NORTH ATLANTIC TREATY
ORGANIZATION

SCIENCE AND TECHNOLOGY
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STO TECHNICAL MEMORANDUM **TM-AVT-308**

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

(Démonstration coopérative de technologies (CDT) pour le modèle de mobilité de référence de nouvelle génération (NG-NRMM) de l'OTAN)

This Report documents the findings of the AVT-308 Cooperative Demonstration of Technology (CDT-308) Next-Generation NATO Reference Mobility Model (NG-NRMM).

Published April 2020

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This Report documents the findings of the AVT-308 Cooperative Demonstration of Technology (CDT-308) Next-Generation NATO Reference Mobility Model (NG-NRMM).

Edited by:
Michael Letherwood, Paramsothy Jayakumar, Richard Gerth, and Jean Dasch

The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

• AVT	Applied Vehicle Technology Panel
• HFM	Human Factors and Medicine Panel
• IST	Information Systems Technology Panel
• NMSG	NATO Modelling and Simulation Group
• SAS	System Analysis and Studies Panel
• SCI	Systems Concepts and Integration Panel
• SET	Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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Table of Contents

Page

Chapter 6 – Takeaways / Follow-On Activities

List of Figures

List of Tables

List of Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
AASHTO	American Association of State Highway and Transportation Officials
ABS	Anti-lock Braking System
ACSI	Adams Co-Simulation Interface
ALE	Arbitrary Lagrangian-Eulerian
AMC	Army Materiel Command
AMSAA	US Army Materiel Systems Analysis Activity
ANCF	Absolute Nodal Coordinate Formulation
AOI	Area of Interest
API	Application Programming Interface
ARL	Army Research Laboratory
ASA	Advanced Science and Automation Corp.
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATV	Adams Tracked Vehicle
AVT	Applied Vehicle Technology
AVTP	Allied Vehicle Testing Publication
BSD	Berkeley Source Distribution
BWJ	Bekker-Wong-Janosi
CAE	Computer Aided Engineering
CCW	Counterclockwise
CDT	Cooperative Demonstration of Technology
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CI	Cone Index
COTS	Commercial Off-the-Shelf
CRREL	Cold Regions Research and Engineering Laboratory
CSIR	South African Council for Scientific and Industrial Research
CSO	NATO Collaboration Support Office
CTIS	Central Tire Inflation System
CTS	Combinatorial Trade Study
CV	Constant Velocity
CVT	Continuously Variable Transmission
CW	Clockwise
DAE	Differential Algebraic Equations
DARTS	Dynamics Algorithms for Real-Time Simulation
DDI	Deep Drainage Index
DEM	Digital Elevation Model
DEM	Discrete Element Method
DEM-C	DEM Penalty-Based
DEM-P	DEM Complementarity-Based
DFDD	DGIWG Feature Data Dictionary
DGIWG	Defence Geospatial Information Working Group
DIGEST	Digital Geographic Information Exchange Standard

DIS	Dynamic Interactions Simulator
DKG	Dynamic Kriging
DLC	Double Lane Change
DMT	Derjaguin-Muller-Toporov
DoD	U.S. Department of Defense
DOE	Design of Experiments
DOF	Degree of Freedom
DTED	Digital Terrain Elevation Data
DVI	Differential Variational Inequality
EDEM	Edinburgh Discrete Element Modeling Software
EEPA	Edinburgh Elasto-Plastic Adhesion Model
EMT+VS	Equilibrium Moisture from Topography, Vegetation, and Soil
ERDC	Engineer Research and Development Center
ESC	Electronic Stability Control
ET	Evapotranspiration
ET	Exploratory Team
FACC	Feature Attribute Coding Catalogue
FEM	Finite Element Model
FOV	Field of View
GDG	Geospatial Data Gateway
GEMM	Generic EDEM Material Model
GIS	Geographical Information System
GPS	Global Positioning System
GPU	Graphics Processing Unit
GUI	Graphical User Interface
HDF	Hierarchical Data Format
HGTM	High-Resolution Ground Vehicle and Terrain Mechanics
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HPC	High-Performance Computing
IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
ISRIC-WISE	International Soil Reference and Information Centre-World Inventory of Soil Emission Potentials
ISTVS	International Society for Terrain-Vehicle Systems
IVRESS	Integrated Virtual Reality Environment for Synthesis and Simulation
JKR	Johnson-Kendall-Roberts
JPL	Jet Propulsion Lab
LFI	Lateral Flow Index
LIDAR	Light Detection and Ranging
LL	Liquid Limit
LSD	Left Side Down
LTF	Left Turn First
M&S	Modeling and Simulation
MBD	Multibody Dynamics
MC	Moisture Content
MCS	Monte Carlo Simulation

MDO	Multi-Discipline Optimization
MGCP	Multinational Geospatial Co-Production
MMP	Mean Maximum Pressure
MPH	Miles per Hour
MPI	Message Passing Interface
MPM	Material Point Method
MSE	Mean Square Error
MSIE	Modeling and Simulation Integrating Environment
MSL	Mars Science Lab
NAAG	NARO Army Armament Group
NATC	Nevada Automotive Test Center
NATO	North American Treaty Organization
NED	National Elevation Dataset
NetCDF	Network Common Data Format
NG-NRMM	Next Generation NATO Reference Mobility Model
NLCD	National Land Cover Dataset
NRC	National Research Council
NRCS	National Resources Conservation Service
NRMM	NATO Reference Mobility Model
NRMM(I)	NG-NRMM for Intelligent Vehicles
NSC	Non-Smooth Contact
NTU	Number of Terrain Units
NWTVM	Nepean Tracked Vehicle Performance Model
NWVPM	Nepean Wheeled Vehicle Performance Model
OBAA	Obstacle Approach Angle
OBH	Obstacle Height
OBW	Obstacle Width
ODE	Ordinary Differential Equations
OGC	Open Geospatial Consortium
PC	Personal Computer
PDE	Partial Differential Equations
PID	Proportional–Integral–Derivative
POMC	Proctor Optimal Moisture Content
RCI	Rating Cone Index
REI	Radiation Evapotranspiration Index
RMS	Root Mean Square
RMSE	Root Mean Square Error
ROAMS	Rover Analysis, Modeling and Simulator
RPM`	Revolutions per Minute
RSD	Right Side Down
RTF	Right Turn First
RTG	Research Task Group
RTO	NATO Research and Technology Organization
RVD	Relative Velocity Dependent
SAE	Society of Automotive Engineers
SAVI	Soil Adjusted Vegetation Index
SBIR	Small Business Innovation Research
SCM	Soil Contact Model
SLA	Straight Line Acceleration

