

# Technical Memorandum

## Cooperative Demonstration of Technology (CDT) for Next-Generation NATO Reference Mobility Model (NG-NRMM)

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**Introduction** - Sponsored by the North Atlantic Treaty Organization's (NATO) Science and Technology Organization (STO), NATO's Applied Vehicle Technology (AVT) Panel formed a Research Task Group (RTG), AVT-248, which consisted of seventy-one persons from fifteen nations to develop a Next-Generation NATO Reference Mobility Model (NG-NRMM). The end result of the AVT-248's four year effort was demonstrated at the NG-NRMM's Cooperative Demonstration of Technology (CDT) event, September 25-27, 2018, held at the Michigan Technological University/Keweenaw Research Center (MTU/KRC) in Houghton, MI, USA. The U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) supported the CDT to showcase the differences between legacy and next generation mobility prediction software.

Headquartered at the U.S. Army's Detroit Arsenal in Warren, Michigan, USA, TARDEC is a major research, development and engineering center for the Army Materiel Command's Research, Development and Engineering Command. The CDT event provided a forum for contributing committee members and software developers to highlight a prototype process that showcases the state-of-the-art in mobility prediction and simulation technologies through a loosely integrated set of methodologies and tools. Attendees were introduced to NG-NRMM technologies through a variety of presentations and demonstrations and were able to witness a physical demonstration of a military prototype vehicle performing select mobility tests in a variety of soil conditions and observe a simulation of the same test with the legacy and next generation mobility prediction software. In addition, participants experienced off- road mobility challenges through multiple ride-along opportunities over a variety of terrains representative of Eastern Europe. This technical memorandum summarizes the CDT event and actions performed, describes the value added, identifies gaps, and outlines a path forward to address many of those gaps.

**Background** - Existing mobility prediction tools are extensively based on the NATO Reference Mobility Model (NRMM), a set of tools based on empirically derived models developed in the late 1960s and 70s. Although NRMM has proven to be of great practical utility to the NATO forces, it has several inherent limitations, particularly when compared to modern multibody dynamic (MBD) modeling and simulation (M&S) capabilities. Many of the off-road mobility algorithms are based on empirical observations, and therefore extrapolation outside of test conditions can lead to inaccurate results. It is heavily dependent on in-situ soil measurements and uses one-dimensional steady state analysis of powertrain performance. Turning performance and lateral vehicle dynamics are not considered. Vehicle dynamic effects are limited to pitch plane for ride quality and all obstacle crossing models are forced to conform to an equivalent walking beam formulation for tracked vehicle suspensions systems. This means that NRMM results are useful for comparisons between existing systems or new systems that are similar to existing systems. However, it should not be used for systems that incorporate advanced mobility technologies, such as active suspension, that are radically different than those on existing systems. Due to its age and intermittent ad hoc development history and reliance on empirical performance data collected at the vehicle level, NRMM's software and data architectures do not easily support evolutionary development in terramechanics or vehicle terrain interaction models such as the fundamental extension to 3D models that support vehicle turning mechanics and more complete mobility metrics. The means for expansion of the analysis techniques to include alternative terramechanics models, advanced vehicle systems, intelligent vehicles, custom mobility metrics, stochastic knowledge of terrain, and terrain data sets for urban areas are driving the development of a NG-NRMM.

The NG-NRMM has the potential to significantly reduce procurement risks by enabling alternative solutions to be considered and it provides operational decision makers with a tool for assessing their own and opposing vehicle mobility in the area of operations, which will increase confidence in mission planning and reduce the risk of mission failures due to compromised vehicles. NG-NRMM brings a physics based approach to the mobility problem by leveraging the latest advances in multibody physics, ever expanding computing power and significant advancements in remote sensing systems. It also holds the potential to significantly improve mobility predictions, while supporting the latest ground interaction geometries. Through this continuing effort, the goal is to attain a mobility model with enhanced capabilities to provide increased flexibility to support operations by assessing the operational mobility of different deployed platforms in different areas of operation and routes as well as increased functionality to assess operational issues. Its development is also

intended to provide improved flexibility as a design and procurement support tool through enhanced fidelity and the ability to model current and emerging mobility technologies.

**Objectives** - The objective of the CDT was to demonstrate the most advanced capabilities in ground vehicle modeling and simulation, with a particular focus on mobility over soft and marginal terrains, typical of ground combat operations. The CDT included technical sessions on simple and complex terramechanics, demonstrations of field soil sampling in relevant soil types, vehicle mobility displays, and simulations using a high mobility platform on representative terrain and soil. The CDT was structured to demonstrate the capabilities of NG-NRMM in six scientific thrust areas:

