. The framework is 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.

Physics-based simulation environments are currently available either commercially, open source, academically, or within Government agencies. New simulation environments are being developed specifically to support current challenges from man-machine interface to complete vehicle autonomy. The vision of the RFI is to collect and use available information for the physics-based vehicle and the environment in which that vehicle operates to establish the criteria for the framework and to conduct a down-select with the outcome being a recommendation for a successful framework that would be available for implementation throughout the NATO member countries within 3 years.

The RFI seeks information specific to ground vehicle dynamics simulation, terrain mapping, and autonomy capabilities. The RFI as sent is found within Appendix E of this report section and includes six different attachments as noted in the RFI.

The RFI included a significant amount of information, identifying the intended details of the vehicle operating environment, summarizing the amount of vehicle data which is considered to be a minimum (based on the current input to the NRMM), and identifying current and future capabilities of interest along with requested information on cost and international support capability.

Initial discussions with Government, Universities, and Industry indicated that appropriate flexible multibody dynamics (MBD) analysis tools do exist and are supported throughout the analysis community. Based on that, as provided in the RFI, descriptions of capabilities in the following areas were requested.

- Integration of various component modules into a complete simulation environment
- Use of standard vehicle terminology, component description, and vehicle related component interface
- A vehicle representative graphical user interface (GUI) instead of individual detailed descriptors
- Ability to customize vehicle system representation to reflect future vehicle technologies
- Description of physics-based dynamics for systems other than traditional ground vehicles (e.g., rail, air vehicle, water craft, etc.)
- Description of the ability, should it exist, to run current NRMM events and then to supplement those events with more detailed terrain elements including expanded description of water to land transition (bank or beach transition) and urban environment events (e.g., steps, rubble piles, etc.)
- Explanation of basic and expert user environments
- Ability to lock and track vehicle component configurations which can be correlated to detailed vehicle drawing packages or existing finite element models
- Database hierarchy to track and store all vehicle parameter references
- Ability to share detailed vehicle component data between users
- Post processing capability to perform evaluation of model fidelity or to quantify the impact of specific components on overall vehicle performance (Design of Experiment)

As noted in the prioritization of the key elements, the ability of the physics-based MBD analysis tools to provide modularity is a key to success. A modular approach to the simulation potentially saves time in development, allows more rapid comparison of the impact and various components, and allows introduction of unique mission-based events without the need to build a completely new simulation. As noted within the RFI additional detail on the approach to modularity, how the various vehicle elements are connected (hard points, control algorithms, etc.) is an important part of the evaluation of the potential capability of the solution. Further the ability to support future analytical solutions (FEM, DEM, terrain elements, etc.) is a key aspect to rating the capabilities of the simulations.

Within the RFI, information and examples of how well the simulation correlated to both on-road and off-road events were requested. Accuracy and validation to measured component and system data are essential to the success of a next generation NRMM simulation. The approach to highly non-linear elements whether tire, suspension, or soil conditions and the validation against measured data is essential information. As noted in Appendix E, the desire is to insure best accuracy and flexibility to insure that the solution can support multiple platforms and future technologies. Cost and sustainment of the tools is also critical as significant investment will be made for successful implementation. The ability to support the tools worldwide and support unique NATO related events is also explored. Availability of training both on line and through technical meetings is addressed with the RFI.

It is recognized that probably no single code will be perfect for all objectives. However within the parameters set by this committee the desire is to identify tools which can meet the intended structural criteria for performance, validation, and future development. As such, information was requested from University, Government and Commercial entities as noted below. Discussions continued with the various organizations with the understanding that the responses would be appropriately scored and evaluated. That information would serve to inform the committee and appropriately inform the next step efforts.

10.3.1 Next Steps

The RFI was developed, reviewed by the committee, and sent out to more than 40 organizations. The RFI specifically addressed and requested additional information on the ground vehicle dynamics simulation environment, the structure of the simulation environment, and the core basis for the tool development (physics-based, empirically based, modular, tool combination, etc.). Scoring criteria and prioritization of capabilities were provided and detailed information on the user environment, training, control algorithms, and description of interface with deformable terrains was requested.

Specific detailed information was also provided through Attachments as shown in the RFI provided in Appendix E. This included specific information on terrain roughness, the use of Wave Number Spectra defined three-dimensional terrain profiles, outline of minimum data as required by the existing NRMM, anticipated minimum physics-based model input requirements, specifics on vehicle dynamics, details on terrain mapping capability and the ability to integrate the terrain mapping with the vehicle simulation environment as a single tool, and finally information was requested on the ability of the simulation environment to include sensors, control algorithms, and other critical parametric elements as would be anticipated for accurately predicting autonomous vehicle performance.

The conceptual Duty Cycle / Mission Profile included detailed information on the following characteristics and requested information on how the existing simulation solution would address these various terrain criteria.

- Primary Roads
  - High quality to highly degraded pavement
- Secondary Roads
  - Loose surface to washboard to Belgian Block
- Trails
  - One lane, loose unimproved road
- Cross-Country Terrain
  - No road or trail exists

The minimum data input requirements identified the typical parameters found in the existing NRMM data input sheets. This includes:

- Typical parameters for interface between vehicle and environment (e.g., tire/track and soil)
- Wheel (or road wheel) and chassis characteristics
- Unique info for tracked vehicles
- Hull geometry
- Powertrain
- Aerodynamics characteristics as applied to the vehicle configuration
- Maximum braking coefficient
- Swim parameters as might be applied to a vehicle which can both swim and transition to landward operation
- Suspension design and characteristics

- Chassis
- Steering
- General vehicle characteristics

The generalized physics-based simulation data and vehicle input configuration requirements requested information on how the simulation environment would address:

- Generalized data input for powertrain model and how it might be made modular with the ability to interface different transmission or torque converter configurations along with the ability to address new technology infinitely variable transmission designs. The solution must include:
  - Engine, torque converter, transmission, transfer case, etc.
- Generalized data input for suspension model template
  - Mounting hard points, mass properties, bushings, motion control, etc.
- Generalized data input for tire model template
  - Geometry, mass, stiffness, etc.
- Generalized data input for track model template
  - Geometry, mass, stiffness, etc.
- Soil properties

For the vehicle dynamics modeling element more than 25 questions were posed. Examples of these inquiries include:

- Does the solver support parallel processing and/or other high performance computing environment? If so, how well does the solution time scale when going from 2 to 1,000 cores? Does the software run on both Windows and Linux?
- Does the model support a template-based approach? If so, describe how this is implemented. What is included in a template? How are the templates created and modified?
- Can the tire-terrain or track-terrain contact support FEA/DEM for deformable terrain at the contact patch/nodes?
- Describe the level of detail included in the powertrain and driveline model.
- How does your software support evaluation of uncertainty in model parameters? Are stochastic methodologies built in? Are capabilities for design of experiment (DOE) included? Describe the capabilities.

For the terrain mapping information in addition to critical soil structure representation the following questions are typical of the level of detail requested.

- Identify the types of terrain data used in the simulation, and the areal extent to be provided along with its precision and fidelity.
- Are the data supported in a wide range of database engines, e.g., Microsoft SQL Server, Oracle, IBM DB2, IBM Informix, Interbase, Firebird, Sybase, PostgreSQL, SQLite, MSJET, etc.?
- Will the data/process support import/export from/to modeling and simulation software platforms? Describe.
- Are the data capable of supporting wide ranges of coordinate systems and projections for on-the-fly projection?
- Are the process/data OGC compliant?

In an effort to address future vehicle system development, beyond traditional wheeled and tracked vehicles, inquiries were made as to the ability to address autonomous vehicle systems. Autonomous vehicles require unique tool capabilities because of their reliance on unique sensor technologies for successful operation. Challenges such as glass-to-glass latency, interaction of digital backbone elements, target recognition and processing time, etc. can all influence the ability of an autonomous vehicle to successfully transit a mobility event. Therefore sample questions include:

- Can the simulation environment present scene-based operations which include the challenges associated with lit and unlit conditions? Can the environment in the simulation be impacted by fog or dust or other environmental conditions which can impact sensor performance? Can it be able to control lighting, fog (that can affect sensing)?
- How are vision-based sensors represented, and what are the metrics for performance? GPU acceleration? Ray tracing?
- Can reflectance properties (e.g., BRDF) be specified for objects needed by sensor models?
- Is there support for modeling interiors of buildings for indoor mobility evaluation?

Approximately three months was made available for the various sources to provide responses. Additional questions and discussions were held throughout.

10.4 RFI DISTRIBUTION

The RFI was sent to the following companies.

Response Received	No Response Received
Motion Port	System Level Simulation, Vi-Grade
MSC Software Corporation	Virginia Tech
Real Time Technologies	Mississippi State
University of Madison, Wisconsin	Comet Solutions
CM Labs	Mathworks
Modelon/Xogeny	Lockheed Martin
Vehicle Simulation Development Corp	Northrop Grumman
Advanced Science & Automation Corp.	ESRI, Inc.
Quantum Signal	Clark Labs
JPL	Hexagon Geospatial
LMS/Siemens	Pitney Bowes
PTC	TatukGIS
SIMPACK USA	Google. Inc.
Altair	

10.5 SCORING

As the RFI responses were received from industry, each was reviewed for content and accuracy of the various questions. If answers provided were vague or non-committal, an email request for clarification was submitted to the organization. All subsequent replies were added to the correct organization's RFI response file. The four Measures of Effectiveness were scored using the Measures of Performance metrics. Each metric utilized answers from the RFI responses that were then scored against the satisfaction level criteria listed in Table 10-2 through 10-5. This would result in a numeric satisfaction level score being assigned to that MOP metric.

The scoring varied from 0.0 to 0.85 using five discrete levels which help delineate the various solutions that were scored. The score for each MOP typically consisted of two or three metrics that were combined for the final score on that specific MOP. If a 0.0 was received, the solution was deemed Unacceptable, the content of the answer was vague, misleading, non-existent, or the solution showed little or no value to the metric. If the answer addressed the question but the solution only showed partial ability or capability of metric it was awarded a Below Threshold value of 0.5. Solutions that fit the criteria for the MOP but did not fully support the requirement were awarded a Threshold value of 0.7. An Above Threshold score of 0.77 was awarded to those solutions that showed the ability to meet or support the capability required for the MOP. Finally, if the solution met in full or exceeded the capabilities of the MOP, the solution was awarded an Objective score of 0.85. A breakdown of the scoring criteria is listed in Table 10-6. The following sections describe in greater detail the MOEs of Accuracy, Flexibility, Cost, and NATO Specific Requirements with associated MOPs and scoring rationale for each.

As each of the RFI responses were received, further information was required to fully vet the information being provided. As a result, a second round of questioning was performed to gain further elaboration. Those answers were scored on an informational basis thereby foregoing the Unacceptable through Objective levels of satisfaction and using an A through D scale to avoid any confusion in the scoring process. Those results are listed in Table 10-20 and 10-19.

Table 10-6. Scoring Values

Objective	**0.85**
Above Threshold	**0.77**
Threshold	**0.7**
Below Threshold	**0.5**
Unacceptable	**0.**

10.5.1 Scoring. Measure of Effectiveness: Accuracy / Robustness

The MOE Accuracy had three measures of performance that were scored using RFI feedback from the vendors. The MOPs reviewed were Physics Based, Validation Through Measurement, and Supports Time and Frequency Domain Analysis.

Physics Based attributes were scored according to the software’s ability to accurately use first principles of physics to represent a vehicle and its interaction with the environment. The vehicle, its components, and the environment can be represented as flexible bodies. A high-fidelity soft surface model is available. Variations in terrain composition and related characteristics are modeled – the soil can be modeled as a heterogeneous mixture of different soil particles with large rock or void inclusions.

In the following tables, the software developers are listed as Organization A to L representing the twelve companies that responded to the questionnaire, for the same of anonymity.

Table10-7. Accuracy - Physics Based

Accuracy - Physics Based	
Organization A Threshold	The software met Threshold because it can import geometry and actively link to a related CAD program. It appears to be capable of flexible body modeling, NVH analysis, and Eigen mode analysis. It can link to outside FEA software, or use its own engine. It did not get "*Above Threshold"* because soil deformation is still under development.
Organization B Objective	The software met Objective because it has integrated 3-D modeling for suspension hard points and necessary vehicle geometry for contact modeling. The software models deformable bodies using finite elements, and is capable of non-linear deformation due to geometry or materials. Further two types of tire models are available: (1) a detailed finite element tire model; and (2) a lumped distributed contact polygonal. Both models are valid for large vehicle speeds and excitation frequencies. Tire- or track-terrain contact support DEM for deformable terrain at the contact patch/nodes. An FEA terrain can also be modeled, but is not good on soft soil.
Organization C Below Threshold	The software scored Below Threshold because it can import CAD models. While the main soil interaction is calculated with Bekker-Wong-Reece terramechanics, a hybrid particle-surface model is used for earthmoving simulations – this could be useful if extended to vehicle mobility. It did not reach Threshold because deformable bodies at the component level do not appear to be possible. Also bodies are described as lumped masses, thus stiffness, damping, and friction characteristics cannot vary. There were no provisions for FEA or DEM analysis.
Organization D Below Threshold	The software scored Below Threshold because CAD data can be imported for both the vehicle and environmental features. The software currently supports a modal approach for flexible multibody dynamics, but there is no internal DEM/FEA solver. Co-simulation is possible, and would be necessary for detailed analysis. The environment is modeled with a grid mesh, but only Bekker-Wong terramechanics are included. Different layers of soil are possible, but they are all assumed to be homogeneous.
Organization E Threshold	The software was scored Threshold because modal bodies can be imported for complex part geometries. A program extension can be used to solve part behaviors internally. The software can work with flexible bodies internally, but it isn't clear how it handles contact. The software heavily stresses its FMI capabilities, so linking to external FEA / DEM solvers should be able to handle internal shortcomings. The software does not include a detailed off-road tire model, but it can interface with FTire which includes both a soft-soil model and particle response model. The software apparent dependence on other packages kept if from scoring higher.
Organization F Threshold	The software scored Threshold because Geometry can be imported from CAD for both vehicle and terrain. Also it has an internal integrated FEA solver that can handle geometric nonlinearities. The standard terrain definition is built on Bekker terramechanics, but a DEM approach is being developed. The software has a highly developed track modeling system, but does not currently have an off-road tire – this feature is under development.

Accuracy - Physics Based	
Organization G Objective	The software scored Objective because it can import CAD models, and an extension of the base software gives pre-defined 2-D and 3-D contact and clearance between arbitrary bodies like parts of the vehicle as well as between vehicle and terrain. The software has integrated deformable bodies, ANCF elements, and a linear modal solver. It can be linked with external software to solve material and geometric non-linearities. The software does not natively include a DEM soil model, but it has been successfully integrated with other software for high-fidelity soft soil model efforts. It offers two off-road tire models: its own proprietary tire model and FTire.
Organization H Below Threshold	The software was scored Below Threshold because it has realistic graphics, but does not appear to be able to import vehicle geometry or parts for a CAD program - vehicles are defined in text XML files. The environment can be imported from a GeoTIFF file. The software allows for contact between the vehicle and the terrain other than the tires or tracks, but the objects are considered rigid bodies. The software does not support deformable bodies. A simple deformable off-road tire model is available based on the Bekker-Wong model, but detailed tire models require a custom software plug-in.
Organization I Unacceptable	The software scored Unacceptable because it uses only generalized vehicle models – geometry cannot be imported from CAD. The environment can be imported through multiple formats, however. It does not currently support deformable bodies. The software has a multidisc tire model that determines the tire deformation from the intersection of the tire with the polygons that define the terrain. The tire-soil or track-soil interactions have been modeled using Bekker's equation and shear displacement. The software is targeted for real-time simulation and not highly detailed FEA/DEM.
Organization J Objective	The software was scored as Objective because it can import CAD geometry and part interaction can be rigid or flexible. OpenCRG is used to import the environment, and this geometry can interact with vehicle parts. Simple, flexible elements can be used for quick model development or for when they provide sufficient fidelity. Modal reduction of flexible components and non-linear deformation are possible with external software. The software includes a modified Bekker soft soil model. A high-fidelity DEM soil model is possible through co-simulation with external software.
Organization K Objective	The software was scored Objective because it can import vehicle models from CAD programs and environmental data can be imported and converted to a mesh. The software accounts for any contact between a vehicle and the terrain. It also has flexible body simulation capabilities using the ANCF and the co-rotational finite element method. Solvers of the ANCF and co-rotational non-linear finite elements are fully integrated. The software has a simple tire model but is being extended to a deformable tire using ANCF. It can co-simulate with external models like FTire. It has deformable/flowing terrain capabilities.
Organization L Below Threshold	The software scored Below Threshold because it is a steady state 2-D model. It only has 2-D vehicle geometry and the terrain is assumed to be homogeneous with constant characteristics. The software has a simple flexible tire model and a track model described through longitudinal stiffness, but cannot interface with an external program for detailed analysis. It uses Bekker-Wong terramechanics; the terrain is assumed to be homogeneous with constant characteristics.

Validation Through Measurement attributes were scored according to the software's ability to track and correlate simulation results with recorded test results. Both vehicle center of gravity gross motion and individual component (e.g., wheel / damper travel) should be available.

Table 10-8. Accuracy – Validation Through Measurement

Accuracy – Validation Through Measurement	
Organization A Threshold	The software scored Threshold because it supports all levels of detail for driveline modeling, including engine, transmission (manual / auto / CVT / etc.), hybrid electric drivelines, torque converters, differentials, and transfer cases. All parts are modeled with physics principles, as well as all-wheel drive dynamics and multi-axle vehicles. The software can handle the suspension geometry, but the spring/damper model isn't thoroughly discussed. However advanced control systems require 3rd-party software.
Organization B Objective	The software scored Objective because it allows advanced controls through JAVA or Python scripting which run concurrently with the simulation and can read the system dynamic response (including displacements, deflections, angles, speeds, forces, etc.) and generate controller actuator forces. HIL is supported. It has detailed powertrain modeling (hybrids, torque converters, transfer cases, diffs, scripts for locking the differentials, all-wheel drive, and clutches) and full kinematic engine model. It also includes various suspension systems (double wishbone, McPherson strut, leaf-spring, walking beam, etc.). The software models suspension deflection and vibrations.
Organization C Threshold	The software scored Threshold because the engine and other drive train components, which include torque converter, transmission, differentials, transfer cases are modeled. Electric drive is available but full hybrid not. Advanced controls can be created C++ or Python, or implemented in Matlab/Simulink. A simulated driver is included based on PID controllers for speed, steering, etc. The suspension can be modeled, but does not appear to allow flexible joints or complex designs.
Organization D Below Threshold	The software scored Below Threshold because it is capable of integration with an external motor controller or hardware. It contains navigation and collision detection algorithms for autonomous vehicle mobility and manipulation, but not a simulated driver. Components are modeled with look-up tables, thus the simulation lacks detail. The software can model the suspension, but it requires coding to run efficiently.
Organization E Above Threshold	The software scored Above Threshold because open and closed loop control is possible and implemented. All driveline dynamics are modeled with a scalable level of detail, ranging from a simple throttle with first order dynamics to complete air path management with in-cylinder representation using an extension, also including either rigid connections or flexible multibody components in all subsystems. The software includes 30 suspension topologies. Compliant bushings are incorporated and active controls are possible, however they require verification.
Organization F Below Threshold	The software scored Below Threshold because it includes a module to model advanced control systems that is similar in functionality to Simulink. It has HIL capability with an offered extension. It does not have preconfigured templates for drive trains though, and the suspension must be modeled manually by the user.

Accuracy – Validation Through Measurement	
Organization G Above Threshold	The software scored Above Threshold because position / forces can be monitored for all components, and sensing is used for a simulated driver. Advanced controls require co-simulation with Matlab or similar FMI compliant software. Several pre-defined transmission types are available: manual, automatic (with torque converter), robotized manual, hybrid, and simple torque, or users are free to customize transmission models. Differentials, transfer cases, AWD, and multi-axle dynamics can be explicitly modeled in as much detail as the user requires. The software can create and modify fully parametric templates interactively by combining low level primitives (parts, joints, forces) and higher level objects (leaf-springs, struts, stabilizer-bars). However HIL requires hard coding.
Organization H Below Threshold	The software scored Below Threshold because advanced controls are possible, but they require a plug-in. A simulated driver is included via a closed loop PID system. The software can model unique suspensions but it appears to require custom code. The drive train model appears to be limited to a torque-speed-efficiency look-up table. It only has rudimentary HIL capability.
Organization I Below Threshold	The software scored Below Threshold because it is proficient at interfacing with user feedback hardware and other vehicle hardware can be integrated in a similar way. It requires Simulink for advanced controls, though. The software is focused on low-fidelity models for real-time simulation, thus the driveline systems appear to be look-up tables. It is based on a general purpose multibody dynamics code that can be used to model many different types of suspensions, but most options appear to require hard coding or co-simulation.
Organization J Objective	The software scored Objective because it has a simulated driver and complete Driver/Software/Hardware-in-the-Loop capabilities with a program extension or through interfacing with MATLAB. The software provides a scalable simulation environment, allowing optimization between fidelity and effort in simulation time or modeling effort. It allows creating unique suspension designs. Rigid body modes of obstacles are taken into account for their movement on collision. With contact modeling, the contact forces are based on the Hertz theory. Deformation is taken into account with a more detailed modal or FE approach.
Organization K Threshold	The software scored Threshold because it is capable of high-fidelity modeling of drive train and suspension components, but editing text files and/or custom code is required. HIL, SIL, and advanced controls have been implemented but require either co-simulation or custom code.
Organization L Below Threshold	The software scored Below Threshold because it can model pivot-arm or translational spring suspensions, with linear or non-linear load deflection characteristics. It does not have control systems or a driver model, and thus cannot simulate HIL/SIL/DIL testing. Also the software does not model powertrain subsystems, look-up tables are used. High-fidelity modeling is not possible.

Supports Time and Frequency Domain Analysis attributes were scored according to the software's ability to analyze model reaction both on-the-fly and in post-processing. The real-time data should allow the replication of complex interactions such as resonance and traction hop. Additional post-processing techniques should be available, such as SRS, PVSS, durability stress/strain life cycles, etc.

Table 10-9. Accuracy – Supports Time and Frequency Domain Analysis

Accuracy – Supports Time and Frequency Domain Analysis	
Organization A Objective	The software scored Objective because sensors can be placed anywhere in the model to extract test data, before or after the simulation. Results can be graphically displayed in an animation. It supports order analysis, FFT, contribution plots, and 3-D display or results. Optimization can be done through co-simulation.
Organization B Objective	The software scored Objective because it is able to create animations, plots, and performing various data analyses including averaging/smoothing and FFT. Data can be displayed internally or exported for further analysis. It is also capable of running Design of Experiment (DOE), stochastic analysis, and parametric studies internally.
Organization C Threshold	The software scored Threshold because time domain plots and animations can be created natively. It includes support for parametric studies of the model. It does not directly provide frequency domain analysis, but the test data can be exported for complex analysis.
Organization D Objective	The software scored Objective because it includes time domain data logging and creation of movie files. Post analysis can be performed using Python scientific computation modules. There are modules for Monte Carlo analysis available for parametric sensitivity and uncertainty analysis. The user can specify the range and statistics for the parameter space to be swept through.
Organization E Threshold	The software was Threshold because it is capable of plotting and post-processing, including frequency analysis, but it requires either scripting or data export. Robust design and statistical engineering methods are integrated in the software, or can be achieved through co-simulation.
Organization F Threshold	The software scored Threshold because it includes extensive model parameterization and DOE capabilities. It also includes time- and frequency-domain analysis as well as animations. There was a lack of detail in their response, however, so specific capabilities are unclear.
Organization G Objective	The software was scored Objective for its time- and frequency-domain analysis. It is capable of simple time history plots, applying sensors to any point in the model to extract forces and motion through the simulation. It is capable of FFT and PSD analysis. It also supports DOE, Monte Carlo analysis, and model parameterization and optimization internally.
Organization H Below Threshold	The software was scored Below Threshold because it is capable of creating animations, but does not have complex time- or frequency-domain capabilities. Simulations can be looped to vary input variables, but more complex DOE is still under development.
Organization I Below Threshold	The software was scored Below Threshold because it only has low-level time-domain analysis and no frequency-domain analysis. There appears to be extensive support for animations, including overlaying graphs with the simulation. There are no internal methods for optimization or DOE, but it is possible through 3rd-party software.
Organization J Threshold	The software was scored Threshold because it has extensive post-processing capabilities, including a dynamic link to time-domain curves and frequency-domain calculations. No examples were given, however. Methods such as DOE and Monte Carlo simulations are available through a program extension.

Accuracy – Supports Time and Frequency Domain Analysis	
Organization K Threshold	The software was scored Threshold because it is capable of time-and frequency-domain plots, but only through custom coding or linking with external software. It is capable of creating animations via two integrated methods, as well as displaying data with the animation. There are no DOE or optimization routines built into the software, but it is possible through custom code.
Organization L Unacceptable	The software scored Unacceptable because it is purely a steady-state model. No time- or frequency-domain analysis is possible. It also does not currently have any methods for DOE, parameterization, or optimization.

10.5.2 Scoring. Measures of Effectiveness: Flexibility

The MOE flexibility had three measures of performance that were scored using RFI feedback from the vendors. The MOPs reviewed were Template Based, Wheeled / Tracked / Amphibious Vehicles, and Automotive Subsystems.

Template Based attributes were scored according to the usability of the software. The software must allow the building of a vehicle from components, subsystems, and systems that are available in a template database included with the software. Different components, subsystems, and systems should be able to be swapped in order to evaluate the change of performance. The process of building the vehicle model should be done in a graphical user interface environment. While custom coding may be available for advanced users, novice users should be able to construct a representative vehicle using the GUI.

Table 10-10. Flexibility – Template Based

Flexibility – Template Based	
Organization A Objective	The software was scored Objective because it has a customizable sub-mechanism structure included with its vehicle database. This includes connecting multiple levels of sub-mechanisms. Editing of the sub-mechanisms is possible from the main model. It supports graphical and text based editing of the model, including editing the 3-D geometry.
Organization B Above Threshold	The software was scored Above Threshold because it has high potential for individual components, but there isn't an extensive library of components ready for the template because the market penetration appears to be small. Its GUI includes a template/wizard/spreadsheet editor that uses figures and tables to show graphically the geometric parameters of the sub-model.
Organization C Threshold	The software was scored Threshold because it has a thorough list of major vehicle systems, but does not model individual components. It provides access to aspects of the simulation through a point-and-click graphical user interface. In addition, it also includes live test and validation capabilities to edit mechanisms while running the simulation to see behavior and changes immediately, without having to run an external application.
Organization D Below Threshold	The software was scored as Below Threshold because any number/level of systems and components can be modeled, but the primary method is through scripting. There is a “tree-augmented” approach to creating the model which appears to be graphically implemented, but the resulting model sacrifices execution speed at run time.
Organization E Objective	The software was scored Objective because systems, subsystems, and components are available via templates and libraries. The GUI allows building models of different fidelities, adapting the modeling process to advanced and novice users.

Flexibility – Template Based	
Organization F Threshold	The software was scored Threshold because it allows for highly detailed modeling of the vehicle track and suspension, but information is limited regarding other systems. Properties of the track related components can be defined through a wizard type interface.
Organization G Objective	The software was scored Objective because it is designed for template-based modeling of system, subsystem, and component level interactions. The template builder environment features a guided user interface, symmetry support, and an interactive graphical model view.
Organization H Unacceptable	The software was scored Unacceptable because component modeling is not possible, and system / sub-system models are typically look-up tables. There is no GUI, the model is created completely through text files.
Organization I Unacceptable	The software was scored Unacceptable because while the vehicle can be split into systems and sub-systems, the models are low-fidelity look-up tables. If high-fidelity component modeling is needed then co-simulation is required. A program extension is available to graphically build a model of a wheeled vehicle (apparently not available for tracks), but the results have not been verified.
Organization J Objective	The software scored Objective because it includes system, subsystem, and components that can be swapped for various levels of fidelity. The vehicle systems, terrain data, and mission profiles can all be edited with GUI based “vertical” applications.
Organization K Threshold	The software was scored Threshold because full systems, subsystem, and component levels are available in templates. The templates are in the form of text files, however. There is no GUI for the software.
Organization L Unacceptable	The software was scored Unacceptable because while it does have a GUI, only basic vehicle and environmental parameters are used. The powertrain is modeled as look-up table, subsystem and component level modeling is not possible.

Wheeled / Tracked / Amphibious vehicle attributes were scored according to the software’s ability to model numerous types of vehicles in the diverse environment required. The type of the tire model was a factor (on-road vs off-road), as well as the detail used. Likewise the ability to model different designs of tracks (single pin, double pin, “live,” “dead,” rubber band, etc.) is required. The software must be able to simulate operation in land, sea, and the littoral transition.

Table 10-11. Flexibility – Wheeled or Tracked Vehicles

Flexibility – Wheeled or Tracked Vehicles	
Organization A Unacceptable	The software was scored Unacceptable because while it includes multiple “standard” tire models used for paved scenarios, there is no off-road tire model. Tracked vehicles are not supported at all. Hydrodynamic modeling is possible, but doesn’t appear to be validated.
Organization B Objective	The software scored Objective because there are two off-road tire models available. Multiple designs of tracks are also available. Smoothed Particle Hydrodynamics (SPH) is included for modeling fluid interaction with rigid and flexible bodies.

Flexibility – Wheeled or Tracked Vehicles	
Organization C Threshold	The software was scored Threshold because while an off-road tire model is available, it is low-fidelity. Similar to wheels, track models are available but they do not differentiate between single- and double-pin designs. Both wheels and tracks could be extended through custom coding, however. The software is more detailed with its hydrodynamic model, though, incorporating drag, lift, buoyancy, and transition to land.
Organization D Unacceptable	The software was scored Unacceptable because only the Fiala tire model is included. The software does not include any track models. Likewise only limited aquatic modeling has been done, with no experience for the sea-to-shore transition. Custom code could be used as a plug-in for all three criteria, however.
Organization E Below Threshold	The software was scored Below Threshold because while it does not have a native off-road tire model, it has interfaces with standard Delft and FTire models. There are not pre-designed tracks, but accurate models could be built from parts or imported from CAD designs. Hydrodynamic forces have been done, but are not included as part of the library.
Organization F Threshold	The software was scored Threshold because it includes several high-fidelity track models. There is currently only a low-fidelity tire model, however. Hydrodynamic forces are modeled by co-simulating with a third party software using smoothed particle hydrodynamics. More development would be needed for the transition phase, however.
Organization G Above Threshold	The software was scored Above Threshold because low and high-fidelity tire models are included. Various templates are available for tracks and track suspensions are included. Water-based effects are only basic, however. Explicit forces can be defined, or higher fidelity achieved through co-simulation.
Organization H Unacceptable	The software was scored Unacceptable because only low-fidelity models are available for both tires and tracks. Hydrodynamics are not offered.
Organization I Unacceptable	The software was scored Unacceptable because it is only capable of a super-element track model. It has a multi-disc tire model, but it doesn't support high-fidelity analysis. It has not been used with any hydrodynamic forces.
Organization J Objective	The software was scored Objective because a dedicated off-road tire model was developed and validated. It includes both low- and high-fidelity methods to create custom tracks. Hydrodynamic forces for buoyancy and drag have been modeled.
Organization K Above Threshold	The software was scored Above Threshold because high-fidelity modeling of tracked vehicles is possible through text templates of the track suspension and components. Only a simplified off-road tire is currently available; a high-fidelity tire is being developed as a deformable body. Hydrodynamic forces are evaluated using a Lagrangian fluid formulation similar to Smoothed Particle Hydrodynamics (SPH).
Organization L Unacceptable	The software was scored Unacceptable because it only includes basic models for both tires and tracks. The software is not designed for predicting the fording or amphibious performance of off-road vehicles.

Automotive subsystems attributes were scored according to the software's ability to accurately create a model down to the component level. Interactions between components are considered. Linear and non-linear characteristics should be possible. Control systems may be required for active suspension, braking, stability, and traction control systems. Vehicle and environmental feedback will be used for autonomous vehicle simulation and control. Hardware and software in the loop may be required.

Table 10-12. Flexibility – Automotive Subsystems

Flexibility – Automotive Subsystems	
Organization A Threshold	The software was scored Threshold because it supports all types of powertrains (gasoline / diesel / hybrid, and manual / auto / IVT). Important systems such as clutches, torque converters, and differentials are also modeled using physics principles. Control systems are possible through internal methods, but co-simulation may be more effective (it is FMI compliant). The organization did not respond to the Autonomous Vehicles questionnaire, thus it cannot be evaluated for full autonomous vehicle development.
Organization B Threshold	The software was scored Threshold because it has perhaps the most detail with the engine models, going down to moving parts and inertias. Active controls, various stability systems, etc. are implemented via JAVA and Python scripting. It is not FMI compliant, but the organization was open to developing this capability if needed. The simulation environment has the detail and data capturing capabilities needed for autonomous vehicle operation, but this hasn't been done yet – more development may be needed.
Organization C Below Threshold	The software was scored Below Threshold because it includes a full featured graphics engine with a detailed environmental condition modeling, including time-of-day specifications, shadow casting, cloud cover, night time, fog, and dust particle modeling. The various powertrain configurations are all possible, but in low-fidelity look-up table form. Controllers are possible, but require custom plug-ins written in C++ or Python, or co-simulation with MATLAB/Simulink. It is unclear whether the software is FMI compliant.
Organization D Below Threshold	The software was scored Below Threshold because the powertrain model is limited to low-fidelity look-up tables. Vehicle controls can be implemented through its application program interface (API) or co-simulation with Simulink. It is unclear whether it is FMI compliant, however. The software includes high-fidelity models for mono and stereo cameras, but does not seem to have other "sensors".
Organization E Threshold	The software was scored Threshold because it includes numerous libraries which allow efficient modeling of various physical systems: vehicle dynamics, powertrain, electronics, heating/cooling, hydraulics, pneumatics, batteries, and specific military ground vehicle libraries. It allows four methods to model vehicle system controls and communication, ranging from importing the control model to exporting the dynamics model or co-simulation. The software is FMI compliant. The organization did not respond to the Autonomous Vehicles questionnaire, however.
Organization F Below Threshold	The software was scored Below Threshold because while it is capable of detailed powertrain modeling, it does not include templates for specific systems like diesel or hybrid designs. It does include an integrated control design module, or is capable of co-simulation with Simulink. It isn't known whether the software is FMI compliant. Also they did not respond to the Autonomous Vehicle questionnaire.
Organization G Above Threshold	The software was scored Above Threshold because while engine dynamics are typically limited, they could be modeled. A full set of templates is available for different transmission types with subsystems like torque converters and clutches. The software has an extension for designing and tuning control systems, as well as being FMI compliant and able to link to Simulink. The software is not designed for simulating autonomous vehicles interacting with the environment, but it could be possible though co-simulation.

Flexibility – Automotive Subsystems	
Organization H Unacceptable	The software was scored as Unacceptable because the engine and powertrain are simply modeled with look-up tables. Any detailed components such as dampers are controlled either with basic PID controls or custom code. Its vehicle model and environment have been designed around real-time simulation of autonomous vehicles. The software is not FMI compliant, though.
Organization I Below Threshold	The software was scored as Below Threshold because while it does offer a variety of powertrain options, they are generalized, low-fidelity components designed for fast simulation. There is a reference to linking third party software, but it is not explicitly stated whether the software is FMI compliant. Control systems can be designed internally. It does support design of autonomous systems, however.
Organization J Above Threshold	The software was scored Above Threshold because it integrates detailed engine, powertrain, and system controls internally. It is FMI compliant, and can link with Simulink if desired. The software has been designed for high-fidelity mechanical simulation rather than complex environmental interaction. It could facilitate autonomous vehicle development, but would require co-simulation with external software.
Organization K Below Threshold	The software was scored Below Threshold because while it is capable of detailed modeling of any system, it is dependent on C++ coding. This applies to the system control as well. The software is FMI compliant, so the controls could be created in external software. When paired with a related graphics package it is capable of autonomous vehicle development, again with C++ coding.
Organization L Unacceptable	The software was scored as Unacceptable because the engine and powertrain are completely generalized as look-up tables. As a steady-state model there are no system control systems possible. It is not FMI compliant. Also they did not respond to the Autonomous Vehicle questionnaire, but given the nature of the model it is not suitable for developing autonomous systems.

10.5.3 Scoring. Measures of Effectiveness: Cost

The MOE cost had three measures of performance that were scored using RFI feedback from the vendors. The MOPs reviewed were License, Run Time, and Training.

License attributes were the initial cost of the license itself and any additional costs that would be incurred such as extra software toolboxes that would be needed and not included in the initial offering from the organizations. Other attributes were the level of support that would be included in the initial price, scores were decreased if support was not included in the initial cost. Score reductions were also given to organizations that did not provide support at all. While open source code was a desired attribute, the associated software support was also examined; items such as data security and how it is protected were reviewed. Some vendors that offered “free” software did not account for the network IT personnel and time that would be required by the customer to accommodate the security threats when this function was built in to other more expensive software packages. The total cost was calculated over a 5 year period and the cost to own per year was then scored. Additional metric was each organization’s ability to provide a NATO trial license for evaluation purposes of their software.