SLAM	Simultaneous Localization and Mapping
SMAP	Soil Moisture Active Passive
SMC	Smooth Contact
SPH	Smoothed Particle Hydrodynamics
SPI	Standard Particle Interface
SPI	Standard Particles Interface
SRTM	Shuttle Radar Topography Mission
SRTM	Shuttle Radar Topography Mission
SSC	Steady State Cornering
SSG	Sand Slope Gradeability
SSS	Side Slope Stability
SSURGO	Soil Survey Geographic Database
ST	Simple Terramechanics
STANREC	Standard Recommendation
STO	NATO Science and Technology Organization
TA	AVT-248 Thrust Area
TAP	Technical Activity Proposal
TARDEC	Tank Automotive Research, Development and Engineering Center
TCS	Traction Control System
TIFF	Tagged Image File Format
TIN	Triangulated Irregular Network
TOR	Terms of Reference
TRL	Technology Readiness Level
TSC	Technology Service Corporation
TV	Tracked Vehicle
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UQ	Uncertainty Quantification
USACE	United States Army Corps of Engineers
USCS	Unified Soil Classification System
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
UW-M	University of Wisconsin – Madison
V&V	Verification and Validation
VCI	Vehicle Cone Index
VEHDYN	Vehicle Dynamics part of NRMM code
VI	Vehicle Intelligence
VSDC	Vehicle Systems Development Corporation
VTI	Vehicle Terrain Interface; Vehicle Terrain Interaction
WD	Wheel Drive
WES	Waterways Experimental Station
WNS	Wave Number Spectra
WTW	Wall to Wall
WVP	Wheeled Vehicle Prototype

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

(STO-TM-AVT-308)

Executive Summary

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.

Démonstration coopérative de technologies (CDT) pour le modèle de mobilité de référence de nouvelle génération (NG-NRMM) de l'OTAN

(STO-TM-AVT-308)

Synthèse

Parrainée par l'Organisation pour la Science et la Technologie (STO) de l'Organisation du Traité de l'Atlantique Nord (OTAN), la Commission de l'OTAN sur la Technologie appliquée aux véhicules (AVT) a formé un groupe de recherche (RTG), l'AVT-248, composé de soixante et onze personnes de quinze pays, afin de développer un modèle de mobilité de référence de nouvelle génération (NG-NRMM) de l'OTAN. Le résultat final des quatre années de travail de l'AVT-248 a été présenté à l'événement de démonstration coopérative de technologies (CDT) du NG-NRMM, du 25 au 27 septembre 2018, qui s'est tenu au Michigan Technological University / Keweenaw Research Center (MTU/KRC) à Houghton, dans le Michigan (États-Unis). Le Tank Automotive Research, Development and Engineering Center (TARDEC) de l'armée des États-Unis a soutenu la CDT pour exposer les différences entre le logiciel de prédiction de la mobilité héritée et celui de nouvelle génération.

Installé à l'arsenal de Détroit de l'armée des États-Unis, à Warren, dans le Michigan, le TARDEC est un grand centre de recherche, développement et ingénierie pour le Research, Development and Engineering Command (RDECOM) de l'Army Materiel Command (AMC). L'événement du CDT a offert un espace de discussion dans lequel les membres contributeurs du comité et les développeurs de logiciels ont pu mettre en lumière un processus de prototypage qui utilise les technologies avancées de simulation et de prédiction de la mobilité à travers un ensemble vaguement intégré de méthodologies et d'outils. Les participants ont découvert les technologies du NG-NRMM au cours de diverses présentations et démonstrations, ont assisté à une démonstration physique d'un prototype de véhicule militaire exécutant certains essais de mobilité dans diverses conditions de sol et ont observé une simulation du même essai avec le logiciel hérité et le logiciel de nouvelle génération de prédiction de la mobilité. En outre, les participants ont pu prendre part à des défis de mobilité tout terrain sur divers terrains représentatifs de l'Europe de l'Est. Le présent document technique résume l'événement de CDT et les actions réalisées, décrit la valeur ajoutée, identifie les lacunes et trace la voie à suivre pour combler beaucoup de ces lacunes.

Chapter 1 – SYNOPSIS

1.1 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's Combat Capabilities Development Command (CCDEVCOM) Ground Vehicle Systems Center (GVSC), formerly, the 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, GVSC is a major research, development and engineering center for the Army Futures Command (AFC). 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 report summarizes the CDT event and actions performed, describes the value added, identifies gaps, and outlines a path forward to address many of those gaps.

1.2 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 Multi-Body 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.

Due to the recognition of the need for an updated model, a NATO Exploratory Team (ET) was proposed during the spring 2014 NATO AVT meeting in Copenhagen, Denmark by Panel Member Dr. David Gorsich, Chief Scientist of TARDEC. The scope of Exploratory Team 148 (ET-148) was to investigate an efficient simulation-based Next-Generation NRMM which concluded in December 2015 with a total of 39 members from 13 nations and a final report was issued in 2017 [1]. Based on the results of the ET, the Research Task Group AVT-248 was approved to develop a Next-Generation NRMM. AVT-248 was initiated in January 2016 and concluded in December 2018 and included 66 appointed members and contributors from 15 nations.

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 multi-body 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.

1.3 CDT OBJECTIVES

The objectives of the CDT were 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]

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 (%No-Go 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/No-Go).

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[1] Please refer to Ref. [2] “AVT-248 Next-Generation NATO Reference Mobility Model (NG-NRMM) Development”, final report, for detailed explanations of each technology area.

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.

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 (STANdardization RECommendation) 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 NATO 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 was initially released to NMSG in December 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 modeling methods, benchmarks, and a soils database that should be applied to all physics-based simulations of operational land and amphibious mobility among the alliance.

Chapter 2 – THE CDT VIRTUAL / PHYSICAL EVENT DEMO

2.1 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.

Ground Vehicle Systems Center's (GVSC) Fuel Efficiency Demonstrator Alpha (FED-Alpha) (Figure 2-1), originally designed and produced by Ricardo Defense [3], 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.[1]

Figure 2-1: FED-Alpha Vehicle. Graphic representation and hardware.

In addition, Aberdeen Proving Ground (APG) had performed independent testing of the vehicle and GVSC made the test report from that effort releasable and available to the CDT participants [4]. In collaboration between the NATO CDT-308 team, GVSC, and the KRC team, a detailed test plan for the automotive and mobility evaluation of the FED-Alpha vehicle was prepared [5]. 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

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[1] All FED-Alpha vehicle data set(s) which consist of 3D geometric CAD information, CAE simulation models, and a complete set of analytical and physical characterization data are available for download and use at MTU/KRC's FTP site ftp://ng-nrmm:thread$panel@nrmm.mtukrc.org. All data located on the site are "DISTRIBUTION A – Approved for Public Release: Distribution Unlimited".