1. Thrust 1 - Geographic Information System (GIS) - Terrain and Mobility Mapping: Identify a GIS-based mapping tool that implements and integrates existing, valid mobility metrics (%NOGO and Speed-Made-Good) in an open architected environment
2. Thrust 2 - Simple Terramechanics (ST): Identify most promising existing parametric terramechanics models supporting NG-NRMM requirements that provide a means of correlating terrain characteristics to remotely sensed GIS data
3. Thrust 3 - Complex Terramechanics (CT): Identify most promising existing physics based terramechanics models supporting NG-NRMM requirements that overcome the limitations of existing models
4. Thrust 5 - Uncertainty Treatment: Identify the practical steps required to embed stochastic characteristics of vehicle and terrain data to enable probabilistic assessment of current deterministic mobility metrics (%Go/NoGo)
5. Thrust 6 - Verification and Validation (V&V): Establish near-term vehicle-terrain interaction benchmarks for verification of candidate NG-NRMM M&S software solutions and lay the groundwork for long term validation data through cooperative development with test organizations and standards committees
6. Thrust 7 - Data Gaps and Operational Readiness: Refine the operational requirements of NG-NRMM and identify where the gaps exist

*(\*\*Please refer to the AVT-248 Final Report for detailed explanations of each technology area\*\*)*

To be clear, NG-NRMM will not be a specific computer code but a set of NATO standards and benchmarks spelled out in a STANREC. A STANREC (STANdardizationRECommendation) is a NATO standardization document

defining processes, procedures, terms, and conditions for common military technical procedures or equipment between the member countries of the alliance. It's a non-binding document employed on a voluntary basis and does not require commitment of the Nations to implement the standards listed therein. A NG-NRMM NATO Standards STANREC, AMSP-06, ver1 Standards Document: "Guidance for M&S Standards Applicable to the Development of Next Generation NATO Reference Mobility Model (NG-NRMM)", Allied Modeling and Simulation Publication-06 (AMSP-06, ver1), assigned by and coordinated with NATO Modeling and Simulation Group (NMSG), is being developed and will be released, after the NMSG review; target date: November 2018 by AVT-248. STANREC 4813, Ed 1: is a covering document that formally recommends the use of AMPS-06, ver1. The AVT-327 Research Task Group (RTG) will establish the enduring process for development and configuration management of AMSP-06. The objectives and scope will be defined as a land vehicle mobility M&S open architectural specification that is applicable to all land vehicle geometric scales, implements GIS-based M&S methods and mobility metrics, promotes modularity, interoperability and portability, embraces scalable M&S at multiple levels of resolution: includes M&S verification and validation maturity scales and practical benchmarks, and includes standards and databases for terramechanics experimental data measurement methods that support the terramechanics models. The STANREC guidance codifies results of the NG-NRMM effort and establishes an enduring artifact. It establishes a baseline as well as a development path for NATO nation's mobility modelling methods, benchmarks, and a soils database that should be applied to all physics based simulations of operational land and amphibious mobility among the alliance.

**Summary of Actions Performed** - The CDT was divided into four (4) phases; PHASE 1 - Collect vehicle test data to calibrate computer-based models, PHASE 2 - Mobility Simulation and Analysis, PHASE 3 - Model Comparison to Live Test Results, and PHASE 4 - the Cooperative Demonstration of Technology (CDT) event. TARDEC's Fuel Efficiency Demonstrator Alpha (FED-Alpha) shown in Figure 1 was designated as the test vehicle for the CDT and was ideal for NG-NRMM purposes as it had considerable design and technical data available, as well as partially validated models for dynamic and powertrain performance.



**Figure 1. FED-Alpha Vehicle. Graphic Representation & Hardware.**

Ricardo Inc. designed the FED-Alpha to be a high-mobility, highly-capable and survivable four passenger tactical vehicle that would maximize fuel efficiency across all vehicle systems. It was selected for this evaluation due to its relevant physical characteristics and performance, which are similar to those of the High-mobility Multipurpose Wheeled Vehicle (HMMWV), without the data sensitivity of a fielded system. Commercial software vendors as well as other interested developers were invited to participate in the AVT-248 committee activities and, subsequently, in the CDT event to gauge their software's effectiveness and accuracy in modeling and simulating vehicles in off-road and soft soil environments. The software developers that participated in the exercise were Advanced Science and Automation (ASA), CM Labs Simulations (CML), MSC Software (MSC), Vehicle Systems Development Corporation (VSDC), RAMDO Solutions (RAMDO), as well as Aarhus University (AU), and the South African Council for Scientific and Industrial Research (CSIR). TARDEC was tasked with modeling the FED-Alpha using the legacy NRMM as a baseline simulation analysis for comparison purposes with participating software developers.

PHASE 1 – Test Data Collection: Field tests were conducted by MTU/KRC to evaluate the automotive performance and mobility of the FED-Alpha vehicle and collect instrumented test data for model calibration and validation. MTU/KRC conducted the specified test events and measured and recorded both terrain data (simulation model inputs) and vehicle performance data (simulation model outputs). Table 1 presents a summary of the tests that were conducted and the corresponding simulation outputs that were collected and evaluated. The vehicle performance data was split into a calibration data set and a live test results data set. All CDT terrain and soil data as well as FED-Alpha vehicle and performance data are scheduled to be released in early 2019 and can be found on the MTU/KRC FTP site ([blizzard.mtukrc.org](http://blizzard.mtukrc.org)).