Table10-13. Cost, Maintenance and Training – Licensing/5 Yr. Cost

Cost, Maintenance and Training – Licensing/5 Yr. Cost	
Organization A Below Threshold	Organization A receives a score of Below Threshold. While they have the ability to provide NATO with a license for evaluation purposes at no cost, the cost per year over 5 years is below threshold. Additional costs are included each year for separate software licenses that are required to supplement the software operations.
Organization B Objective	Organization B meets Objective with the ability to provide NATO with a license for evaluation purposes at no cost, and showing a cost per year over a five year period that meets objective. Additional costs are included each year for separate software licenses that are required to supplement the software operations.
Organization C Above Threshold	Organization C is Above Threshold illustrating the ability to provide NATO with a license for evaluation purposes at no cost. Yearly cost meets objective cost per year over a five year period. The software does not require additional software licenses to support operations.
Organization D Unacceptable	Organization D receives a score of Unacceptable as they did not communicate the ability to provide a trial license at no cost for evaluation of their software. Organization D did provide a threshold cost per year over 5 years. Additional costs are included each year for separate software licenses which will be required to supplement the software operations.
Organization E Unacceptable	Organization E receives a score of Unacceptable as they did not communicate the ability to provide a trial license at no cost for evaluation of their software. Organization E does meet objective cost per year over five years. Additional costs are included each year for separate software licenses which will be required to supplement the software operations.
Organization F Unacceptable	Organization F receives a score of Unacceptable as they did not communicate the ability to provide a trial license at no cost for evaluation of their software. Organization F did provide an above threshold cost per year over 5 years. The software does not require additional software licenses to operate as desired.
Organization G Above Threshold	Organization G scores Above Threshold illustrating the ability to provide NATO with a license for evaluation purposes at no cost. Organization G meets threshold cost per year over a five year period. The software does not require additional licenses to operate as desired.
Organization H Above Threshold	Organization H scores Above Threshold overall. The price meets objective cost per year over five years. Additional costs are included each year for separate software licenses which are required to supplement the software operations. Organization H is willing to provide a six month license at no cost for purposes of evaluating the software.
Organization I Objective	Organization I meets Objective with the ability to provide NATO with a license for evaluation purposes at no cost. Organization I also meets objective cost per year over a five year period. The software does not require additional software licenses to operate as desired.
Organization J Above Threshold	Organization J is Above Threshold illustrating the ability to provide NATO with a license for evaluation purposes at no cost. Organization J meets threshold cost per year over a five year period. The software does not require additional software licenses to operate as desired.
Organization K Above Threshold	Organization K is Above Threshold illustrating the ability to provide NATO with a license for evaluation purposes at no cost. Yearly cost is above threshold per year over a five year period. Additional costs are included each year for separate software licenses which are required to supplement the software operations.

Cost, Maintenance and Training – Licensing/5 Yr. Cost	
Organization L Unacceptable	Organization L scores an unacceptable due to not have a pricing structure and indicating that number of licenses would dictate the cost which would have to be negotiated. No information was given with regard to trial licenses and their associated cost.

Run time attributes were scored on the software's ability to support multi-core/multi-processor, shared memory through parallel computers/nodes. This ability is twofold with regard to customer costs. First the multi-core/multi-processor approach allows parallel computers working together to decrease simulation time. Second the use of high powered computers is not a necessity when using this type of processing therefore decreasing operational costs for the customer. Finally, each of the vendor's offerings was examined to see their compatibility with Linux and Windows based operating systems. Compatibility with both was scored higher.

Table 10-14. Cost, Maintenance and Training – Run Time

Cost, Maintenance and Training – Run Time	
Organization A Above Threshold	Organization A is Above Threshold with the ability to operate on Windows and Linux operating systems. The software supports multi-core operations up to a 16 core maximum for efficiency purposes.
Organization B Threshold	Organization B meets Threshold because the solver currently runs on shared-memory parallel computers/nodes, including multi-core/multiprocessor computers and Intel Phi coprocessors. The solver runs on both Windows and Linux. However, the pre- and post-processor runs only on Windows.
Organization C Above Threshold	Organization C is Above Threshold with the ability to operate on Windows and Linux operating systems. The software supports multi-core operations up to a 16 core maximum for efficiency purposes. Organization C states that collision detection and multiple vehicles or multiple experiments can always be solved in parallel. The amount of parallelism, however, depends on the dynamics system being solved.
Organization D Below Threshold	Organization D is Below Threshold since its solver is primarily targeted for workstation and embedded use – not parallel processing. The software is only compatible with Linux operating systems.
Organization E Above Threshold	Organization E is Above Threshold because its software can perform parallel computations utilizing numerous cores and is compatible with both Windows and Linux operating systems.
Organization F Above Threshold	Organization F is Above Threshold because its software can perform parallel computations utilizing numerous cores and is compatible with both Windows and Linux operating systems, however the graphical user interface is only supported on Windows at this time.
Organization G Objective	Organization G met objective because its software supports multi-core parallel computations. Utilizes 64-bit operating platforms to increase performance. Compatible with both Windows and Linux operating systems.
Organization H Below Threshold	Organization H is Below Threshold. Support for parallel processing does not exist but is under development. Linux compatibility also under development. System is currently compatible with Windows operating system.

Cost, Maintenance and Training – Run Time	
Organization I Below Threshold	Organization I is Below Threshold because the software has limited support for multi-core processes. It is however, compatible with both Windows and Linux operating systems.
Organization J Objective	Organization J meets Objective because the software can run in parallel with multi-cores and is compatible with Windows and Linux operating systems.
Organization K Above Threshold	Organization K is Above Threshold because the software is capable of parallel multi-core CPU computing. Organization K’s software is compatible with both Windows and Linux operating systems.
Organization L Unacceptable	Organization L receives an Unacceptable score because the software does not perform parallel processing and is compatible with Windows operating system only.

Training attributes were scored on the vendor’s level of support and how that support was structured. Questions such as, did the vendor have sufficient staff to be able to travel to the customers site for training sessions, did the vendor have the staff to provide support via telephone or videoconference, did the vendor display sufficient market penetration to exhibit a large user community for support. Other support parameters were examined, such as the amount of web-based support in the form of chat rooms, tutorials, user manuals etc.

Table 10-15. Cost, Maintenance and Training – Training

Cost, Maintenance and Training – Training	
Organization A Threshold	Organization A meets Threshold because they provide automated support such as a website with Q&A support community, message boards etc. They also provide support via email, WebEx, and phone. Organization A was not forthcoming on whether or not they physically will travel to a site and provide training.
Organization B Below Threshold	Organization B scores Below Threshold, but it is very strong in technical training and support through internet based video conferencing. Organization B does not address on site support, either at their facility or the customers. Website solutions are limited.
Organization C Objective	Organization C meets Objective and will provide training on site at their facility or the customers. They also have a large web based automated training capability as well as live support via email, phone and video conferencing.
Organization D Below Threshold	Organization D is Below Threshold. Organization D will host visitors at its site to collaborate on joint efforts but no formal training is offered.
Organization E Unacceptable	Organization E receives an Unacceptable score because available personnel does not constitute a large mobile training force. If needed Organization E can “ramp up” efforts to meet the needs of the customer. There is a web-based education center but no interactive support is offered.
Organization F Threshold	Organization F meets Threshold by offering training from its regional offices, either on site at their office or the customers. Automated support is not mentioned but interactive support such as phone, email, video conference is offered but for additional costs.

Cost, Maintenance and Training – Training	
Organization G Objective	Organization G meets Objective offering on-site training at their site or the customers. Organization G also offers an online “Knowledge base” for Q&A, blogs, message centers, etc. Technical support is also offered through phone, emails, and video conferencing.
Organization H Unacceptable	Organization H receives an Unacceptable. Organization H will not provide training at their site or the customers. There is a website that can be utilized to contact them for any issues but no formal training is mentioned.
Organization I Above Threshold	Organization I is Above Threshold because it will provide training at their site or the customers. They offer unlimited emails and phone support. Automated support is limited.
Organization J Threshold	Organization J meets Threshold because they provide support via phone or email. Web page support is limited and Organization J does not support onsite training, either at their facility or the customers.
Organization K Unacceptable	Organization K receives an Unacceptable score because it utilizes a web based “issue tracker” to solve problems if encountered. No live support via phone or video conference is offered. Organization K does not travel to customer sites and does not host training.
Organization L Above Threshold	Organization L is Above Threshold because it will provide training on site at either their facility or the customers. Organization L also provides training through phone calls, emails and video conferencing. Automated support such as web pages etc is limited.

10.5.4 Scoring. Measure of Effectiveness: NATO Specific Applications

The MOE NATO Specific Applications MOE was supported by MOPs that looked at the vendors offering ability to support unique terrain or mission definition, the availability worldwide of the vendors’ offerings and what world wide support is available for each.

The vendors support of unique terrain or mission definitions was scored based on the software’s ability to provide variable terrain in a three dimensional setting with options to customize the terrain in general as well as provide the soil properties and interaction with heterogeneous soil conditions. Finally, the terrain could further be altered via simulated climate conditions. Two-dimensional terrain that is not variable was deemed unacceptable.

Table 10-16. NATO Specific Applications – Supports unique terrain or mission definition

NATO Specific Applications – Supports unique terrain or mission definition	
Organization A Threshold	Organization A meets Threshold because it can support 3-D terrain but is vague on importing GIS type data. The soil data is UDF and would need some additional conversion to implement.
Organization B Objective	Organization B meets Objective. It can support 3-D terrain and imports GIS and converts to polygonal surface or x, y, z point data for any application. The software implements DEM and can be used to specify soil conditions.
Organization C Threshold	Organization C meets Threshold because it can support 3-D terrain but would take some additional development for GIS and NRMM functionality. Organization C does provide sun/solar variables in the input but does not elaborate.

NATO Specific Applications – Supports unique terrain or mission definition	
Organization D Below Threshold	Organization D is Below Threshold. Organization D Supports 3-D terrain but provides no way to import GIS data. Climate and soil properties are not included in the base offering. It is unclear if an additional module is available that supports soil properties.
Organization E Unacceptable	Organization E receives an Unacceptable score with 3-D terrain partially supported using 3rd party software. Once the terrain is defined, no soft soil model capability exists so it is not possible to have climatic influences. GIS currently cannot be imported.
Organization F Threshold	Organization F meets Threshold because 3-D terrain is supported in dimensions only and not deformable. GIS data can be imported; soil types are existent but need additional development.
Organization G Objective	Organization G meets Objective with numerous 3-D formats supported, software can import all GIS data using 3rd-party software. Contains a working DEM for soil property manipulations.
Organization H Above Threshold	Organization H is Above Threshold because 3-D terrain and import of GIS data is fully supported. Soil is specified in layers and the response was unclear as to how the soil properties are handled for each.
Organization I Above Threshold	Organization I is Above Threshold because 3-D terrain is supported, numerous options for importing and manipulating GIS type data. Allows terrain soil type definitions with lookup tables. Soil changes with climate is under development.
Organization J Above Threshold	Organization J is Above Threshold because 3-D terrain is supported and soil properties can be specified and simulated for varying climate. GIS data has not been imported until recently and is still under development.
Organization K Objective	Organization K meets Objective because 3-D terrain is supported and provides soil data in look up tables and is defined per USCS standards. GIS data can be imported via several methods using third-party software.
Organization L Below Threshold	Organization L is Below Threshold because no capability for 3-D terrain exists and cannot import GIS data. Organization L's response was vague on soil properties but can be classified per USCS standards. No mention of climate effects and if they can be modeled.

Worldwide availability was scored based on whether or not the vendor had the resources to support sales NATO countries and worldwide. This included multidisciplinary staff to meet the demands of a wide range of customers in a wide range of geographic areas. Would this affect updates to the software and the update distribution worldwide?

Table 10-17. NATO Specific Applications – Tool Support

NATO Specific Applications – Tool Support	
Organization A Objective	Organization A meets Objective and currently supports a worldwide customer base spanning the NATO countries.
Organization B Objective	Organization B meets Objective stating it will travel worldwide to provide on-site technical training and support.

NATO Specific Applications – Tool Support	
Organization C Objective	Organization C meets Objective and will travel worldwide to provide on-site technical training and support.
Organization D Below Threshold	Organization D is Below Threshold because it does not consider itself a commercial operation and there is no formal training program or support. They do however, invite guests to their site for collaborative efforts.
Organization E Threshold	Organization E meets Threshold because the number of trainers and locations would probably have to be updated, potentially by “training the trainers,” but can be achieved in a relatively short time frame.
Organization F Objective	Organization F meets Objective because it has regional offices worldwide and offers on-site training at the customer’s facilities.
Organization G Objective	Organization G meets Objective because it has regional offices worldwide and offers on-site training at the customer’s facilities.
Organization H Threshold	Organization H meets Threshold because it can provide support worldwide but the additional cost will be charged to the customer.
Organization I Objective	Organization I meets Objective because it has regional offices worldwide and offers on-site training at the customers facilities.
Organization J Objective	Organization J meets Objective because it has offices around the globe that support both technical and training needs.
Organization K Below Threshold	Organization K is Below Threshold since only automated support is offered. Representatives are not physically present worldwide.
Organization L Below Threshold	Organization L is Below Threshold because support will only be provided via phone or email. Representatives are not physically present worldwide.

Worldwide tool support was examined referencing the software’s long term availability, will this candidate have the ability to support and maintain NATO specific modeling events for 7-12 years after implementation. The licensing structure and track record of each vendor was also examined to see how information would be secured and firewalled during validation efforts.

Table 10-18. NATO Specific Applications – Worldwide Tool Availability to Approved Sources

NATO Specific Applications – Worldwide Tool Availability to Approved Sources	
Organization A Objective	Organization A meets Objective because they are capable of supporting their product for up to 20 years with worldwide representation and established firewall protocol.
Organization B Objective	Organization B meets Objective because they are capable of supporting their product long term with a worldwide customer base and provide proven firewall protocol to support a large customer base.

NATO Specific Applications – Worldwide Tool Availability to Approved Sources	
Organization C Objective	Organization C meets Objective by providing guaranteed support for 7-12 years with flexible licensing options for company growth. Organization C operates worldwide with commercial and military customers utilizing firewall protocols.
Organization D Below Threshold	Organization D is Below Threshold as it provides daily build and release cycles of the software. This appears to be problematic from a security/firewall aspect and also with respect to standard NATO events.
Organization E Objective	Organization E meets Objective citing that industry is increasingly using Organization E's software for model-based development, specifically, many automotive companies, such as Audi, BMW, Daimler, Ford, Toyota, Volvo and VW. Large worldwide user base with successful firewall capabilities.
Organization F Objective	Organization F meets Objective because it has regional offices, a large customer base and can provide long term support for their product. Organization F is also firewall capable.
Organization G Objective	Organization G meets Objective saying it has network licenses or node-locked options available. Software is firewall capable, and serves a large customer base. They can provide long term support.
Organization H Threshold	Organization H meets Threshold and can support long term if needed, but the additional cost will be charged to the customer.
Organization I Above Threshold	Organization I is Above Threshold because they can provide long term support in excess of 20 years. Each piece of software is typically node-lock licensed with firewall capabilities but this is not described in any further detail by Organization I.
Organization J Objective	Organization J meets Objective because it has been in business for over 30 years and can continue to provide long term support. Currently supporting thousands of users utilizing firewall protocols without interruption.
Organization K Threshold	Organization K meets Threshold because they can provide long term support for the next 7-12 years. Firewall protection is limited, a by-product of its open licensing structure.
Organization L Below Threshold	Organization L is Below Threshold stating that the licensing agreement is optional but can be used under a license agreement if agreed upon. Customer base and firewall precautions are limited.

10.5.5 Final Scoring

The weights given in Table 10-1 MOE and MOP Weighting are used with the scores for the individual MOPs discussed above to combine the results into a single weighted average score for each Organization as shown below in Table 10-19.

Table 10-19. Final Weighted Scores.

MOE	*MOP*	A	B	C	D	E	F	G	H	I	J	K	L
Accuracy/ Robustness	**Physics Based**	0.75	0.85	0.50	0.50	0.70	0.75	0.85	0.59	0.37	0.85	0.85	0.59
	Validation through measurement	0.75	0.85	0.70	0.59	0.79	0.37	0.79	0.59	0.59	0.85	0.75	0.37
	Supports time and frequency domain analysis	0.85	0.85	0.70	0.85	0.75	0.75	0.85	0.59	0.37	0.75	0.70	0.00
Flexibility	**Template based**	0.85	0.79	0.75	0.63	0.85	0.75	0.85	0.16	0.16	0.85	0.75	0.16
	Wheeled or tracked vehicles	0.37	0.85	0.73	0.00	0.63	0.73	0.77	0.00	0.37	0.85	0.77	0.37
	Automotive Subsystems	0.73	0.73	0.52	0.52	0.73	0.69	0.77	0.37	0.52	0.80	0.69	0.00
Cost, Maintenance, and Training	**License**	0.68	0.85	0.81	0.35	0.43	0.39	0.78	0.78	0.00	0.78	0.77	0.00
	Run Time	0.79	0.75	0.79	0.55	0.79	0.83	0.85	0.55	0.61	0.85	0.79	0.48
	Training	0.71	0.68	0.85	0.50	0.37	0.74	0.85	0.42	0.82	0.70	0.34	0.82
NATO specific applications	**Supports unique terrain or mission definition**	0.73	0.85	0.73	0.63	0.37	0.73	0.85	0.77	0.77	0.77	0.85	0.50
	Worldwide tool availability to approved sources	0.85	0.85	0.85	0.50	0.85	0.85	0.85	0.50	0.85	0.85	0.50	0.50
	Worldwide tool support	0.85	0.85	0.85	0.50	0.70	0.85	0.85	0.50	0.85	0.85	0.50	0.50
	Weighted Average Scores	0.69	0.83	0.69	0.45	0.67	0.68	0.82	0.42	0.45	0.82	0.74	0.34

10.6 ADDITIONAL QUESTIONS IDENTIFIED DURING AVT MEETING IN POLAND

At the conclusion of the review and discussion of the information submitted in response to the RFI, some additional questions were posed by members of the committee. The intent of these additional questions was to clarify in more specific terms how well the various tools could deal with the deformable soil conditions, how efficiently the codes might be able to run, and whether the reaction of the soil was part of the core simulation or if a "co-simulation" approach was used. The additional questions posed are shown below.

1. How is the vehicle to soil interaction simulated for off-road operations within your solution?
2. Is the vehicle system formulated in multibody dynamics code or in finite element code? Is the simulation of the vehicle run separately from the vehicle to soil interaction or does a "co-simulation" process exist?
3. Does your solution utilize a classical terramechanics approach (Bekker-Wong) or does your solution utilize an alternative approach such as discrete elements or finite element analysis? A description of your methodology would be helpful and if already submitted, could you reattach specifically to your response for the purpose of clarification?
4. How do the vehicle model and the soil model interface during the simulation?
5. How has your solution been made available for commercial use (e.g., soft soil applications for agriculture or heavy earth moving or other?) Do you have a special designation or name for this particular simulation solution?
6. Have you previously validated your soft soil model through physical test and if so when did this occur? How widely distributed within the commercial or government user market is your soft soil simulation solution?

Because of the limited amount of time provided to the organizations to develop a response and the fact that follow-up questions and explanations had to be limited due to time constraints, a simpler scoring methodology was utilized. The criteria for meeting an A through D level response was developed and the various responses were scored accordingly. The criteria and results are shown below.

Table 10-19. Additional Questions Scoring Criteria

	1. How is the vehicle to soil interaction simulated for off road operations within your solution?	2. Is the vehicle system formulated in multibody dynamics code or in finite element code? Is the simulation of the vehicle run separately from the vehicle to soil interaction or does a co-simulation process exist?
A	Complete technical response explaining approach to vehicle soil interaction identifying approach beyond Bekker-Wong and referencing information provided within RFI	Vehicle and terrain fully integrated approach. Co-simulation discussed where appropriate. Fully integrated physics-based discussion of multibody vehicle, flexible body and soil interaction, reference to both time and frequency domain.
B	Methodology referenced but not completely explained. Approach more vague but includes explanations involving FEA, DEM, or other more physics-based approach to soil mechanics, sinkage and soil shoving approaches described	Examples of co-simulation or integrated simulation provided including multi body dynamics. Fewer details or examples provided. Some work in progress referenced and solution not complete
C	Explanation and methodology limited to Bekker-Wong or use of a combination of empirical and other traditional soil mechanics relationships (Janosi-Hamamoto) Explanation of physics-based approach is very limited and is not clearly defined or solution is referenced as provided by another source for soil mechanics. DEM or other more detailed representations not provided	Separate codes utilized. Integration or interaction of codes not fully described. MBD integrated with other tire or track terrain interface models. Ability to maintain full dynamic interaction between MBD vehicle system and terrain not completely explained
D	Vague or incomplete response. Capability not developed	Vague or incomplete response. Capability not developed

	3. Does your solution utilize a classical terramechanics approach (Bekker-Wong) or does your solution utilize an alternative approach such as discrete elements or finite element analysis? A description of your methodology would be helpful and if already submitted, could you reattach specifically to your response for the purpose of clarification?	4. How do the vehicle model and the soil model interface during the simulation?
A	DEM, FEA or other physics-based approach described. Soil variables accounted for, examples of dynamic sinkage and terrain soil interaction provided.	Clear description of the methodology utilized to integrate vehicle and soil interaction. Examples provided.
B	Description of methodology not complete but expanded beyond traditional Bekker-Wong. Integration of component models with deformable soil representations described. DEM in progress but not fully developed or released. FEA methods described. Methods not applied to both vehicle types (tracked and wheeled) but work in progress.	Methodology not as well defined. Generic examples provided or identified as work in progress. Actual tire to soil or track to soil dynamics and resulting soil deformation or load reaction not as well defined but discussed.
C	Only provides Bekker-Wong or traditional VCI/RCI parameters from NRMM. Physics-based soil interaction not well explained or references as potential work in progress for the future.	Solution explained in relatively simple terms or identified as using Bekker-Wong or other traditional (Janosi-Hamamoto) relationships. Empirical relationships or look up tables identified from other soil dynamics criteria. Soil strength variables and interaction with tire or track contact points not well defined. Dynamic shear response not fully explained.
D	Terramechanics capability not well explained, vague references to Bekker-Wong or existing NRMM tools.	Vague or incomplete response. Capability not developed.

	5. How has your solution been made available for commercial use (i.e., soft soil applications for agriculture or heavy earth moving or other?) Do you have a special designation or name for this particular simulation solution?	6. Have you previously validated your soft soil model through physical test and if so when did this occur? How widely distributed within the commercial or government user market is your soft soil simulation solution.
A	Tool deployed and accepted within Industry or Government. Examples of users provided relative to the intended use of Next Generation NRMM.	Validation examples provided for wheeled and tracked vehicles. Discussion of intended upgrades and lessons learned based on validation efforts
B	Tool partially developed or deployed to other users. Beta sites identified. Ongoing research and investments discussed and provided. Discussion of multi-platform evaluations ongoing.	Partial validation provided. System use for prediction purposes and prediction of fielded systems. Developmental examples provided or in process. Full vehicle systems identified including correlation to test results such as sinkage or tractive effort or dynamic response
C	Tool only deployed in an R and D or development capacity, only used by provider to support development contracts	Validation only at the component or laboratory level. Full system validation information not provided. Prediction of vehicle performance correlated with actual test results not provided
D	No Deployment outside of provider, no example of use by others or for other system evaluation for designated customers	No validation information provided

Table 10-20. Additional Questions - Organizations A through F

Question	Organization A	Organization B	Organization C	Organization E	Organization F
1. How is the vehicle to soil interaction simulated for off road operations within your solution?	C	A	B	C	C
2. Is the vehicle system formulated in multibody dynamics code or in finite element code? Is the simulation of the vehicle run separately from the vehicle to soil interaction or does a co-simulation process exist?	B	A	B-	B-	B
3. Does your solution utilize a classical terramechanics approach (Bekker-Wong) or does your solution utilize an alternative approach such as discrete elements or finite element analysis? A description of your methodology would be helpful and if already submitted, could you reattach specifically to your response for the purpose of clarification?	B-	A	C+	C-	C
4. How do the vehicle model and the soil model interface during the simulation?	B-	A	B	C	A
5. How has your solution been made available for commercial use (i.e., soft soil applications for agriculture or heavy earth moving or other?) Do you have a special designation or name for this particular simulation solution?	C	C	B	C	A
6. Have you previously validated your soft soil model through physical test and if so when did this occur? How widely distributed within the commercial or government user market is your soft soil simulation solution.	C	B-	B+	D	B+
Average Grade	C+	B+	B	C	B
Equivalent Score	**0.73**	**0.81**	**0.76**	**0.69**	**0.77**

Table 10-21. Additional Questions - Organizations G through K

Question	Organization G	Organization H	Organization I	Organization J	Organization K
1. How is the vehicle to soil interaction simulated for off road operations within your solution?	A	B	C	A	A
2. Is the vehicle system formulated in multibody dynamics code or in finite element code? Is the simulation of the vehicle run separately from the vehicle to soil interaction or does a co-simulation process exist?	A	B	B	A	B
3. Does your solution utilize a classical terramechanics approach (Bekker-Wong) or does your solution utilize an alternative approach such as discrete elements or finite element analysis? A description of your methodology would be helpful and if already submitted, could you reattach specifically to your response for the purpose of clarification?	B	C	C	A	A
4. How do the vehicle model and the soil model interface during the simulation?	A	A	C	A	A
5. How has your solution been made available for commercial use (ie soft soil applications for agriculture or heavy earth moving or other?) Do you have a special designation or name for this particular simulation solution?	A	D	A	A	B-
6. Have you previously validated your soft soil model through physical test and if so when did this occur? How widely distributed within the commercial or government user market is your soft soil simulation solution.	B+	C	D	C+	C
Average Grade	A-	B-	C+	A-	B+
Equivalent Score	**0.84**	**0.74**	**0.73**	**0.84**	**0.79**

10.7 SUMMARY OF RESULTS

It was determined that currently available tools exist which can fill most of the committee needs. Many of the solutions met above threshold or objective levels in the given criteria of Accuracy, Flexibility, Cost, and NATO specific applications.

Accuracy for vehicle system performance is the biggest limitation of the current NRMM. Validated physics-based methods will potentially be an improvement over the current empirical methods for evaluating original vehicle and suspension designs. Likewise known NRMM shortfalls with tire dynamics and soft soil behavior can be addressed with new methods and be in a position to meet the emergence of deformable terrain contact models.

Additional findings show that industry as a whole is providing solutions that are well supported not only in terms of technical support but also the accessibility to support with many organizations boasting a worldwide presence. This increased use in industry has led to broader applications such as robotics, powertrain, engine combustion, aviation industry, etc. This, in turn has created a substantially increased user base with multiple users at each site. This has further assisted the development of various licensing structures that allow streamlined use and increased firewall protection for the users and ultimately decreased costs. Another by-product of commercial solutions becoming more mainstream over the past few decades is the increased ease of use by implementing more template-based solutions and additional GUI options and adaptations as opposed to expert user requirements noted for some open source solutions. This increased usage and worldwide support also equates to many commercial solutions having the ability to support NATO-specific applications while maintaining, supporting, and protecting NATO members who are users.

Currently, there is no other NATO Government approved mobility analysis tool solution available. As noted above, there are both commercially based software and potentially university developed (“open source”) solutions that are available which, based on the information submitted, can meet the needs established by the committee for next generation NRMM. Developing a new start solution has potential drawbacks as seen with the current NRMM, particularly as it relates to a permanent funding and organizational support effort. A responsible organization will help to address some of the issues that are prevalent now such as various software releases, outdated versions, and invalidated add-on modules circulating throughout the user community (configuration management). This will constitute the need for a continuous funding stream. This then benefits the user community with up-to-date software versions to all users, consolidated training which insures proper use, and standardization of processes and data formats for more seamless data flow within the user community. The committee discussed potential funding sources and the effort will continue to solicit and provide that funding to support the future RTG effort. Before this can be implemented, however, there remains significant work to be done to establish appropriate controls, formats and validation verification methodologies to approve any new tool and insure it benefits the user community. The current priorities identified in the initial MOE/MOP process were adequate for an initial query of industry but with the realized influx of information and the knowledge gained, the existing MOE/MOP may need to be reviewed and updated. Examining items such as mobility as a survivability enhancement feature is emphasized for current and future vehicle development.

10.8 RECOMMENDED NEXT STEPS

Continued Evaluation for Validation

As discussed in the summary of results, it is apparent that the multibody dynamic tools which are available from commercial and university sources are capable of supporting the analysis and prediction of wheeled and tracked vehicle systems over deformable soil conditions. However, the focus of most of these tools has been for commercial vehicle system development. Many of the potential providers are not fully familiar with all of the capabilities of the existing NRMM, particularly as it relates to developing specific terrain units which are appropriate for worldwide deployment. The strength of the tools varies; some are capable and have been thoroughly validated for on-road operation and yet only limited off-road deformable soils work has been accomplished. Others focused primarily on off-road soft soil terrain but have no capability for determining on-road stability and associated dynamic control. All of the information submitted by the various organizations in response to the RFI had very limited validation and verification information. In some cases this was due to the fact that the data was controlled by the OEM who provided all of the vehicle details; in other cases, the work was purely theoretical and the tools had not been compared to physical results. Some of the validation was conducted on events which are not representative of the worldwide deployment requirements. For this reason it was determined that additional validation and verification is required to better quantify the functionality of the various tools.

To rapidly complete this validation effort it is necessary to have measured vehicle and associated test data to compare against the predictions. Theme 5 made a set of Recommendations for Benchmarking the tools described above to Theme 7, the team dealing with Verification and Validation. Theme 5's recommendations are contained in Appendix F.

10.9 CONCLUSIONS

The results of this effort indicate that a variety of organizations and tools exist and have previously demonstrated the ability to accurately simulate complex vehicle system performance on both deformable and non-deformable surfaces. Further, data exists which can be used to evaluate and validate the performance of any new tool set while including the latest in ground vehicle system technology. These advances are primarily driven by investment from commercial industry and are focused on those environments. These results demonstrate that it will not be necessary to initiate a new, expensive, and time consuming development effort. However, because the needs of the NATO community are unique, particularly in the area of providing predictions of soft soil mobility while utilizing temporal environmental information, additional investment in the validation of potential tools and solutions will be required.

Existing solutions support both tracked and wheeled vehicle three-dimensional, physics-based multibody dynamic analysis and therefore it is anticipated that one simulation environment can provide mobility analysis for combat and combat support vehicle systems. However, recent mobility performance data for new vehicle systems are relatively limited. Therefore investment in detailed measurement efforts to quantify tire or track terrain interface in order to support the tool validation process should be anticipated.

The validation and verification next step effort must consider the vehicle as a system and not be unnecessarily focused on the tire or track interface. Suspension and powertrain dynamics which provide the most uniform ground contact pressure and uniform power delivery have demonstrated best soft soil mobility. Success of future tools will be dependent upon the ability of these tools to accurately represent the environment and the vehicle system reaction to that environment.

As noted by the committee, pure mobility measurement over a homogenous soil represents a small but important part of the current NRMM tool. Predicted speed made good, dash speed, performance over individual terrain units, visibility, etc. are all aspects of the current NRMM which can be addressed by the future MBD tools. As noted in the summary of results, the available tools are affordable, supported worldwide and are able to quickly complete mobility predictions once all necessary parametric data has been input. Revisiting the criteria and level of importance for each of the evaluation elements throughout the next step process will be important to the success of the effort. Continued interaction with industry has verified that physics-based MBD tools exist which meet the various criteria including affordability. Furthermore by implementation of multi-core co-simulation techniques, industry has proven that high-speed computing capability, while helpful, may not be essential. Available modularity in the various analysis codes has helped to insure necessary flexibility to address future concepts and designs. Next step determination of Verification and Validation techniques, configuration management, software release version management, etc. will be essential to the success of the effort given the substantial increase in emphasis on enhanced vehicle mobility. .

Based on the information gathered it is recommended that the evaluation process continue as replacement/update of the current NRMM is critical. Knowledge of geotechnical properties and knowledge of vehicle system properties including electronic controls will be essential to the success of the effort. Substantial additional funding requirements are anticipated to support this more detailed validation and verification effort. It is recommended that a tiered approach be taken, evaluating potential solutions against the relatively simpler events and then including the more challenging soft soil traction, turning, obstacle avoidance, and negotiation events. It is recommended that worldwide events, significant to the various countries and operational environments be included. Based on the current participation and capabilities within the committee the following support could be considered.

Road roughness – Conditions in Turkey run the gamut, from original stone roads from Roman times to the most advanced highway system technology. Substantial investment and knowledge of these conditions and use of that data will help insure a representative and robust solution for the broad range of road and trail roughness.

Environmental variables – USA CRREL has spent many years in the study of erosion, freeze thaw impacts on soil strength, trail roughness measurement, and how the terrain conditions change with traffic. This input will be very helpful to the future validation process.

Soft soil conditions – Estonia – Their current efforts to accurately quantify soil type, plastic and liquid limit, impact on ground bearing strength, correlation to ground contact pressure, and their available data on a range of load and tire deflections will add substantially to the available database. This support can be used for both input to simulations and for validation purposes.

Impact on mobility and soil strength as a function of vegetation spacing, root structure, and demands on maneuver – Czech Republic – Their significant studies on the impact of vegetation on soil strength and structure, and thus the demands on vehicle tractive effort and uniform ground contact pressure, can provide essential measurement, test, and validation data in support of next generation tool evaluation.

Overarching application of next generation tool – Canada – Their current work in evaluation of both single and multiple vehicle system performance and identification of critical output elements for the purpose of vehicle capability evaluation and comparison will be essential toward the future tool development.

Application of alternative metrics – Germany – The limitations of single axis measurements such as vertical absorbed power (6 Watt) have been fully recognized and as such Germany has implemented alternative ISO-based dynamics measurements and associated simulation development. Such a three-dimensional validation approach to account for the performance of the entire vehicle system over complex terrain will be essential for the success of the next generation simulation environment.

Vehicle dynamics analysis – Denmark – Based on investment in vehicle safety, vehicle handling, and surface to vehicle interaction, their support to properly define representative events for vehicle stability and control, validation of the simulations for those events, and the integration of those events into the overall mission profile will help insure that the final next generation solution will successfully address vehicle performance on surfaces with low coefficients of friction.

With full NATO support the team can be assembled to properly evaluate each step of the validation and verification process and can insure that the subsequent tool selection can successfully meet the necessary range of conditions for worldwide deployment.

Chapter 11 – THEME 6: INPUT DATA AND OUTPUT METRICS

Brian Wojtysiak

11.1 GOALS AND DELIVERABLES

The goal of the Input Data / Output Metric subcommittee (Theme 6) is to define the Input / Output data requirements that will inform the Next-Generation NRMM tool development / selection processes.

The Input Data / Output Metric subcommittee (Theme 6) intends to develop the following set of deliverables including:

- A list of important NRMM inputs parameters / variables
- A list of output products that should be generated by the Next-Generation NRMM
- Identification of proper data resolution levels for inputs / outputs
- Identification of any potential data standards (OGC compliant)
- Identification of key input / output considerations that will shape / affect the software system design

11.2 INPUT DATA / OUTPUT METRIC SUBCOMMITTEE MEMBERSHIP

On August 26, 2014, the NATO AVT ET-148 Study Leadership established the Input Data / Output Metric subcommittee (Theme 6); and, on September 08, 2014, asked representatives from the US Army Materiel Systems Analysis Activity (AMSAA) to lead it. As mentioned above, the subcommittee membership (listed below) was asked to further refine the Input / Output requirements that were derived from an initial NRMM Modernization survey, distributed to the committee membership, which solicited feedback on the positive / negative aspects of the current NRMM and areas where improvements were needed.

The theme members are shown below:

Country	**Name**
Canada	Mayda, William
Czech Republic	Rybansky, Marian
Estonia	Vennik, Kersti
USA	Gunter, David
USA	Jayakumar, Paramsothy
USA	Letherwood, Michael
USA	Ngan, James
USA	Shoop, Sally
USA	Ward, Derek
USA	**Wojtysiak, Brian: Leader**

11.3 INPUT DATA / OUTPUT METRIC REFINEMENT APPROACH AND RESULTS

In preparation for discussions at the NATO meetings in Brussels, Belgium from October 13-17, 2014, the subcommittee grouped the Input / Output data feedback received from the committee into four (4) main categories of data that loosely correlate with the existing data categories utilized within the NRMM framework. These data categories were:

1. Vehicle Data
2. Terrain Data
3. Environment / Scenario Data
4. Operator Data

Over the course of the ET, these data categories evolved to incorporate three (3) additional data categories (in addition to the four (4) identified above):

5. Human Factors Data
6. Autonomous / Semi-Autonomous Vehicle Data
7. Scale / Resolution Modes

In addition to capturing the types of data needed to support the modeling effort, the subcommittee needed to consider other critical Input / Output data factors including:

- Finding a balance between model fidelity, availability of required input data, time to construct model input data sets, model execution runtimes, and desired output products
  - The model must be able to model everything from paper concepts to detailed engineering designs
  - The model must be able to allow for quick input file construction (i.e. willing to sacrifice some fidelity to conduct analyses for short suspense items)
  - The model's minimum Input data requirements must consider the level of data available (at all data resolution levels throughout the system's development / acquisition cycle)
- Incorporating data elements needed to evaluate "new" vehicle technologies (i.e. physical implementations, control systems, autonomous systems, bipedal movement)
- Enabling the Next-Generation NRMM to handle time-series data
- Developing mechanisms for updating NRMM's "static" terrain libraries to reflect new operational areas of interest / evolving terrain conditions
- Identifying what terrain response characteristics are needed:
  - Currently NRMM factors in deformable soils, snow / ice, vegetation, obstacles, surface roughness, amphibious operations, weather effects
  - "Non-traditional" terrain surfaces (e.g. robotic platforms – carpet, slate, tile, etc.)
- Identifying what improved human factors representations are needed:
  - NRMM currently considers vibration doses, visibility, response times, etc. Are there others?
  - Do we need to modify any of these approaches (i.e. vibration dose at multiple vehicle locations, seated vs. supine – e.g. casualty evacuation)?
- Improving User Interface / Data Validation and Error Handling to ensure erroneous results are not inadvertently generated due to a user's lack of familiarity with the model parameters / user inputs
- Determining the modes of operation:
  - Batch vs. Individual runs

    - Real-time vs. Non-Real-time
    - User Experience and / or Role-Based Interfaces (Novice, Intermediate, Advanced or Developer, Practitioner, Supervisor / Practitioner, Novice / Operational User)
- Defining the output products / level of detailed needed:
    - Common, easy to understand metrics for leadership/stakeholders
    - Detailed, intermediate metrics (e.g. reason codes, rut depth, overriding forces) for the subject matter expert to provide insights on final results
- Defining all “potential” mobility metrics
    - Current: Trafficability (GO/NOGO), “speed made good,” VCI
    - Next-Gen: Other on-road mobility metrics (e.g. acceleration, maneuvers) applied to off-road performance; path-finding; operational scenario metrics (e.g. mission time, speed), etc.
- Characterizing uncertainty associated with precision of model input data
    - Stochastic vs. Deterministic approach
- Reducing time / effort needed to summarize results into products that are easy-to-understand
- Ensuring Next-Generation NRMM conforms to commercial, military, and open source vehicle and geospatial analysis data standards to promote data interoperability with other analysis tools / data sources

Following the meeting in Brussels, Belgium, the Input / Output subcommittee further refined the Input / Output requirements and decomposed the Input / Output data categories into smaller and smaller data elements (e.g. subsystems, assemblies, components, data elements).