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). GVSC was tasked with modeling the FED-Alpha using the legacy NRMM as a baseline simulation analysis for comparison purposes with participating software developers.

2.2 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. Specified test events were conducted and testers recorded both terrain data (simulation model inputs) and vehicle performance data (simulation model outputs). MTU/KRC collected terrain data on all terrains and courses run during CDT. The terrain dataset included geospatial data which consisted of aerial images, high resolution topology, map11 and GeoTIFFs, as well as terrestrial scan information. Soil data included both laboratory soil results; triaxial, sieve and hydrometer combined, proctor, organic content, direct shear, and in situ soil results (field tests); soil types and location, friction data, bevameter specifics, cone traces, raw bevameter data, bevameter results, and field measurement results. Table 2-1 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. For a complete description of all data collection and tests conducted, please refer to "KRC Final Report: Next-Generation NATO Reference Mobility Model Cooperative Demonstration of Technology" in Annex A.[2]

Table 2-1: Model Simulation / Physical Test Matrix. Red indicates Courses that NRMM Could Model.

	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

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[2] All CDT terrain and soil data as well as benchmarking and validation performance data are available for use and are located at MTU/KRC's FTP site ftp://ng-nrmm:thread$panel@nrmm.mtukrc.org. All data located on the site is "DISTRIBUTION A – Approved for Public Release: Distribution Unlimited".

	Test Name	Soil	Simulation Outputs
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
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	Natural Terrain Composite/Engr Cour	Varied including speed-made-good map

2.3 PHASE 2 – MOBILITY SIMULATION AND ANALYSIS

The objective of Phase 2 was to develop a NG-NRMM modeling process, and then create and calibrate simulation models of specified physical test events that were performed during Phase 1. Phase 2 consisted of simulating mobility testing and predicting performance of physical 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 2-2 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/No-Go 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/No-Go 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. GVSC modeled and conducted the same analysis of the FED-Alpha where applicable using the current NRMM legacy code for comparison purposes. For a detailed description of each software developer's CDT M&S analysis, please see their respective final reports in the respective annex.

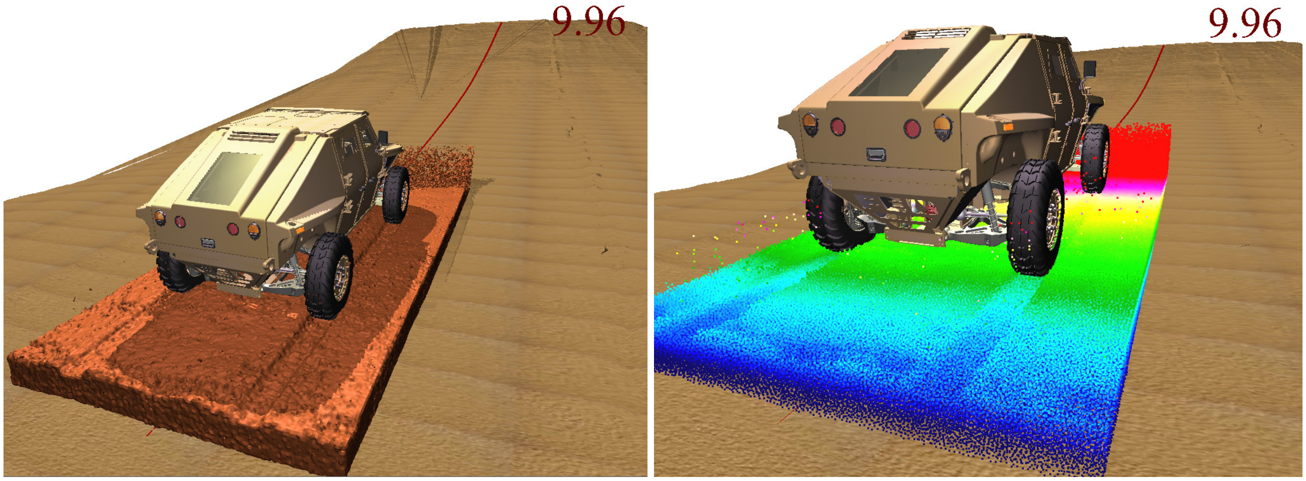

Figure 2-2: Example of Simulation Models.

2.4 PHASE 3 – MODEL COMPARISON TO LIVE TEST RESULTS

2.4.1 Introduction

This phase consisted of comparing the Phase 2 simulation results to physical test results as illustrated in Figure 2-3 improving the Phase 2 models, and quantifying model performance. Each participant compared the model results to the physical 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 2-3: 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/No-Go 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 accurately. For a complete description of the exercise, please refer to the V&V final report in Annex K.[3] The site includes data acquisition information, Vbox 3i information, weather, as well as paved data (wall to wall turning, lane change, constant cornering, braking, acceleration), off-road data (sand grade (post-test scans)), RMS, draw bar pull (two different tests), and mobility traverse data (GPS trace and driver inputs, side slope obstacle avoidance, vertical steps, v-ditch, 60 percent paved grade, half rounds, gravel lane change data). Find MTU/KRC's complete and final test report entitled, "MTU/KRC Final Report: Next-Generation NATO Reference Mobility Model Cooperative Demonstration of Technology" in Annex A.

2.4.2 Process/Methodology

The test events defined in Ref. [5] constitute the entire test series performed as part of the CDT and are referred to as the physical tests. These tests can be divided into two main categories and sub-categories:

- On and Off-Road Vehicle Performance Tests;
- Automotive Tests (Hard Surface);
- Soft Soil Tests for Cross-Country Mobility (Drawbar Pull and Climb on Sand Grade); and
- Mission Profile through the Mobility Traverse (to demonstrate the vision of NG-NRMM on a set of terrain segments including 3D vehicle maneuvering and off-road conditions).

The participating software developers were tasked to simulate these events. Some calibration data were made available. Validation was possible against the tests performed with the FED-A.

Test Cases:

- Wall to wall turn radius;
- Steady state cornering;

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[3] All CDT benchmarking and validation test data are available for use and located at MTU/KRC's FTP site ftp://ng-nrmm:thread$panel@nrmm.mtukrc.org and are labeled "DISTRIBUTION A – Approved for Public Release: Distribution Unlimited".

- Straight line acceleration;
- V-Ditch;
- Double Lane Change;
- Side Slope Stability;
- Half-Round Test;
- 60% Grade, Paved; and
- RMS Symmetric and Asymmetric: Absorbed Power.