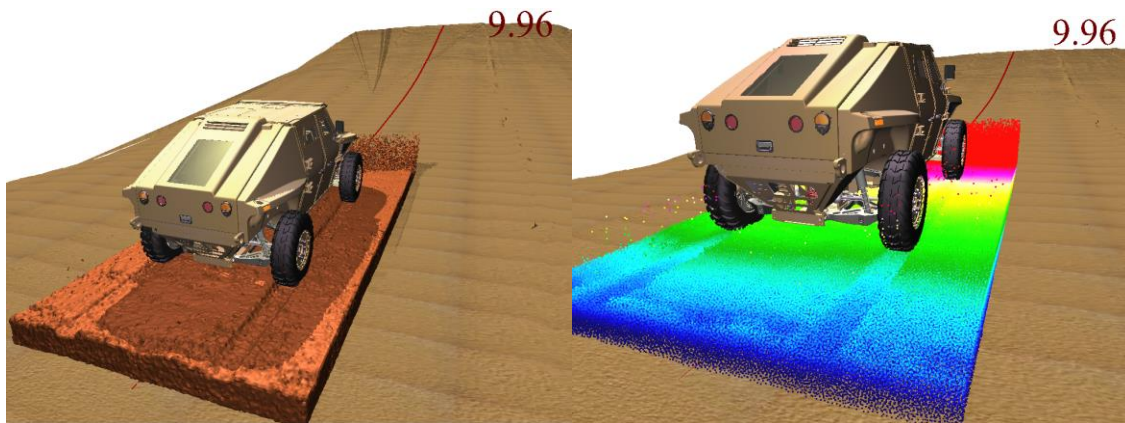
Test Name	Soil	Simulation Outputs
1 Straight Line Acceleration	Pavement	Position, speed, acceleration histories
2 Wall to Wall Turn Circle Radius	Pavement	max diameter of tightest circle position, speed, clockwise and ccw
3 Steady state cornering (30 m radius) (SAE J2181)	Pavement	Understeer/oversteer characteristics, steering angle, max. speed, lateral acceleration
4 NATO Double lane change (AVTP 03-160 W)	Pavement	Speed, path, steering angle, lateral acceleration, yaw rate, roll angle
5 NATO Double lane change (AVTP 03-160 W)	Gravel	Speed, path, steering angle, lateral acceleration, yaw rate, roll angle
6 Side slope with obstacle avoidance steer	Hard-packed crushed mine rock	Side slope, speed, pass/fail
7 60% Longitudinal grade	Pavement	Speed, grade, pass/fail
8 0 to 30% Longitudinal grade	Coarse grain sand	Max grade at set speed, pass/fail
9 4 inch half-round	Pavement	Speed when 2.5g vert acc at driver's position
10 8 inch half-round	Pavement	Speed when 2.5g vert acc at driver's position
11 10 inch half-round	Pavement	Speed when 2.5g vert acc at driver's position
12 12 inch half-round	Pavement	Speed when 2.5g vert acc at driver's position
13 18 inch vertical step	Concrete	Go/no-go and identify any interference
14 24 inch vertical step	Concrete	Go/no-go and identify any interference
15 V-ditch	Concrete	Go/no-go and identify any interference
16 Drawbar Pull	Fine Grain Organic/ Silty Sand - Wet	Drawbar pull vs. slip
17 Drawbar Pull	Fine Grain Organic/ Silty Sand - Dry	Drawbar pull vs. slip
18 Drawbar Pull	Coarse Grain Sand - Dry	Drawbar pull vs. slip
20 Asymmetric 1-1.5 inch RMS	Hard-packed crushed mine rock	6-Watt absorbed power speed
21 Asymmetric 1.5-2 inch RMS	Hard-packed crushed mine rock	6-Watt absorbed power speed
22 Symmetric 1 inch RMS	Hard-packed crushed mine rock	6-Watt absorbed power speed
27 Symmetric 1.5 inch RMS	Hard-packed crushed mine rock	6-Watt absorbed power speed
28 Symmetric 2 inch RMS	Hard-packed crushed mine rock	6-Watt absorbed power speed
29 Symmetric 3 inch RMS	Hard-packed crushed mine rock	6-Watt absorbed power speed

	Test Name	Soil	Simulation Outputs
30	Symmetric 4 inch RMS	Hard-packed crushed mine rock	6-Watt absorbed power speed
31	Symmetric 5 inch RMS	Hard-packed crushed mine rock	6-Watt absorbed power speed
32	Mobility Traverse	Composite of Natural Terrain & Engineered Courses	Varied including speed-made-good map

**Table 1. Model Simulation/Live Test Matrix.** *(For more information on test plan, please refer to MTU/KRC's "Detailed Test Plan for the Automotive Performance and Mobility Evaluation of the TARDEC Fuel Efficiency Demonstrator Concept A (FED-A) Vehicle")*