For example, the Vehicle Information category was decomposed into smaller data segments including:

1. Vehicle Physical Dimensions
2. Traction Information
3. Driveline Information
4. Suspension Information
5. Multi-Axle / Multi-Unit Considerations
6. Other

Following this step, the subcommittee identified the data elements within each of these sub-classifications. For example, the additional data deconstruction for the Vehicle Driveline is outlined below:

1. Driveline Information
    a. Engine Parameters
        i. Mass
        ii. Moment of Inertia (3 axes)
        iii. Mounting Locations
        iv. Rotating Mass (Crankshaft) Inertia
        v. Mounting Locations
        vi. Mount Stiffness (Force vs. Displacement) (all directions)
        vii. Damping Force vs. Velocity
    b. Power / Torque Curves

c. Torque Converting Characteristics
    i. Mass
    ii. Moment of Inertia
    iii. Center of Gravity Location
    iv. Locking Logic
d. Transmission Characteristics
    i. Mass
    ii. Moment of Inertia
    iii. Center of Gravity Location
    iv. Mounting Location
    v. Mount Stiffness (Force vs. Displacement) (all directions)
    vi. Damping Force vs. Velocity
    vii. Number of Gears and Ratios
    viii. Efficiency
e. Shifting Logic
f. Differential / Gear Hubs
    i. Mass
    ii. Moment of Inertia
    iii. Center of Gravity Location
    iv. Mounting Location
    v. Mount Stiffness (Force vs. Displacement) (all directions)
    vi. Damping Force vs. Velocity
    vii. Number of Gears and Ratios
    viii. Efficiency
g. Hybrid / Electric Powerplants – Regeneration
h. Turning Diameter / Skid Steer
i. Engine Fuel Map
j. Engine Cooling Demands

The complete decomposition is reflected in Tables 11-2 to 11-4 which follow.

A similar process was used to map / trace the inputs to the output products / decisions supported. The Input / Output subcommittee developed an initial list which was shared and vetted with the NATO AVT ET-148 membership at the NATO meeting in Rzeszow, Poland. The final list of Output Products / Output Considerations approved by the membership of NATO AVT ET-148 is captured in Table 11-5 below.

Finally the Input / Output subcommittee generated a series of “Other Data Input / Output Factors to Consider”. These factors include:

1. Data Availability
2. Data Resolution / Scale
3. Customization Capability
4. Stochastic vs. Deterministic
5. Open Source/GOTS vs. Proprietary

6. Future Growth
7. Ease of Use / Reuse
8. Steady State vs. Non-Steady State Behavior
9. Real-time vs. Non-Real-Time
10. Data Standards
11. Spatial Data Capabilities
12. User Interface – GUI / Command Line
13. Modes of Operation

Each of these “Other Factors” are explained in more detail in Table11-6 (which follows).

	Classification	Parameters	Used to determine	GIS applications
Vehicle Info	Vehicle Dimensions	Length, Width, Height, Frontal / Side Profile	Envelop clearance (tunnels, bridges, overhead wires...), frontal area (aerodynamics)	Go / No-Go constraints for urban terrain mobility analysis
		Bottom profile (3 dimensional)	Under carriage clearance	Obstacle Go / No-Go Layer
		Clearance	Under carriage clearance	Obstacle Go / No-Go Layer
		Hard points (e.g. control arms, bump stops, rebound stops, spring / shock mounts, tie rod, wheel center, drive shaft, sub-frame, anti-roll bar, spring lengths)	Forces acting upon components, deflection of components under stress	
		Mass / Material properties (mass, material strength, cg location, moments, force vs. velocity curves, forces vs. displacement curves, etc)	Forces acting upon components, deflection of components under stress	
		Pushbar height / geometry (i.e. frontal area - CAD representation?)	Go / No-Go in vegetation area (override vegetation force)	Vegetation Go / No-Go Layer
	Traction Info	Wheeled vehicle: Tire size, Outside Diameter, rim diameter, deflection, rolling radius, ground contact area (tireprint), number of axles, number of tires per axle (dual, single), axle spacing, tread width, tread depth, track width, tire inflation pressure (static vs. dynamic - CTIS); tire construction materials; tire models	Tire factor, speed limitation due to tire type, VCI	Tire speed limiter layer, Go / No-Go layer
		Tire type: Pneumatic vs. non-pneumatic; type bias ply, radial, rigid, airless, run-flat	Tire factor, speed limitation due to tire type, VCI	Tire speed limiter layer, Go / No-Go layer
		Tracked vehicle: Track length, track width, ground contact area, grouser height / pitch, track shoe area, roadwheel spacing, idler / sprocket / roadwheel radius; track models; track tension	Track factor, ground factor, VCI	
		Non-standard vehicles: Bi-pedal robots, driven wheel hubs, etc.	Track factor, ground factor, VCI	
		Slip at maximum drawbar pull - Mu slip / Mu alpha curve	Tractive effort	
		Braking coefficient / transmission retarder / engine braking	Maximum braking force, stopping distance (No-Go if visibility distance < stopping distance)	Visibility
		CG height - position (x, y, z)	Rollover characteristics	
		Right track / Left track path (e.g. 2D bicycle model to 3D model)	Ride dynamics, Vehicle Trafficability (VCI)	
		GVW, CG location (height, longitudinal, lateral), Weight per axle, Spring / damping characteristics	Ride dynamics, Vehicle Trafficability (VCI)	Ride dynamic speed limit layer / Go / No-Go layer

Table 11-2: Vehicle Information Parameters (Dimensions, Traction Information) (1 of 2)

	Classification	Parameters	Used to determine	GIS applications
Vehicle Info	Driveline Info	Engine parameters (mass, moment of inertia (3 axes), rotating mass (crankshaft) inertia, mounting locations, mount stiffness (force vs. displacement) (all directions), damping (force vs. velocity)	Tractive effort	
		Power / torque curves	Tractive effort	Tractive effort Go / No-Go layer
		Torque converter characteristics (e.g. mass, moment, cg location) / locking logic	Tractive effort	Tractive effort Go / No-Go layer
		Transmission characteristics: mass, moments, cg location, mounting locations, mount stiffness (force vs. displacement) (all directions), damping (force vs. velocity), number of gears and ratios, efficiency	Tractive effort	Tractive effort Go / No-Go layer
		Shifting logic	Tractive effort, Fuel Performance	Tractive effort Go / No-Go layer
		Differential / gear hubs: mass, moments, cg location, mounting locations, mount stiffness (force vs. displacement) (all directions), damping (force vs. velocity), number of gears and ratios, efficiency	Tractive effort, Fuel Performance	Tractive effort Go / No-Go layer
		Hybrid / Electric Power Plants - Regeneration	Tractive effort, Fuel Performance	Tractive effort Go / No-Go layer
		Turning Diameter / Skid Steer	Urban Maneuverability	Go / No-Go constraints for urban terrain mobility analysis
		Engine Fuel Map	Fuel Performance	
		Engine Cooling Demands	Degradation in Tractive Effort	Tractive effort Go / No-Go layer
	Suspension Info	Subsystem Characteristics	Ride dynamics, Vehicle Trafficability (VCI)	Ride dynamic speed limit layer / Go / No-Go layer
	Multi-axle / Multi-unit Info	Trailers, multiple steered axles, tandem trailers, etc.	Dynamics / Maneuverability	
	Other	Drawbar, rolling resistance	Tractive effort	Tractive effort Go / No-Go layer
		Parasitic power losses - cooling fans, vehicle electronics, etc.	Loss of propulsion power - reduced tractive effort	Tractive effort Go / No-Go layer
		Control logic - Electronic Stability Control / Traction Control / Anti-Lock Braking / Active and Semi-Active Suspension Systems	Vehicle intervention to maintain stability / control	
		Environmental factors - (e.g. hot vs. cold effects)	Loss of propulsion power - reduced tractive effort	Tractive effort Go / No-Go layer
		Operation with degraded state	Vehicle Trafficability (VCI), Speed limiter	All GIS layers
		Swimming / fording speeds	Go/No-Go in water	Water bodies Go / No-Go layer

Table 11-2: Vehicle Information Parameters (2 of 2)
(Driveline, Suspension, Multi-Axle / Multi-Unit, Other)

	Classification	Parameters	Used to determine	GIS applications
Terrain	**Spatial Orientation**	Spatial orientation of data (lat / long, MGRS, etc), vector feature data (point, lines, polygons), raster data (DTED, LIDAR, etc), Compliant with GIS data standards	Spatial capabilities, Ability to quickly / easily update terrain data	All GIS layers
	Off-road	Surface slope (%)	Slope resistance	Slope Go / No-Go Layer
		Surface materials (soil type, soil classification system, soil moisture), soil cohesion, snow depth / density, soil strength (RCI, CI), hard surface rolling resistance, soil sinkage, soil compaction / density, frost / thaw depth, split mu - gravel shoulder, road edge, surface material reflectance	Soil resistance, VCI (FGS, CGS, Muskeg) - bearing capacity / sheer strength, reflectance affects autonomous sensing capabilities	Soil strength Go / No-Go Layer
		Surface roughness	Go / No-Go area, speed limiter	Ride dynamic speed limit layer
		Natural obstacles: cliffs, ridges, trenches, mounds, embankment climbing, ...	Go / No-Go area, speed limiter	Obstacle Go / No-Go Layer, Maneuverability layer, Amphibious Egress Locations
		Man made obstacles: cuts, pipe lines, rubble piles	Go / No-Go due to obstacles	Obstacle Go / No-Go Layer, Maneuverability layer
		Non-standard terrain surface materials: friction co-efficients / rolling resistances for surfaces such as tile, carpet, slate floors, etc.	Go / No-Go area, speed limiter	Ride dynamic speed limit layer, Obstacle Go / No-Go Layer
		Vegetation, stem size, stem spacing	Go / No-Go due to vegetation	Vegetation Go / No-Go layer, Maneuverability layer
		Water bodies: lakes, ponds, oceans, streams, surf zones, drainage (rivers, canals), velocity of flowing water	Go / No-Go, speed limiter due to water bodies	Limit accessible area, Water Go / No-Go Layer
		Number of vehicle passes (e.g. V1 vs. V50)	Go / No-Go limiter	Limit accessible area
		Railroad tracks	Limit accessible area	Limit accessible area
	On-road	Road super elevation angle	Sliding, tipping, rollover	Urban mobility
		Road width	Go / No-Go in urban terrain	Urban mobility
		Surface type / roughness coefficient	Speed limiter	Ride dynamic speed limit layer
		Road radius of curvature	AASHTO curvature speed limit, sliding, tipping, rollover	Urban mobility
		Infrastructure Limitations - Military Load Classification of Bridges, pavement weight capacity limits, etc	Go / No-Go limiter	Limit accessible area
		Overhead (overpass, wire, bridge)	Go / No-Go due to overhead clearance	Urban mobility
Scenario		Snow covered, ice covered roads	On road surface traction condition	
		Day / Night	Visibility / Sensor performance	
		Dry, Wet, Wet-Wet, Snow, Sand, Fog	Soil strength per operating scenario, Visibility	Soil Go / No-Go layer

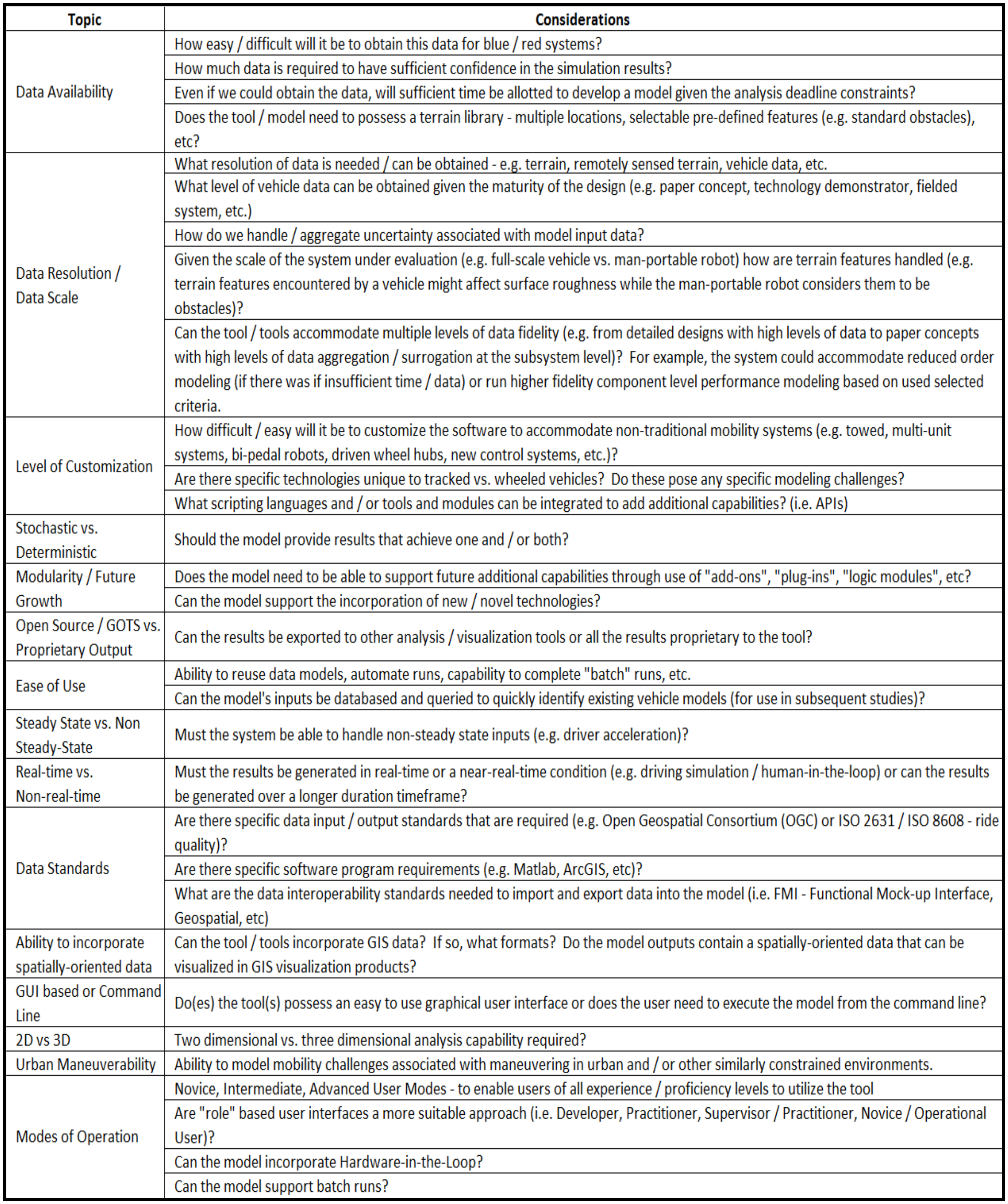
Table 11-3: Terrain / Scenario Parameters

Classification	Parameters	Used to determine	GIS applications
Human Factors	Ride / shock	Speed limitation due to "comfort"	Ride dynamic speed limit layer
	Multiple ride / shock locations	Speed limitation due to "comfort" - e.g. driver seat and MEDEVAC litter	Ride dynamic speed limit layer
	Eye height	Go / No-Go, Visibility controlling speed for each slope	
Operator Behavior	Path / Line Selection (requires time series capability) / driver model	Dynamics / Maneuverability, Sliding, tipping, rollover	
	Visibility	Speed limiter	
	Response time (e.g. braking)	Speed limiter	
	Human-in-the-loop feedback	Dynamics / Maneuverability, Sliding, tipping, rollover, speed limiter	
	Non-steady-state behavior (e.g. acceleration / deceleration, steering inputs, etc.)	Dynamics / Maneuverability, Sliding, tipping, rollover	
Autonomous Semi-Autonomous Vehicles	Situational Awareness - Sensor Height, Sensor Range, Sensor Resolution, GPS location, GPS error, inertial navigation schema, inertial navigation limits	Ability to sense environment	
	Autonomy Level - full, teleoperation, semi-autonomous, shared control, none, etc.	Ability to remotely communicate / operate system remotely	
	A-priori terrain knowledge	Ability to navigate / respond to environmental stimuli	
	Decision logic / control systems	How the system will respond to environmental stimuli	
	Constrained by Traffic rules (lanes, signals, speed limits)	How the system will respond to environmental stimuli	
	Performance limits (e.g. vibration levels to prevent damage to electronic circuitry / sensor degradation, temperature / humidity effects, slippage, balance / stability issues, etc)	Speed limitation due to "comfort", performance degradations	Ride dynamic speed limit layer
	Performance limits associated with any payloads - (i.e. vibration limits for sensor suites, munitions, etc)	Speed limitation due to "comfort", performance degradations	Ride dynamic speed limit layer
	Teleoperation - RF communication capability, latency / lag time in communication between system / operator; Use of pre-determined "waypoints", human-in-the-loop inputs; bandwidth / spectrum limitations	Ability to remotely communicate / operate system remotely	
Scale / Resolution Modes	System level, Subsystem Level, Component Level	Ability to support all data fidelity levels	
	Empirical Soil / Detailed Soil (Physics-based)	Ability to support all data fidelity levels	

Table 11-4: Humans Factors, Operator Behavior, Autonomous / Semi-Autonomous and Scale / Resolution Parameters

Item #	Output Products / Output Considerations
1	Cartographic Map products and / or spatially-oriented data that can be imported into a GIS visualization tool (OGC / Military Compliant)
2	Speed comparisons between vehicles / Top Speed
3	Trafficability comparisons between vehicles
4	No-Go / Speed limiting reason codes
5	Vehicle stability / handling results - lateral acceleration, static / roll stability, etc.
6	Urban Maneuverability Modeling
7	Path Modeling
8	Obstacle Negotiation
9	Backward compatibility to previous NRMM model (VCI / RCI)
10	Fuel Consumption / Economy
11	Vehicle Range
12	Acceleration / Deceleration Characteristics
13	Separate On-road vs. Off-Road Performance Summary
14	Minimize Effort Required to Post-Process Model Results into Analytical Products
15	Multiple output product levels - operational, engineering-level, etc.
16	Spatial analysis considerations in result generation (e.g. elimination of spatial No-Go "islands")
17	Uncertainties associated with Output Values
18	Powertrain and braking torque applied at each traction element (e.g. wheel, track element)
19	Buoyancy / Amphibious Speed
20	Ride Quality / Absorbed Power
21	Minimum Turning Radius - wall-to-wall, curb-to-curb
22	Maximum grade capability - longitudinal and vertical
23	Portability to real-time simulator
24	Error Handling / Diagnostic Reason Codes- Easy to troubleshoot
25	Multi-pass vs. Single Pass results
26	Average and Minimum RCI values
27	Rut depths with spatial location data

Table 11-5: Necessary Next-Gen NRMM Output Products / Considerations



Topic	Considerations
Data Availability	How easy / difficult will it be to obtain this data for blue / red systems?
	How much data is required to have sufficient confidence in the simulation results?
	Even if we could obtain the data, will sufficient time be allotted to develop a model given the analysis deadline constraints?
	Does the tool / model need to possess a terrain library - multiple locations, selectable pre-defined features (e.g. standard obstacles), etc?
Data Resolution / Data Scale	What resolution of data is needed / can be obtained - e.g. terrain, remotely sensed terrain, vehicle data, etc.
	What level of vehicle data can be obtained given the maturity of the design (e.g. paper concept, technology demonstrator, fielded system, etc.)
	How do we handle / aggregate uncertainty associated with model input data?
	Given the scale of the system under evaluation (e.g. full-scale vehicle vs. man-portable robot) how are terrain features handled (e.g. terrain features encountered by a vehicle might affect surface roughness while the man-portable robot considers them to be obstacles)?
	Can the tool / tools accommodate multiple levels of data fidelity (e.g. from detailed designs with high levels of data to paper concepts with high levels of data aggregation / surrogation at the subsystem level)? For example, the system could accommodate reduced order modeling (if there was if insufficient time / data) or run higher fidelity component level performance modeling based on used selected criteria.
Level of Customization	How difficult / easy will it be to customize the software to accommodate non-traditional mobility systems (e.g. towed, multi-unit systems, bi-pedal robots, driven wheel hubs, new control systems, etc.)?
	Are there specific technologies unique to tracked vs. wheeled vehicles? Do these pose any specific modeling challenges?
	What scripting languages and / or tools and modules can be integrated to add additional capabilities? (i.e. APIs)
Stochastic vs. Deterministic	Should the model provide results that achieve one and / or both?
Modularity / Future Growth	Does the model need to be able to support future additional capabilities through use of "add-ons", "plug-ins", "logic modules", etc?
	Can the model support the incorporation of new / novel technologies?
Open Source / GOTS vs. Proprietary Output	Can the results be exported to other analysis / visualization tools or all the results proprietary to the tool?
Ease of Use	Ability to reuse data models, automate runs, capability to complete "batch" runs, etc.
	Can the model's inputs be databased and queried to quickly identify existing vehicle models (for use in subsequent studies)?
Steady State vs. Non Steady-State	Must the system be able to handle non-steady state inputs (e.g. driver acceleration)?
Real-time vs. Non-real-time	Must the results be generated in real-time or a near-real-time condition (e.g. driving simulation / human-in-the-loop) or can the results be generated over a longer duration timeframe?
Data Standards	Are there specific data input / output standards that are required (e.g. Open Geospatial Consortium (OGC) or ISO 2631 / ISO 8608 - ride quality)?
	Are there specific software program requirements (e.g. Matlab, ArcGIS, etc)?
	What are the data interoperability standards needed to import and export data into the model (i.e. FMI - Functional Mock-up Interface, Geospatial, etc)
Ability to incorporate spatially-oriented data	Can the tool / tools incorporate GIS data? If so, what formats? Do the model outputs contain a spatially-oriented data that can be visualized in GIS visualization products?
GUI based or Command Line	Do(es) the tool(s) possess an easy to use graphical user interface or does the user need to execute the model from the command line?
2D vs 3D	Two dimensional vs. three dimensional analysis capability required?
Urban Maneuverability	Ability to model mobility challenges associated with maneuvering in urban and / or other similarly constrained environments.
Modes of Operation	Novice, Intermediate, Advanced User Modes - to enable users of all experience / proficiency levels to utilize the tool
	Are "role" based user interfaces a more suitable approach (i.e. Developer, Practitioner, Supervisor / Practitioner, Novice / Operational User)?
	Can the model incorporate Hardware-in-the-Loop?
	Can the model support batch runs?

Table 11-6: Other Data Input / Output Considerations for the Next-Gen NRMM

11.4 INPUT DATA / OUTPUT POTENTIAL NEAR-TERM STOP-GAP SOLUTIONS

At the NATO meetings in Brussels, Belgium, AMSAA presented some potential solutions they developed to address short-term NRMM capability gaps. Three products were highlighted:

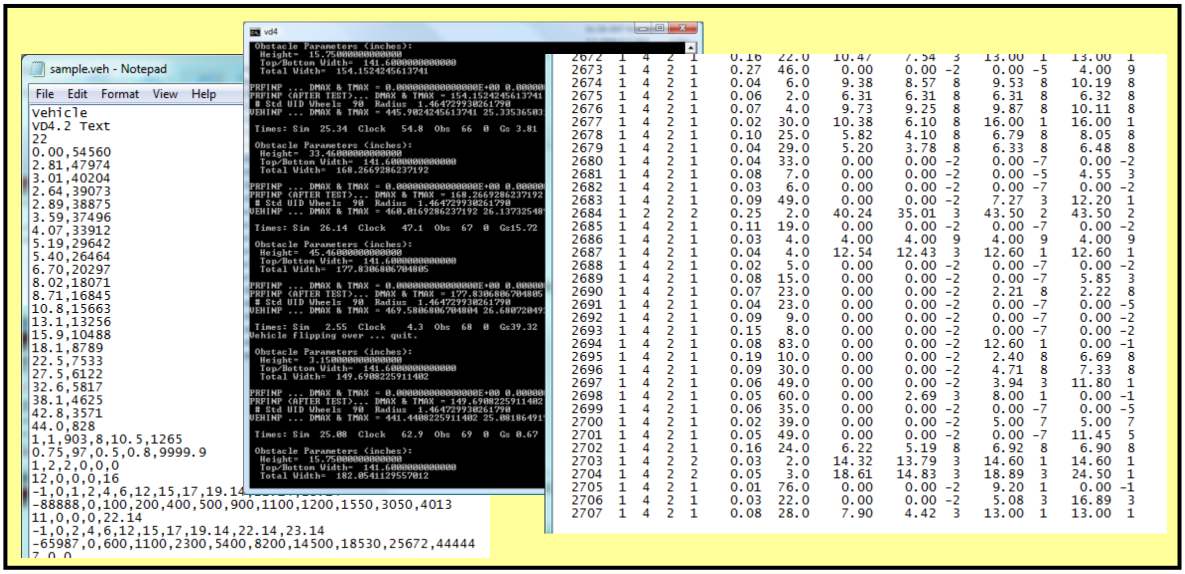
1. The System Level Analysis Mobility Dashboard (SLAMD) – a Python-based NRMM wrapper that improves the end-user experience, integrates the various NRMM modules (ObsMod, VehDyn, etc.) into one user interface, reduces vehicle file development time with improved error handling capabilities, improves data post-processing capabilities, etc.
2. 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
3. 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

11.4.1 System Level Analysis Mobility Dashboard (SLAMD)

AMSAA has realized the following benefits since developing SLAMD:

1. Improved consistency in analysis methodology across all NRMM users
2. Streamlined analysis processes to allow users to more quickly respond to customer requests, including vehicle configuration changes, support trades analyses
3. Automation of repetitive data collection and post processing tasks to permit more time for in-depth analysis of results
4. Leveraged existing analysis tools (NRMM, VEHDYN, etc.) without re-coding them
5. Databased model inputs and outputs to improve analysis efficiency
6. Includes elements to streamline use of NRMM and other potential M&S tools
7. Configuration management and control of all Input / Outputs data elements through the use of a centralized data storage repository.