Soft soil tests:

- Drawbar Pull; and
- Variable Grade Sand Slope.

Mission Profile:

- Mobility Traverse.

2.4.3 Participating Software Developers

The simulation participating organizations and their particular software tools are listed in Table 2-2. Additionally, the table indicates the type of soft soil modeling capability used: ST for Simple Terramechanics, such as Bekker-Wong type models, and CT for Complex Terramechanics such as Discrete Element Modeling type soft soil models.

Table 2-2: CDT Simulation Participants, Country of Origin and Name of Software Product.

Software Developer	Country	Software
Advanced Science and Automation Corporation	USA	IVRESS/DIS CT
MSC Software	USA	ADAMS ST/CT
CM Labs	CAN	Vortex Studio ST
Vehicle Systems Development Corporation	CAN	NTVPM/NWVPM ST
Aarhus University/Jet Propulsion Lab (JPL)	DNK/USA	ROAMS ST
NRMM	USA	NRMM ST
CSIR	ZAF	MOBSIM ST
RAMDO Solutions	USA	Uncertainty Quantification

2.4.4 Calibration and Full Test Events, Automotive Tests

This section contains all the calibration and full test events. The goal of the calibration load cases was to verify and tune the computational models of the FED-Alpha vehicle on a few select test events that exercises most of the vehicle dynamics such as longitudinal and lateral acceleration, steering system, suspension vertical and roll dynamics as well as one terramechanics event.

The calibration events were:

- One Straight Line Acceleration;
- One Speed (25 mph) Constant Cornering;
- One Speed (30 mph) Double Lane Change;
- One Symmetric RMS Course; and
- One Soft Soil Drawbar Pull Event.

The simulation results are presented in the following sections as delivered by the software developers. In a few cases it is only the best performing software developer's results that are presented against test data.

2.4.4.1 Straight Line Acceleration

The straight-line acceleration test is used to validate the implementation of the drivetrain into the simulation models. The aerodynamic drag, gear ratios, shift-points and gear losses must be included to obtain the correct acceleration and top speed. The tests at MTU/KRC are performed on a flat surface. The Test Operations Procedure, TOP 2-2-602 [6] requests the test to be performed in both directions to account for the slope and wind effects. The slope should be less than 1%. The MTU/KRC tests include three up and three down slope tests as seen in Figure 2-4. The software developers are able to predict the acceleration performance while NRMM over-predicts the acceleration.

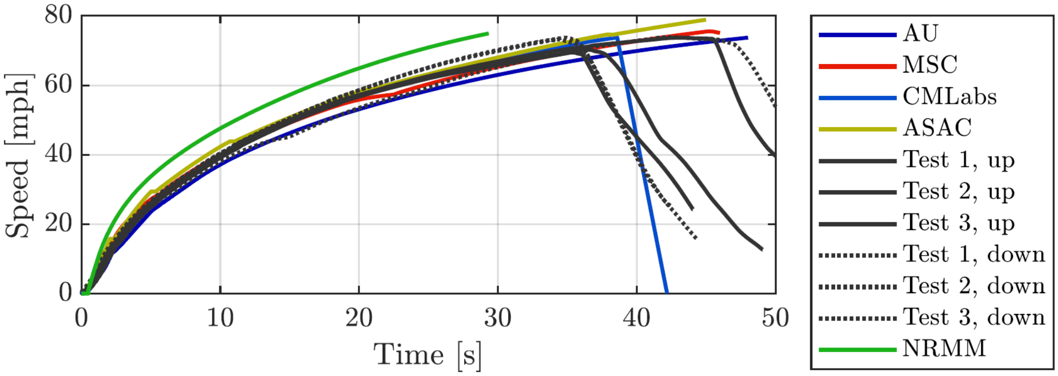
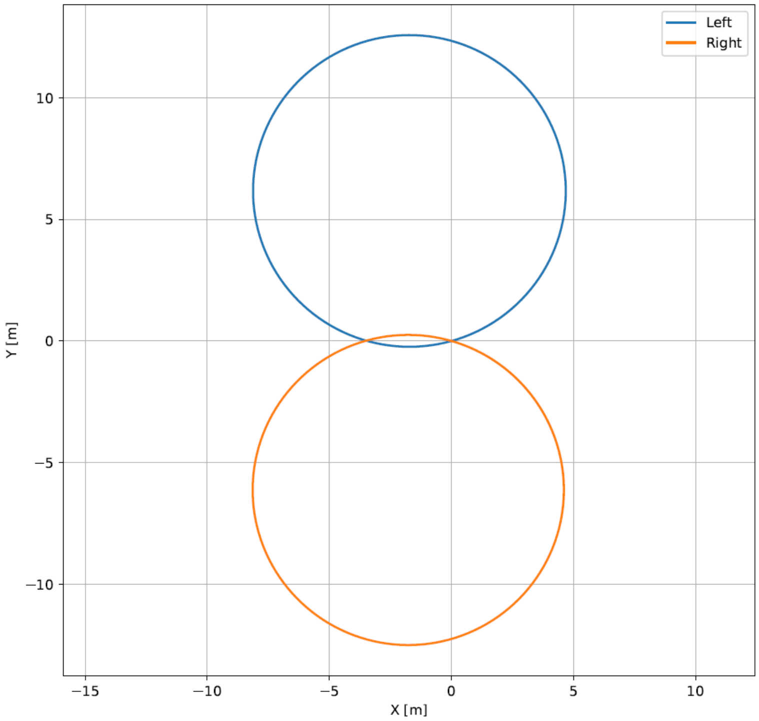


Figure 2-4: Straight Line Acceleration Tests and Simulation Results.

2.4.4.2 Wall to Wall Turn

The purpose of the wall to wall turn is to verify the steering geometry of the simulation models. The test is performed by turning the steering wheel to the left hard stop. The vehicle is driven slowly forward until at least one complete revolution is reached. The diameter of the trajectory is measured and reported. Since this test is intended for calibration, software developers are allowed to tune their models to match the test result. This test is intended for verification of steering linkage implementation as well as steering mechanism hard stop modeling. The AU simulation results for left and right turn are displayed in Figure 2-5.



(a) Wall to Wall Left and Right Turn by AU Team.

(b) Left Turn Test at KRC.

Figure 2-5: AU Simulation Results for Left and Right Turn.

A picture of the actual test at MTU/KRC is shown in the same figure where a chalk path is drawn on the surface indicating the bounding wall to wall diameter. The MTU/KRC individual test results as well as the average along with the software developer simulated results are listed in Table 2-3.

Table 2-3: Wall to Wall Test and Software Developer Results.