*\*\*Red indicates courses that NRMM could model\*\**

**Error! Reference source not found.:** the objective of PHASE 2 was to develop a NG-NRMM modeling process, and then create and calibrate simulation models of specified live test events that were performed during PHASE 1. PHASE 2 consisted of simulating mobility testing and predicting performance of live testing. Each participant obtained the vehicle and terrain data and the CDT test calibration data; developed a 3D, high-resolution, physics-based computer simulation model of the FED-Alpha vehicle completing each test (Figure 2 illustrates an example of a software developer's FED-Alpha representation); ran the model over the set of digital terrain courses; analyzed simulated results; calibrated the model to the calibration test data; predicted the performance of the FED-Alpha wheeled vehicle; and reported results. Software developers communicated and shared best practices, including terrain data file formats and test scenario modeling, in developing the NG-NRMM modeling processes. In addition, software developers developed a Go/NoGo terrain map of the MTU/KRC terrain for the FED-Alpha vehicle and determined for each specified MTU/KRC unique terrain unit the maximum traversable speed in omni-directions. They also developed an Uncertainty Quantification (UQ) Map from the Go/NoGo Map developed in the prior task. This required an estimate of max speed for each terrain unit under the variation limits of the terrain with the range of speed estimates being computed into a probability, which was then mapped. Diverse and multiple solution methods, including ST and CT, were preferred and encouraged. TARDEC modeled and conducted the same analysis of the FED-Alpha using the current NRMM legacy code for comparison purposes.



**Figure 2. Example of simulations models.**

PHASE 3 - Model Comparison to Live Test Results: this phase consisted of comparing the PHASE 2 simulation results to live test results as illustrated in Figure 3, improving the PHASE 2 models, and quantifying model performance. Each participant compared the model results to the live test results for all tests conducted and, subsequently, verified model behavior and identified areas for model improvement, such as, more accurate mass and inertial properties, more accurate suspension stiffness and damping characteristics, and integration of improved bushing and tire models.



**Figure 3. Model comparisons to live test results.**

Simulations were then re-run using improved model parameters, monitoring those parameters, and comparing improved model performance with live test data. Go/NoGo and Uncertainty Quantification Maps developed in PHASE 2 were also updated based on new information which allowed an updated comparison of the maximum speed made good for the traverse runs to the map results. Participants refined and reran their model(s) as necessary to quantify model mobility performance as accurately as possible.



PHASE 4 - CDT Event: The three-day event was held at the MTU/KRC test facility (Figure 4), and was comprised of presentations and demonstrations of the latest technology developments in modeling and simulation of off-road mobility of ground vehicle systems. Approximately 160 persons attended each day and the full, three day agenda is included in Annex D.



**Figure 4. NATO CDT event in Houghton, MI, USA.**

The meeting was intended to be a critical peer review of the NG-NRMM AVT-248 and AVT-308 committee's NG-NRMM's multi-year effort(s). Attendees were introduced to NG-NRMM technologies through the following presentations:

1. History, Motivation, and Goals for NG-NRMM
2. NATO Task Group and CDT Objective
3. NG-NRMM Virtual and Physical Demonstration Plan
4. Thrust 1- Geospatial Terrain and Mobility Mapping
5. Thrust 2 - Simple Terramechanics Model & Data
6. Thrust 3 - Complex Terramechanics Model & Data
7. NG-NRMM Virtual Demonstration
8. Thrust 5 - Uncertainty & Stochastic Mobility Maps
9. Thrust 6 - NG-NRMM Verification and Validation
10. NG-NRMM Standard
11. Thrust 7 - Gaps and Operational Readiness
12. CDT Results and Vision for the Future

*\*\*Presentations located in Annex E\*\**

The NG-NRMM Virtual Demonstration was an “end to end software demo” that demonstrated how NG-NRMM adopted new technologies, modeling techniques, and computational tools to enable physics-based simulation of any vehicle design, in complex environments and scenarios. It described how an open and modular architecture was used to weave together CDT technologies to include GIS data inputs, terrain and soils data, the latest modeling and simulation technology,

terramechanics, mobility event studies, uncertainty quantification, and mobility maps into an integrated set of tools and methodologies for mobility prediction that allows for incorporation of new methods as they become available. In addition, each participating software developer prepared suitable presentation materials for the event, which included live and/or recorded animations of the simulation events in the same orientation as videos of the live test events so that they could be compared and played in parallel. They also produced charts, explanatory materials and other artifacts relevant to demonstrate the quality of the work within the operational context of the NG-NRMM environment. The software developers presented the following talks:

- 13. MSC - Military Vehicle Simulation with Adams: Mobility and Beyond
- 14. CSIR - South African Mobility Prediction Software MOBSIM
- 15. CML - Real-Time Vehicle Simulation using Vortex Studio
- 16. VSDC - Wheeled Vehicle Mobility Prediction using NWVPM
- 17. AU - ROAMS, a Fast Running Mobility Simulator Utilizing GeoTIFF Terrain Maps
- 18. ASA - DIS/A Complex Terramechanics Software Tool for Predicting Vehicle Mobility

*\*\* Presentations located in Annex E\*\**

On the first and second days of the CDT, participants were able to walk some of the courses and witness vehicle demonstrations of the vehicle traversing select terrains (RMS, soil pit, side slope, and sand grade courses) as seen in Figure 5.