Figure 11-1 below shows the current text-based, command line NRMM Input data files as compared to the improved GUI interface, data development environment provided by SLAMD (shown in Figures 11-2 to 11-4).



```
Vehicle
VD4.2 Text
22
0.00,54560
2.81,47974
3.01,40204
2.64,39073
2.89,38875
3.59,37496
4.07,33912
5.19,29642
5.40,26464
6.70,20297
8.02,18071
8.71,16845
10.8,15663
13.1,13256
15.9,10488
18.1,8789
22.5,7533
27.5,6122
32.6,5817
38.1,4625
42.8,3571
44.0,828
1,1,903,8,10.5,1265
0.75,97,0.5,0.8,9999.9
1,2,2,0,0,0
12,0,0,0,16
-1,0,1,2,4,6,12,15,17,19.14
-88888,0,100,200,400,500,900,1100,1200,1550,3050,4013
11,0,0,0,22.14
-1,0,2,4,6,12,15,17,19.14,22.14,23.14
-65987,0,600,1100,2300,5400,8200,14500,18530,25672,44444
7,0,0
```

```
 Obstacle Parameters (inches):
  Height=  15.7500000000000
  Top/Bottom Width=  141.600000000000
  Total Width=  154.1524245613741

PRFINP ... DMAX & TMAX = 0.0000000000000000E+00 0.000000
PRFINP (AFTER TEST)... DMAX & TMAX = 154.1524245613741
 # Std UID Wheels  90  Radius  1.464729930261790
VEHINP ... DMAX & TMAX = 445.9024245613741 25.3353650

 Times: Sim  25.34  Clock   54.8  Obs  66  0  Gs 3.81

 Obstacle Parameters (inches):
  Height=  33.4600000000000
  Top/Bottom Width=  141.600000000000
  Total Width=  168.2669286237192

PRFINP ... DMAX & TMAX = 0.0000000000000000E+00 0.000000
PRFINP (AFTER TEST)... DMAX & TMAX = 168.2669286237192
 # Std UID Wheels  90  Radius  1.464729930261790
VEHINP ... DMAX & TMAX = 460.0169286237192 26.1373254

 Times: Sim  26.14  Clock   47.1  Obs  67  0  Gs15.72

 Obstacle Parameters (inches):
  Height=  45.4600000000000
  Top/Bottom Width=  141.600000000000
  Total Width=  177.8306806704805

PRFINP ... DMAX & TMAX = 0.0000000000000000E+00 0.000000
PRFINP (AFTER TEST)... DMAX & TMAX = 177.8306806704805
 # Std UID Wheels  90  Radius  1.464729930261790
VEHINP ... DMAX & TMAX = 469.5806806704804 26.6807204

 Times: Sim   2.55  Clock    4.3  Obs  68  0  Gs39.32
Vehicle flipping over ... quit.

 Obstacle Parameters (inches):
  Height=  3.15000000000000
  Top/Bottom Width=  141.600000000000
  Total Width=  149.6908225911402

PRFINP ... DMAX & TMAX = 0.0000000000000000E+00 0.000000
PRFINP (AFTER TEST)... DMAX & TMAX = 149.6908225911402
 # Std UID Wheels  90  Radius  1.464729930261790
VEHINP ... DMAX & TMAX = 441.4408225911402 25.0818649

 Times: Sim  25.08  Clock   62.9  Obs  69  0  Gs 0.67

 Obstacle Parameters (inches):
  Height=  15.7500000000000
  Top/Bottom Width=  141.600000000000
  Total Width=  182.0541129557012
```

```
2672  1  4  2  1    0.16  22.0  10.47   7.54  3  13.00  1  13.00  1
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2674  1  4  2  1    0.04   6.0   9.38   8.57  8   9.53  8  10.19  8
2675  1  4  2  1    0.06   2.0   6.31   6.31  8   6.31  8   6.32  8
2676  1  4  2  1    0.07   4.0   9.73   9.25  8   9.87  8  10.11  8
2677  1  4  2  1    0.02  30.0  10.38   6.10  8  16.00  1  16.00  1
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2679  1  4  2  1    0.04  29.0   5.20   3.78  8   6.33  8   6.48  8
2680  1  4  2  1    0.04  33.0   0.00   0.00 -2   0.00 -7   0.00 -2
2681  1  4  2  1    0.08   7.0   0.00   0.00 -2   0.00 -5   4.55  3
2682  1  4  2  1    0.03   6.0   0.00   0.00 -2   0.00 -7   0.00 -2
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2684  1  2  2  2    0.25   2.0  40.24  35.01  3  43.50  2  43.50  2
2685  1  4  2  1    0.11  19.0   0.00   0.00 -2   0.00 -7   0.00 -2
2686  1  4  2  1    0.03   4.0   4.00   4.00  9   4.00  9   4.00  9
2687  1  4  2  1    0.04   4.0  12.54  12.43  3  12.60  1  12.60  1
2688  1  4  2  1    0.02   5.0   0.00   0.00 -2   0.00 -7   0.00 -2
2689  1  4  2  1    0.08  15.0   0.00   0.00 -2   0.00 -7   5.85  3
2690  1  4  2  1    0.07  23.0   0.00   0.00 -2   2.21  8   2.22  8
2691  1  4  2  1    0.04  23.0   0.00   0.00 -2   0.00 -7   0.00 -5
2692  1  4  2  1    0.09   9.0   0.00   0.00 -2   0.00 -7   0.00 -2
2693  1  4  2  1    0.15   8.0   0.00   0.00 -2   0.00 -7   0.00 -2
2694  1  4  2  1    0.08  83.0   0.00   0.00 -2  12.60  1   0.00 -1
2695  1  4  2  1    0.19  10.0   0.00   0.00 -2   2.40  8   6.69  8
2696  1  4  2  1    0.09  30.0   0.00   0.00 -2   4.71  8   7.33  8
2697  1  4  2  1    0.06  49.0   0.00   0.00 -2   3.94  3  11.80  1
2698  1  4  2  1    0.05  60.0   0.00   2.69  3   8.00  1   0.00 -1
2699  1  4  2  1    0.06  35.0   0.00   0.00 -2   0.00 -7   0.00 -5
2700  1  4  2  1    0.02  39.0   0.00   0.00 -2   5.00  7   5.00  7
2701  1  4  2  1    0.05  49.0   0.00   0.00 -2   0.00 -7  11.45  5
2702  1  4  2  1    0.16  24.0   6.22   5.19  8   6.92  8   6.90  8
2703  1  4  2  2    0.03   2.0  14.32  13.79  3  14.60  1  14.60  1
2704  1  4  2  2    0.05   3.0  18.61  14.83  3  18.89  3  24.50  1
2705  1  4  2  1    0.01  76.0   0.00   0.00 -2   9.20  1   0.00 -1
2706  1  4  2  1    0.03  22.0   0.00   0.00 -2   5.08  3  16.89  3
2707  1  4  2  1    0.08  28.0   7.90   4.42  3  13.00  1  13.00  1
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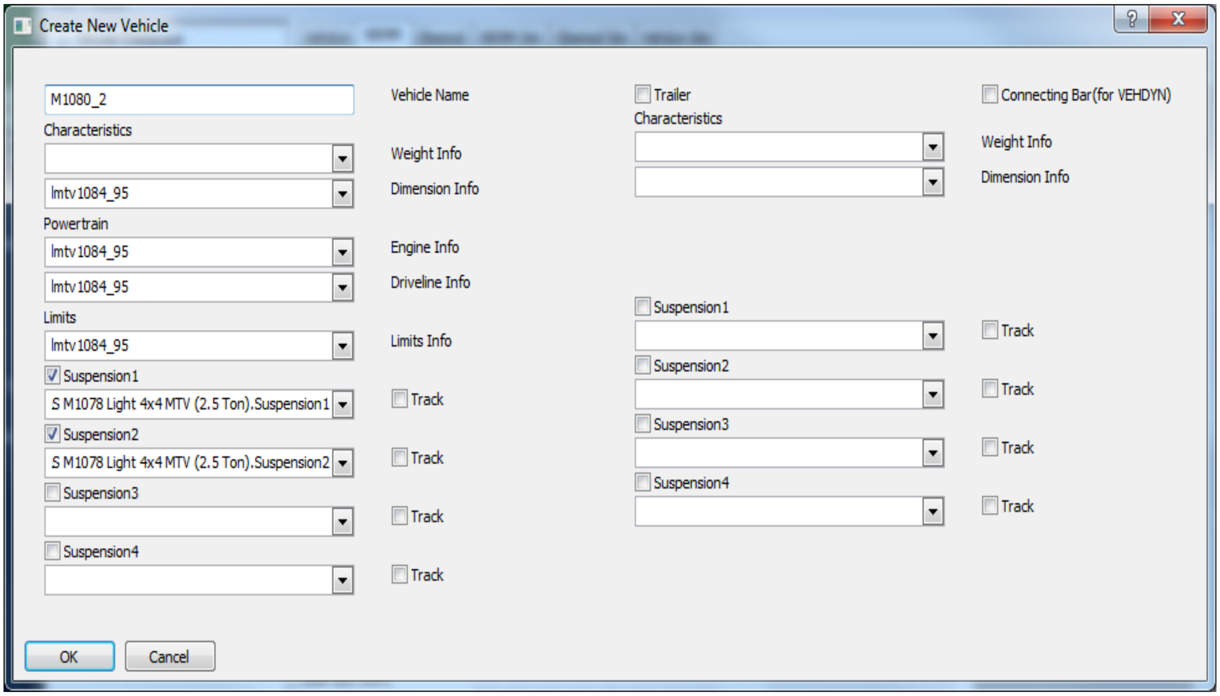
Figure 11-1: Existing Text-Based / Command Line Interfaces for NRMM Input Data File Construction and Execution



M1080_2 Vehicle Name

Characteristics

Weight Info

lmtv1084_95 Dimension Info

Powertrain

lmtv1084_95 Engine Info

lmtv1084_95 Driveline Info

Limits

lmtv1084_95 Limits Info

☑ Suspension1

S M1078 Light 4x4 MTV (2.5 Ton).Suspension1 ☐ Track

☑ Suspension2

S M1078 Light 4x4 MTV (2.5 Ton).Suspension2 ☐ Track

☐ Suspension3 ☐ Track

☐ Suspension4 ☐ Track

☐ Trailer

Characteristics

☐ Suspension1 ☐ Track

☐ Suspension2 ☐ Track

☐ Suspension3 ☐ Track

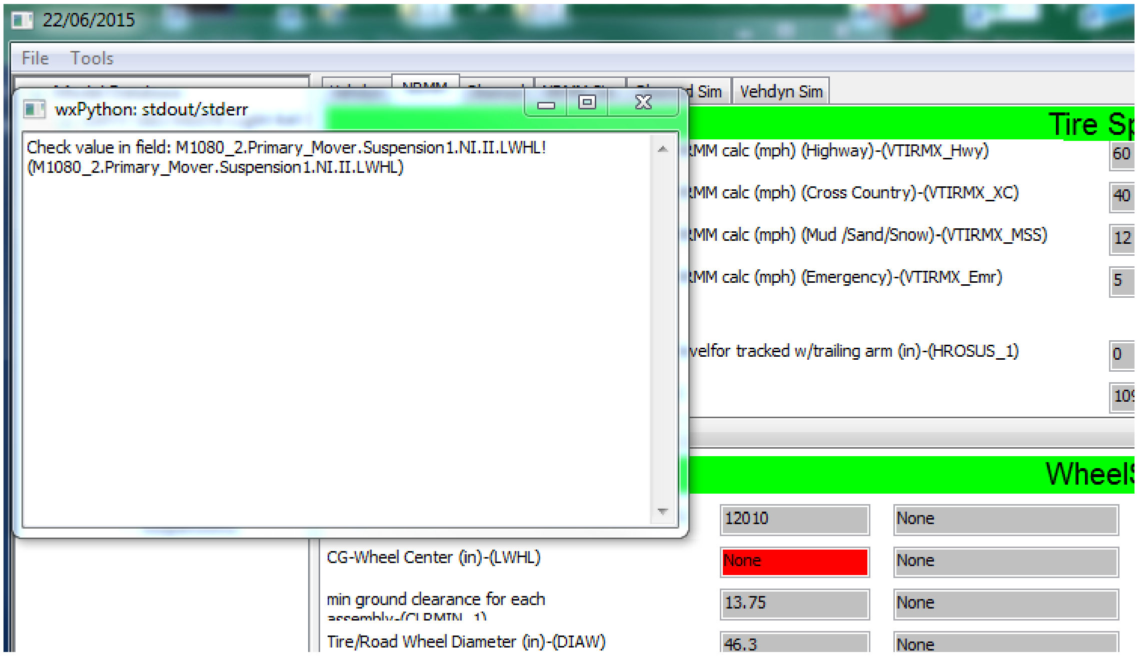
☐ Suspension4 ☐ Track

☐ Connecting Bar(for VEHDYN)

Weight Info

Dimension Info

Figure 11-2: SLAMD Improved Vehicle Data Creation Interface (Template-Based)



wxPython: stdout/stderr

Check value in field: M1080_2.Primary_Mover.Suspension1.NI.II.LWHL!
(M1080_2.Primary_Mover.Suspension1.NI.II.LWHL)

MM calc (mph) (Highway)-(VTIRMX_Hwy) 60

MM calc (mph) (Cross Country)-(VTIRMX_XC) 40

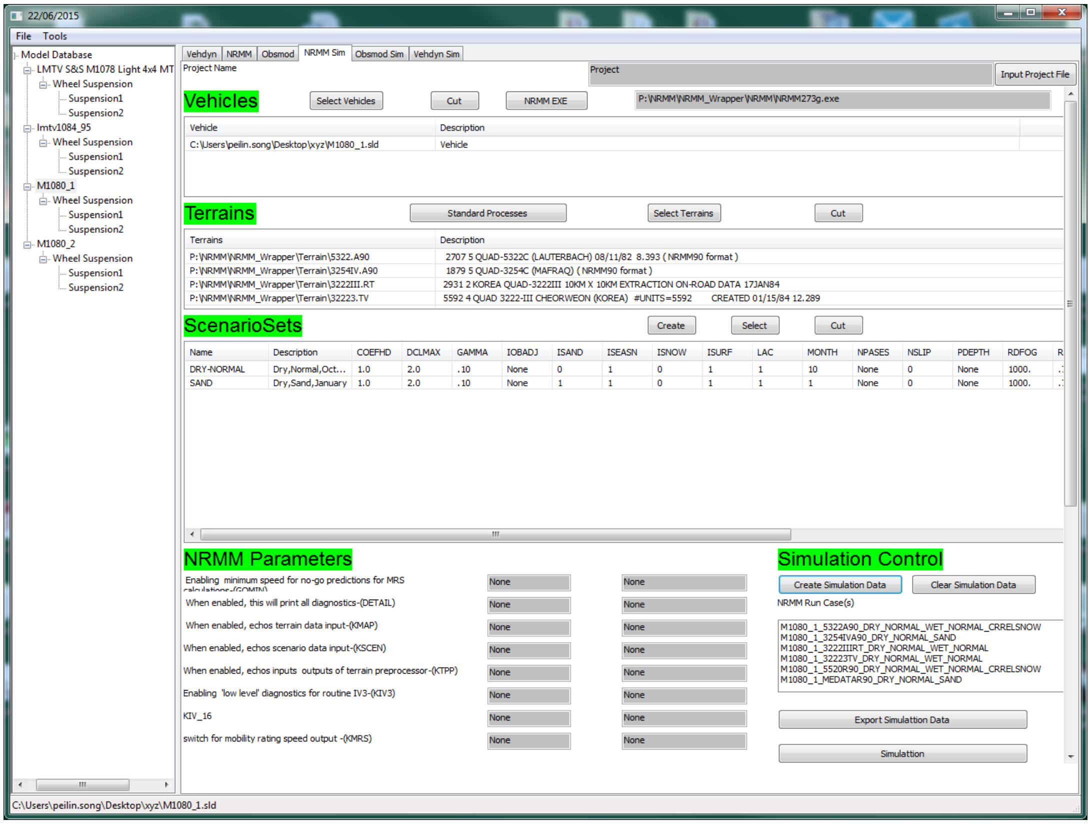
MM calc (mph) (Mud /Sand/Snow)-(VTIRMX_MSS) 12

MM calc (mph) (Emergency)-(VTIRMX_Emr) 5

velfor tracked w/trailing arm (in)-(HROSUS_1) 0

	12010	None
CG-Wheel Center (in)-(LWHL)	None	None
min ground clearance for each assembly-(CLRMIN_1)	13.75	None
Tire/Road Wheel Diameter (in)-(DIAW)	46.3	None

Figure 11-3: SLAMD Improved Data Validation / Error Handling



- Model Database
  - LMTV S&S M1078 Light 4x4 MT
    - Wheel Suspension
      - Suspension1
      - Suspension2
  - lmtv1084_95
    - Wheel Suspension
      - Suspension1
      - Suspension2
  - M1080_1
    - Wheel Suspension
      - Suspension1
      - Suspension2
  - M1080_2
    - Wheel Suspension
      - Suspension1
      - Suspension2

P:\NRMM\NRMM_Wrapper\NRMM\NRMM273g.exe

Vehicle	Description
C:\Users\peilin.song\Desktop\xyz\M1080_1.sld	Vehicle

Terrains	Description
P:\NRMM\NRMM_Wrapper\Terrain\5322.A90	2707 5 QUAD-5322C (LAUTERBACH) 08/11/82 8.393 (NRMM90 format)
P:\NRMM\NRMM_Wrapper\Terrain\3254IV.A90	1879 5 QUAD-3254C (MAFRAQ) (NRMM90 format)
P:\NRMM\NRMM_Wrapper\Terrain\3222III.RT	2931 2 KOREA QUAD-3222III 10KM X 10KM EXTRACTION ON-ROAD DATA 17JAN84
P:\NRMM\NRMM_Wrapper\Terrain\32223.TV	5592 4 QUAD 3222-III CHEORWEON (KOREA) #UNITS=5592 CREATED 01/15/84 12.289

Name	Description	COEFHD	DCLMAX	GAMMA	IOBADJ	ISAND	ISEASN	ISNOW	ISURF	LAC	MONTH	NPASES	NSLIP	PDEPTH	RDFOG
DRY-NORMAL	Dry,Normal,Oct...	1.0	2.0	.10	None	0	1	0	1	1	10	None	0	None	1000.
SAND	Dry,Sand,January	1.0	2.0	.10	None	1	1	0	1	1	1	None	0	None	1000.

Enabling minimum speed for no-go predictions for MRS calculations-(GOMIN)	None	None
When enabled, this will print all diagnostics-(DETAIL)	None	None
When enabled, echos terrain data input-(KMAP)	None	None
When enabled, echos scenario data input-(KSCEN)	None	None
When enabled, echos inputs outputs of terrain preprocessor-(KTPP)	None	None
Enabling 'low level' diagnostics for routine IV3-(KIV3)	None	None
KIV_16	None	None
switch for mobility rating speed output -(KMRS)	None	None

NRMM Run Case(s)

M1080_1_5322A90_DRY_NORMAL_WET_NORMAL_CRRELSNOW
M1080_1_3254IVA90_DRY_NORMAL_SAND
M1080_1_3222IIIRT_DRY_NORMAL_WET_NORMAL
M1080_1_32223TV_DRY_NORMAL_WET_NORMAL
M1080_1_5520R90_DRY_NORMAL_WET_NORMAL_CRRELSNOW
M1080_1_MEDATAR90_DRY_NORMAL_SAND

C:\Users\peilin.song\Desktop\xyz\M1080_1.sld

Figure 11-4: SLAMD Graphical User Interface (GUI) for VehDyn, ObsMod, NRMM

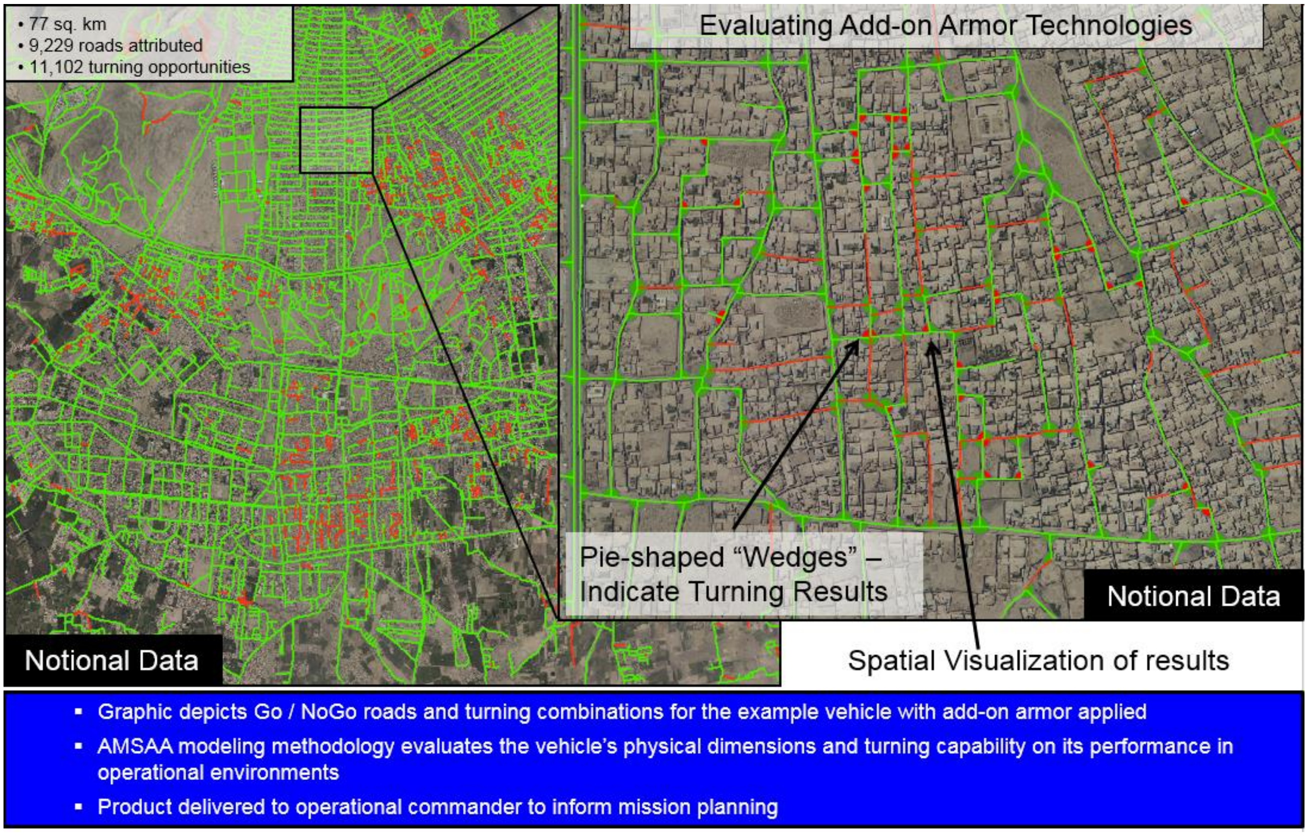
SLAMD's Graphical User Interface (GUI) steeply reduces the learning curve associated with learning how to use the NRMM. This improved user interface delivers the following benefits:

- Steeply reduces NRMM learning curve and makes it accessible to all user experience levels
    - Eliminates need to learn NRMM variable names and parameters
    - Transitions NRMM from command line execution to GUI-based execution which is more intuitive to users
    - Provides "help" functions through the GUI to assist users with data input to support vehicle file creation
    - Incorporates data validation – to ensure input data results are reasonable and "flags" values that are beyond reasonable ranges for further user investigation
    - Consolidates all NRMM executables into one easy-to-use interface
- Facilitates improved post-process visualization of multiple vehicle / scenario NRMM results

SLAMD (or another similar approach) might be able to address some of the use / usability capability gaps until the release of the Next-Generation NRMM.

11.4.2 AMSAA Urban Mobility Model.

AMSAA had previously been working to address another capability gap identified by the NATO-AVT ET-148 membership – urban maneuverability modeling.



- Graphic depicts Go / NoGo roads and turning combinations for the example vehicle with add-on armor applied
- AMSAA modeling methodology evaluates the vehicle's physical dimensions and turning capability on its performance in operational environments
- Product delivered to operational commander to inform mission planning

Figure 11-5: Notional Urban Maneuverability Analysis Product – Evaluating Maneuverability Degradation Associated with Add-On Armor

AMSAA's Urban Maneuverability Model (UMM) leverages high-resolution satellite imagery and vehicle performance and characteristics data to analyze vehicle maneuverability performance on-road within constrained urban environments. Geospatial software is used to calculate the geometry of the road networks and overlay vehicle performance to create cartographic products.

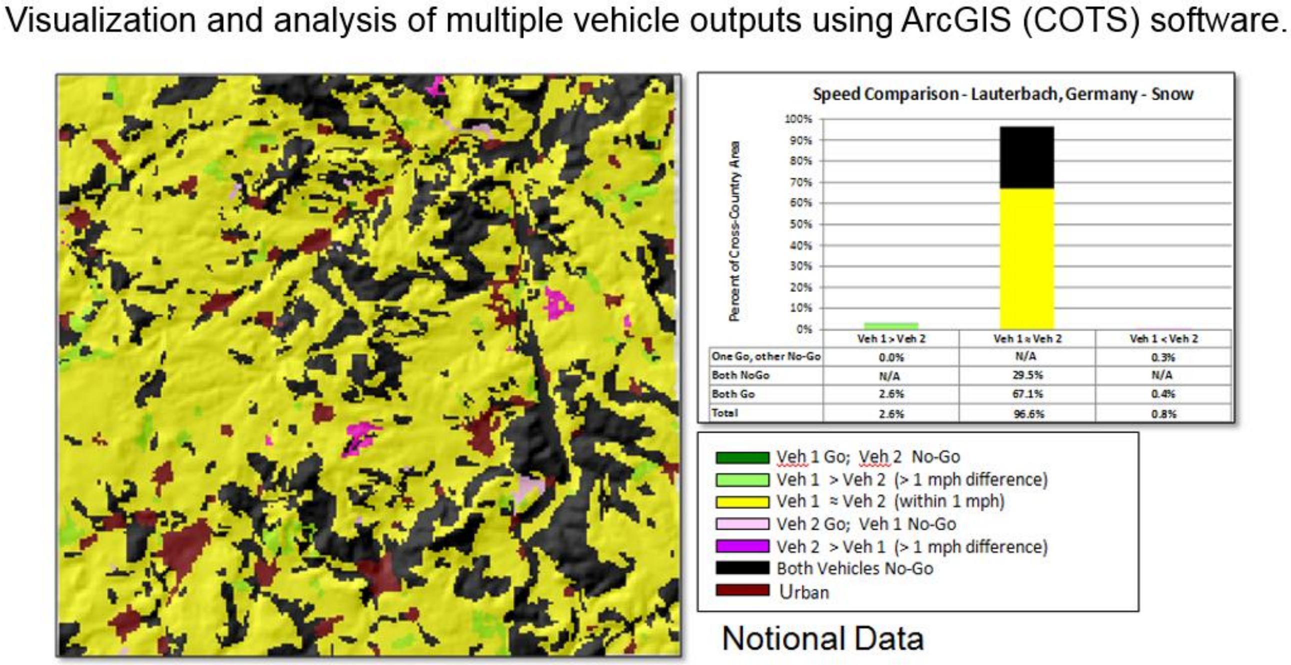
The model requires a road network to be digitized using high resolution satellite imagery and the features attributed. Digitization is the extraction of features such as road networks, canals, bodies of water, buildings, etc, and it also establishes the geospatial location of the object. When a road is digitized it is represented spatially by a series of polylines which connect to form the road network. A polyline is a feature that consists of line segments connected to each other to form a line.

As these polylines are created they are saved to a shapefile, which is a file that consists of geospatial vector data. Vector data can include points, lines, and polygons, and it is the backbone of most geospatial analysis. The attribution process involves associating important feature properties / characteristics to each geospatial feature. The software allows the model to extract road network information such as road width, road construction, number of lanes, etc.

The extracted features are overlaid onto a terrain area to verify all features have been properly extracted from high resolution satellite imagery. By overlaying features, the geospatial software is able to provide a multi-dimensional view of the various data layers and combine information between feature layers. This process extends the analysis capability by adding information to the road attributes for slope, soil type, and moisture content that is not inherent in the road layer alone. Once the road network has been digitized and attributed, a vehicle’s maneuverability performance can be analyzed. Statistical and cartographic products can be created to quantify and visualize the results. In the graphic above, the color-coded roads indicate whether or not a vehicle can “fit” down the road, while the color-coded pie-shaped wedges between the roads indicate whether or not a vehicle can negotiate a turn from one road to another (Green = Go / Red = NoGo). AMSAA has further refined the model to evaluate the connectivity of the road network – essentially removing any areas deemed “Go” but offer no viable path into / out of this area of the road network.

AMSAA has historically run this model to inform vehicle design decisions regarding: the physical dimensions of vehicles; modifications to the steering, driveline, and suspension systems (which may affect the turning capability of the vehicle); and the effects of add-on armor technologies.

The modular nature of the NRMM terrain files and the ability to import / export spatially-oriented GIS terrain data enables NRMM results to be visualized cartographically. Despite the complexity of the various terrain input data layers (i.e. slopes, soils, moisture content, surface roughness, etc), GIS software enable users to spatially join these layers together to create new NRMM terrain files. Figure 11-6 below depicts a notional comparative speed / trafficability analysis of two vehicles operating in Lauterbach, Germany with a snow scenario.



	Veh 1 > Veh 2	Veh 1 ≈ Veh 2	Veh 1 < Veh 2
One Go, other No-Go	0.0%	N/A	0.3%
Both NoGo	N/A	29.5%	N/A
Both Go	2.6%	67.1%	0.4%
Total	2.6%	96.6%	0.8%

Figure 11-6: Notional Vehicle Speed / Trafficability Comparison Product Generated Using NRMM and ESRI ArcGIS

AMSAA has historically exported the statistical results of NRMM into GIS software for additional analysis / visualization purposes. At the NATO AVT ET-148 meeting in Brussels, attendees confirmed that both the French and German militaries were developing similar geospatial mobility analysis capabilities; however, since some of these activities were tied to mission / operational planning capabilities, they were classified at the NATO//SECRET level or above.

11.4.3 AMSAA's Optimal Path Model

AMSAA's Optimal Path Model (AOPM) enhances the potential spatial analysis capabilities, inherent within NRMM's modular terrain data framework, by enabling the importation of NRMM on-road and off-road speed and trafficability predictions; and, plotting the optimal path between geospatially-oriented point locations.

NRMM's modular terrain framework allows end users to import GIS terrain data into spatial analysis tools such as ESRI's ArcGIS. Then, ArcGIS can be used to generate new NRMM terrain units that represent each unique combination of the terrain characteristics present within the terrain playbox. NRMM can ingest the new terrain file, built with these new NRMM terrain units, to make on-road and off-road speed predictions. AMSAA's OPM can then import the NRMM results and aggregate the on-road and off-road performance into a single speed performance map. Additional "cost surfaces" can be added to incorporate other path modeling considerations, (i.e. fuel economy, concealed movement, enemy engagement ranges). The model then uses Dijkstra's algorithm to optimize the path across the combined cost surfaces to find the optimal, idealized path through the network of points. Figure 11-7 below provides a flow chart outlining the steps in the AOPM methodology. The model enables mobility performance results to be evaluated within specific mission contexts as shown in the Mission Completion Time Estimates generated for vehicles conducting Medical Evacuation (MEDEVAC) missions – see Figure 11-8.

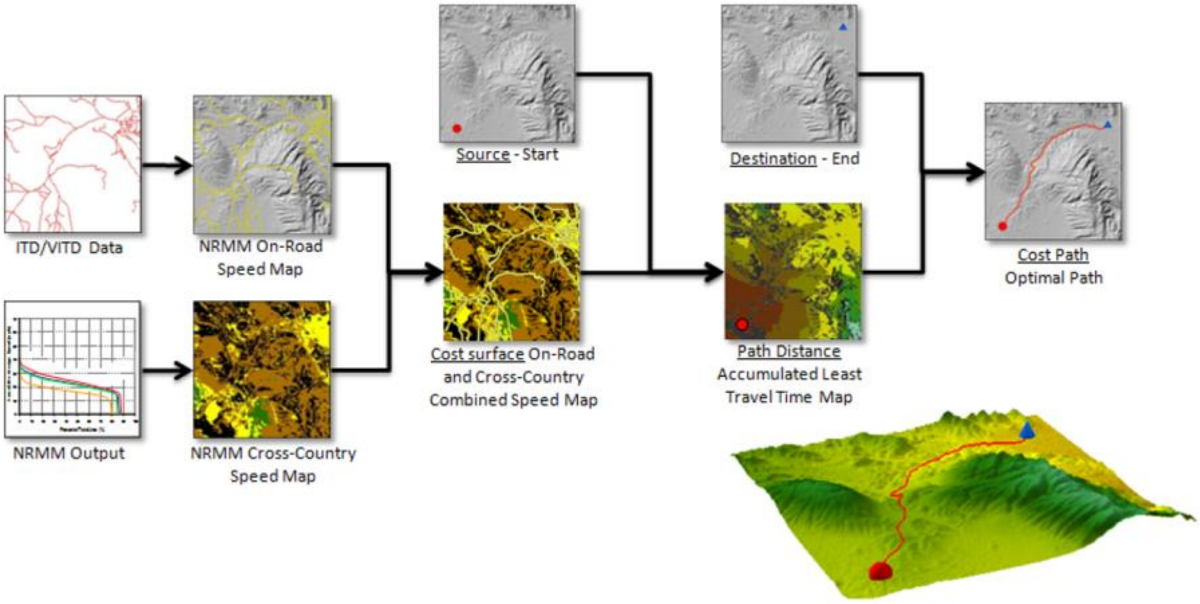
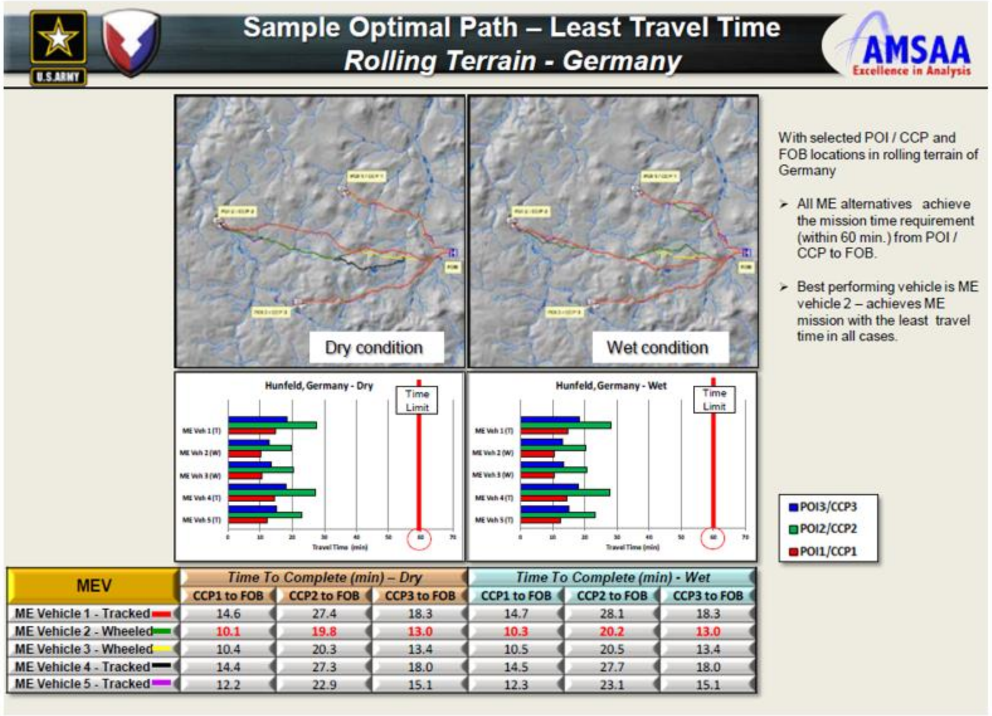


Figure 11-7: Notional MEDEVAC Mission Effectiveness Product Generated Using NRMM and ESRI ArcGIS

Path modeling results applied to mission Medical Evacuation (MEDEVAC) scenario



Sample Optimal Path – Least Travel Time

Rolling Terrain - Germany

With selected POI / CCP and FOB locations in rolling terrain of Germany

- All ME alternatives achieve the mission time requirement (within 60 min.) from POI / CCP to FOB.
- Best performing vehicle is ME vehicle 2 – achieves ME mission with the least travel time in all cases.

MEV	*Time To Complete (min) – Dry*			*Time To Complete (min) - Wet*		
	CCP1 to FOB	CCP2 to FOB	CCP3 to FOB	CCP1 to FOB	CCP2 to FOB	CCP3 to FOB
ME Vehicle 1 - Tracked 🟥	14.6	27.4	18.3	14.7	28.1	18.3
ME Vehicle 2 - Wheeled 🟩	10.1	19.8	13.0	10.3	20.2	13.0
ME Vehicle 3 - Wheeled 🟨	10.4	20.3	13.4	10.5	20.5	13.4
ME Vehicle 4 - Tracked ⬛	14.4	27.3	18.0	14.5	27.7	18.0
ME Vehicle 5 - Tracked 🟪	12.2	22.9	15.1	12.3	23.1	15.1

Figure 11-8: Notional MEDEVAC Mission Effectiveness Product Generated Using NRMM and ESRI ArcGIS

Therefore, the Next-Generation NRMM must retain the capability to import geospatial terrain data and comply with military, commercial, and Open Geospatial Consortium (OGC) data standards to preserve data interoperability between analysis tools. Additionally, the results generated by the Next-Generation NRMM should be able to be exported and visualized using GIS analysis and cartographic visualization software.

11.5 FUTURE WORK / RECOMMENDATIONS

Near Term:

- Continue to develop modular interim solutions to close vehicle / terrain modeling gaps and / or address end user usability issues.
- Improve methodologies to transform high resolution satellite imagery / remotely-sensed GIS data into accurate NRMM terrain representations.
- Investigate the potential to develop data / interface standards to promote data interoperability between Multi-Body Vehicle Dynamic simulations and commercial GIS software solutions.
- Map the Input Data Requirements / Output Products to end user roles / user experience levels.
- Map the Input Data Requirements / Output Products to various modeling levels (Reduced Order Modeling through Detailed Engineering Analysis).

Long Term:

- Pursue a modular development approach – leveraging Vehicle Multi-Body Dynamic Analysis Tools, Geospatial Terrain Development / Cartographic Visualization Tools.
- Publish Next-Generation NRMM Data Interoperability Standards – to ensure NRMM outputs maintain linkages to spatially oriented data to facilitate visualization using COTS GIS tools.
- Pursue Scalable Levels of Fidelity to Model Systems from Paper Concepts to Detailed Engineering Designs (accommodating expedient to more lengthy analysis timelines).
- Incorporate modules to model many of the advanced vehicle technologies identified.
- Incorporate improvements to the terrain / environment development processes; and the operator behavior, human factors, and autonomous / semi-autonomous vehicle characterization methodologies.

Chapter 12 – THEME 7: VERIFICATION & VALIDATION

Michael Letherwood

12.1 GOALS AND DELIVERABLES

The goals of Theme 7 are to provide a process for conducting a successful tool Verification and Validation (V&V) program on the Next Generation NRMM (NG-NRMM). The intent of the ET is the development of a set of standards to guide the implementation of the NG-NRMM, as well as its use and management. It's driven by the need for highly accurate numerical models for making vehicle system mobility and performance capability predictions to support current systems as well as future acquisition programs. The expected deliverable of Theme 7 is a benchmarking verification and validation plan to assess potential NG-NRMM developers' modeling methodologies, capabilities, and component models for vehicle dynamics, off-road mobility, intelligent vehicle operation, and geospatial data use and mapping, which will ultimately lead to the development of a set of standards to guide the implementation of NG-NRMM, as well as its use and management. Software V&V is fundamentally different from model V&V and is required when a computer program or code is the end product and, conversely, tool V&V is required when a predictive model is the end product. As such, this report will discuss primarily tool V&V activities and evaluation of developer's responses to see which groups can adequately address the long list of NG-NRMM requirements.

The Theme 7 path forward deliverables are to:

- Phase I: To conduct a Tool Benchmarking V&V with developers to provide a common basis for evaluating tool capabilities in the context of NG-NRMM requirements

- Phase II: To develop NG-NRMM standards version 1.0 and associated benchmarks and to establish the basis and process for on-going future development, configuration management, and tool qualification

The theme members are shown below:

Countries	**Name**
Denmark	Balling, Ole
Germany	Gericke, Rainer
USA	Gunter, David
USA	Jayakumar, Paramsothy
USA	**Letherwood, Michael: Leader**
USA	McCullough, Michael

12.2 OBJECTIVES

The ET's Theme 5, Tool Choices team was able to effectively identify critical elements of a physics-based, next generation mobility model utilizing strength and weakness criteria provided by an initial "pros and cons" review of the current NRMM and, subsequently, integrate/coordinate those tool choice evaluations with other themes, particularly requirements and methodology themes. They went on to identify potential solutions throughout the technical community and user nations and then surveyed the ability of current and future physics-based simulation environments to provide accurate and timely results that can be used to support vehicle system development, acquisition, prediction of vehicle performance in an adverse operational environment, and force projection metrics. They were able to investigate the ability of a limited number of commercially available physics-based simulation tools to address the needs of the current NRMM tool set and determine the ability of those tools to augment empirically based historic analytical solutions providing a path to full physics-based analysis and prediction of the vehicle-terrain interaction. The team successfully completed those taskings and the job of developing a plan to evaluate those capabilities fell to the Theme 7 Team: Verification & Validation. Although late getting started, the objectives of the team has been, ultimately, to verify & validate NG-NRMM prospective objective methodologies of component models for off-road mobility, vehicle dynamics, and intelligent vehicles.

Hence, the Phase I, Tool Benchmarking V&V with developers is intended to provide a common basis for evaluating tool capabilities in the context of NG-NRMM requirements. The objectives are to;

- Determine if adequate physics based M&S tools exist either in the public domain or can be provided by industry
- Determine if those tools can be used to accurately represent the key mobility elements which affect ground vehicles
- Determine if those tools are affordable and implementable

The benefits for prospective software developers will be to:

- Gain familiarity with the development of NG-NRMM program requirements
- Provide current data which can be used to inform the requirements
- Demonstrate the realm of the possible
- Recognize the simulation capability gaps
- Provide off-the-shelf simulation tools to relevant NATO nations and vehicle OEMs
- Improve capabilities utilizing the NATO benchmark
- Suggest additional applicable benchmarks

12.3 QUESTIONS TO BE ADDRESSED

As discussed earlier, since the final NG-NRMM standards/code is still a work in progress, the NATO RTO Task Group committee will define the full scope of the resulting Phase II NG-NRMM Code

V&V efforts. The Phase I, Tool Model Benchmarking V&V discussions resulted in the following open questions that were posed and addressed as follows;

1. What problems or events or scenarios do we need to V&V?

The following events will be used during benchmarking exercise:

1. Steady State Cornering
2. Double Lane Change w/wo Autonomy
3. Side Slope Stability
4. Grade climbing
5. Ride and Shock Quality
6. Step climb and ditch crossing
7. Off road trafficability w/wo autonomy
8. Urban navigation at different levels of autonomy

2. What vehicles do we want to use for the benchmarking?

- Wheeled Vehicle
- Tracked Vehicle

3. What test data are available and who can provide the test data?

Wheeled Vehicle

- TBD

Tracked Vehicle

- Drawbar pull force vs. slip – on sandy terrain (LETE Sand), muskeg (Petawawa Muskeg B), and snow (Petawawa Snow A)
- Bevameter parameters – for sandy terrain (LETE Sand), muskeg (Petawawa Muskeg A and B), and snow (Petawawa Snow A and B)

4. What vendor tools do we want to benchmark against the test data?

Based on the results of the Theme 5: Tool Choices team Request for Information (RFI), the top eight best-qualified, prospective developers were selected to visit the ET-148 committee during the NATO meeting in Prague and to describe their capabilities. One of the questions that will need to be answered is whether to re-engage only the original developers or to invite others to participate. It is expected that the technology associated with prediction of vehicle performance in extreme conditions will continue to improve and therefore new tools may be available throughout the process. As the efforts move forward the ET and RTG committees will continue to share lessons learned and will use that information to establish suitable benchmarks, dominant criteria, integration of terrain and vehicle parameters etc

5. Will any additional tests need to be done during the benchmarking exercise?

At this time it has not been decided what new tests need to be run to support the benchmarking exercise. Rainer Gericke is prepared to collect more MAN truck data if necessary.

12.4 TEST VEHICLES

A description of the two test vehicles is detailed below.

Wheeled Vehicle

- TBD

Tracked Vehicle

- Fully tracked armored personnel carrier
- Detroit 6V53 V6 two-stroke diesel engine of 318 cubic inches (5,210 cc) with an Allison TX-100-1 3-speed automatic trans
- Aluminum armor that made the vehicle much lighter than earlier vehicles and very mobile
- Vehicle total weight, sprung and unsprung weight
- Sprung weight x (long.) and y (vert.) CG coordinates
- Drawbar hitch x-coordinate and y-coordinate
- Fixed (sprocket/tensioning) wheels - wheel radius, x and y coordinates of wheel centers
- Torsion Bar Suspension/Road Wheels - x and y coordinates of pivot points, arm angles at free positions (i.e., the angular positions of the arms at which suspension spring elements are not subject to any load), torsion bar stiffness, wheel radius
- Track parameters - weight per unit length, width, pitch, grouser height, thickness, track tension-elongation relationship
- Initial track tension at rest
- Static equilibrium position, wheel loads, and natural frequency
- Belly shape
- Wheel centers
- Drawings - in 3 dimensions showing locations (attachment points) of the chassis, major component cg locations, vehicle hitch point; suspension system components trailing arms, torsion bars, panhard bars, torque rods, chains, etc.

12.5 SOFTWARE DEVELOPERS

Based on the results of the RFI developed by Theme 5, the top eight software developers were invited to Prague to present their capabilities. A brief summary is below. All were invited to participate in the Benchmarking exercise.

Advanced Science & Automation (ASA): Tamer Wasfy described the software package known as IVRESS/DIS. DIS stands for Dynamic Interactions Simulator. It incorporates multi-body dynamics (MBD), Finite Element Models (FEM), Discrete Element Models (DEM), and Smoothed Particle Hydrodynamics (SPH) with pre-processors for user-friendly or expert applications.

CM Labs: Justin Webber and Sebastien Miglio discussed their Vortex Dynamics software, which was spun off from MathEngine. They stressed Vortex as real-time simulation software. Their expertise is in autonomous driving and driver-in-the-loop simulations. They use real vehicles to create simulation training. Vortex is not FEA, but a Simulation Development Platform. It can run real-time simulations on an ordinary PC.

Dassault Systems 3DS: Bob Solomon and Frederic Dot represented Dassault and described their Simpack software, which was recently purchased by Dassault. Simpack technology was developed by DLR, the German aerospace group. They can do co-simulation with Abaqus FE application, which provides a powerful soil model. They don’t currently do track simulations.

FunctionBay: Uwe Eiselt presented the information about their MBD software known as Recurdyn. The work started in South Korea in the 1990s. They have a fully integrated FE model. They include DEM through a third party, but it is also integrated in their software. They showed some simulations demonstrating autonomous control. They produce both an easy Excel version for less skilled users and ProcessNet for skilled programmers. They stress ease of use.

Modelon: Hubertus Tummescheit presented the material from Modelon, which began in Sweden. He emphasized that you should tie yourself to standards, not to tools. He discussed the software tool, Dymola, for simulating the dynamic behavior of systems. It is based on the Modelica open standard for component-oriented modeling of complex systems and includes the Functional Mock-Up Interface (FMI) toolbox. Modelica was selected by DARPA for their FANG challenge. Due to the open code, the user can drill down and find the relevant equations and change them if needed. Dymola can produce real-time simulations. They believe that to do autonomy, you must have real-time simulations or know the latency exactly. They have not done soft-soil simulations or dealt with tracked vehicles. They would concentrate on a Chrono integration for tracked vehicles.

MSC Software: Peter Dodd, Kyle Indermuehle and Henrik Skovbjerg were visitors from MSC Software and described their Adams software. The firm started 50 years ago as an offshoot from NASA. They produce Adams/Car and Adams/ATV, a toolkit for tracked vehicles on soft soil. They were unsure if they could handle our soft soil applications and have not dealt directly with intelligent vehicles. They use EDEM Co-Simulation for DEM work, such as for soft soil.

Siemens: Sebastian Flock and Iurie Terna discussed Siemen’s software, LMS Virtual Lab, also with FMI compatibility. They also use EDEM for soft soil applications. They do not have expertise in geospatial terrain or autonomy applications. On the positive sign, one of their slides showed a quote from Mike McCullough touting their product. The software can be leased or purchased.

U. of Wisconsin: This team included Dan Negrut, Radu Serban, Alessandro Tasora and Hiroyuki Sugiyami from U. Wisconsin and Brian Gerkey from Open Source Robotics Foundation (OSRF). Negrut discussed Chrono software and Gerkey discussed Gazebo. Chrono is a toolkit for modeling and visualization of wheeled and tracked vehicles. The University has a super computer funded by US DoD. As Negrut said, "Hardware is Plentiful, Software is Not." Gazebo provides the robotic application using Robot Operating System (ROS) and Gazebo for robot simulation. They take pride that their software is all open-source. On the soil issue, they have two projects with ERDC and TARDEC. They have submodules for the driveline, but they are not validated. Chrono has been validated against Adams. They believe that they can deal with our events. With Gazebo, they can deal with autonomy.

12.6 TOOL BENCHMARKING V&V SCOPE

Phase I – "Tool Benchmarking V&V" with developers will be conducted as follows:

- Prospective developers will be provided with sufficient vehicle data to set up high-fidelity, physics-based models of one wheeled and one tracked vehicle
- Prospective developers will be asked to simulate required performance scenarios, and subsequently, provide their simulation data to NATO RTO task group for evaluation
- NATO RTO Task Group will evaluate accuracy and capabilities of developer submissions

The developer's responses will be assessed by the NATO RTO Task Group committee as follows:

• Assessment Attribute	• Score
	•
• Geospatial Data Analysis and Mapping	•
• 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	•
• Any vehicle morphology	•
• Full range of ground vehicle geometric scales	•
• VTI models at multiple levels of theoretical and numerical resolution -On road wheels	•

• VTI models at multiple levels of theoretical and numerical resolution -On road tracks	•
• VTI models at multiple levels of theoretical and numerical resolution -Off road wheels (Bekker-Wong, etc)	•
• VTI models at multiple levels of theoretical and numerical resolution -Off road tracks (Bekker-Wong, etc.)	•
• Full coupling capability with FEM/DEM/DVI/SPH deformable soil models	•
• Full coupling with power trains	•
• Full coupling with embedded control systems	
• Full coupling with flexible bodies	•
• Amphibious operations modeling	•
• Coupling with autonomous and human cognition models	•
• Useful for vehicle design	•

• M&S environment	• Score
• Interfaces to broad range of tools	•
• Tools for automation and standardization	•
• Parallelization and HPC compatibility	•
• Tools for handling stochastic parameters	•
• Modular interoperability (ability to plug and play subsystems)	•
• Portable to most common computing environments	•
• Distributable to NATO designated stake holders	•
• Enduring and supported (not likely to become easily obsolete)	•