Vendor	CW [m]		CCW [m]	
TEST	T1: 15.51	Avg: 15.58	T1: 15.54	Avg: 15.48
	T2: 15.58		T2: 15.51	
	T3: 15.58		T3: 15.42	
	T4: 15.58		T4: 15.45	
ASAC	14.90		14.90	
MSC	15.27		15.32	
CM Labs	15.10		14.8	
AU	16.70		16.70	

2.4.4.3 Steady State Cornering

The handling characteristics of the vehicle as determined by the steady state cornering test were performed in both counter- and clockwise direction. The test is performed in accordance with SAE J2181. The vehicle drives with constant speed on a circular track with a 30 meter radius. During the test, the steering wheel angle and lateral acceleration are recorded and used for analysis. The speed is kept constant at increments of 8 km/hr, increased, and then kept constant to achieve steady state lateral acceleration levels of 1 acceleration until it becomes too large for safe operation of the vehicle. An example of a simulation showing steady state lateral acceleration is illustrated in Figure 2-6.

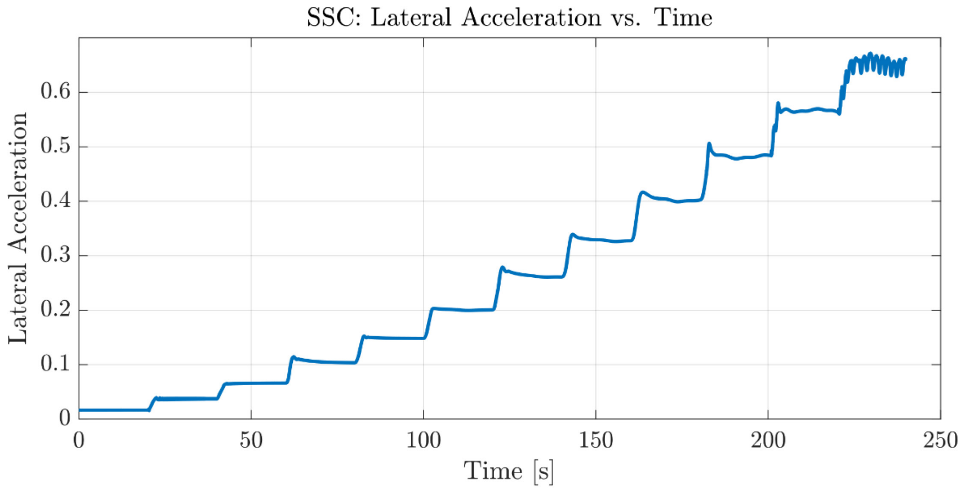


Figure 2-6: Example Steady State Lateral Acceleration Increments.

Due to the complexity of the steering column compliance and the detail of the power steering system functionality it was agreed at the AVT-248 technical meeting in Torino, Italy, Spring 2018, among the committee and the software developers that the pitman arm angle would be used to compare handling characteristics instead of steering wheel angle. The pitman arm was instrumented on the vehicle and its angle measured with 0 degrees being equivalent to straight line driving. This angle was used for comparison between test and simulation. In Figure 2-7, the pitman arm angle is plotted as delivered by the software developers. Some are directly from the simulations and others were delivered with some data processing. The data from the test has been processed by MTU/KRC for display here.

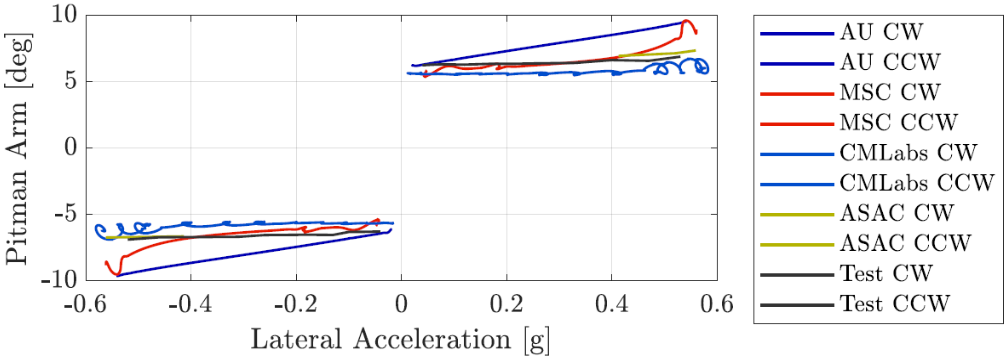


Figure 2-7: Steady State Cornering, Left and Right Turn, Pitman Arm Angle vs. Lateral Acceleration.

As indicated by the black plot of the steady state cornering test results in Figure 2-7, it is seen that the vehicle is slightly understeered. The software developers were able to demonstrate the understeering characteristics as plotted against test data in Figure 2-7.

2.4.4.4 V-Ditch and Wall Climbing

These tests provide a method for evaluating the vehicle's obstacle negotiating capability. For the CDT, two obstacles are considered, the V-Ditch, also named trench crossing, and wall climbing. The V-Ditch (Figure 2-8) test predicts whether the vehicle is able to negotiate a specific V-Ditch according to TOP 2-2-611 [7]. The results of the test and simulations are presented in Figure 2-4. During the test and simulation, if any vehicle projections interferes with the negotiation of the obstacle, the test was rendered as a No-Go. The test and the simulations are in agreement from all submitted results as shown in the comparison Table 2-4.

Table 2-4: V-Ditch Performance, Go/No-Go.

Entry	Go/No-Go
TEST	Go
ASAC	Go
MSC	Go
CM Labs	Go
AU	Go
NRMM	Go

Figure 2-8: V-Ditch Performance, Go/No-Go.

The second obstacle negotiation test is the wall climbing, which consisted of 12”, 18” and 24” high obstacles (Figure 2-9). The test and simulation results are in agreement as seen in Table 2-5.