**Figure 5. NATO CDT vehicle/course demonstrations.**

Demonstrations also included two types of ride-alongs running continuously all three days along the traverse terrain course. The traverse terrain course consisted of fourteen segments that included RMS, various slopes, sand grades, soil pits,

obstacles, gravel and secondary roads, obstacle avoidance, max acceleration, 90 degree turn, and moisture dependent course sections. One of the ride-alongs was in a ten-passenger van that took approximately 30 minutes to complete; it was narrated by the MTU/KRC driver with stops at each section of the course. Passengers were supplied with maps of the course and could ask questions while traversing each segment. The second ride-along was in a four passenger, 4x4, off-road, open air, all-terrain vehicle that traversed each segment at an elevated speed so that passengers could experience the course with maximum effect. The event also featured software vendor booths as well as displays from other CDT participants.

**Results / Lessons Learned** - Although NRMM remains a useful tool for limited applications, the future of analytical soft soil mobility analysis clearly rests with NG-NRMM. It holds the promise of allowing manufacturers, planners, and users the ability to model virtually any platform, over any soil and terrain type. The CDT has demonstrated that NG-NRMM can offer significantly better mobility and trafficability predictions although the results are limited to the vehicles modeled and terrain traversed. Work is still required to demonstrate the accuracy of predictions over other vehicle, terrain, and soil types, which will still require investments in research and development to bring it to a fully mature state. The automotive test simulations highlighted the fact that NRMM lacks 3D dynamics capability and therefore only straight line tests could be simulated, whereas NG-NRMM based models were able to simulate all of the tests; Straight Line Acceleration, Low Speed and High Speed Cornering, Double Lane Change, 60% Grade, Ride Quality, 2.5G Half Round Speed, 6 Watt Absorbed Power, Symmetric/Asymmetric, Go/No-Go, V-Ditch, and Step Incline.

During the soft soil tests, drawbar pull (DBP) and variable sand slope (VSS), NRMM was only able to predict the DBP well in wet, fine grain soil and showed a large variation in VSS. It is well known that ST is challenged on sloped terrain, however, in the course of the CDT, predicting DBP and VSS in coarse grained sand also proved to be difficult. CT was better able to predict VSS and the DBP results across all soil types, except dry course grain. Rut depth measurements were disturbed by flowing sand, and only a few developers were tracking multi-pass effects. Again, NG-NRMM predicted all soft soil events (with validation possible), except coarse grain dry.

On the mobility traverse, NRMM over-predicted the average speed compared to tests, whereas NG-NRMM was within 25% of the test speed in more than 75% of the traverse segments. It should be mentioned that NG-NRMM driver models do not

have the same perceived speed limits as an actual test driver and will inherently drive faster than drivers may feel comfortable doing themselves. Without question, NG-NRMM simulations were demonstrated to be in better test agreement with test results than NRMM.

**Capability Gaps & Challenges** – The committee compiled a suggested list for future actions with comments as follows;

1. Data quality and quantity - Available and future actions, standardization/use of GeoTIFF format, data processing tasks, wheel and track. STANREC RTG (AVT-327) has been established to develop a recommendation on the local high resolution format (such as TIN, Triangulated Irregular Network) for terrain in addition to the more global data format that is available as postings on a grid.
2. Uncertainty qualification - Challenges and remedies. Need to develop specifics of how to develop variance data for each model type. Wheel based sensors for ST provides a valid approach but other point by point methods continue to suffer from geospatial sparsity.
3. Correlation of data and models - Thrust 6 results breakdown (Test/NRMM/ST/CT), conclusions, recommendations, next steps. Need to update and formalize packaging of benchmark data sets: vehicle, terrain, event descriptions and soil data used for each benchmark. A benchmark is defined as a combination of both a specific vehicle and a specific terrain and event set. By contrast, there will be a DATABASE of Terramechanics properties and a CATALOG of global terrain data sets (this currently includes Monterrey and CDT data set when released).
4. Soft soil simulation - Test standards, lack of required improvements (e.g. drawbar pull test); relating model and physical parameters, CT using MPM (currently DEM), scalability of model-computation-V&V, CT particle size/shape/moisture. STANREC will solidify lessons learned for side slope event, drawbar pull, 3D terrain roughness metric, methods of in-situ geotech data capture. The differences between model calibration and validation were demonstrated which also highlighted the continuing important challenges in complex terramechanics. Each of these deserves a focused sub-group to initiate efforts and report back.