• Expansion (no financial, legal, technical, or architectural limits to mobility research and development)	•
•	•
• 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	

12.7 SUFFICIENCY – VALIDATION METRICS

V&V is undertaken to quantify confidence and build credibility in a numerical model for the purpose of making a prediction which can be defined as the “use of a computational model to foretell the state of a physical system under conditions for which the computational model has not been validated.” They are the primary processes for quantifying and building confidence (or credibility) in numerical models. Verification is the process of determining that a model implementation accurately represents the developer’s conceptual description of the model and the solution to the model. It is concerned with identifying and removing errors in the model by comparing numerical solutions to analytical or highly accurate benchmark solutions. Validation, on the other hand, is concerned with quantifying the accuracy of the model by comparing numerical solutions to experimental data. It is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. In short, verification deals with the mathematics associated with the model, whereas validation deals with the physics associated with the model. Verification and validation are processes that collect evidence of a model’s correctness or accuracy for a specific scenario; thus, V&V cannot prove that a model is correct and accurate for all possible conditions and applications, but, rather, it can provide evidence that a model is sufficiently accurate. Therefore, the V&V process is completed when sufficiency is reached. Defining an acceptable level of sufficiency for evaluation of the accuracy of the software developer’s responses will be decided by the NATO RTO Task Group committee.

12.8 SCOPE OF WORK / SCHEDULE (DRAFT)

The tentative schedule for the Phase 1, Benchmarking exercise is the following:

- 1 Jan 2016 – Solicit openly for developers to participate
- 1 Apr 2016 - Provide vehicle(s) data, event data, and validation data to participants
- 1 Aug 2016 – Receive participant responses
- 1 Sep 2016 - Report demonstration results to NATO RTO

*Schedule may be pulled forward to meet the NATO meeting schedule of April and September 2016.

12.9 CONCLUSIONS

Since Theme 7’s responsibility thus far has been to come up with a path forward regarding evaluation of software developer’s responses, no real conclusions can be drawn at this point. Once the Phase I “Tool Benchmarking V&V” with developers has been completed, the larger NATO RTO Task Group committee will be able to assess the state-of-the-art and determine a more focused path forward. The committee will then continue on with Phase II to develop NG-NRMM standards version 1.0 and associated benchmarks and establish the basis and process for on-going future development, configuration management, and tool qualification. Phase II will be much larger in scope and although undefined at this time, will most likely involve a full scale code V&V. Those efforts will determine the full scope of the NG-NRMM standards and the resulting V&V processes. They will most likely include development of the conceptual, mathematical, and numerical models; design and performance of V&V experiments; incorporation of independent data into the V&V process; code and model verification efforts; and full scale code evaluations. The expected final deliverables of the NATO RTO Task Group effort will be:

- A set of standards to guide the implementation of the NG-NRMM, as well as its use and management
- A set of benchmarks that can be used by any nation/developer to demonstrate compliance with NG-NRMM standards
- An identification of developer(s) that can deliver software to adequately address mobility

Chapter 13 – CONCLUSIONS AND RECOMMENDATIONS

Jean Dasch

NATO Exploratory Team 148 (ET-148) was proposed and approved in the spring of 2014 with the goal of evaluating the need for a Next-Generation NATO Reference Mobility Model (NG-NRMM). The current NRMM is a simulation tool developed in the 1970s by the U.S. Army to predict the capability of a vehicle to move over a specified terrain. Due to improvements in simulation capabilities since that time, the ET's task was to evaluate if an improved model could be developed. To enable that evaluation, seven theme areas were delineated in the areas of Requirements; Methodologies; Stochastics; Intelligent Vehicles; Tool Choices; Input Data and Output Metrics; and Verification and Validation. A short summary of the results from each theme area are covered below.

13.1 REQUIREMENTS

The goal of Theme 1 was to capture, consolidate and summarize the mobility modeling capabilities desirable for the NG-NRMM. The entire membership was queried as to the pros, cons, and missing capabilities of the NRMM. From the hundreds of items submitted, the list was gradually winnowed down to requirements for a Near-Term Solution (Threshold) and for a Far-Term Solution (Objective) (Figure 6-1). The Near-Term Solution would be based on physics-based models such as Becker-Wong rather than empirical assessment. The Far-Tem Solution would rely on more advanced Discrete Element Method (DEM) models and Finite Element Models (FEM) requiring high-performance computers.

The NG-NRMM would include larger scale terrains with variable resolutions dependent on the area covered. There would be a necessary trade-off between computational efficiency and model fidelity. Two areas that were under consideration that were not part of the original NRMM were Stochastics or Uncertainty (Theme 3) and Intelligent Vehicles (Theme 4).

13.2 METHODOLOGIES

The NRMM model is used in vehicle design, acquisition, and operational planning. The vision of the Methodology Theme area was to develop an Open-Architecture model with a Semi-Analytical approach most possible in the short time frame (Threshold) with a long-term goal of an Analytical Model (Objective). The Open Architecture would provide a framework for modular, interoperable capabilities with the simplest form being a set of mobility standards or specifications, designated as NORMMS for NATO Operational Reference Mobility Modeling Standards. The NORMMS framework was defined as a modeling and simulation architectural specification that promotes standardization, integration, modular interoperability, portability, expansion, verification and validation of vehicle-terrain interaction models.

Other recommendations are to develop a requirements dashboard, Verification and Validation benchmarks, a software assessment matrix and to follow standards similar to those of the National Agency for Finite Element Methods and Standards (NAFEMS).

13.3 STOCHASTICS

This theme area sought to describe a framework for a stochastic approach for mobility predictions over large regions that could be integrated into NG-NRMM, where both the terrain profile and vehicle-terrain interaction play a key role. The uncertainty in these variables leads to unreliable model results. This theme area evaluated the stochastics of elevation as determined by remote sensing, and the physical properties of the terrain such as soil cohesion and internal friction angle.

A framework was described for a stochastic approach for vehicle mobility prediction over large regions (> 5 x 5 [Km^2]). In this framework, a model of the terrain is created using geostatistical methods. The performance of a vehicle is then evaluated while considering the terrain profile and the vehicle-terrain interaction. In order to account for uncertainty, Monte Carlo simulations are performed, leading to a statistical analysis. Uncertainty in elevation is due to the new interpolated terrain model to a higher spatial resolution than the original DEM (through a geostatistical method called Ordinary Kriging). Uncertainty in soil properties is obtained considering the variability of the parameters involved in the well-known Bekker-Wong (BW) model, rather than Cone Index.

The algorithm and hardware must be selected; reduced order models can be run online on a laptop, whereas complex models could require offline use on a HPC. Software for geostatistical functions would be required such as ArcGIS.

13.4 INTELLIGENT VEHICLES

The goal of this theme was to define an NG-NRMM approach and requirements to assess mobility for intelligent vehicles. Intelligent vehicle technology is rapidly evolving and NRMM must grow and adapt with it. Some of the path-forward questions are the following:

- What is the scope of intelligent vehicles to consider?
- What methods to address and priorities?
- What tools need to be developed?
- What benchmark problems should we pilot?

During the next phase a pilot project could help flesh out requirements, challenges and gaps for intelligent vehicles. This pilot would show sliding levels of autonomy under multiple scenarios and output quantitative risk and performance, leading to a new capability development.

13.5 TOOL CHOICES

The goal of this theme was to identify the critical elements needed in an NG-NRMM, identify potential solutions throughout the technical community and provide a robust review through a Request for Information. Responses from twelve software packages were evaluated through a Combinatorial Trade Study process. This effort demonstrated that tools do exist from commercial and academic sources that meet most of the future needs, so a major development effort by the NATO community should not be required.

Accuracy of vehicle system performance is the biggest limitation of the current NRMM which is empirically based. Validated physics-based methods will potentially be an improvement over NRMM. The strength of the physics-based tools varies. Some are capable and have been thoroughly validated for on-road operation and yet only limited off-road deformable soils work has been accomplished. Others focused primarily on off-road soft soil terrain but have no capability for determining on-road stability and associated dynamic control. Furthermore, many of the potential physics-based tool providers are not familiar with the existing capabilities of NRMM, particularly as it relates to developing specific terrains appropriate for worldwide deployment. A Verification and Validation exercise is required to evaluate and help develop the existing tools, which could require substantial funding.

13.6 INPUT DATA AND OUTPUT METRICS

The goal of this theme was to define the inputs and output requirements that will inform the NG-NRMM tool development/selection process. Seven data categories of inputs were designated: vehicle; terrain; environment/scenario; operator; human factors; intelligent vehicle; and scale/resolution modes. Several near-term, stop-gap solutions were described that were developed by AMSAA to enhance the current NRMM including a System Level Analysis Mobility Dashboard, an Urban Maneuverability Model and an Optimal Path Model.

Future challenges will include the following areas: develop methodology to transform high resolution satellite imagery, remotely-sensed GIS data, etc. into accurate NG-NRMM terrain representations; develop interoperability standards between multi-body vehicle dynamic simulations and commercial GIS software solutions; and pursue multiple levels of fidelity solutions.

13.7 VERIFICATION AND VALIDATION

The goal of Theme 7 was to provide a process for conducting a successful tool and software code Verification and Validation (V&V) program on NG-NRMM. Plans were made to conduct a Phase I Tool Benchmarking using test data from one wheeled and one tracked vehicle to provide a common basis for evaluating tool capabilities. Eight software developers attended the NATO meeting in Prague to describe their capabilities and to become informed of the future V&V plans.

This will be followed by a Phase II to develop NG-NRMM standards version 1.0 and associated benchmarks and to establish the basis and process for on-going future development, configuration management, and tool qualification

Chapter 14 –SUPPORTING MATERIAL

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Richmond, P.W, A.A. Reid, S.A. Shoop, G.L. Mason (2006). Terrain Surface Codes for an All-Season, Off-Road Ride Motion Simulator. The MSIAC online Journal http://www.msiac.dmso.mil/journal/ <http://www.msiac.dmso.mil/journal/>

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Shoop, S., Kestler, K. and Haehnel, Rl, "Finite Element Modeling of Tires on Snow." Tire Science and Technology, V. 34, Jan-Mar 2006, 2-37.

Shoop S.A., "Terrain Characterization for Trafficability," CRREL Report 93-6, June 1993.

Wong, J.Y. (1988)NEPEAN Tracked Vehicle Performance Model (NTVPM-85, Contract Report 17/88, prepared for Defence Research Establishment Suffield, Dept of National Defence, Great Britain.

Appendix A – ET-148 TECHNICAL ACTIVITY PROPOSAL (TAP)

<table>
<tr><td>ACTIVITY REFERENCE NUMBER</td><td>AVT-ET</td><td colspan="2" rowspan="2">ACTIVITY TITLE
Next-Generation NATO Reference Mobility Model (NRMM) Development</td><td>APPROVAL
TBA</td></tr>
<tr><td>TYPE AND SERIAL NUMBER</td><td>**Exploratory Team**</td><td>START
5/2014</td></tr>
<tr><td colspan="2">LOCATION(S) AND DATES</td><td colspan="2">In conjunction with AVT PBWs</td><td>END
4/2015</td></tr>
<tr><td colspan="2">COORDINATION WITH OTHER BODIES</td><td colspan="3">None</td></tr>
<tr><td colspan="2">NATO CLASSIFICATION OF ACTIVITY</td><td>NU</td><td colspan="2">Non-NATO Invited
No</td></tr>
<tr><td colspan="2">PUBLICATION DATA</td><td>TM, Misc</td><td colspan="2">NU</td></tr>
<tr><td>KEYWORDS</td><td colspan="4">Mobility, Ground Vehicle, NRMM</td></tr>
</table>

A.1 BACKGROUND AND JUSTIFICATION (RELEVANCE TO NATO):

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 can be used for on-road and cross-country scenarios, it can account for several parameters such as terrain type, moisture content, terrain roughness, vehicle geometry, driver capabilities, etc.

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) over several decades, and has been revised and updated throughout the years, resulting in the most recent version, NRMM II. NRMM is traditionally used to facilitate comparison between vehicle design candidates and to assess the mobility of existing vehicles under specific scenarios.

Although NRMM has proven to be of great practical utility to the NATO forces, when compared to modern modeling tools it exhibits several inherent limitations:

- It is based on empirical observations, and therefore extrapolation outside of test conditions is difficult or impossible.
- It is heavily dependent on in-situ soil measurements.
- Only one-dimensional analysis is possible; lateral vehicle dynamics are not considered.
- It does not account for vehicle dynamic effects, but instead only considers steady-state condition.
- It is specific to wheeled/tracked vehicles.

- It is not easily implementable within modern vehicle dynamics simulations.
- It exhibits poor (or poorly understood) inter-operability and inter-scalability with other terramechanics and soil mechanics models.
- It is only suitable for mobility analysis, and does not provide auxiliary outputs (e.g. power efficiency analysis).

The proposed exploration is vital to NATO's mission. It promises to enable new capabilities in the design, modeling, and simulation of a broad class of vehicles. These modeling capabilities are of high importance to current and future NATO missions because they have the potential to significantly reduce costs and improve performance. The new tool will be applicable to various running gear morphologies, including conventional wheels and tracks, and more novel bio-inspired limb designs. This could yield a new paradigm for ground vehicle mobility, which surpasses traditional analysis based on NRMM's GO/NOGO basis. An important aspect of modern simulations is the possibility to model complex vehicle maneuvering in high fidelity. Relying on High Performance Computing (HPC), it will be possible to utilize statistical representations of terrain profile and properties and to exploit very large-scale Monte Carlo simulations to yield rich outputs over a broad parameter space.

A.2 OBJECTIVE(S):

This scope is to investigate an efficient simulation-based next-generation NRMM. Specifically, the proposed activity will focus on the following fundamental scientific objectives:

- Identify scale-invariant terrain descriptions for representing topographic map data (obtained at various scales) within a suitable multi-body dynamic simulator. This will enable automated analysis of regions of interest, given heterogeneous map data products as inputs.
- Develop efficient, automated, parallelizable experimental design methods (i.e. sampling methods) for extracting metrics of interest from Monte Carlo simulations of the multi-body dynamic simulator, including mobility-related metrics and auxiliary metrics. This will yield rich statistical mobility-related outputs in a computationally efficient manner, which will allow use of modern HPC resources.
- Explore the use of compact representations of vehicle dynamics (i.e. response surface methods or other approximation methods) within the multi-body dynamic simulator, with a goal of further reducing computational cost.
- Establish compact, user-friendly representations of output metrics that capture important dependencies. This will yield an update to classical "speed made good" or "go/no go" maps.

A.3 TOPICS TO BE COVERED:

Modernizing the NRMM involves several topics of effort:

- Identification of vehicle - terrain interaction models, i.e., terramechanics models, that balance fidelity with computational efficiency.
- Development of in-situ and online measurement tools to identify required terrain parameters.
- Identification of the type and form of desired responses, to yield rich mobility predictions and (ideally) useful auxiliary outputs.

- Integration of terramechanics models into modern dynamic simulation software, and develop efficient, automated computation tools, which will ideally enable the use of high performance computation techniques.
- Since the next-gen NRMM is expected to be extremely computationally intensive, there exists a need to investigate numerical methods to improve algorithmic efficiency and automate NRMM output generation, such as Monte Carlo sampling techniques and stochastic response surfaces.

A.4 DELIVERABLE AND/OR END PRODUCT:

The Exploratory Team will prepare a report of findings and recommendations on the benefits and value of the Next-Generation NATO Reference Mobility Model for enhanced vehicle design and mobility performance. The report will also detail the various resources required and committed by the various member nations to develop this model. This summary report will detail the current state-of-the-art and provide recommendations for the next-gen NRMM that will be more predictive, more general, and more scalable than the current NRMM.

It is expected that the findings of this ET will lead to a RTO Task Group (RTG) which will work on this cooperative research project in the 2015-2018 timeframe. The future RTG will bring together experts in the field from all NATO and supporting nations to first develop the technical research required to develop the next Generation NRMM model, and secondly develop computer algorithms to rapidly compute and automate NRMM output generation. It is also possible that one or more RTO Workshops (RWS) may be necessary in conjunction with the bi-annual AVT Meetings to focus on specific aspects of the challenges facing the RTG. A Final Technical Report is expected to be delivered in or around Oct 2018.

A.5 TECHNICAL TEAM LEADER AND LEAD NATION:

Co-Chair: Dr. Paramsothy Jayakumar (U.S. Army TARDEC), USA

Co-Chair: TBD

Lead nation: USA

AVT Panel Mentor: Dr. David Gorsich (U.S. Army TARDEC), USA

A.6 NATIONS WILLING/INVITED TO PARTICIPATE:

Canada, Czech Republic, Estonia, France, Germany, Italy, Poland, Romania, Slovakia, Turkey, United Kingdom, USA

A.7 NATIONAL AND/OR NATO RESOURCES NEEDED:

The Exploratory Team will need meeting space during AVT Panel Business Weeks.

Standard support for a Workshop (RWS) and/or Specialists (RSM) meeting and Exploratory Team. This will include:

- National support for the Exploratory Team activity
- Technical Evaluator for the Workshop/Specialists meeting
- Distribution of Workshop/Specialists announcements
- Publication of the Proceedings of the Workshop/Specialists meeting on the RTO Website
- Publication of the Exploratory Team Report

A.8 RTA RESOURCES NEEDED:

Standard support for a Workshop (RWS) and/or Specialists (RSM) meeting and Exploratory Team.

This will include:

- Technical Evaluator for the Workshop/Specialists meeting
- Distribution of Workshop/Specialists announcements
- Publication of the Proceedings of the Workshop/Specialists meeting on the RTO Website
- Publication of the Exploratory Team Report

Appendix B – FINAL REPORT FOLLOWING ET-148 MEETING IN BELGIUM

Some Thoughts on the Development of the Next-Generation NRMM

J.Y. Wong
Vehicle Systems Development Corporation
Ottawa, Ontario, Canada

1. Introduction

The NATO AVT-ET-148 meetings were held in Brussels, October 13-17, 2014, to discuss the framework within which the next-generation NRMM may be developed. The discussions focused on its goals, requirements, methodology, input and output metrics, and related topics. To provide the necessary background information for discussions, the following presentations on various themes were made at the meetings:

(A). Next-Gen NRMM Goals and Themes, by Dr. P. Jayakumar, TARDEC
(B). Theme 1: Requirements, by Jody Priddy and Wendell Gray, ERDC
(C). Theme 2 a: Methodology, by Dr. Mike McCullough, BAE
(D). Theme 2 b: Methodology-Stochastics, by Dr. Karl Iagnemma, MIT
(E). Theme 2 c: Tool Choices, by Henry Hodges, NATC
Mobility Tool Choices of Germany and France, by Dr. Michael Hoenlinger, Germany
(F). Theme 2 d: Methodology – Intelligent Vehicles, by Dr. Karl Iagnemma, MIT
(G). Interim Report of the Project "Evaluation of NTVPM for Assessing Tracked Vehicle Cross-Country Performance", by Dr. J.Y. Wong, VSDC. The project is sponsored by TARDEC
(H). Theme 3: Input Data and Output Metrics, by James Ngan and Brian Wojtysiak, AMSAA
(I). Theme 4: All Other Items, by Dr. P. Jayakumar, TARDEC

Inspired by these presentations and on reflection of the ensuing discussions, some of the thoughts on the development of the next-generation NRMM were offered in this brief report by the author, as consultant to the NATO Science and Technology Organization (STO), Collaboration Support Office (CSO). This brief report is intended to summarize the issues that should be addressed in the development of the next-generation of NRMM. It is not, however, intended to provide any recommendation for its execution. This can only be made after an in-depth analysis and evaluation of all the issues involved, which is beyond the scope of the tasks stipulated in the Consultancy Contract with NATO STO CSO (CP-AVT-ET-148-14-807).

Goals

It is suggested that the primary goals of the next-generation NRMM be:
Providing military agencies of NATO countries with advanced tools
(a). to evaluate ground vehicle candidates in sufficient detail in the procurement process;
(b). to perform operational planning for the deployment of military ground vehicles in the field;
(B). providing industry with a reference in the development of ground vehicles to meet military requirements.

The next-generation NRMM should incorporate the latest advancements in modeling and simulations of ground vehicles, which include but are not limited to advances in the analysis of the mechanics of vehicle-terrain interaction, terrain characterization, simulation techniques, and military ground vehicle technologies.

Requirements

The requirements for the next-generation NRMM include but are not limited to the following:
(A). physics-based, that is, based on the understanding of the physical nature of vehicle-terrain interaction and on the detailed analysis of its mechanics;
(B). capability in evaluating military ground vehicle performance and behavior in three dimensions;
(C). capability in modeling military ground vehicle performance and behavior on both rigid surfaces and deformable terrains; measurement and characterization of deformable terrain behavior be consistent with Requirement 3 (A);
(D). capability of simulating legged vehicles, robotic vehicles, and intelligent/autonomous vehicles, in addition to conventional wheeled and tracked vehicles;
(E). capability in modeling ground vehicle performance and behavior equipped with various sub-systems, including but not limited to antilock braking systems, traction control systems, dynamic stability control systems, active/semi-active suspensions, and powertrain systems, as well as vehicle fuel economy;
(F). capability in integrating driver models in simulations of ground vehicle performance and behavior;
(G). sufficient accuracy (fidelity) to enable meaningful differentiation of the performance and behavior of military ground vehicles of various configurations and designs, in accordance with the Goal noted in 2 (A) (a);
(H). modular structure to enable the expansion of its capabilities to meet new challenges in the future;
(I). user-friendly in input and output and ease of its operations;
(J). verification and experimental validation of its predictive capabilities on rigid surfaces and on representative deformable terrains (such as, fine- and coarse- grained soil, muskeg (organic terrain), and snow-covered terrain).

4. Implementation

In the development of the next-generation NRMM, the implementation issues to be considered include but are not limited to the following:
(A). investigating the feasibility of establishing a framework (or “backbone”) for the next-generation NRMM, with which various modules may be connected with standardized input formats and from which specific output with standardized formats may be obtained. The framework is a computer simulation architectural specification applicable to the full range of ground vehicle geometric scales that promotes standardization, integration, interoperability, expansion, verification, and validation of vehicle-terrain interaction models at multiple levels of analytical and numerical resolution [1];
(B). examining whether the framework be based on commercial software or be established with specially developed codes, taking into account the costs, security, legal implications, sustainability, and training;
(C). various aspects of ground vehicle performance and behavior to be predicted using separate modules, including but not limited to:
(a). on-road performance prediction module;
(b). cross-country performance prediction module (since the widely accepted practice is to evaluate cross-country performance under steady-state operating conditions, it is much more efficient to obtain output metrics through solving a set of vehicle and sub-system dynamic equilibrium equations than by time integration of a set of equations of motion);
(c). ride quality prediction module for rigid surfaces and deformable terrains;
(d). handling characteristics prediction module for rigid surfaces and deformable terrains (including urban maneuverability);
(e). obstacle crossing performance prediction module; (f). amphibious capability prediction module.

(D). evaluating the methodologies for measuring and characterizing deformable terrain behavior in accordance with Requirement 3 (A) (including methodologies based on the cone penetrometer, bevameter, and traditional devices utilized in civil engineering soil mechanics);
(E). incorporating uncertainties, stochastic and sampling methods into terrain data acquisition and characterization, as well as the propagation of uncertainty of terrain input to output metrics;
(F). template-based input for vehicle sub-systems;
(G). establishing output metrics, such as, mobility map, mobility profile, gradeability, tractive performance, and fuel economy for cross-country operations; acceleration time and distance, braking distance, gradeability, and fuel consumption for on-road operations; weighted root mean squared acceleration, absorbed power, instantaneous peak acceleration, and frequency response for ride quality; minimum turning radius, yaw velocity response, lateral acceleration response, curvature response for handling characteristics, etc. [2];
(H). utilizing high-power computing (HPC) resources, if necessary.

Research in Support of Implementation

Research in support of the initial phase of development of the next-generation NRMM includes but is not limited to the following:
(A). in simulating ride quality of vehicles over deformable terrains, the usual practice is to use springs and dampers to model the terrain. In essence, the terrain is assumed to be a visco-elastic medium. In accordance with Requirement 3 (A), the plastic deformation of deformable terrains should be considered, so that the modification to the terrain profile due to vehicle-terrain interaction is properly taken into account;
(B). models for simulating maneuverability of ground vehicles, including tracked vehicles, on non-deformable surfaces have been established [2, 3]. In accordance with Requirement 3 (A), the mechanics of vehicle-terrain interaction during maneuvers on deformable terrains should be examined.

Priority

In the development of the next-generation NRMM, priority should be established in accordance with the urgency of needs and their potential impacts. In the initial phase of its development, the following should be considered:
(A). the establishment of the framework, as noted in 4 (A), is key to the development of the next-generation NRMM and should be given top priority;
(B). cross-country performance is one of the focuses in the evaluation of military ground vehicle mobility. In the current NRMM, the cross-country performance prediction sub-module is entirely based on empirical relations. This indicates that the development of physics-based, cross-country performance prediction methodology should be given priority;
(C). in the current NRMM, there is no provision for evaluating the handling characteristics of ground vehicles. This suggests that the development of maneuverability prediction methodology also be given priority.

7. Collaboration

Collaboration with professional organizations in the field of vehicle mobility, such as the international Society for Terrain-Vehicle Systems (ISTVS), would be useful. The collaboration may be in the form of organizing special workshops and/or forums at ISTVS international or regional conferences, at which advice of experts may be sought or topics of interest may be discussed.

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(2114-10-24)

Appendix C – INITIAL TEAM SURVEY

C.1 WHAT ARE THE THINGS THAT YOU LIKE ABOUT NRMM?

Canada, William Mayda

- not just a pure "mobility" tool. Includes other human factors
- relatively good correlation when soil conditions known

Romania, Ticusor Ciobotaru

- Exhaustive covering wheeled and tracked vehicles from small robot to tanks sizes
- Fast and facile method for soil characteristics
- Impressive experimental sustentation
- Allows simulations/predictions for expensive test (mobility on soft soils, suspensions characteristics)
- Used by several NATO countries

USA, Dave Gunter

- Provides measure of mobility performance in "Operational" terms
- Portability (desktop capable)
- Runs quickly
- Easy to develop models

USA, Karl Iagnemma

- The ambition to model multiple effects related to terrain, environment, vehicle, and operator
- A clear, unambiguous output metric

USA Mike McCullough

- Stable mobility metrics and criteria creates a level playing field for use in trade studies
- Most metrics have a trace-able theory that enables linkage from performance results to design attributes
- Available, open source and supported for use by industry

USA, Jody Priddy

- NRMM is currently the only available modeling and simulation (M&S) product that can realistically quantify 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.
- One of its key strengths originates from the methods used to compute force projection metrics by integrating engineering-level (i.e., proving ground type) performance capabilities on different terrain features with geo-specific quantifications of the types of terrain feature interactions that will occur in different theaters of

operation around the world. Metrics associated with fundamental engineering level performance tests are very important for sound decision making in ground vehicle design, but there is also a critical need, which NRMM fulfills, to extend engineering-level performance metrics beyond controlled proving grounds and into force projection metrics that quantify real-world, mission based, operational capabilities.

- Another key strength of NRMM is the viable nature of the underlying models and relationships for achieving usable force projection capability assessments in a reasonable amount of time without a requirement for excessive information on vehicle and terrain characteristics that can be highly restricted or not realistically attainable. Both the vehicle and terrain characteristics required for NRMM are robust in scope, yet very attainable.