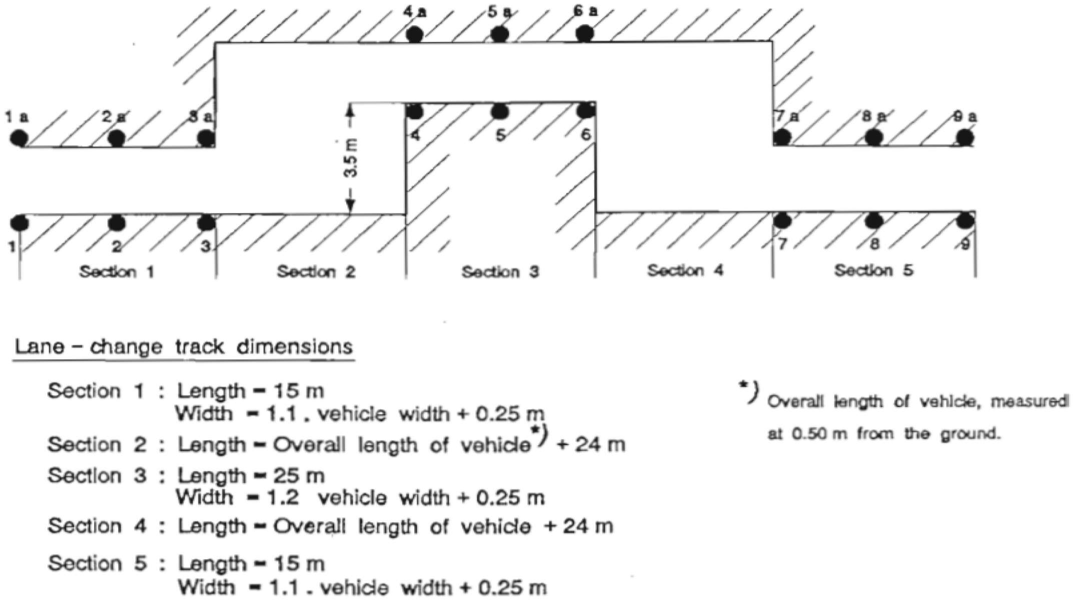
Table 2-5: Wall Climbing Results, Go/No-Go.

Entry	12”	18”	24”
TEST	Go	No-Go	No-Go
ASAC	Go	No-Go	No-Go
MSC	Go	No-Go	No-Go
CM Labs	Go	No-Go	No-Go
AU	Go	No-Go	No-Go
NRMM	Go	No-Go	No-Go

Figure 2-9: Wall Climbing Results, Go/No-Go.

2.4.4.5 Double Lane Change

The intent of the double lane change test is to evaluate the vehicle's dynamic stability during an avoiding action and follows the guidelines of NATO's Allied Vehicle Testing Publication AVTP 03-160 W [8]. The NATO double lane change test area layout (Figure 2-10) is determined based on vehicle dimensions in order to handle the large variations in military vehicle size. The achieved performance depends on both the vehicle response and the driver interaction. The aim is to complete the avoidance maneuver at the fastest speed possible through the test area while keeping the speed as steady as possible. Due to the different driver model implementations by the software developers, the time histories of the simulation and test data were not expected to be an exact match. In fact, the test was not performed at the maximum speed possible in order to protect the vehicle against damage. The test results from one 30 mph run through the double lane change test area was given to the software developers for calibration purposes (Figure 2-11).



Lane – change track dimensions

Section 1 : Length – 15 m
Width – 1.1 . vehicle width + 0.25 m
Section 2 : Length – Overall length of vehicle*) + 24 m
Section 3 : Length – 25 m
Width – 1.2 vehicle width + 0.25 m
Section 4 : Length – Overall length of vehicle + 24 m
Section 5 : Length – 15 m
Width – 1.1 . vehicle width + 0.25 m

*) Overall length of vehicle, measured at 0.50 m from the ground.

Figure 2-10: NATO Double Lane Change Layout, AVTP 03-160 W.

The software developers were asked to provide maximum speed for the double lane change test on Paved and Gravel surface for both Right Turn First (RTF) as well as Left Turn First (LTF). The developers were free to choose path and closed loop controller to generate these results. The results are shown in Table 2-6.

Table 2-6: Double Lane Change Max. Speed Results (No Test Results).

Vendor	Speed DLC RTF Paved, mph	Speed DLC LTF Paved, mph
ASAC	49	49
MSC	44	44
CMLabs	50	50
AU	42	42

Vendor	Speed DLC RTF Gravel, mph	Speed DLC LTF Gravel, mph
ASAC	43	44
MSC	40	40
CMLabs	41	41
AU	34	34