5. Standardization (addressed with AVT-327) - CDT-enhanced version to be filed with NMSG next month; include test standards. STANREC 4813 and AMPS-06 will be initially released to the NMSG for review in December 2018. AVT-327 is the forum in which many of the on-going issues will be delineated and planned for future clarification and hopefully resolution in so far as the activities necessary for their resolution are able to be accomplished by NATO itself, individual participating nations, or related independent developments in the research areas that normally address these challenges.
6. Remote sensing - for GIS, soil properties, moisture, resolution, data size. Related efforts are being funded and this is an active area of research to be promoted in the future. ASTM committees recommending national data base wherein test labs report common test results on various soils as they are tested.
7. Identify new research topics - MURI, Quantum computing, etc. Suggestions for new research topics could include vehicle as a sensor, ST extensions to handle slopes, soil flow and transport, use of CT (FEA models) to demonstrate arbitrary nature of bevameter constant stress across shear planes and under platens that is just as valid, if not more so, to get the average under rolling wheel sensor.
8. Gaps - vegetation, non-homogeneity, layers, geographic size, visibility, urban. All to be addressed in AVT-327 as gaps with future plans TBD.
9. Data collection methods - vehicle as a sensor, running gear alone test. Common database needs to be developed to consolidate.
10. Database. Same comments as Data Collection Methods.
11. Survey results. Annex F.
12. Intelligent Mobility - Revive Thrust 4 through the new Autonomy ET. Revive Thrust 4 through the new Autonomy ET.
13. Software development - Address where software vendors go from here; NG-NRMM compliance including GIS; further development; Active SBIR; etc. Finish and improve earlier benchmarks to demo their capabilities to include multi-pass effects in ST models. Have SBIR participants report the relevance of their results.



14. Apply to vehicle programs - NGCV, OEM & International participation, etc.  
NGCV, OEM & International participation, etc

The gaps and challenges identified by the committee members fell into three categories; input, modeling, and output. Modeling input gaps were data availability (especially soil), resolution, lack of a long term configuration management approach to a soil and terrain database, and advancement of the vehicle as a sensor method. Other input issues were with obtaining vehicle data, especially with increasing vehicle complexity, storing data with implications for adaptability and interoperability, and data security with increased complexity for data handling. Legacy terrain data also presents challenges such as; how to enhance obstacle representations, data gaps and how to generate additional soil parameters, and data that changes over time which impacts the ability to update and subsequently use legacy data. Data confidence is another area where NG-NRMM will need improved methods for capturing data quality and confidence.

Modeling was the second area where gaps/challenges were identified: moisture and vegetation effects, temperature and seasonality effects, vehicle-soil slip-sinkage parameter quantification methods, addressing bulldozing phenomena, experimental methods that address soil layer and load rate effects, and leveraging CT developments to extend the ST database. The ability to validate/calibrate high-fidelity finite element tire – soil models (Discrete Element Method) would be a more cost effective path forward for better modeling of the deformable tire and soil interface. Standardization across industries and solution providers is also critical. To date, advancements in NG-NRMM solutions (the use of multi-body physics, ST and CT and other tools) has been slowed by the lack of a unifying standard to govern their development and implementation. A single solution is not required, but a single, unifying standard is, which will ensure optimal interchange of data and incorporation of new knowledge as it comes to light.

Output was identified as the third area with model validation and verification as the biggest challenge. A benchmarking verification and validation plan will be necessary to assess potential NG-NRMM modeling methodologies, capabilities, and component models for vehicle dynamics, off-road mobility, intelligent vehicle operation, and geospatial data use and mapping, which will need to be included in the set of standards to guide the implementation of NG-NRMM, as well as its use and management. There is also concern that developing NG-NRMM for legged and small vehicles may not be viable in the near term as well as the capability to model

and simulate performance in/around water, ingress and egress, obstacles, and vegetation. NG-NRMM is well suited for a wider exploitation and will provide a revolutionary step-up in mobility performance analysis capability. The challenge will be to understand how to carry that improvement forward, e.g. logistic and combat simulations, since NG-NRMM alone does not address the ‘so what’ of improved discrimination between vehicles.

**Recommendations / Way Forward to Tackle Remaining Gaps** - Based on CDT results, it is clear that the need for continued investment in NG-NRMM is both warranted and required, and further, investments need to be focused in several directions: the generation of relevant soil and terrain datasets using remote sensing such as GIS to obtain soil properties, moisture, resolution, data size; understanding how legacy datasets may be leveraged for application in today’s physics based mobility modeling and assessment methodologies; understanding, interpreting and correlating disparate data sources, such as cone index, bevameter, remote sensed topography, moisture content, historical land use etc.; and finally, uncertainty quantification, which will require a better understanding of both the probability distribution of key parameters, and the sensitivity of soft soil mobility prediction results.