- An additional key strength is the comprehensive nature of NRMM from a terrain perspective, especially for mobility performance in non-urban and off-road environments. It can currently account for the influence of most major soil, snow, and ice ground surface conditions (to include rainfall induced slipperiness effects on soils), varying slope grades, rough undulating terrain surfaces, discrete shock inducing ground obstacles, dry and water-filled linear-feature gaps, vegetation and other override resisting obstacles, visibility restricting terrain features, and general speed-limiting features of road networks.
- Finally, NRMM is free software for all NATO end-users who have access. End-users incur no hefty upfront purchasing costs or recurring maintenance costs, both of which are typical for most commercial engineering software products. In the case of NRMM, development and maintenance costs of the software products and the unique embedded M&S knowledge are funded through government research and development investments, and the software is freely distributed for use in government purposes only.

USA, Brian Wojtysiak

- Quick run times
    - Allows us to support Army studies involving multiple vehicles under relatively short deadlines with an appropriate level of fidelity
- Assesses the combined effects of a variety of off-road challenges (soil strength, grades, obstacles, vegetation, ride & shock tolerances, weather conditions, human factors, etc)
- Provides diagnostic reason codes to help understand results
- Empirical relations (i.e. VCI vs. drawbar/resistance) that provide a level of self-validation
    - Excellent item/system-level performance estimation tool. One of the only tools that can be used to conduct wheeled and tracked vehicle off-road mobility analysis.
- The effects of sub-system design changes can be rapidly assessed.
- Provides strong capability to execute comparative mobility analysis (including backwards comparability).
- NRMM outputs can be represented with maps (speed maps, speed comparison maps.) for better visualization / comparison (if digital terrain file available). Although this process can be time consuming and cumbersome.

C.2 WHAT ARE THE THINGS THAT YOU DISLIKE ABOUT NRMM?

Canada, William Mayda

- lack of friendly user interface

- inability to extrapolate beyond existing vehicle types/weights
- inability to accommodate new and novel drivetrains

Romania, Ticusor Ciobotaru

- Data input/output, software running
- Lack of friendly GUI for input/output data
- Lack of modules covering the steering of the tracked vehicles

USA, Dave Gunter

- No error handling (crashes when data entered incorrectly with no message indicating where the error came from)
- Impossible to verify many of the predictions through test (Mission Rating Speeds, %NOGO, etc.)
- 2D-dynamics
- Not possible to evaluate modern technologies (active/semi active suspensions, esc, abs, etc.)
- Simple tire model
- Small portion of globe incorporated (areal terrain maps need to be expanded)
- Split Mu
- No Braking
- No rocky evaluation capabilities
- Urban maneuverability

USA, Karl Iagnemma

- Its reliance on ad hoc correction factors to model the effects of many distinct effects, which likely leads to substantial uncertainty in the resulting output
- Its lack of representation of output uncertainty levels, making it difficult to assign confidence to the output

USA Mike McCullough

- Ride Quality metric needs significant updates
    - 3D vehicle multibody dynamics models that are more precisely representative of vehicle designs (must include flexible/deformable bodies to be general)
    - 3D Deformable terrain in the simulations
    - Terrain specification in mission profiles
        - Spectral content
        - material response, i.e., soil type and moisture content
        - Ergodic and stationary sample lengths w.r.t. ride quality response parameters (accounting for skid plate and/or spider contact events)

    - Driver feedback loop model for speed and direction control of 3D vehicle dynamic model
    - Automated iterative loops for 6watt and 2.5G speed limits
        - access to intermediate and lower level results plots such as speed vs power, acceleration
- Obstacle crossing metrics need significant updates
    - 3D vehicle multibody dynamics models that are more precisely representative of vehicle designs (must include flexible/deformable bodies to be general)
    - 3D Deformable terrain with embedded hard obstacles in the simulations
    - Rubble pile definition and standardization
        - could include dynamic rubble
    - library of obstacles that are selectable and tailorable to vehicle and mission requirements
    - amphibious operations obstacles
        - stream/lake fording
        - surf zones including rocky shores
        - ship launch
- Needs powertrain performance on slopes and fuel economy/range

USA, Jody Priddy

- The biggest weakness of the current version of NRMM is the dated nature of the software code, which leads to nonuser friendliness and a lack of modularity for ease of upgrades and variations. The development and maintenance investments over time for NRMM have largely been piecewise and project focused, with no formalized funding process identified within NATO or the contributing nations specifically for software maintenance and updates. There have been research and development investments in unique embedded knowledge and capabilities for NRMM by contributing nations, but a lack of funding directed solely at software maintenance purposes has resulted in the current outdated state of the software. It is important that formalized software maintenance strategies be pursued to ensure that future versions of the NRMM software can be kept up-to-date in terms of computing standards and capabilities.
- NRMM does not currently model the influence of active traction control systems such as anti-lock braking (ABS), automatic brake modulation (ABM), or electronic stability control (ESC). Active controller-based systems for traction can provide significant benefits for on-road stability and performance, but their effects on off-road performance can actually be detrimental and must be quantified for a complete assessment of a vehicle's performance capabilities. NRMM currently assumes that each traction element (e.g., wheel, track, etc.) is either fully unpowered or powered (i.e., towed or driven mode), where it is assumed that there is ample torque to fully mobilize all of the traction available from the terrain for the powered case. The influence of active traction control systems on performance could be modeled in NRMM with appropriate upgrades to eliminate this binary assumption.
- NRMM does not currently model the influence of active suspension systems. Active suspension systems are a future technology with great potential to produce improvements in off-road performance. More robust vehicle dynamics software products are needed for modeling active suspension systems prior to the development of physical prototypes. Incorporation of controller logic algorithms in the current vehicle dynamics preprocessor VEHDYN (a relatively "light weight" 2-D simulation tool) could largely overcome

the associated limitations, but integration of controller M&S and full-featured 3-D vehicle dynamics simulation tools is achievable and would likely provide the best overall capability improvements for NRMM.

- The empirical nature of the current vehicle-terrain interaction relationships results in one of the key strengths of NRMM since the correlation relationships have been robustly founded on large quantities of physical measurements with vehicles and single traction elements that ensure realistic predictions of force projection capabilities, but the resulting total dependence on physical test data to derive these terramechanics relationships also results in a key weakness for NRMM due to a continuing requirement for complex and expensive physical testing. The empirical relationships provide good prediction confidence for typical ground vehicles, not only because of the robust underpinning data, but also because of their underlying physics basis, which derives from consideration of the controlling physical interactions at the ground interface involved in traction, motion resistance, sinkage, etc. However, correlation relationships will always be limited in applicability to the empirical range of the underlying data and the bounding assumptions behind the relationships, which demands continuous consideration of new performance data to ensure or expand the applicability of the terramechanics relationships to evolving and atypical vehicle designs. The terramechanics relationships in NRMM essentially predict the response characteristics of terrain to loadings imposed by ground vehicles, where the terrain response characteristics typically limit the mobility performance of military vehicles. Modeling terrain response characteristics through numerical simulations that quantify the physics of stress and deformation propagation within terrain media (e.g., soil, snow, ice, vegetation obstacles, etc.) has historically presented overly formidable challenges that have precluded their use over empirical correlation approaches, but recent advancements in numerical methods and high performance computing capabilities are now beginning to offer real promise for enhancing, expanding, or replacing physical testing with virtual performance-knowledge generators.

USA Brian Wojtysiak

- The user interface (text files and command line) is not user-friendly. (AMSAA is currently developing a user interface “wrapper” to address this issue).
- Terrain data is old, not up-to-date and new terrains cannot be easily built from geospatial data.
- It would be nice to be able to execute with less data fidelity (especially with “red” systems where there is often little to no data availability).
- Empirical relations limit extrapolation and validity of assessing future technologies making it difficult to incorporate new vehicle technologies unless the analyst can identify the impacts on certain vehicle sub-systems.
- Statistical outputs and speed profiles - do not inform mission operations – (e.g. the mission / route planning context).
- Statistical output does not consider accessibility – e.g. a NTU may be represented as “Go”; however the entire NTU is surrounded by “NoGo” terrain and therefore is inaccessible. To correct this issue, additional spatial analysis post-processing is needed.
- The vehicle configuration used in Obsmod submodule does not represent the actual vehicle configuration.
- Mobility for on and off road are traditionally evaluated separately.
- Outdated interface for input and output files (the VEHDYN preprocessor can be particularly problematic).
- Outputs (i.e. VXX speeds) can be difficult to understand for non-technical personnel.

- Lack of validation with NRMM updates.
- Requirement for some input curves (i.e. ride & shock) to be continually decreasing – this is not always the case in real world due to resonances, suspension characteristics, etc. (e.g. in reality they are not “smooth” curves – “real-world” data may have “spikes” to account for this type of behavior).
- Current method for determining No-Go reason codes could be improved – for example, there could be multiple reasons for No-Go, but currently only one reason is revealed with the current algorithms.
- Obstacle No-Go restricted by the slightest of clearance interference – doesn’t represent the ability of the vehicle to override the obstacle with vehicle horsepower.

C.3 WHAT ARE YOUR REQUIREMENTS FOR THE NEXT-GENERATION NRMM?

Canada, William Mayda

- Enhanced user interface
- Enhanced graphical output (graphs, charts, visuals etc.)
- Add on modules for unique soil conditions (soft soil, snow etc.) with physics base
- "Lite" version that would allow non-trained users to vary selected parameters easily (perhaps power, weight etc.) without requiring in-depth knowledge....quick "what if" scenarios

Canada, J.Y. Wong

- In the development of the Next-Gen NRMM, the methodology for assessing the cross-country performance should be given priority. The reasons for this are well articulated in Dr. Jayakumar's presentation on the inherent limitations of the current version of NRMM.
- In the discussions of the objectives of the Next-Gen NRMM, perhaps the following issues should be given sufficient attention:

    - The evaluation of vehicle candidates, from the cross-country performance perspective, using the current version of NRMM is based on a limited number of criteria, such as "go/no go,” "maximum possible speed (speed-made-good),” etc. Should the number of criteria be expanded to include other factors, such as efficiency?
    - The level of fidelity at which the Next-Gen NRMM is aiming should be carefully considered, in relation to the proposed time frame and the resources available. For instance, should it be aiming at replicating vehicle performance/behavior in the field in detail or providing a simulation tool for evaluating/comparing vehicle candidates on a relative, yet well-founded, basis?

Czech Republic, Neumann Vlastimil

- Improvements (definition) of terrain
- Utilization of simulating technologies in process of vehicle mobility evaluation (obstacles negotiation)

Estonia, Kersti Vennik

Prioritized requirements (objectives) list for next-gen NRMM:

- first of all I think the new NRMM should be easy to use and to install;
- it should work in non-soil scientist mode, i.e. with easy No-Go and Slow-Go estimation option, as well in terramechanic specialist mode, where more detail and parameters about soil as well vehicle can be inserted and modeled with different soil-vehicle interaction models (models based on RCI values, models based on soil strength (internal friction, cohesion) values, etc.);
- the modeling output should be in digital map form and Open Geospatial Consortium standards for the digital maps should be used, so that final results could be loaded to different GIS and C2 systems;
- possible modeling outputs should be:
    - off-road speed estimation for particular vehicle,
    - rut depth estimation for first and for 0th pass for particular vehicle,
    - soil susceptibility to increase of moisture
    - moving possibilities in thawing soil situation as well as for different depth of snow situation.

Germany, Michael Hoenlinger

From development perspective I would prioritize the (TAP) objectives as follows:

- Identify scale-invariant terrain descriptions for representing topographic map data (obtained at various scales) within a suitable multi-body dynamic simulator. This will enable automated analysis of regions of interest, given heterogeneous map data products as inputs.
- Develop efficient, automated, parallelizable experimental design methods (i.e. sampling methods) for extracting metrics of interest from Monte Carlo simulations of the multi-body dynamic simulator, including mobility-related metrics and auxiliary metrics. This will yield rich statistical mobility-related outputs in a computationally efficient manner, which will allow use of modern HPC resources.
- Explore the use of compact representations of vehicle dynamics (i.e. response surface methods or other approximation methods) within the multi-body dynamic simulator, with a goal of further reducing computational cost.
- Establish compact, user-friendly representations of output metrics that capture important dependencies. This will yield an update to classical “speed made good” or “go/no go” maps.

Another approach could be to establish an interface between NRMM and MBS software. The advantage is that both software systems could be updated and optimized independent and only the interface has to be adapted.

Romania, Ticusor Ciobotaru

Objectives:

- Requirements for a friendly GUI
- Conceptual framework for dealing with steering
- Evaluation of the impact of new technologies on the NRMM modules (hybrid, or electric traction, skid steering for wheeled vehicles)

USA, Dave Gunter

- Need to research testable mobility metrics.
- Need to research rationale for asymmetric terrains (how to quantify asymmetry, and why it's needed).
- Need to research terrain roughness index (for both symmetric and asymmetric terrains).
- Need to research split mu metrics (gravel shoulder correction).
- Need to research dynamic stability control metrics.
- Improved Tire/Track to soil interface force predictions (addresses split mu, too)
- 3D dynamics (also includes computer control ABS/ESC/active/semi-active, etc.)
- Urban maneuverability

USA, Karl Iagnemma

- Rigorous representation and propagation of uncertainty through to output metric(s)
- Exploitation of modern numerical multibody dynamic modeling methods to mitigate reliance on ad hoc correction factors

USA, Mike McCullough

Incremental evolutionary approach that addresses low-hanging fruit first

- closed form model cleanup and expansion (removes some parameter redundancies, expands some metrics)
- undercarriage clearance,
    - power train characteristics, fuel economy
    - turning performance
    - vehicle intrinsic amphibious characteristics (i.e. function of weight and CG and geometry and does not require dynamic simulations of amphibious operations)
- stationary, ergodic, spectrally general terrain sample definitions for ride quality
- driver feedback loop for speed control
- 3D Multibody vehicle dynamic models for ride quality, including driver heading control
- Deformable terrain in terrain and mission profile definitions (soil type and moisture content)
- 3D Multibody vehicle dynamic models for obstacle crossing including library of selectable and expandable standard obstacles
- Add dynamic simulation of powertrain performance on slopes and fuel economy/range with 3D mission profiles to account for turning effects on fuel economy
- Expansion of obstacle library
    - rubble pile definition
- amphibious operations defined by dynamic simulations

USA, Jody Priddy

- Complete software recoding using modern programming languages, software engineering techniques, graphical user interfaces, and a highly modular software architecture.
- Software licensing that imposes minimal, and preferably no, upfront purchasing or recurring
- Maintenance costs on end-users for use in government purposes.
- Software license rights for use in government purposes that closely result in “unlimited rights”, as defined in the Defense Federal Acquisition Regulation Supplement (DFARS) of the U.S. Department of Defense.
- New powertrain performance modeling capabilities that can quantify the amount of driving and braking torque that will be applied to each traction element of ground vehicles with conventional powertrain architectures during mobility operations involving a comprehensive array of vehicle terrain interaction scenarios, which should include powertrain cooling considerations.
- New 3-D multibody dynamics M&S capabilities that comprise all the proven capabilities of the current 2-D vehicle dynamics preprocessor VEHDYN and the flexibility to address numerous ground vehicle mobility problems well beyond the scope of VEHDYN.
- New capabilities for quantifying the influence of steering system performance on mobility.
- New capabilities for predicting other mobility performance metrics, with particular emphasis on including additional output metrics desired by other NATO nations in addition to those preferred by the United States.
- New capability to select from and use multiple analytical terramechanics modeling alternatives, based on the end-user’s preference, which could include the ability to “plug-in” end-user developed terramechanics algorithms.
- New terrain characterization and terrain-state forecasting capabilities for producing theater specific data sets in less time, with higher resolution and accuracy, and accounting for a broader array of terrain features, to include urban features.
- New capabilities to account for the influence of urban features on mobility performance of ground vehicles (e.g., constricted areas due to high urban traffic and clutter, tight intersections, narrow roads, etc.).
- New capabilities to appropriately account for the influence of passive and active control systems for traction, suspension, etc. on mobility performance, which could include the ability to “plugin” secured, proprietary, vendor-developed controller-logic modules.
- New numerical modeling capabilities for terrain physics that can reduce the reliance on physical testing for terramechanics relationships while providing good prediction confidence for typical, evolving, and atypical ground vehicle designs.
- New powertrain performance modeling capabilities that can quantify the amount of driving and braking torque that will be applied to each traction element of ground vehicles with hybrid electric and fully electric powertrain architectures during mobility operations involving a comprehensive array of vehicle-terrain interaction scenarios, which should include powertrain cooling considerations.
- New capabilities to address mobility performance considerations for manned and unmanned ground vehicles that require quantified influence of sensor, perception, and autonomy system capabilities on mobility performance.
- Improved human response M&S capabilities for broader quantification of human-specific biophysical

limiters on mobility performance of manned ground vehicles.

- Improved M&S capabilities that account for 3-D effects during fording and swimming performance in water-filled linear-feature gaps and coastal features.

USA Brian Wojtysiak

- Speedy execution (single run in minutes or less, not hours or days)
- Ability to “play” multiple fidelity levels (e.g. low data resolution – “red” systems / paper concepts and high fidelity – 3D modeling and vehicle dynamic behavior) (fidelity tradeoffs are sometime necessary)
- Improve user interface – (e.g. graphical user interface (GUI) for inputs, outputs, and data management)
- Ability to build new and / or update existing terrains with GIS data
- Improve NRMM / Geospatial (ArcGIS) interface to produce cartographic products
- Ability to verify and validate model predictions with vehicle performance data (test data)
- Update NRMM to include prediction capabilities for light weight systems (such as unmanned ground vehicles, robotic systems)
- Eliminate errors in statistical output generation – (e.g. inaccessible areas surrounding a “Go” area - ArcGIS mapping software can be used to eliminate obvious inaccessible areas)
- Similar metrics for measuring how "good" a vehicle performs (both linear and areal).
- More robust reason codes and options for diagnostics
- Allow reporting of multiple reasons for No-Go
- Be able to easily view desired calculated variable values (e.g. display intermediate prediction results)
- Allow for hull contact with surfaces and factor in the associated resistance for obstacle performance
- Eliminate issue with discrete terrain unit transitions – step function differences in performance at NTU borders – results should “blend / transition” at the NTU boundaries

Appendix D – THEME 2, NORMMS DETAILED METHODOLOGY

Michael McCullough

The NG-NRMM requirements described in Chapter 6 and Appendix C are a broad list of capabilities that can be broken down into two broad categories: mobility modeling process improvements and mobility metric (i.e., "product") improvements. "Process" refers to how mobility models should be implemented to promote commonality and standardization as well as ease of use, etc. These requirements and recommendations refer to the latest modeling methods tools, templates, data and computational capabilities that are now commonly available, but which the current NRMM is not able to leverage to advantage. "Product," in the context of mobility models, refers very specifically to new or updated mobility metrics, including adoption of specific algorithms and standards.

The NORMMS address both process and product improvements for the NG-NRMM and can be developed in a top down, incremental spiral approach with progressively higher levels of resolution developed in each iteration. The NORMMS development process also provides high level "buckets" into which the early "ground level" contributions and issues associated with very specific improvements to existing metrics are captured. Eventually the top-down spiral development process will progress to the lowest level and each of these early detailed specifications will be already complete and ready for inclusion in the standard. This approach also promotes collaborative parallel development as each member of the RTG can work the issues unique to their expertise and concern.

Some specific examples of "ground level" improvements that are already being proposed are provided below.

1. Ride Quality. Rainer Gericke proposed that the NG-NRMM should expand the available ride quality metrics to include ISO 2631-5 using 3D metrics applied to results from vehicle testing or 3D multibody dynamics models with embedded high resolution tire and track models. He also proposed that road and terrain roughness measures be defined and reported consistent with ISO 8608. Consistent with this proposal and the need to maintain the historical databases, this draft ground level specification is written to include both the existing metrics and the proposed new metrics. Rainer has also offered a validation data set and some code that implements some of these calculations.
    a. NG-NRMM Threshold: Driver's Vertical Ride Quality shall be computed as 6 watt absorbed power ride limiting speeds versus terrain RMS elevation roughness for vertical acceleration motion inputs at the occupant seat pans where the absorbed power transfer function from Pradko (1966) is applicable and the terrain RMS elevation roughness is measured for a de-trended terrain profile using an exponentially weighted de-trending filter with lambda = 10 ft, per Murphy (1984). The vertical acceleration data must be generated from test or a verified and validated vehicle dynamics model. Ride quality can be additionally computed and specified using the metrics specified in ISO 2631-5. Terrain roughness can be additionally described and reported per ISO 8608.

        i. Verification/Validation Basis: Current VEHDYN 4.3 supplied data and examples

   b. NG-NRMM Objective: Driver's ride quality limits shall be computed in all three orthogonal directions with the following respective ride limiting speeds: 6 watts vertical, X watts longitudinal, Y watts lateral. These must be based upon acceleration motion inputs at the occupant seat pans where the absorbed power transfer functions from Pradko (1966) are applicable and the terrain RMS elevation roughness is measured for a de-trended terrain profile using an exponentially weighted de-trending filter with lambda = 10 ft per Murphy (1984). These data must be generated from test or a verified and validated vehicle dynamics model. Ride quality shall be additionally computed and specified using the metrics specified in ISO2631-5. Terrain roughness shall be additionally described and reported per ISO 8608.
   c. Verification/Validation Basis: Public domain data set on a standard vehicle (e.g., HMMWV)

2. Trafficability. Dr. J. Y. Wong has submitted a formal proposal for a module to compute off-road traction and speed-made-good using a steady state force balance based on the application of Terra-mechanics and actual Bevameter measurements. It addresses the threshold NG-NRMM requirements by focusing on conventional manned wheeled and tracked vehicles using physics basis at a level of geometric resolution appropriate for tire and track interaction with terrain (i.e., Bekker-Wong-Janosi basis for terrain strength modeling), while accounting for grades, soils, moisture content, and snow. Extension to 3D by directly embedding the vehicle terrain interaction computation of this module into a multibody dynamics code, allows it to address autonomous vehicles and the broader range of 3D metrics to include turning, fuel economy, integration with flexible bodies, vehicle powertrain, and steering and control systems. Dr. Wong also summarized the available documentation and approach to leveraging benchmarks examples for validation and a realistic path to accumulation of vehicle terrain interaction (VTI) data for future validation. Trafficability has traditionally been computed using lower resolution whole-vehicle empirical metrics such as Vehicle Cone Index (VCI) and mean maximum pressure (MMP). Those legacy approaches have been widely used in their respective countries of origin and represent valuable legacy metrics with large legacy databases. The latest version of NRMM (version 2.8.2) and its associated vehicle dynamics program, VEHDYN4.3, implement rating cone index (RCI) based pressure sinkage relationships that attempt to move incrementally in the direction of a more semi-empirical approach envisioned for the NG-NRMM. Therefore the following draft NORMMS are proposed to facilitate an orderly transition away from the purely empirical approach:
   a. NG-NRMM Threshold: Trafficability maps must be based on validated VTI models that utilize soil properties that are available from validated remote sensing methods. Use of vehicle cone index (VCI) values that have been demonstrated via test with a real vehicle are acceptable where necessary, but users should be forewarned that VCI has demonstrated limitations and will eventually be superseded by formulations implementing terramechanics and continuum mechanics models of VTI which have the potential to enable eventual utilization of remote sensing data for soil characterization and calculation of trafficability at the tire and track block level of resolution.

        i. Verification Basis: Current NRMM v2.8.2b supplied data and examples and any additional VTI data supporting Bekker-Wong-Janosi (or equivalent) models at the tire and track block level of resolution.

    b. NG-NRMM Objective: Trafficability maps and models must be based on validated VTI models at the tire and track block level of resolution and below (continuum models), that utilize soil properties that are valid for extrapolation to terrains for which the only data available are from remote sensing methods.
        i. Verification Basis: to be developed (TBD)

3. Real time mobility model metrics. Dr. Vladimir Vantsevich has suggested that many of these metrics may find useful application in real time control of vehicle systems and therefore their efficient formulation for these purposes might become an important branch of the NG-NRMM effort.

Murphy, N. R. Jr., 1984. A Method for Determining Terrain Surface Roughness, US Army Waterways Experimentation Station, Geotechnical Laboratory, Vicksburg MS, Sept 1984.

Pradko, F., R. Lee and V. Kaluza, V. 1966. Theory of Human Vibration Response, presented at the Winter Annual Meeting and Energy Systems Exposition of the American Society of Mechanical Engineers, New York.

Appendix E – REQUEST FOR INFORMATION (THEME 5)

Henry Hodges

E.1 LETTER INTRODUCING REQUEST FOR INFORMATION

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Nevada Automotive Test Center
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Carson City, Nevada 89702-0234
Phone: (775) 629-2000
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email: hhodgesjr@natc-ht.com

17 March 2015

Mr. XXX
Company
Address

Email:

Subject: Request for Information on Tools which can provide a Ground Vehicle Mobility Simulation Environment

Dear

NATO Applied Vehicle Technology (AVT) Panel has established an Exploratory Team (ET) to potentially identify and recommend **physics based** simulation tools which can be used to substantially improve the capabilities of the existing NATO Reference Mobility Model (NRMM). Your organization has been identified as having developed simulation tools which could be used to substantially improve the Modeling and Simulation environment necessary to accurately predict vehicle performance in both established and marginal terrain conditions. The attached document explains the type of information required to support this evaluation effort and identifies the criteria to be used.

Please provide your information and questions regarding this effort to the ET Theme 5: Tool Choices Lead identified below.

Henry Hodges
President
Nevada Automotive Test Center
PO Box 234
Carson City, Nevada 89702

USA

hhodgesjr@natc-ht.com

Phone: 775-629-2000

The process for evaluation is expected to be similar to that used for the United States Marine Corps Simulation Based Acquisition effort utilized during the Logistics Vehicle System Replacement program. As such the information provided will be reviewed as appropriate by the NATO ET-148 committee and more specifically by technical representatives of the US Army TARDEC and US Marine Corps Systems Command. Solutions which are capable of providing and supporting the future mobility systems analysis architecture for wheeled and tracked vehicles including autonomous vehicle systems will be identified.

The efforts of the NATO ET-148 Committee will be published and that information provided to the appropriate Governmental and Commercial user communities.

Your response must be provided **not later than 16 March 2015** in order to support the full ET meeting and review scheduled for the week of 20 April. Early submittal of the information will allow time for discussions to insure that your approach is clearly understood. Additional questions will be provided as necessary.