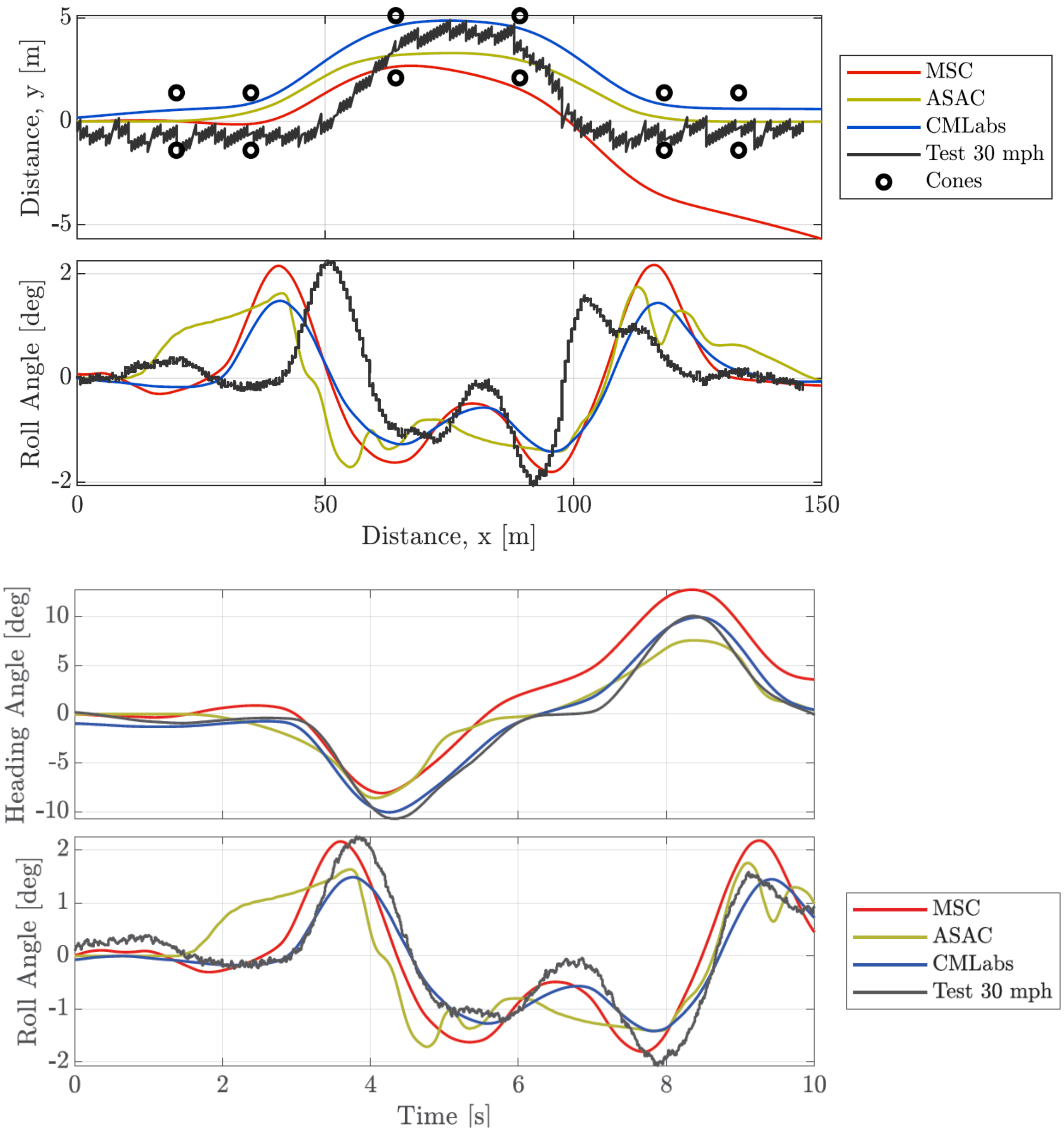


Figure 2-11: Calibration Results, 30 mph.

2.4.4.6 Side Slope Stability

The purpose of the side slope stability test is to investigate the vehicle's directional stability on a low friction side slope. The defining layout of the test is shown in the top right diagram of Figure 2-12 according to the test description [5], and the results are illustrated. It should be noted that the steering data from the software developer ASAC has not been captured by the automated plotting routine. The challenge in this test is turning back up the slope after clearing the obstacle within the 15 meter distance to the next set of cones.

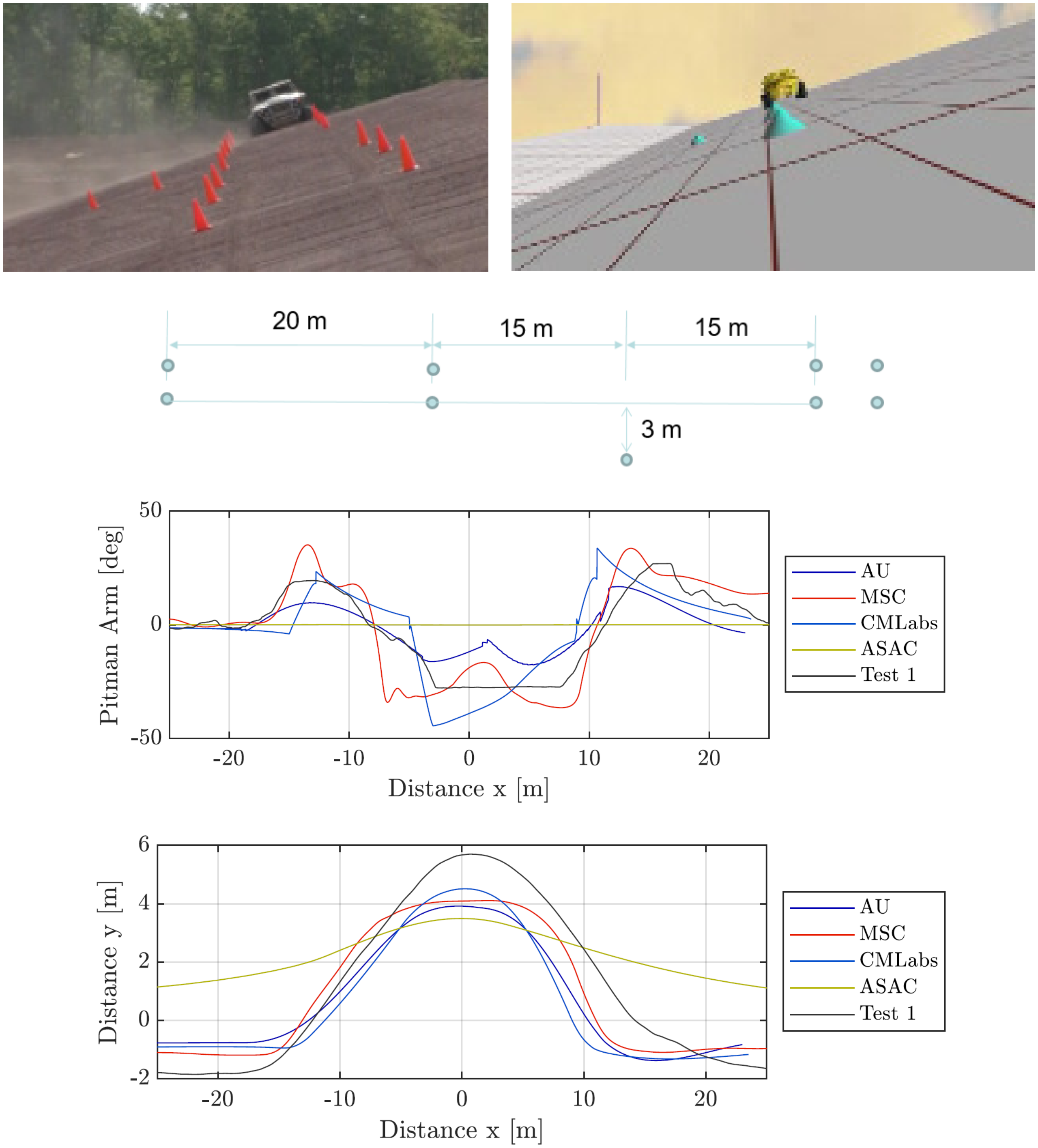


Figure 2-12: Side Slope Stability Layout and Results.

For clarity of the maneuver, an example plot of the results with axis of equal scale and symbols indicating the cones is depicted in Figure 2-13 for the test and one example of simulation results.