CDT software developers will need to finish and improve earlier benchmarks to demonstrate their capabilities while moving towards NG-NRMM compliance including multi-pass effects in ST models and the use of GIS to define terrains/soils. CDT terrain and soil data are scheduled to be released in early 2019 and a new STANREC RTG (AVT-327) will take up the development of a recommendation on the local high resolution format (such as TIN) for terrain in addition to the more global data format that is available as postings on a grid. CDT benchmark data sets will be updated and formally packaged to include vehicle, terrain, event descriptions and soil data used for each benchmark. There will also be established a DATABASE of Terramechanics soil properties and a CATALOG of global terrain data sets which will include the Monterey data set used in AVT-248 and the CDT data set when released. Challenges remain with uncertainty quantification such as how to develop variance data for each model type. Wheel based sensors provide a valid approach to measuring soil conditions whereas other point by point methods continue to suffer from geospatial sparsity. Improving data collection methods such as using the vehicle as a sensor and consolidating common databases will be useful and addressed by the STANREC and AVT-327.

Soft soil simulation will also remain a critical investment requirement and understanding the range of soil types, and the effect of moisture (and other parameters, such as vegetation) on the soil trafficability is vital to its success. The STANREC will solidify lessons learned for side slope, drawbar pull, 3D terrain roughness metric, and methods of in-situ geotech data capture. The differences between model calibration and validation were demonstrated which also highlighted the continuing important challenges in complex terramechanics. Each of these deserves a focused sub-group to initiate efforts and report back. CT shows the most promise, but more research, development, and testing are needed in areas such as: CT soil model validation for all soil types (homogeneous and non-homogeneous), development of a calibrated CT soil models database (including moisture and temperature effects), and fundamental research into micro-scale soil models. Other research areas could include investigating/developing a soil classification system designed for vehicle mobility applications, and a terramechanics experiment to measure soil damping, viscosity, and dilation. There is also a need to improve the parallel scalability of the CT models and develop novel models for multi-layer terrains, water-covered, soft-soil terrains, heterogeneous terrains, vegetation, and urban obstacles. Vegetation, non-homogeneity, layers, geographic size, visibility, urban, slip-sinkage, multi pass, snow/ice/freeze, etc. will be addressed in AVT-327 as gaps with future plans for resolution.

It should not be assumed that all implementations of NG-NRMM will have the same aspirational end state since there will be divergent requirements and use cases will impact having a single solution. Although simple NG-NRMM has the greatest potential for exploitation across use cases, there will still be a case for a common, minimum NATO capability. A recommended Levels and Layers system will need to be adopted, and the STANREC will need to define Levels and refine Layers. Gaps and challenges other than terrain and soil, such as walking vehicles, small UGVs, vehicle data, utilizing NRMM2 legacy terrain will require different tools and novel solutions. The tools considered have demonstrated breadth against the new requirements but significant gaps and challenges remain.

**Takeaways** - Using modern methods, such as NG-NRMM, can significantly improve the ability to make more accurate mobility predictions and assessments which holds the promise of reducing prediction errors by an order of magnitude. There are simplified NG-NRMM solutions, running real time or better that can replace NRMM for use in operational planning, training, and field deployment. There are also high fidelity solutions which are suitable for research and development work at the technology and procurement level where statistics and

confidence maps could be implemented. Although there has been significant progress in NG-NRMM development, further work and investment is needed to make it the new standard.

**Follow-on Activities** - The AMSP-06 STANREC will be an enduring artifact and development path for the NATO nation's mobility modeling methods, benchmarks and source databases that should be applied to physics based simulations of all operational land and amphibious mobility among the alliance. STANREC 4813 and AMPS-06 will be initially released to the NMSG (NATO Modeling and Simulation Group) for review in November 2018, and a new RTG, AVT-327, will manage revisions and maintenance. AVT-327 is the forum in which many of the on-going issues will be delineated and planned for future clarification, and hopefully, resolved by, NATO itself, individual participating nations, or related independent software developers.

## **Annex A – Official Membership List - Christoph**

## **Annex B – CDT Attendee List - Christoph**

## **Annex C – Acknowledgements – Christoph**

## **Annex D – CDT Program**

### **CDT Program**

<b>Monday 24 September 2018, DAY 0</b>
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1500-1800 Registration and Social

*Rozsa Center for the Performing Arts*

<b>Tuesday, 25 September 2018, DAY 1</b>	<b>Theme: Technology</b>
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0730 Registration and Transport to *Tent Site*

*KRC Main Building*

0830 Safety / Logistics Information

Scott Bradley

0845 Welcome

Jay Meldrum

0900 NATO Task Group and CDT Objective

Michael Hoenlinger

0945 \*\* Break

1045 \*\* NG-NRMM Virtual and Physical Demonstration Plan

Ole Balling / Scott Bradley

1145 **	Thrust 1: Geospatial Terrain and Mobility Mapping	Matt Funk / Ryan Williams / Russ Alger
1230 **	Lunch	
1330 **	NG-NRMM Physical Demo / Walk-Around or Visit Booths	Scott Bradley, Lead
1530 **	Break	
1600 **	Thrust 2: Simple Terramechanics Model & Data	Michael McCullough
1645 **	Thrust 3: Complex Terramechanics Model & Data	Tamer Wasfy
1730	Summary and Tomorrow's Preview	Paramsothy Jayakumar
1800	Transport to <i>KRC Main Building</i>	