Should you have any questions please contact Henry Hodges as identified above or Dr. Paramsothy Jayakumar (paramsothy.jayakumar.civ@mail.mil).

Respectfully,

Henry Hodges
President

NEVADA AUTOMOTIVE TEST CENTER

E.2 INTRODUCTION

Ground vehicles are deployed worldwide in many challenging environments. Whether tracked or wheeled, the challenges for successful and safe operation continue to increase due to environmental extremes and regional instabilities. Over the past 20 years ground vehicle technology has vastly improved, allowing vehicles to successfully operate over rugged terrain. However, often times the design and production of those vehicles is generated thousands of miles from where those vehicles operate. The ability of the vehicles to successfully complete a humanitarian or operational mission cannot be determined until the vehicles are in the field and this creates significant risk to all involved. Through satellite and other data collection methods, the ability to identify terrain conditions in terms of vegetation, slope, obstacles, and environmental extremes due to excessive rain or drought has approached near real time information. Therefore, it is appropriate to consider a physics based simulation environment which can assess and predict the performance of wheeled and tracked vehicles in these operating conditions. Such a simulation environment would allow not only the accurate development of a successfully mobile and reliable vehicle but also a predictive tool to determine the applicability of that vehicle to current operational requirements. It is also recognized that the availability of high performance computing is further enabling cost and time effective detailed modeling of the vehicle terrain system providing high fidelity simulations.

The purpose of this Request for Information is to determine the availability of such tools and to establish a sustainable simulation environment which has the flexibility to incorporate new simulation solutions as they are developed. It is further noted that continuing and new research development are necessary in specific technology areas. As such a “template” based simulation environment is envisioned under the following charter **The framework is 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**.

Physics-based simulation environments are currently available either commercially, open source, academically, or within Government agencies. New simulation environments are being developed specifically to support current challenges from man-machine interface to complete vehicle autonomy. The vision of the RFI is to collect available information for the physics-based vehicle and the environment in which that vehicle operates to utilize that information to establish the criteria for the framework and to conduct a downselect with the outcome being a recommendation for a successful framework which would be available for implementation throughout the NATO member countries within three years.

This RFI seeks information specific to ground vehicle dynamics simulation, terrain mapping and autonomy capabilities. A separate questionnaire for each of these is provided in the attachments.

E.3 HISTORY

Empirically based tools such as the current NATO Reference Mobility Model (NRMM) have been used to compare and generally rank order the mobility capability of tracked and wheeled vehicle systems. This tool was originally developed during the 1970 time frame and has been updated several times since then. While this tool has generally successfully served its purpose, current technology, both in terms of computing speed and physics based simulation, can now potentially provide a significant improvement both in terms of accuracy and the ability to predict vehicle performance in near current conditions and for both traditional and future concept vehicle configurations.

Many tests and evaluations have been performed utilizing the principle tenets of the NRMM. It is appropriate to build on those lessons learned and therefore take advantage of the capabilities established from NRMM. These capabilities have included: The ability to compute tactical mobility metrics by integrating engineering level performance capabilities onto different terrain conditions. This approach allowed successful comparison of various vehicle systems and capabilities over varied terrain surfaces, obstacles, vegetation, weather scenarios, grades and other features which can adversely impact vehicle performance.

The NRMM was provided without charge to approved end users. Attachment 2 provides a list of the typical data input requirements for NRMM. This data is expected to be a subset of the requirements for a more advanced simulation environment.

Features included:

- Quick run times allowing studies involving multiple vehicles to be completed in relatively short time frames
- The ability to assess the combined effects of a variety of off-road challenges (soil strength, grades, obstacles, vegetation, ride and shock tolerances, weather conditions, human factors, etc.)
- Diagnostic reason codes to help understand results
- Empirical relations (i.e., VCI vs. drawbar/resistance) that provide a level of self-validation
- The ability to conduct evaluation of both wheeled and tracked vehicles over similar terrain conditions
- The ability to rapidly evaluate the effects of sub-system design
- Outputs which can be represented with maps (speed maps, speed comparison maps) for better visualization/comparison (if digital terrain file available).

E.4 GROUND VEHICLE MOBILITY SIMULATION ENVIRONMENT

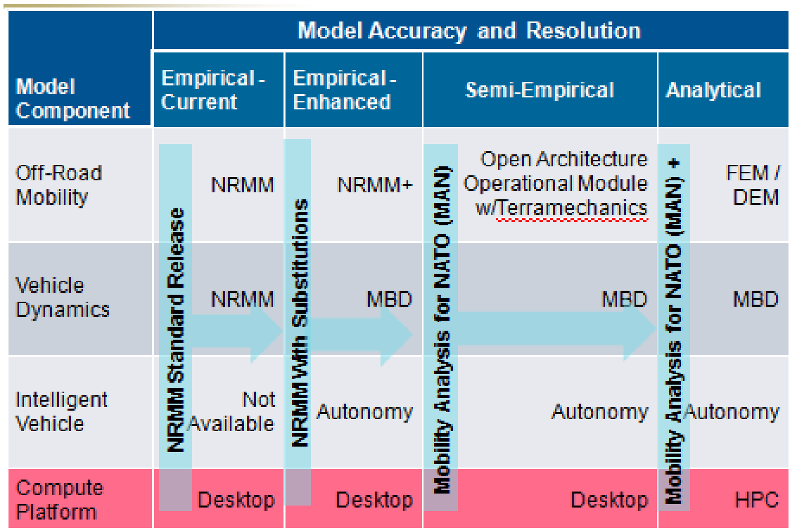
It is intended that the next generation analysis tool would retain the positive attributes of NRMM while overcoming a number of limitations identified which have adversely impacted the ability to quantify the performance of vehicle systems which utilize technologies not previously been incorporated into the empirical nature of the tool.
Some of the goals for the next generation physics based modeling and simulation tool include:

1. The ability to evaluate ride quality and mobility of the vehicle over a three dimensional terrain environment which would include the following
    a. 3D vehicle multi-body dynamics models that are more precisely representative of vehicle designs, including flexible/deformable bodies, stabilization and control system hardware and software, etc.
    b. Multiple deformable terrain surface types within the simulation, including soil, snow, ice, freezing/thawing ground, vegetation effects, etc.
    c. Terrain specifications for mission profiles
        i. Spectral content of the elevation geometry & roughness
        ii. Variable soil and vegetation type
        iii. Ergodic and stationary geometric sample lengths with respect to ride quality response parameters (accounting for skid plate, drive sprocket or idler contact events)
    d. Driver feedback loop model for speed and direction control of 3D vehicle dynamic model, including drivers with different levels of experience (beginner, novice and advanced)
    e. Automated iterative loops for determining the speed limits to obtain 6 watts of absorbed power and 2.5 g vertical response at occupant locations, or similar metrics as specified.
        i. Access to intermediate and lower level results plots such as speed vs power, acceleration
2. Improved obstacle crossing metrics which include for example
    a. 3D Deformable terrain with embedded hard obstacles in the simulations
    b. Rubble pile definition and standardization
        i. Could include dynamic rubble
    c. Library of obstacles that are selectable and tailorable to vehicle and mission requirements
    d. Amphibious operations obstacles
        i. Stream/lake fording
        ii. Surf zones including rocky shores
        iii. Ship launch
3. Off-road mobility
    a. Prediction of tire and track sinkage in various soil conditions
    b. Prediction of vehicle ability to negotiate dry and wet soil slopes
    c. Prediction of vehicle maneuverability while turning in soft soil conditions
    d. Ability to load current or near real time terrain information to establish optimum travel path based on vehicle capabilities and environmental conditions
    e. Stability while negotiating severe terrains on various slopes while avoiding obstacles
    f. Predicted fuel economy during mobility operations

4. On road performance
    a. Prediction of speed on grade
    b. Analysis of vehicle during dynamic maneuvers including obstacle avoidance, severe lane change, moose avoidance, road departure recovery
    c. Analysis of run flat and variable tire pressure on vehicle stability, understeer/oversteer characteristics, driver in the loop
5. Autonomous (Intelligent) vehicle mobility
    a. Integration of control algorithms for all drive by wire functions
    b. Optimization of control functions for terrain and operational requirements
    c. Ability to provide real time feedback from vision, LIDAR and vehicle sensor arrays
    d. The autonomous vehicle mobility challenges are increased due to the requirement to stop-sense- determine – proceed functionality. This places higher demands on the soft soil mobility prediction capability due to the increased torque and braking impulse loads and the fact that the system can no longer rely on inertia to negotiate short duration high mobility demand events.
6. Improved powertrain representation which reflects digitally controlled engine, transmission, transfer case, differentials, geared reduction hubs, hybrid electric technology, etc., which allows accurate performance prediction for soft soil slopes and fuel economy/range prediction over terrain which produces variable motion resistance conditions
7. Improved uncertainty analysis as a function of vehicle and terrain variability or available data precision/imprecision
8. Simulation capability to run on various platform from desktop to HPC
    a. In order to meet the objective to rapidly provide comparative results it is expected that a version of the next generation mobility simulation will function capably in a desktop parallel processor based platform. A more robust and detailed version which would retain fidelity of soil conditions through the thermal degradation of shock absorbers would then function successfully in a much higher speed processing environment
    b. Within the simulation environment, evaluation of hardware in the loop is expected. As noted later in this document, dynamic analysis including control feedback loops at relatively high update rates are required to reflect current vehicle technologies

Table 1 generally describes the vision of how the modeling approach will progress from the current empirically based environment to a full physics based simulation environment. Throughout this process lessons will be learned to identify the critical elements for successful prediction of manned and unmanned systems.

Table E.1. Next Generation NRMM Methodology Classifications



Model Component	Model Accuracy and Resolution			
	Empirical - Current	Empirical - Enhanced	Semi-Empirical	Analytical
Off-Road Mobility	NRMM	NRMM+	Open Architecture Operational Module w/Terramechanics	FEM / DEM
Vehicle Dynamics	NRMM	MBD	MBD	MBD
Intelligent Vehicle	Not Available	Autonomy	Autonomy	Autonomy
Compute Platform	Desktop	Desktop	Desktop	HPC

Attachment 3 provides a list of model data requirements which could be expected in an advanced vehicle simulation to achieve these goals.

E.5 SIMULATION STRUCTURE

As noted above the intent of the effort is to develop a structure which allows current and future tools to be introduced in a core simulation environment. An open architecture structure is anticipated which will allow specifically developed tools to support improvement of simulation fidelity. A significant level of effort involved in physics based simulation is the development, input and connection of vehicle component parameters to successfully represent the entire vehicle system. Detailed simulations can be developed which range from analysis of the combustion dynamics of an engine to driver-in-the-loop/cognitive recognition estimations. When predicting or comparing vehicle capabilities and performance over different mission events, the level of fidelity of certain components or capability may be more important for certain vehicle aspects than for others. The intent of the effort is to create a simulation environment which will allow the level of fidelity or precision for various components or systems to be varied from simple to complex to aid in the speed of the analysis. For example, retaining non-linear bushing attributes while determining a 300-mile mission profile fuel economy comparison is not necessary. However, when predicting accurate soft soil mobility, retention of precise dynamic tire footprint force, shear and pressure parameters along with soil reaction may be critical. Regardless of simulation intent, the environment should allow data to be drawn from a common vehicle system data set as appropriate for the intent of the simulation. A description of this capability is requested as part of the response to this RFI.

The physics based environment should successfully provide

- Vehicle based GUI instead of generic modeling and simulation interface
    - Automatic left/right symmetry where appropriate
    - Vehicle terminology and correlation to Bill of Materials for the configuration
    - Include custom vehicle simulation events

  - Include vehicle specific post processing
- API to extend the system to meet future demands
- Utilities to support unique modeling elements, such as tire models.
- Library of vehicle templates
  - Build on previously established and validated vehicle simulations
  - Evaluate alternative suspension, drive train, stability control systems
  - Provide access to existing component data (tires, bushings, springs, etc.)
  - Provide access to existing terrain and soil data
- Standard modeling practices
- Database hierarchy for storing all data
- Standardized format
- Interface with various FEA simulation tools for flexible bodies, and automatic stress and fatigue calculation. Embedded FEA technology could be a plus
- Interface with various controls simulations or embedded controls functionality with a sufficient library to satisfy the modeling of modern controls system, now and in the future
- Ability to incorporate hydraulic systems
- Interface with man- and hardware-in-the-loop (MIL and HIL) simulations
- Evaluation of suspension characteristics before integrating with full vehicle
- Tire/Track/Soil system models
  - Off-Road with 3D terrain
  - Deformable tire/terrain
- Mechanical Subsystems fully represented:
  - Suspension (for wheeled and tracked vehicles)
  - Powertrain
  - Tires (including runflats)
  - Tracks (including dynamic track tension adjustment)
  - Structure
  - Steering
  - Brakes
- Native ability to support design-of-experiments, stochastic studies (e.g. Monte Carlo), design studies and optimization
- Utilization of parallel processing or other demonstrated techniques to yield world-class model execution times. This includes the support of cloud computing on common cloud HPC (high performance computing) platforms

When implemented the simulation environment would provide capabilities including:

- The ability to validate vehicle dynamics and terrain interaction templates through physical test
- The ability to evaluate vehicle system performance against events which are representative of the operating environment
- Prediction of vehicle durability and impact of design on life cycle cost through fatigue damage

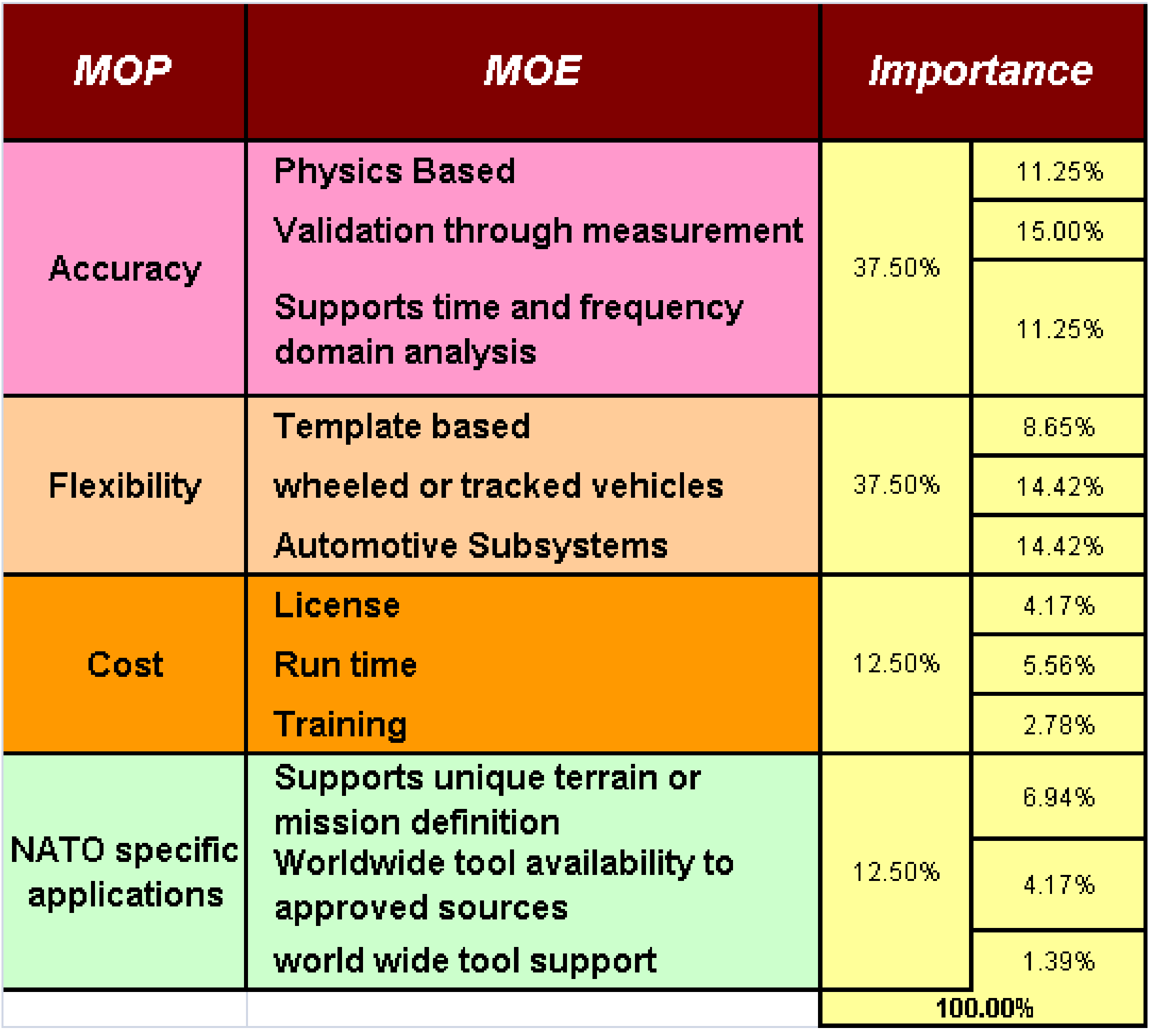
analysis

- Analysis of system performance including impact of system degradation on vehicle capability and safety
- Simulation Based Acquisition tools which can be used to support selection of vehicle systems and components for vehicle improvement
- Integration of electronic controls
- Improved tire and track dynamics models capable of implementation on deformable terrain
  - Low fidelity and high fidelity options
- Improved deformable terrain models capability of representing a broad range of terrain and environmental conditions (different soils, soil strength and/or moisture, variable snow conditions, ice, freeze/thaw layering)
  - Low fidelity and high fidelity options
- Saved and geospatially referenced terrain deformation information (such as rutting).
- Mobility predictions on deformable soils including the ability to traverse level, rough, and variable slope terrain

E.6 COMBINATORIAL TRADE STUDY

The information provided in response to the RFI will be evaluated using various criteria ranging from the fidelity of the simulation environment to the operating cost of the environment to the ability to validate the simulations against controlled test events which match the simulation environment. While low cost is an important parameter, the fidelity of the simulation and the ability to validate the results of the simulation are very important, as is the ability to perform simulations quickly. To address these conflicting requirements, a combinatorial trade study (CTS) analysis will be conducted which utilizes measures of performance (MOP) and measures of effectiveness (MOE). Currently the following criteria is anticipated in broad terms. This CTS criteria approach is intended to aid your understanding of the need for the effort, and identifies the priority placed on the various elements associated with the simulation environment. It is expected that within your RFI response that each of the elements would be addressed. Based on the range of responses received, the CTS will be updated to best reflect those elements which will ensure the most flexible and accurate solution for next generation mobility simulations.

Table E.2. Toolset Scoring Matrix



MOP	MOE	Importance	
Accuracy	Physics Based	37.50%	11.25%
	Validation through measurement		15.00%
	Supports time and frequency domain analysis		11.25%
Flexibility	Template based	37.50%	8.65%
	wheeled or tracked vehicles		14.42%
	Automotive Subsystems		14.42%
Cost	License	12.50%	4.17%
	Run time		5.56%
	Training		2.78%
NATO specific applications	Supports unique terrain or mission definition	12.50%	6.94%
	Worldwide tool availability to approved sources		4.17%
	world wide tool support		1.39%
		100.00%	

E.7 USER ENVIRONMENT AND SUPPORT

The simulation environment will support both occasional and expert user capabilities and that online training as well as consulting services capability would be available. As part of your response please explain the capability of your simulation environment to provide a controlled user environment with appropriate graphical user interface (GUI) as well as an expert user environment where new capabilities can be developed and supported. The expert user should be provided a robust API to allow easy creation of new functionality. Use of common languages, such as Python, is a plus. As part of support, identify the market penetration of your solution as well as the presence of user groups and consulting support.

The template style environment will be developed to aid in the speed and fidelity of the simulation environment. As such, once a complete vehicle model is developed, it is anticipated that components and subsystems can be rapidly changed and the simulation rerun without the need to completely rebuild the simulation. For example, it is anticipated that the suspension system envelope would be defined in the base model and that geometrically similar passive spring and dampers, or semi active struts, or adaptive suspension, or fully active suspensions could be implemented within that simulation envelope and the simulation rerun to quickly contrast and compare the impact on the overall system performance. As such the suspension might be represented in the simulation as shown below.

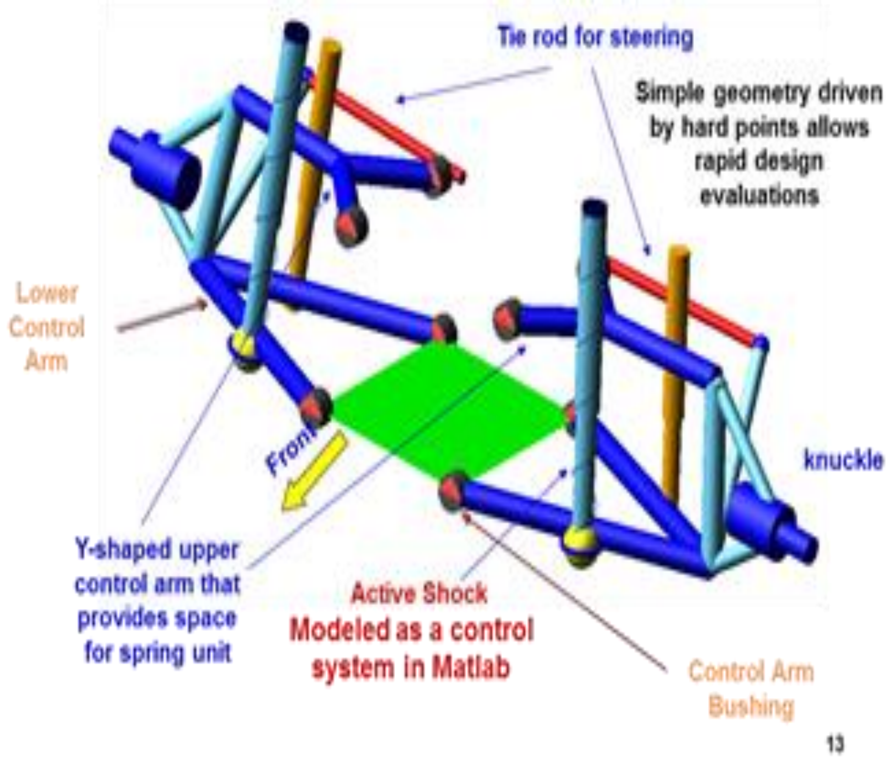


Figure E1. Suspension envelope created using templates and GUI

An input table as part of an existing GUI would be able to accept various vehicle components and configurations and would include both flexible and rigid components. As noted below, the vehicle system would then be assembled and evaluated over representative terrain conditions producing predicted results ranging from dynamic stability to flexible body fatigue analysis to deformable terrain tractive effort.

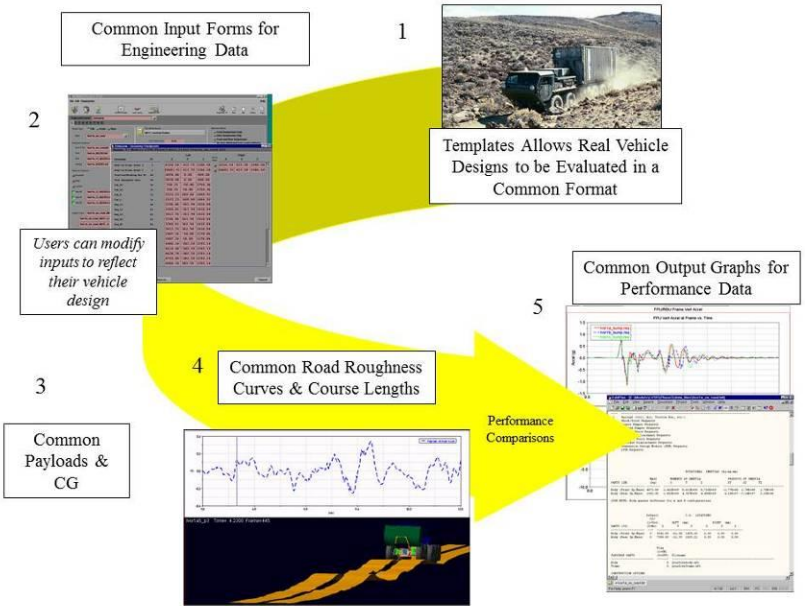
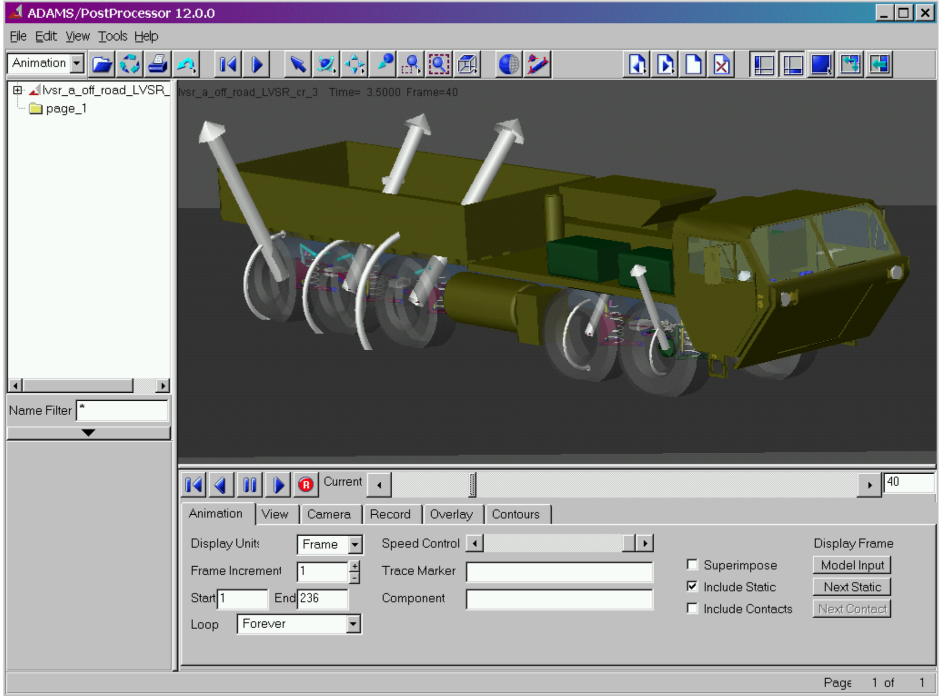


Figure E2

Specific performance events on paved, gravel and variable surface conditions would be performed and compared directly to physical test events.



lvsr_a_off_road_LVSR_cr_3 Time= 3.5000 Frame=40

Display Units Frame
Frame Increment 1
Start 1 End 236
Loop Forever
Speed Control
Trace Marker
Component
☐ Superimpose
☑ Include Static
☐ Include Contacts

40

Figure E3

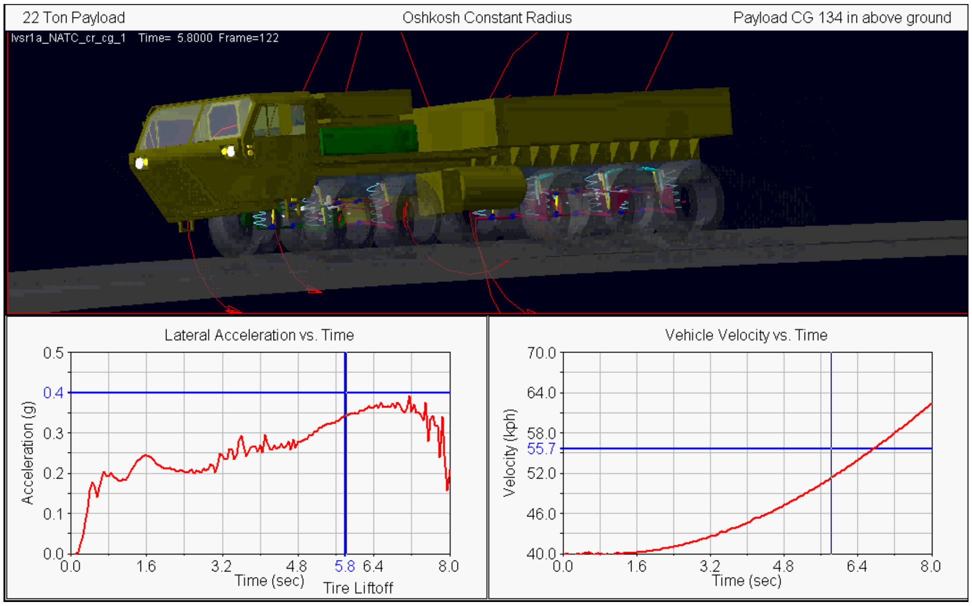


Figure E4

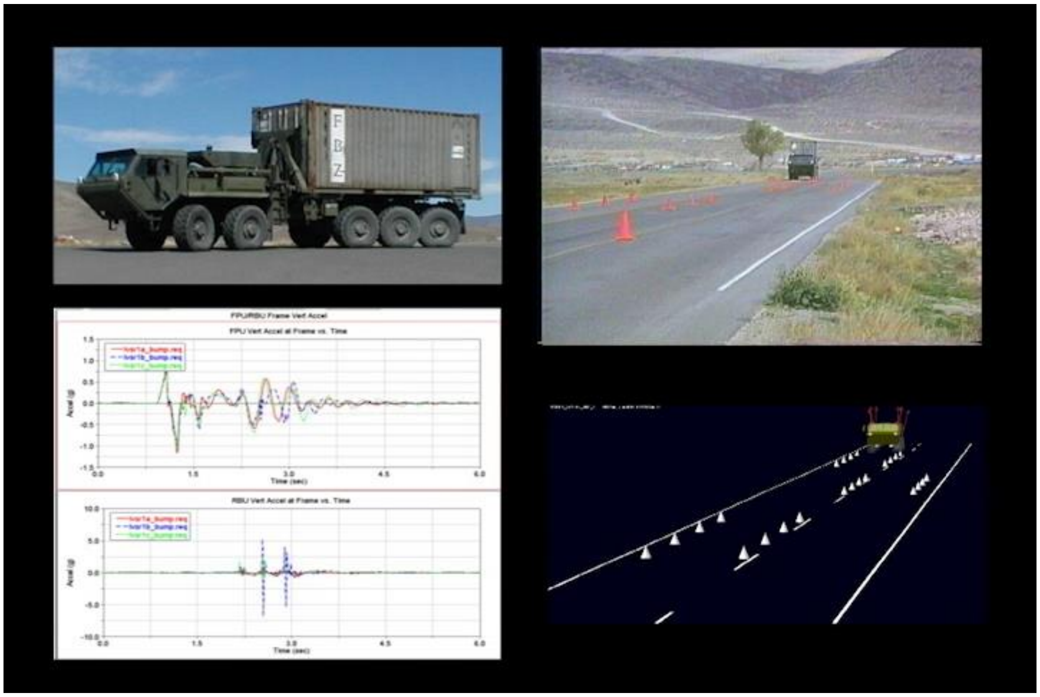


Figure E5

Typical List of Events

- Constant Radius
- Double Lane Change - Paved And Gravel Surface
- Road Edge Recovery
- 30% - 40% Side Slope Slalom
- Mission Profile Trails & Cross-Country
- Washboard Event
- 30% Dry Sand Grade
- 40% Dry Sand Grade
- Split-Coefficient ABS Stop
- 24 - 36 Inch Vertical Step
- 6 Inch, 8 Inch, 10 Inch Half Round
- Speed on 5% Paved Grade
- Straight Line Acceleration
- Traditional RMS Course
- Traditional WNS Course

Figure E6

E.8 CONTROL ALGORITHMS

Wheeled and tracked vehicles whether equipped with traditional powertrains, hybrid electric or other alternative systems are digitally controlled. Therefore, the ability of the simulation environment to support accurate representation of the algorithms which control the interaction of the components is essential to accurate results. From ABS to traction control to stability control to engine and transmission systems, electronic control of the various systems dominates the performance of the vehicle. Please explain the ability of your simulation environment to accommodate those control relationships both in terms of software and hardware in the loop. As vehicle systems trend toward smart or autonomous operation, incorporation of on-vehicle and remote sensing, including vision based systems which require gigabit rate connectivity, it is necessary to accurately represent these control or input relationships to successfully represent the vehicle system.

E.9 VEHICLE-TERRAIN INTERFACE

In an off-road environment, the tire or track soil interaction is critical and the ability to accurately represent that envelope is vital to the success of the simulation. The intended usage for a deformable soil model is to evaluate motion resistance (for example in fuel economy simulations) as well as vehicle tractive effort capabilities to determine trafficability. The models should be able to differentiate performance when operating on different types of soil and soil conditions, for example dry coarse grained soil versus wet fine grained soil.

In additional to the variety of soil types and strengths needed, the weather effect on the terrain is also critical, thus, the capability to represent soil freeze/thaw in addition to snow and ice conditions are critical elements.

It is recognized that there are many approaches to soft soil modeling, including Bekker-Wong, particle based models, finite element, boundary element, and discrete element methodologies. In addition to soil deformation, factors such as tire deformation, footprint, pressure distribution, and tire tread pattern can all significantly impact the results. Effects such as bulldozing, and the sink/slip relationship for the tire in deformable soil should be addressed. The response to this RFI should clearly define the approach taken for deformable soil modeling, the data requirements, and the model capabilities.

E.10 TERRAIN REPRESENTATION

It is anticipated that within the advanced simulation environment more accurate terrain information will be made available and the vehicle performance over that terrain successfully simulated.

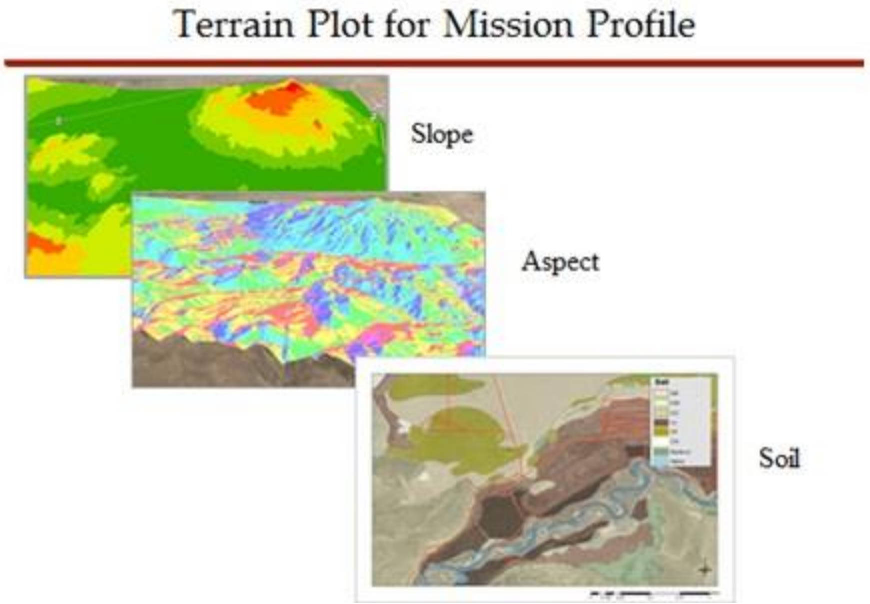


Figure E7

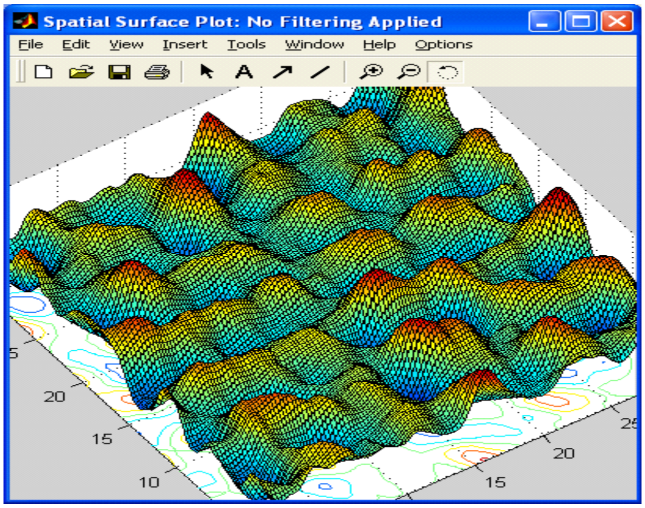


Figure E8 Roughness

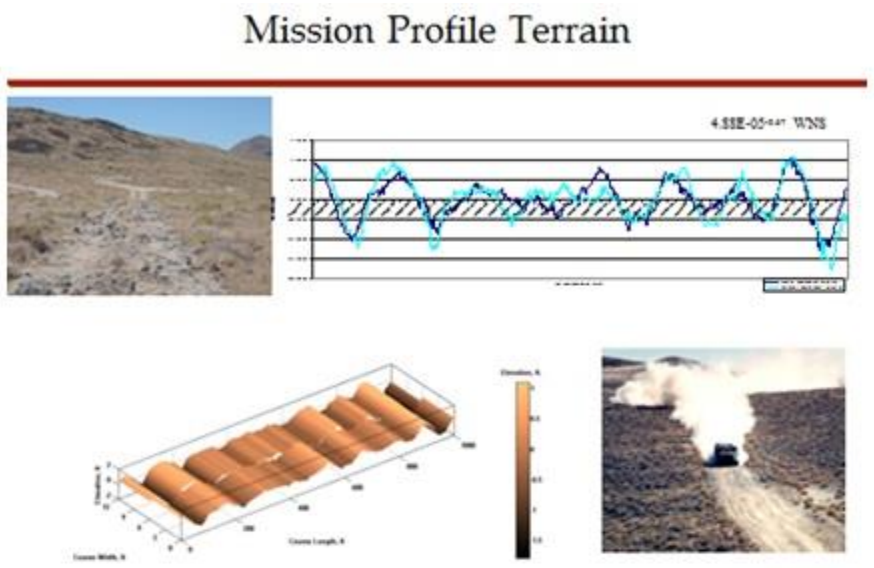

Mission Profile Terrain

Figure E9

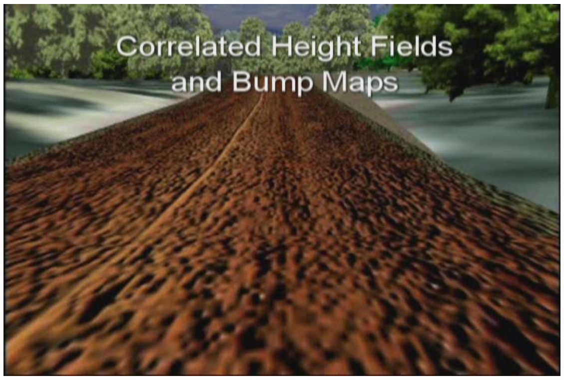


Figure E10

The integrated simulation environment would allow three dimensional operation over the range of terrain conditions as described in attachment 2 represented in the following definitions.

The terrain elements could be updated for current conditions resulting from environmental changes as may occur due to rain, snow, vegetation, and other seasonal events.

Terrain elements will be given values according to a terrain code using algorithms for the distribution of vegetation and climate conditions including rain and snow. These algorithms will be derived from data sets typically associated with geographic information systems (GIS). The data will be used to construct real world based simulation in the modeling environment and to accurately depict this environment in a visual format such as a 3D map where possible. Slope, aspect, and soil type data will be combined with the climate condition and land cover data and include such variation as deciduous versus coniferous trees, tree spacing, and the height and extent of forest canopy, all of which have a direct effect on the watershed of rain or snow melt. Combined with soil strength and composition, these combined elements have a direct impact on vehicle mobility. These terrain and climate elements are essential to building an accurate modeling and simulation environment for vehicle mobility predictability.

These geographic data should be exportable for import into modeling and simulation software or, if already in an applicable format, exportable to Open Geospatial Consortium (OGC) formats or other industry standard file types, such as shapefiles, for inclusion into mapping software.

At a minimum, these elements would include the following data types and resolutions.

- Slope in the form of a digital elevation model (DEM) or digital terrain model (DTM) with 0.5 to 5 meter resolution
- Land cover/vegetation data at 1 to 30 meter resolution
- Soil information consistent with NRCS data best resolution and including engineering soil type exportable to a lookup table. This should also reflect rock and boulder spacing and size as well as vegetation spacing
- Climate data by month (from present and going back 10 years) at 10 meter resolution minimum

Import/export capability should specifically include a fully 3D route “swath” either as designated by the use or automatically generated by the software.

E.11 RESPONSE

The above information and the following attachments are intended to provide background and guidance in responding to the questionnaires. Responders may include additional information which will be considered. Product information videos and presentations will be accepted as part of the RFI.

Attachment 1 – Concept mission profile database
Attachment 2 – Minimum data input requirements
Attachment 3 – General physics based model data input requirements
Attachemnt 4 – Vehicle dynamics model product questionnaire
Attachemnt 5 – Terrain mapping product questionnaire
Attachment 6 – Autonomous Vehicle questionnaire

Operational Mission Profile

Surface	RMS Range (in)	%	WNS	IRI	Other..
Primary Roads	0.1 to 0.3	10%			
Secondary Roads	0.3 to 1.0	20%			
Trials	1.0 to 3.4	30%			
Cross-Country	1.5 to 4.8	40%			

Duty Profile/Mission Cycle

The following definition describes the notional MPCTD duty profile/mission cycle. Unless otherwise specified, performance shall be demonstrated on surfaces such that 10% is completed on Primary Roads, 20% on Secondary, 30% on Trails, and 40% Cross-Country. The DoD has defined mission profile duty cycle percentages and RMS values for surface roughness. The wave number spectrum (WNS) formulas are based on the following example.

WNS Formula:

$$Gxx(n) = 1.4 \times 10^{-8}(n)^{-2.9}$$

Where:

Gxx(n) = spectral of the road elevation in ft2/cycle/ft

n = wave number in cycle/ft

1.4×10^{-8} = roughness coefficient (amplitude of spectrum at 1 cycle/ft)

$^{-2.9}$ = slope of the wave number spectrum.

Note: The random roughnesses expressed through the straight-line wave number spectrum relationships are average values and actual road roughness will naturally contain variability. The upper and lower limits for the random portion of the road roughness have a +/- 3 dB envelope.

- **Primary Roads**

There are four types of primary roads: high quality paved, secondary pavement, rough pavement, and highly degraded pavement. All may consist of two or more lanes, all weather, maintained, hard surface (paved) roads with good driving visibility used for heavy and high density traffic. These roads generally have lanes with a minimum width of 108 inches, road crown to two (2) degrees and the legal maximum GVW/GCW for the county and state is assured for all bridges. (a) High quality paved roads are typified by rural US interstates. (b) Secondary pavement can include degraded concrete, macadam concrete or asphalt pavements (small potholes, alligator cracking, freeze/thaw breakup). (c) Rough pavement consists of two lane roads with degraded shoulders, and marginal subgrades which produce long wavelength swells and additional degradation of the surface. (d) Highly degraded pavement consists of large potholes in various states/quality of repair, significant surface degradation, and marginal to poor subgrades.

Attachment 1
Concept Mission Profile

Surface	Wave Number Spectrum	RMS Roughness (inches)	Average Speed	% Total Miles
High Quality Paved Road	$G_{xx}(n)=1.4 \times 10^{-8} (n)^{-2.9}$	0.1	65-75	3%
Secondary Pavement (Two Lane Paved Road)	$G_{xx}(n)=1.9 \times 10^{-7} (n)^{-2.5}$	0.2	55-65	3%
Rough Pavement (Degraded Paved Road)	$G_{xx}(n)=8.0 \times 10^{-7} (n)^{-2.5}$	0.3-0.5	45-55	3%
Highly Degraded Pavement	$G_{xx}(n)=2.3 \times 10^{-5} (n)^{-2.4}$	0.5-0.7	35-45	1%

- **Secondary Roads**

There are three types of secondary roads: loose surface, loose surface with washboard and potholes, and Belgian Block. These roads are one or more lanes, all weather, occasionally maintained, varying surface (e.g., large rock, crushed rock and gravel) intended for medium-weight, low-density traffic. These roads have no guarantee that the legal maximum GVW/GCW for the county and state is assured for all bridges.

Surface	Wave Number Spectrum	RMS Roughness (inches)	Average Speed	% Total Miles
Loose Surface	$G_{xx}(n)=3.0 \times 10^{-5} (n)^{-1.8}$	0.3-0.6	30	8%
Loose Surface with Washboard & Potholes(1)	$G_{xx}(n)=4.0 \times 10^{-5} (n)^{-2.4}$	0.4-1.2	30	10%
Belgian Block(2)	$G_{xx}(n)=5.5 \times 10^{-5} (n)^{-2.2}$	0.3-1.2	20	2%

(1) Loose surface with washboard roads have a peak amplitude of 5.0×10^{-3} ft^2/cycle/ft at 0.3 to 0.5 cycle/ft (2 to 3-foot wavelengths). Loose surface roads with a high density of potholes have a peak amplitude of 9.0×10^{-3} ft^2/cycle/ft at 0.1 to 0.2 cycle/ft (5 to 10 foot wavelengths). Generally, washboard occurs in operational areas that are dry, whereas pothole gravel roads occur in wet operational areas.

(2) Belgian Block secondary roads have a peak amplitude of 8.0 x 10-2 ft^2/cycle/ft at 0.083 cycle/ft (12 foot wavelengths) and these wavelengths are 180° out-of-phase left to right which produces a racking input to the vehicle. The cobblestone blocks dominate the amplitude of the wavelengths at 1 cycle/ft.

- **Trails**

One lane, unimproved, seldom maintained, loose surface roads, intended for low density traffic. Trails have no defined road width and can include large obstacles (boulder, logs, and stumps) and no bridging.

Surface	Wave Number Spectrum	RMS Roughness (inches)	Average Speed	% Total Miles
Trails (A)	$G_{xx}(n)=2.6 \times 10^{-5} (n)^{-2.6}$	1.0-3.4	10-20	30%
Trails (B)	$G_{xx}(n)=4.6 \times 10^{-5} (n)^{-2.2}$			

- **Cross-Country Terrain**

Vehicle operations over terrain not subject to repeated traffic. No roads, routes, well-worn trails, or man-made improvements exist. (This definition does not apply to vehicle test courses that are made to simulate cross-country terrain.) In addition, cross-country terrain can consist of tank trails with crushed rock or having large exposed obstacles (rocks, boulders, etc.).

Surface	Wave Number Spectrum	RMS Roughness (inches)	Average Speed	% Total Miles
Cross-Country(1)	$G_{xx}(n)=9.2 \times 10^{-1} (n)^{-2.1}$	1.5-4.8	10-20	40%

(1) Road Left and Right Track Correlation. Fixed frequency, RMS, and half-round obstacles shall include roughness or events where the left and right wheel paths are shifted longitudinally up to +/- 45 degrees (approximately 6 1/2 ft (2m)).

Definitions:

Road Roughness

Spectral characteristics of road surface measured and analyzed in terms of wave-number spectra, rms, IRI, or other suitable metric.

Root Mean Squared (RMS)

A measurement used to describe the roughness of a terrain.

Washboard Effect

A periodic component in space that appears in the wave number spectrum as a sharp peak at a wave number corresponding to the reciprocal of the “washboard” wavelength. Generally, washboard roads occur in operational areas that are dry.

Wave Number Spectrum

Wave number spectrum epresents road roughness data as a straight-line relationship on a log-log plot with ft2/cycle/ft on the y-axis (wavelength in feet or spatial frequency of the distance between the bumps). It is a technique for measuring and monitoring long sections of various terrain types, including paved roads and off-highway durability test courses, that can be used to describe all potential deployment areas of a vehicle. Wave number spectrum provides a vehicle and speed independent measure of the roughness of a road.

Typical Soil Parameters for Consideration

- K_c, k_f and n (Bekker)
- C, Phi and K (modulus of deformation for shear)
- % Compaction
- Density
- Moisture
- Depth and layering
- Surface coefficient

- Soil Impedance
- Bulk Density
- Bearing Capacity
- Proctor
- Cone Index
- Soil constitutive model parameters
- Others




When the tire, track, vehicle, and terrain data are combined within a physics based model then the following simulation and validation approach is anticipated.

3D Terrain contact model

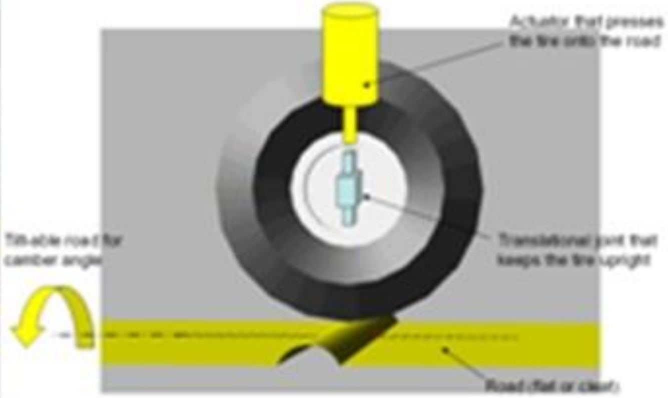
- Historically used for off Road Courses and Bumps
- Road Modeled With Triangular or other Elements (Like FEA model)
- Tire Deflection Calculated As “Weighted Average” Based on Volume of Penetration Into Each Element
- Includes Tire Carcass Shape Effect
- Fidelity over obstacles with enveloping.
- Frequency of road input

Such a simulation environment would provide high fidelity contact force generation on any type of 3D terrain profile and it would be possible to input tread pattern and develop detailed contact force distribution on the terrain surface.

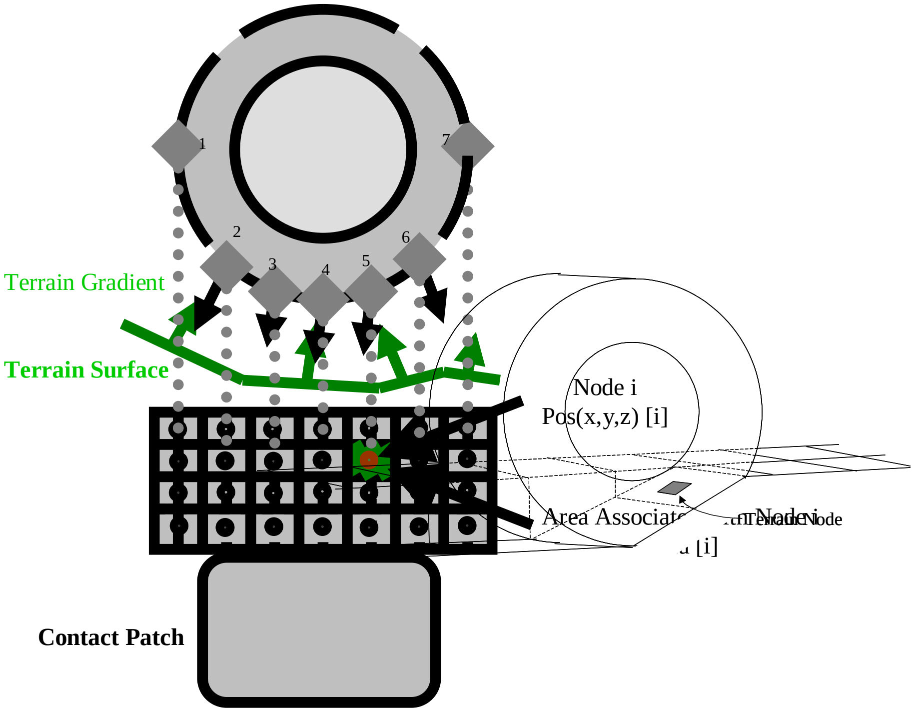
The tire and track models could be validated both based on laboratory measurements and full vehicle sytem measurements. This requires the ability to interact with rigorous models (FEA) which may be developed during tire and band track design

Physical Test Rig

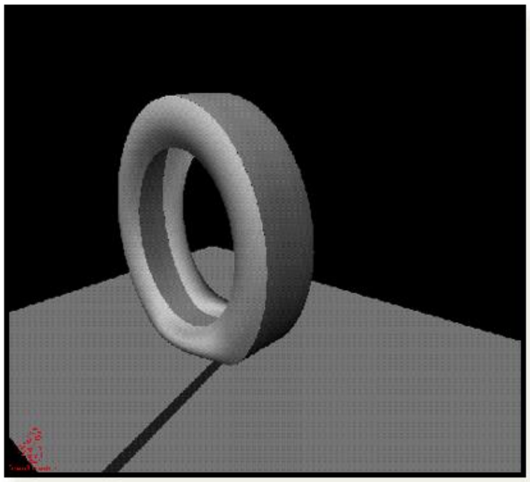
Virtual Test Rig (Model)

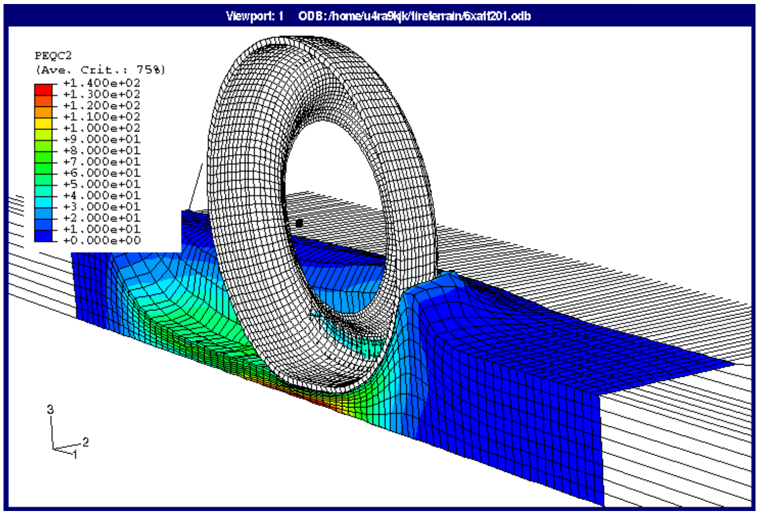


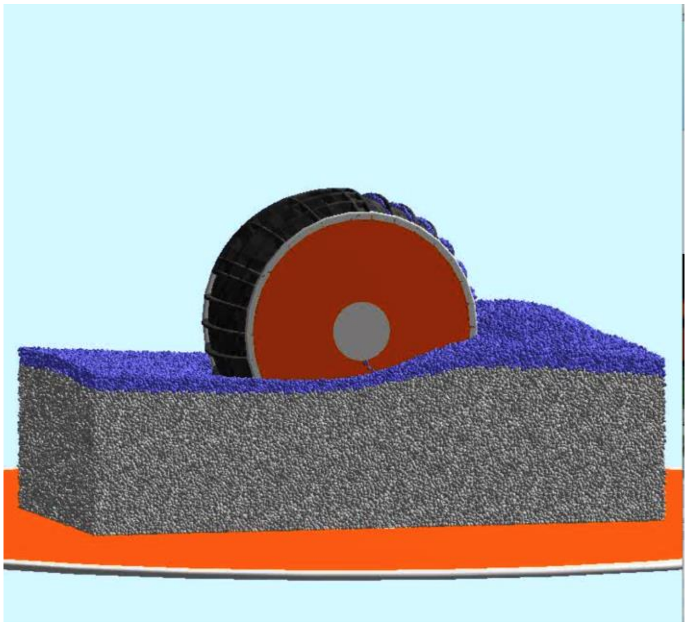
The tire and track soil interface simulations have been developed with varying levels of fidelity and success. Tire tread and rubber compound can be dominant parameters when predicting tractive effort on slippery surfaces including ice and snow. Correlation between the terrain element and individual tire or track element is often critical to successful simulation as indicated below



Attachment 1
Concept Mission Profile



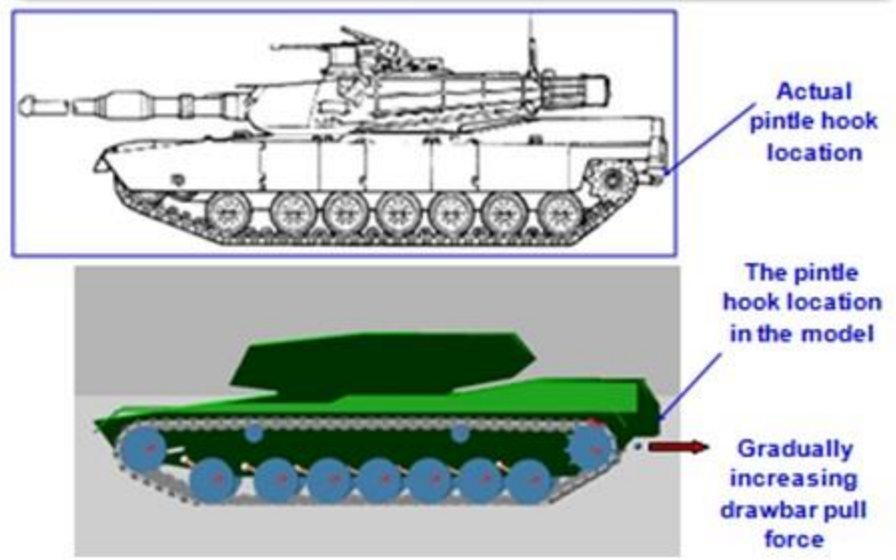




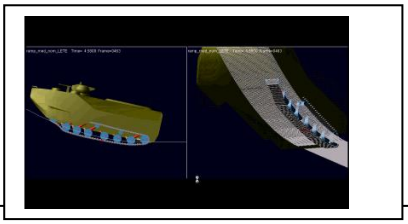
Tracked Terrain Simulation Environment

- Approach
  - Detailed track model
    - All track elements included
    - Bushings
    - Grousers
    - Single Pin/Double Pin/Rubber track
    - Suspension
    - Track tensioner
    - Driven by contact force with sprocket
  - Terrain Material Model

Model Setup



- Simulate at different levels of fidelity
  - Detailed for tractive effort and soil interaction – includes soft soil model
  - Simplified "string track" model for low freq events
- Validate
  - Tractive effort
  - Ride quality



  - Discrete bump events

The following are considered the minimum subsystem representations (based on the existing NRMM) within the simulation to provide results which can successfully trend or compare performance between vehicle configurations. Of interest is how your simulation environment can accommodate these parameters and how these parameters may be enhanced or integrated into a more accurate simulation environment.

Powertrain Information

- Tractive effort vs. speed curve
- Engine characteristics (type, displacement, number of cylinders, max torque)
- Engine speed versus engine torque
- Total net engine power, each engine
- Engine to torque converter gear ratio and efficiency

Aerodynamic Characteristics

- Drag coefficient
- Frontal area
- Hydrodynamic drag coefficient

Maximum Braking Coefficient

Swim

- Combination vehicle draft
- Combination fording depth
- Vehicle swamp angle during egress
- Vehicle swamp angle during ingress
- Maximum fording speed
- Maximum swim speed with auxiliary propulsion

Suspension Characteristics

- Spring force/deflection curve(s)
- Damper force/velocity curve(s)
- Jounce and Rebound stop location and rates
- Suspension geometry including gross motion, travel etc.
- Track system spring rates

Suspension Design

- Tracks vs. Wheels
- Bogie/walking beam/independent/hard mounted
- Driver's seat location/suspension (spring and damper)
- Driver's mass

Chassis

- Maximum pushbar force vehicle can withstand overriding vegetation stems

Steering

- Vehicle minimum turning radius Left and Right, Case

Attachment 2
NRMM Data Input Requirements

General Vehicle Characteristics

- GVW
- Pitch mass moment of inertia
- CG measurement
- All vehicle system dimensions
- Settled body angle relative to ground

Wheel (or roadwheel) and Chassis Characteristics

- Wheel (or roadwheel) diameter and mass
- Wheel (or roadwheel) longitudinal position
- Wheel (or roadwheel) force/deflection/damping
- Wheel (or roadwheel) weight (vehicle weight by wheel position)
- Is wheel driven / braked force distribution
- Contact path dimensions
- Tire deflection at relevant central tire pressure settings
- Maximum tire speed limit for each deflection scenario
- Tire stiffness at each pressure; Tire / Track revolutions per mile

Unique info for Tracked Vehicles

- Drive sprocket/idler characteristics
- Information for track model (uniform tension/local tension/interconnecting spring models)
- Track width
- Length of track on ground (in)
- Grouser height
- Maximum allowable sinkage
- Track tension (lbf)
- Track tensioner spring / damping rate
- Track shoe contact areas
- Damping coefficient for each Sprocket or idler assembly
- Track grouser height for each assembly

Geometry

- Belly Geometry
- Horizontal distance from CG to rear axle of prime mover
- Minimum ground clearance
- Driver’s eye height above ground
- Vehicle projected frontal area

- Vehicle maximum height including all external fixtures
- Vehicle minimum height (excluding vertical perfusions, fixtures, etc.) minimum overhead clearance requirement
- Length of each vehicle unit (from connection point to connection point)
- Pitch mass moment of inertia about the CG of sprung mass (ib-sec^2-in)
- Mobility Performance1 pass vehicle cone index for fie grained soils for each assembly.
- Vehicle lateral stability
- Vehicle absorbed ride quality at various locations

Attachment 3
General Physics Based Model Data Input Requirements

The following represents subsystem data which is anticipated as required to support a high fidelity high granularity simulation environment. It is assumed that the lower fidelity simulation environment would be a subset of the high fidelity simulation environment.

Generalized Data Input for Powertrain Model Template

Engine

- Mass and inertia properties
- CG location
- Location of all mounts
- Stiffness (force versus displacement) curves for mounts in all directions
- Damping (force versus velocity) curves for mounts in all directions
- Data for engine torque as a function of rpm and throttle position
- Engine braking data (if desired)
- Data for accessory loads on engine (AC, fan, alternator, etc.)
- Idle and maximum rpm

Torque Converter

- Mass properties
- Characteristics curves for performance (i.e. torque and speed ratio curves)

Transmission

- Mass properties
- Location of all mounts
- Stiffness (force versus displacement) curves from mounts in all directions
- Damping (force versus velocity) curves for mounts in all directions
- Number of gears and gear ratios
- Shift profiles (up and down shift)
- Efficiency (or loss data)

Transfer Cases and Differentials

- Mass properties
- Location of all mounts
- Stiffness (force versus displacement) curves for mounts in all directions
- Damping (force versus velocity) curves for mounts in all directions
- Gear ratio
- Functional description (i.e., open, biased, locking, etc.)
- Functional data (depending on above description)

Drive Shafts and Half Shafts

- Mass properties

Hubs

- Mass properties
- Gear Ratio (if geared hub is used)

Generalized Data Input for Suspension Model Template

Actual data required depends on suspension type. The example below is for SLA independent using conventional spring and damper.

Hard Points

- Upper control arm (front, rear and outer)
- Lower control arm (front, rear and outer)
- Bumpstop (upper and lower)
- Rebound stop (upper and lower)
- Spring mount (upper and lower)
- Shock mount (upper and lower)
- Tie rod (inner and outer)
- Wheel center
- Drive shaft (inner and outer)
- Subframe (front and rear)
- Anti-roll bar

Mass properties for all components (weight, CG, mass moments of inertia)

- Control arms
- Spindles
- Half shafts
- Springs
- Shocks
- Subframe
- Tie rod
- Anti-roll bar
- Bushings

Bushings

- Define bushing orientation and preload
- Translational stiffness curve
- Rotational stiffness curve
- Translational damping curve
- Rotational damping curve

Attachment 3
General Physics Based Model Data Input Requirements

Dampers
- Force versus velocity curves

Springs
- Define installed length or preload
- Force versus displacement curves

Generalized Data Input for Tire Model Template

Actual data required depends on the specifics of the tire model employed

Geometric Properties
- Tire section width
- Tire aspect ratio
- Rolling radius
- Contact area (footprint) as a function of inflation pressure and load/deflection
- Rim width
- Rim diameter
- Tread depth
- Other

Mass and Stiffness Properties
- Wheel end assembly weight
- Center of Gravity
- Mass moment of inertia
- Load deflection curve
- Vertical stiffness
- Lateral stiffness
- Longitudinal stiffness
- Cornering stiffness
- Slip characteristics
- Other

Generalized Data Input for Track Model Template

Geometric Properties
- Track width
- Track contact length
- Track design (i.e., single pin, double pin, rubber)
- Sprocket radius
- Grouser height
- Grouser pitch

- Area of the shoe
- Roadwheel radius
- Radius of the idler
- Roadwheel spacing
- Other

Mass and Stiffness Properties

- Roadwheel height
- Mass moment of inertia
- Initial track tension
- Suspension design (arms, springs, dampers, etc.)
- Bushings
- Simplified track model
    - String track
    - Track superelement
    - Other

Soil Model

Data input depends on soil constitutive model

Attachment 4
Vehicle Mobility Model Product Questionnaire

1. Does the solver support parallel processing and/or other High Performance Computing environment? If so, how well does the solution time scale when going from 2 to 1000 cores? Does the software run on both Windows and Linux?
2. Is the modeling environment compatible with the legacy empirically based NATO Reference Mobility Model?
3. Does the interface provide a simplified "non-expert" user interface? If so, describe the functionality. As associated to non-expert versus expert usage, does the environment allow for a reduced fidelity approach which substantially reduced run time? Does the non-expert interface verify that the user enters valid data?
4. Can three dimensional terrain (i.e. rough, slopes, sideslopes) surfaces be simulated? How are they defined? Can GIS data be utilized? If so what format is required?
5. Is an off-road tire model available? If so, what frequency range is it valid for? Describe the tire model, including ability to discern contact patch size and pressure. Can a custom tire model be implemented? If yes, how
6. Can tracked vehicles be modeled? Describe capabilities for building the tracks, suspension elements, track tensioning, etc. Is there an option for both detailed track models and fast running track models such as a string track or track super-element? Can the model differentiate between single pin, double pin, and rubber tracks?
7. Does the model support a template based approach? If so, describe how this is implemented. What is included in a template? How are the templates created and modified?
8. Does the model support deformable bodies? If so, does it support ANCF (absolute nodal coordinate formulation). Does it provide a modal approach for complex flexible bodies? Is there an internal finite element solver? Is there an ability to include material and geometric non-linearities either through an internal non-linear finite element solver or via co-simulation with external non-linear finite element solvers?
9. Can advanced control systems, including digital discrete multi-rate controllers, be included in the simulation? If so, describe the approach.
10. Does the modeling approach allow for contact between the vehicle and the terrain other than the tires or tracks? If this is possible, how is the contact modeled? How is the terrain and hull geometry for contact modeled? Describe the approach and capabilities.
11. Describe the level of detail included in the power train and driveline model.
    a. Are the engine dynamics modeled? Describe the approach taken. How are engine losses and accessory loads accounted for? How is the engine integrated with transmission designs? Can Transmissions ranging from manual to automatic to continuously variable to infinitely variable be considered?
    b. Is there an ability to model hybrid-electric drives? What is the modeling approach?
    c. Is the torque converter explicitly included? How is it modeled and what data is required?
    d. Are the differentials and transfer cases explicitly modeled? Can features such as differential locking, clutches, and torque biasing be included?
    e. Can the driveline be configured to support all-wheel drive on multi-axle vehicles?

12. Is a simulated driver included? Does the driver control throttle, brake, clutch, steering, and shifting?

13. Is the driver open loop or closed loop? If it is closed loop, describe the control approach. Can it perform realistic human driver inputs, for example to determine end limits on a double lane change maneuver?
14. Describe how a “unique” suspension design would be modeled. Can it be modeled by a user, or does it require custom code development?
15. Can deformable terrain be included in the model? If so, describe the modeling approach and data input requirements, and how the model is applicable for tractive effort evaluation and soft soil grade climb simulations. Can the model discern between soil types, such as coarse grain dry sand (S per USGS classification) and fine grain (CH/CL per USGS classification), peat, layered soil, various snow conditions, etc.
16. Can the tire-terrain or track-terrain contact support FEA/DEM for deformable terrain at the contact patch/nodes?
17. Can the model include hydrodynamic forces as might be encountered by a vehicle in a fording event? How are the forces computed? Can the model be used to predict the ability of a vehicle to transition from water to a bank or ramp?
18. Will the model support hardware in the loop simulations? If so, describe specific hardware/software requirements.
19. Can the model be used to calculate fuel economy over a desired mission profile, which may include grades, rough terrain, obstacles, deformable soil, weather scenarios, and variable speeds? If so, describe the approach and data requirements.
20. How is the software licensed? If multiple software modules exist, define what is needed to perform vehicle mobility simulations including control systems, flexible bodies, tires, driver, and deformable surfaces.
21. What is the software cost? Is it available for both purchase and lease? Is a short term or on-demand lease available?
22. Is there an existing capability for worldwide training and support? If so, describe. Where is the training performed? How is technical support provided?
23. Describe the post processing capabilities for creating animations and plots, and for performing data analysis. Can animations (movie files) be created and exported? Can simulated test data be imported for cross plot and correlation? Can frequency domain calculations (FFT and PSD) be performed?
24. What is the current version of the software, and when was it released? When is the next planned software release? Will the next release feature new capabilities applicable to ground vehicle mobility simulation? If so, please describe.
25. In user support provided in the licensing? Describe the extent of user support and how it is obtained.
26. How does your software support evaluation of uncertainty in model parameters? Are stochastic methodologies built in? Are design of experiment (DOE) capabilities included? Describe the capabilities.

Attachment 5
Terrain Mapping Product Questionnaire

Product Questionnaire

1. Identify the types of terrain data used in the simulation, and the areal extent to be provided along with its precision and fidelity?

2. Has a prototype process of similar integration between the vehicle modeling environment and GIS been developed and tested?

3. Has a production version of item 2 been developed and tested?

4. Is the process/software currently in production in any application? If so, in what industry?

5. Is the data currently applicable to or compatible with NRMM?

6. Is support documentation currently available for the process/software (white paper, etc.)?

7. Is the data migration process easily adaptable through built-in scripting and API?

8. Are the data capable of supporting wide ranges of coordinate systems and projections for on-the-fly projection?

9. Are the data supported in a wide range of database engines, i.e., Microsoft SQL Server, Oracle, IBM DB2, IBM Informix, Interbase, Firebird, Sybase, PostgreSQL, SQLite, MSJET, etc.?

10. What kind of training would be required for users of the data and is it readily supported?

11. Do you provide data or does it come from a third party vendor?

12. Is there an existing customer base for this product? Describe.

13. Does the process support import/export of CAD or other modeling data?

14. Are the process/data OGC compliant?

15. Are the data predominantly raster or vector?

16. Is there a report-generating component in the program?

17. Are the geospatial data easily adaptable for editing and customization among different data types and software platforms?

18. Is there sufficient metadata and internal data description to support linking to complex look up tables?

19. Will the data/process support import/export from/to modeling and simulation software platforms? Describe.

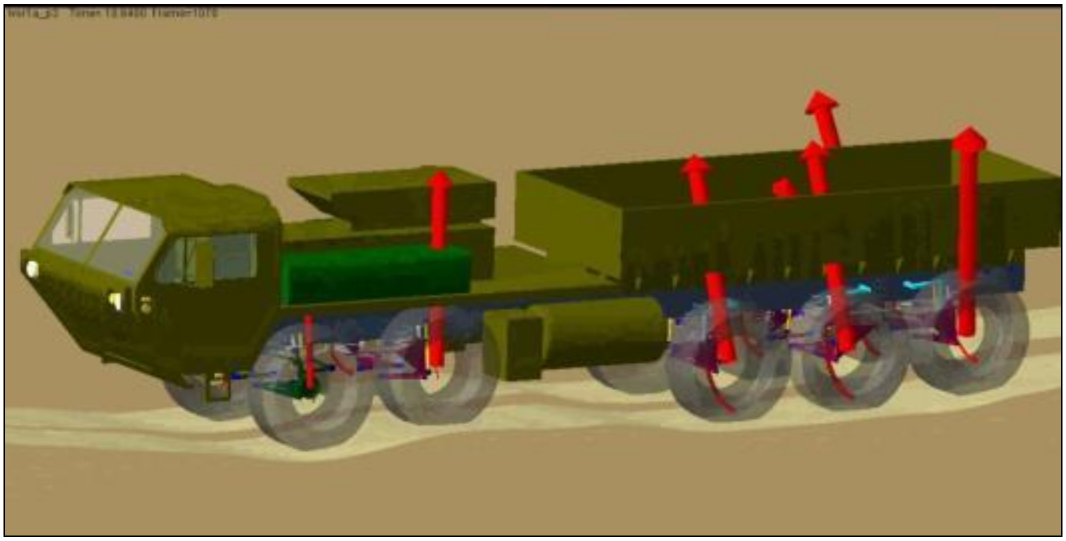
Simulations of Autonomous vehicle systems require unique tool capabilities in addition to those identified in the previous attachments. Further, autonomous vehicles have a broad range of configurations from walking/legged systems to ultra-light systems intended for operation inside buildings to 20,000 pound transport vehicle systems. However, the systems rely on similar sensor types to insure successful operation. As such any speciality solutions to support autonomous operations should be described. In addition to traditional vehicle dynamics the following are considered in support of the analysis of autonomous vehicle systems

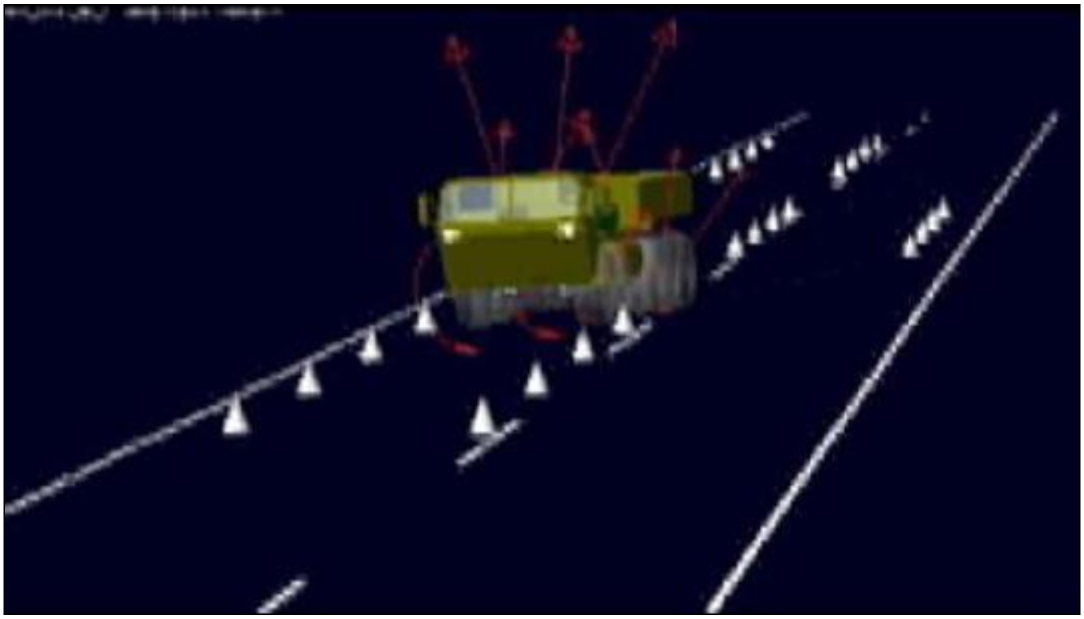
- Can the simulation environment present scene-based operations which include the challenges associated with lit and unlit conditions? Can the environment in the simulation be impacted by fog or dust or other environmental conditions which can impact sensor performance? Be able to control lighting, fog (that can effect sensing)
- Can the objects be presented as 3D objects with variable surfaces and surface coefficients?
- How are the obstacles represented and how do the obstacles react during loading, are deformable surfaces included?
- Available support for user to edit/sculpt existing terrain data sets?
- Be able to support dynamic scenes, i.e. where items (iconic pedestrians, other vehicles) are moving in the scene. Intelligent vehicles will need to be able to detect and avoid static as well as such moving entities.
- Be able to specify textures in addition to geometry for objects
- Be able to specify reflectance properties (eg. BRDF) for objects needed by sensor models
- How are vision-based sensors represented, what are the metrics for performance? GPU acceleration? Ray tracing?
- Are terrain data sets geo-referenced?
- Can terrain models include multiple layers including large low-res and hi-res insets needed for sensors and sensor performance validation?
- Is ephemeris support available for sun and satellite positioning for comm modeling?
- Is there an ability to specify map data such as locations of stop signs, traffic signals etc. Intelligent vehicles may be expected to follow traffic rules.
- Support for modeling interiors of buildings for indoor mobility evaluation?
- How are the inputs from the sensors applied to the vehicle simulation and what is the representative control system update rate.

APPENDIX F –THEME 5 RECOMMENDATIONS FOR A VALIDATION EFFORT

To rapidly complete this validation effort it is necessary to have measured vehicle and associated test data to compare against the predictions. By way of example, data from a capable 10-wheel drive, all-wheel steer technology demonstrator vehicle, developed by the Office of Naval Research (ONR) and the US Marine Corps, was made available. In this particular case, operational test data had been developed over mission profile representative events. Full vehicle dynamics simulations which included powertrain, suspension, tire soil interaction, etc. had been developed, thereby establishing that sufficient information was available so that accurate models over events of interest could be constructed.

A representative photograph and prior simulation activities of the vehicle are shown below.





Vehicle component, powertrain, tire soil interface, tractive force slip, and other parametric data necessary to support the anticipated level of accuracy had already been developed and could be provided in the following representative formats to assist in more rapid evaluation of the available tools from the various organizations.

The following general vehicle, system, and subsystem data is required to create a detailed physics-based model of a given vehicle. The vehicle selected to model should contain modern suspension technology, powertrain, limited slip differentials, ABS brakes, electronic control systems (traction control, stability control, etc.).

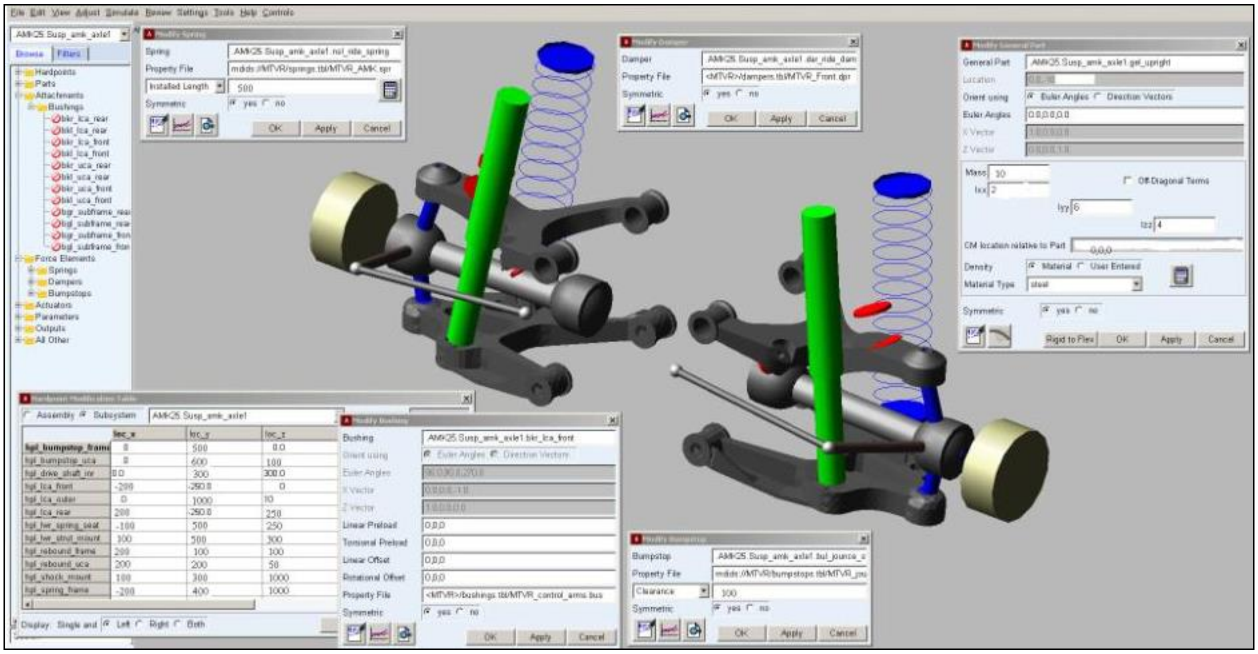
- Full Vehicle:
  - mass at current payload
  - center of gravity of truck
  - center of gravity of payload
  - wheel base
  - track width
  - number of axles
  - number of driven axles
  - traction control system

A typical list of required vehicle and component input data is provided below.

- Powertrain:
  - Engine:
    - mass
    - mass moment of inertia about X, Y, and Z axes
    - center of gravity location (X, Y, Z)
    - rotating mass (crankshaft) inertia
    - location of all mounts
    - stiffness (force versus displacement) curves for mounts in all directions
    - damping (force versus velocity) curves for mounts in all directions

  - data for engine torque as a function of rpm and throttle position
  - engine braking data (if desired)
  - data for accessory loads on engine (AC, fan, alternator, etc.)
  - idle rpm
  - max rpm
- Torque Converter:
  - mass
  - mass moment of inertia about X, Y, and Z axes
  - center of gravity location (X, Y, Z)
  - characteristic curves for performance (e.g., torque and speed ratio curves)
- Transmission:
  - mass
  - mass moment of inertia about X, Y, and Z axes
  - center of gravity location (X, Y, Z)
  - location of all mounts
  - stiffness (force versus displacement) curves for mounts in all directions
  - damping (force versus velocity) curves for mounts in all directions
  - number of gears and gear ratios
  - shift profiles (up and down shift)
  - efficiency (or loss data)
- Transfer cases and differentials
  - mass
  - mass moment of inertia about X, Y, and Z axes
  - center of gravity location (X, Y, Z)
  - location of all mounts
  - stiffness (force versus displacement) curves for mounts in all directions
  - damping (force versus velocity) curves for mounts in all directions
  - gear ratio
  - functional description (e.g., open, biased, locking, etc.)
  - functional data (depending on above description)
- Drive shafts and halfshafts
  - mass
  - mass moment of inertia about X, Y, and Z axes
  - center of gravity location (X, Y, Z)
- Hubs
  - mass
  - mass moment of inertia about X, Y, and Z axes
  - center of gravity location (X, Y, Z)
  - gear ratio (if geared hub is used)

Data Input for Suspension



Spring: AMK25 Susp_amk_axle1.nsl_ride_spring
Property File: mdids://MTVR/springs.tbl/MTVR_AMK.spr
Installed Length: 500
Symmetric: ● yes ○ no

Damper: AMK25 Susp_amk_axle1.dar_ride_dam
Property File: <MTVR>/dampers.tbl/MTVR_Front.dpr
Symmetric: ● yes ○ no

General Part: AMK25 Susp_amk_axle1.gel_upright
Orient using: ● Euler Angles ○ Direction Vectors
Euler Angles: 0.0,0.0,0.0
Mass: 10
Ixx: 2
Iyy: 6
Izz: 4
☐ Off-Diagonal Terms
CM location relative to Part: 0,0,0
Density: ● Material ○ User Entered
Material Type: steel
Symmetric: ● yes ○ no

○ Assembly ● Subsystem: AMK25 Susp_amk_axle1

	loc_x	loc_y	loc_z
hpl_bumpstop_frame	0	500	0.0
hpl_bumpstop_uca	0	600	100
hpl_drive_shaft_inr	0.0	300	300.0
hpl_lca_front	-200	-250.0	0
hpl_lca_outer	0	1000	10
hpl_lca_rear	200	-250.0	250
hpl_lwr_spring_seat	-100	500	250
hpl_lwr_strut_mount	100	500	300
hpl_rebound_frame	200	100	100
hpl_rebound_uca	200	200	50
hpl_shock_mount	100	300	1000
hpl_spring_frame	-200	400	1000

Display: Single and ● Left ○ Right ○ Both

Bushing: AMK25 Susp_amk_axle1.bkr_lca_front
Linear Preload: 0,0,0
Torsional Preload: 0,0,0
Linear Offset: 0,0,0
Rotational Offset: 0,0,0
Property File: <MTVR>/bushings.tbl/MTVR_control_arms.bus
Symmetric: ● yes ○ no

Bumpstop: AMK25 Susp_amk_axle1.bul_jounce_s
Property File: mdids://MTVR/bumpstops.tbl/MTVR_jou
Clearance: 100
Symmetric: ● yes ○ no

- Suspension
  - – Hard points (X, Y, and Z):
    - o upper control arm (front, rear, and outer)
    - o lower control arm (front, rear, and outer)
    - o bumpstop (upper and lower)
    - o rebound stop (upper and lower)
    - o spring mount (upper and lower)
    - o shock mount (upper and lower)
    - o tie rod (inner and outer)
    - o wheel center
    - o drive shaft (inner and outer)
    - o subframe front and rear
    - o anti-roll bar
  - – Mass properties for all components (weight, CG, mass moments of inertia)
    - o control arms
    - o spindles
    - o halfshafts
    - o springs
    - o shocks
    - o subframe
    - o tie rod
    - o anti- roll bar
    - o bushings
  - – Bushings
    - o define bushing orientation and preload

    - linear stiffness curve
    - rotational stiffness curve
    - linear damping curve
    - rotational damping curve
  - Dampers
    - force versus velocity curves
  - Springs
    - define installed length or preload
    - force versus displacement curves
- Deformable Tire
  - Operating Conditions
    - Inflation Pressure
    - Tread Depth
    - Ambient Temperature
  - Basic Data And Geometry
    - Tire Section Width
    - Tire Aspect Ratio
    - Rim Diameter
    - Load Index
    - Speed Symbol
    - Rim Width
    - Rolling Circumference
    - Tire Mass
    - Belt Width
    - Tread Width
    - Interior Volume
    - Belt Lat Curvature Radius
  - Static and modal data for each inflation pressure
    - Tire Long Stiffness
    - Tire Lat Stiffness
    - Tire Tors Stiffness
    - Tire Long Stiffness Progr
    - Tire Lat Stiffness Progr
    - Cornering Stiffness
    - Pneumatic Trail
    - Camber Stiffness
    - Belt Lat Bend Stiffness
    - Belt Rad Torsion Stiffness
    - Belt Torsion Stiffness
    - Belt Twist Stiffness
    - Belt Torsion Lat Displ Coupl
    - Belt Torsion Twist Damp
    - Belt Lat Bend Damp
    - Rad Dynamic Stiffening
    - Tang Dynamic Stiffening
    - Time Const Dynamic Stiffening
    - Radial Hysteretic Stiffening

    - Radial Hysteresis Force
    - Tang Hysteretic Stiffening
    - Tang Hysteresis Force
    - Belt Extension At Vmax
    - Rel Long Belt Memb Tension
    - Rel Long Belt Memb Tension Red
- Tread Properties
    - Tread Depth
    - Tread Base Height
    - Rel Min Tread Shoulder Height
    - Rel Tread Shoulder Width
    - Stiffness Tread Rubber
    - Stiffness Progr Tread Rubber
    - Tread Positive
    - Tread Pattern Shape Factor Tang
    - Tread Pattern Shape Factor Long
    - Lat To Long Tread Stiffness Ratio
    - Sidewall To Tread Stiffness Ratio
    - Damping Tread Rubber
    - Max Friction Velocity
    - Sliding Velocity
    - Blocking Velocity
    - Low Ground Pressure
    - Med Ground Pressure
    - High Ground Pressure
    - Mu Adhesion At Low P
    - Mu Max At Low P
    - Mu Sliding At Low P
    - Mu Blocking At Low P
    - Mu Adhesion At Med P
    - Mu Max At Med P
    - Mu Sliding At Med P
    - Mu Blocking At Med P
    - Mu Adhesion At High P
    - Mu Max At High P
    - Mu Sliding At High P
    - Mu Blocking At High P
    - Time Const Tire Heating
    - Time Const Tread Heating
    - Tire Temp At Ref Slip Low V
    - Tread Temp At Ref Slip Low V
    - Tread Temp At Ref Slip Med V
    - Tread Temp At Ref Slip Vmax
    - Temp Ref Slip
    - Perc Frict Power Heating Tread
    - Wear Rate Coefficient
    - Wear Rate Exponent
- Tire Imperfections

    - Static Balance Weight
    - Static Balance Ang Position
    - Dynamic Balance Weight
    - Dynamic Balance Ang Position
    - Radial Non Uniformity
    - Radial Non Unif Ang Position
    - Tang Non Uniformity
    - Tang Non Unif Ang Position
    - Ply Steer Percentage
    - Conicity
    - Run Out
    - Run Out Ang Position
  - Control Tire Inflation System
    - Inflation Pressure
    - Inflation Pressure 2
    - Cleat Width
    - Rim Inertia

Typical characteristics required for soil properties simulations include:

- Liquid limit
- Plastic limit
- Moisture content
- Density
- Particle size distribution
- Soil shear properties

In addition, detailed terrain data and the measured vehicle response in terms of traction, acceleration, ride quality, stopping distance, stability, etc., had been quantified over conditions similar to those indicated below.

TRAILS

CROSS-COUNTRY

SAND

EMBEDDED ROCK

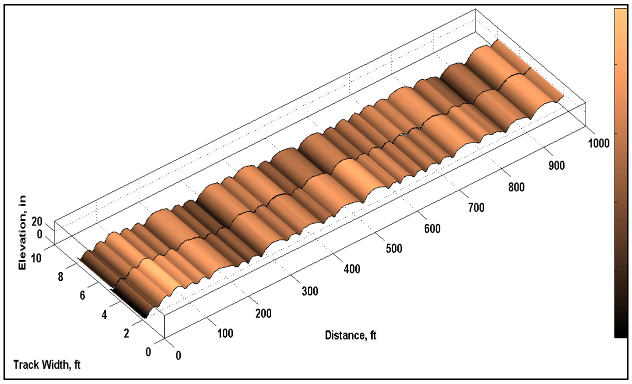
CLAY

LOAM/SILT

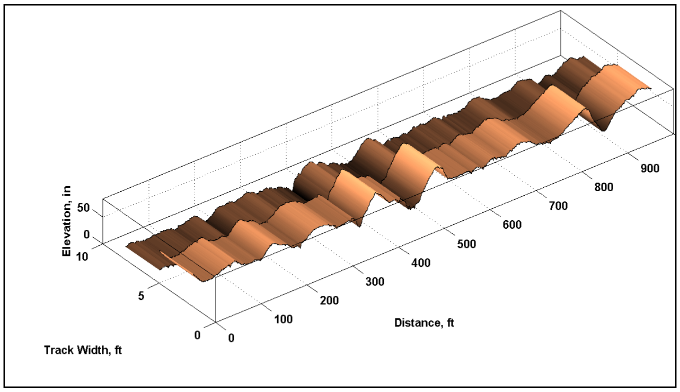
Of particular interest is the ability of the potential vehicle dynamics tools to accurately predict speed and ride quality and damaging energy to the vehicle. Historically NRMM only considered "half" the vehicle and therefore all of the ride quality test conditions required that the bumps be identical under both left and right wheel path. Current vehicle and analysis technology provides for substantially improved ride quality over complex terrain and, therefore, representative terrain roughness moving away from the traditional RMS and toward WNS conditions would be used for the evaluation of the various solutions.

TRADITIONAL

NATURAL



TRADITIONAL



NATURAL

Available Test and Simulation Events

The committee was briefed that data for the following events was available. During that discussion, it was recognized that requiring too many events during this basic evaluation stage could require too much time and cost to accomplish the evaluation. The discussion identified that results were desired in approximately 6 months.

Constant Radius	Speed on 5% Grade
Double Lane Change - Paved & Gravel Surface	Straight Line Acceleration
Road Departure Recovery	Straight Line Braking
30% - 40% Side Slope Slalom	Washboard Event
Mission Profile Trails & Cross Country	Traditional RMS Course
30% Dry Sand Grade	Traditional WNS Course
40% Dry Sand Grade	Tractive Effort
24–36-inch Vertical Step	Vehicle Cone Index (VCI)
Discrete Events (Potholes, Speed Bumps)	MOUT Rubble Pile
6-inch, 8-inch, 10-inch Half-Rounds	MOUT Crater
V-Ditch Obstacle	

Based on the discussions, the following 10 events were identified as appropriate for evaluation of the potential solutions.

- Fundamental Handling:
  - Straight Line Acceleration
  - Straight Line Braking
  - Constant Radius
  - Double Lane Change - Paved & Gravel Surface
- Deformable Surfaces:
  - 30% Side Slope Slalom
  - 30% Dry Sand Grade
  - Tractive Effort
  - Vehicle Cone Index (VCI)
- 2-D vs 3-D Path Track:
  - Traditional RMS Course
  - Traditional WNS Course

The top three scored solutions were then approached. Two of the top three indicated that results could be provided within the 6-month time frame and the third indicated that solutions were possible within approximately 9 months. However it was identified that funding would be required to all of the potential providers to support their efforts. The funding requirements ranged from \$200,000 to \$400,000 depending upon the number of organizations chosen.

With this baseline established, it was apparent that a variety of solutions are available from commercial and university based efforts. Further, it was apparent that if the necessary vehicle component and system test data are available it is possible to rapidly and cost effectively identify capable next step solutions. Based on subsequent meetings and guidance from the head of the committee, the decision was made to forego the interim next step and move forward to the more formal and lengthy Validation and Verification process. This activity will be led by Theme 7.