<b>Wednesday, 26 September 2018, DAY 2</b>		<b>Theme: Operational Scenario</b>
0730	Registration and Transport to <i>Tent Site</i>	<i>KRC Main Building</i>
0830	Safety Brief	Jay Meldrum
0845	NATO Welcome	Steen Sondergaard & Christoph Mueller
0915	TARDEC Welcome	Paul Rogers
0930 **	History, Motivation, and Goals for NG-NRMM	David Gorsich
1000 **	Break	
1030 **	NG-NRMM Physical Demo / Walk-Around or Visit Booths	Scott Bradley, Lead
1230 **	Lunch	
1330 **	NG-NRMM Virtual Demonstration	Radu Serban, Lead
1500 **	Break	
1545	Thrust 6: NG-NRMM Verification and Validation	Ole Balling / Frederik Homaa
1630	Transport to <i>KRC Main Building</i>	
1800	Cocktail Hour	<i>Memorial Union Ballroom</i>
1900	Dinner Reception	
	After-Dinner Speaker	Richard Koubek, President, MTU

<b>Thursday, 27 September 2018, Day 3</b>		<b>Theme: Future</b>
0800	Registration and Transport to <i>Tent Site</i>	<i>KRC Main Building</i>
0900	Review of First Two Days and Plans for Today	Paramsothy Jayakumar
0930	Thrust 5: Uncertainty & Stochastic Mobility Maps	Nick Gaul / KK Choi
1015 **	Break	
1045 **	Thrust 7: Gaps and Path Forward	Michael Bradbury
11:45**	NG-NRMM Standard	Michael McCullough
1215 **	Lunch	
1315	Software Developer Presentations	
	MSC	Military Vehicle Simulation with <i>Adams: Mobility and Beyond</i> - Eric Pescheck
	CSIR	<b>South African</b> Mobility Prediction Software <i>MOBSIM</i> – David Reinecke



	CM Labs	<b>Real-Time</b> Vehicle Simulation using <i>Vortex Studio</i> - Martin Hlrschkorn	
	VSDC	Wheeled Vehicle Mobility Prediction using <i>NWVPM</i> – Joe Wong	
	AU	<i>ROAMS</i> , a Fast Running Mobility Simulator Utilizing <b>GeoTIFF Terrain Maps</b> –Louise Bendtsen	
	ASA	<i>DIS</i> – A <b>Complex Terramechanics</b> Software Tool for Predicting Vehicle Mobility – Tamer Wasfy	
1515	Break		
1545	CDT Results and Vision for the Future		William Mayda
1630	Path Forward and Open Discussion		Paramsothy. Jayakumar
1700	Conclusion of CDT; Transport to <i>KRC Main Building</i>		

### **Parallel Activities**

Exhibitor Booths

Traverse Ride-Alongs: Sign-in Sheet

Terrain Ride-Alongs: Sign-in Sheet

Soil Data Collection

MSC Driving Simulator in KRC Main Building: Sign-in sheet

MTRI Drone Topology Fly-Over

## **Annex E – CDT Presentations - Christoph**

## **Annex F - CDT Post-event Survey**

### **Quick Survey**

This CDT arose from work by scores of individuals, including months of testing and simulations starting in 2017. We would like your response to the following three questions on whether you thought the effort was successful. Please check the appropriate box below and feel free to add comments. 69 surveys received

1. Did you have an understanding of NG-NRMM technologies based on the presentations?

☐ Yes 67 ☐ Maybe 2 ☐ No 0

-Very Clear what technologies are being used for NG-NRMM.

2. Were the virtual and physical demonstrations experienced and understood?

☐ Yes 68

☐ Maybe 1

☐ No 0

- Very clear which events were run and how the vendors replicated the tests.
- Based on committee involvement more than the presentations.

3. Did the presentations and demonstrations convince you of the worth of NG-NRMM?

☐ Yes 47

☐ Maybe 19

☐ No 3

**Comments:**

- Maydas' presentation was more helpful than the V&V presentation.
- The presentations and demonstrations were rather disconnected. Smaller groups, more 1 on 1 xxxxx (smaller student/teacher ratio) and immediate reinforcement by physical demonstration would be better.
- Depends on metrics of success
- Need to address the criteria of %GO, %No-Go. How Next Gen NRMM calculate these numbers. Need to give an example of the comparison between NRMM & NG\_NRMM to show where the %Go, %NO Go difference comes from.
- Limitations
  - Handling snow/ice/frozen ground
  - Handling vegetation in soft soil
  - How is this NG-NRMM going to be used in the acquisition process
  - Seems like this CDT is not ready for STANREC.
- Congratulations KRC.
- Well organized and perfect execution.
- Thanks for everything.
- KRC was amazing