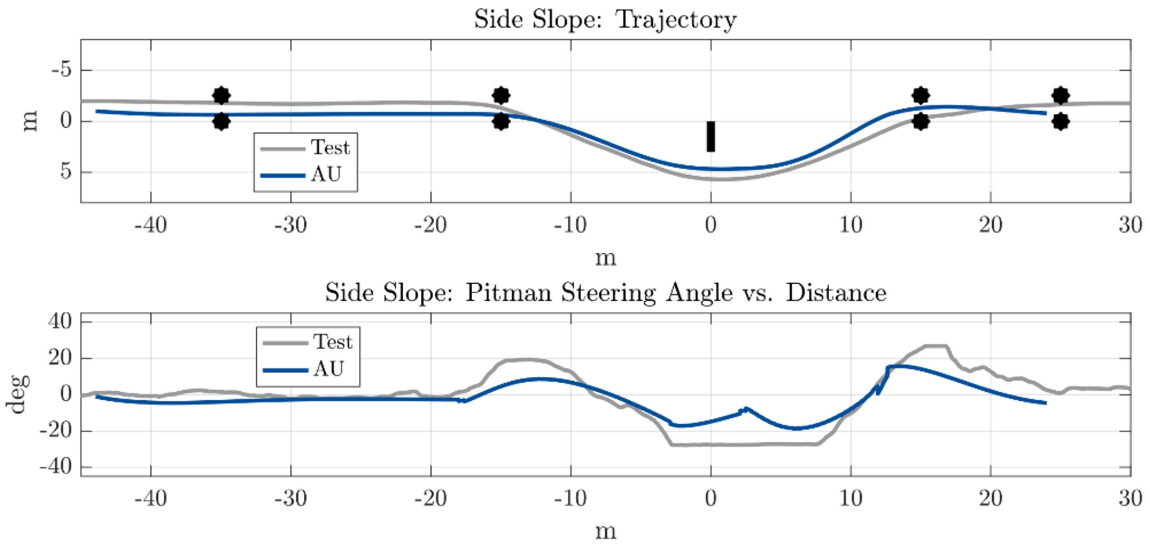


Figure 2-13: Top: Test and Simulation Trajectory with Matching Axis Scale; Bottom: Corresponding Steering.

The vehicle as well as all software developers except one were able to successfully negotiate the side slope stability test. ASAC did not pass the test; it is believed that a misinterpretation of the test description is the cause of this.

2.4.4.7 60% Grade, Paved

The objective for the 60% grade paved test is twofold as stated in the Test Operations Procedure 2-2-610 [9]: to determine Go/No-Go ability to climb the slope and to test the service and parking brake by driving up the slope, coming to a stop, applying the parking brake and releasing the service brake. If the vehicle parking brake holds the vehicle, the engine is shut off for a minimum of two minutes then restarted and the vehicle is driven up the hill. The surface and vehicle are inspected for fluid leaks throughout the test. In the simulations, it is only the Go/No-Go performance that is evaluated and the results from the test as well as the simulations are shown in Table 2-7 and Figure 2-14.

Table 2-7: 60% Paved Grade Test Results.

Vendor	Go/No-Go
TEST	Go
ASAC	Go
MSC	Go
CMLabs	Go
AU	Go
VSDC	Go
NRMM	Go

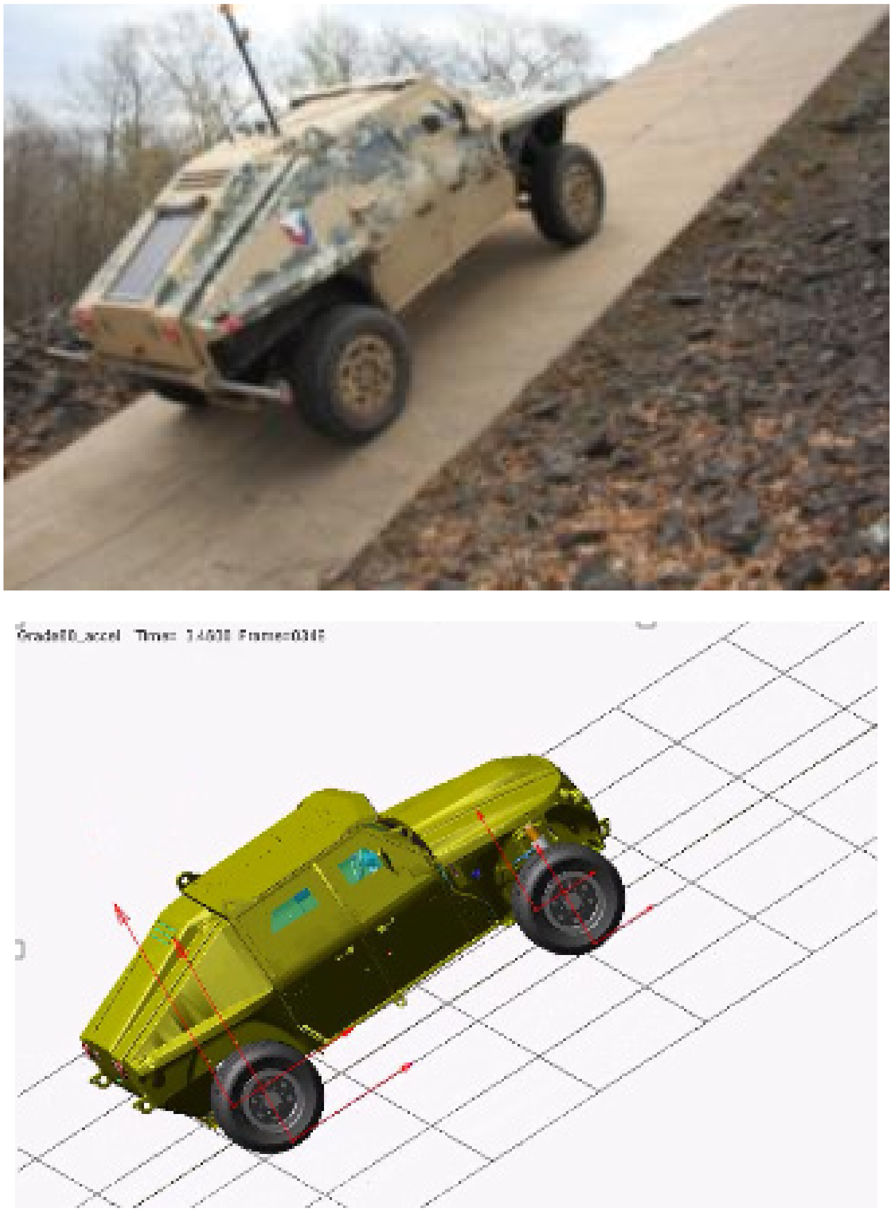


Figure 2-14: 60% Paved Grade Test and Simulation.

2.4.4.8 Half-Round Test

Ride quality is evaluated in accordance with Test Operations Procedure TOP 1-1-014 [10]. The vehicle drives across a half-round obstacle at speed increments of 2 mph until the speed resulting in 2.5 g vertical acceleration measured at the floor beneath the driver's seat can be found. The test is performed on half rounds with heights of 4", 8", 10" and 12" respectively. The measured and simulated results are shown in Figure 2-15. The 4" results are left out, as the 2.5 g speed limit was never reached. This test is used for evaluation of the simulation model's ability to predict spring and damper performance. The spring and dampers were particularly challenging to model for the participating software developers as they were frequency selective type dampers and air springs.

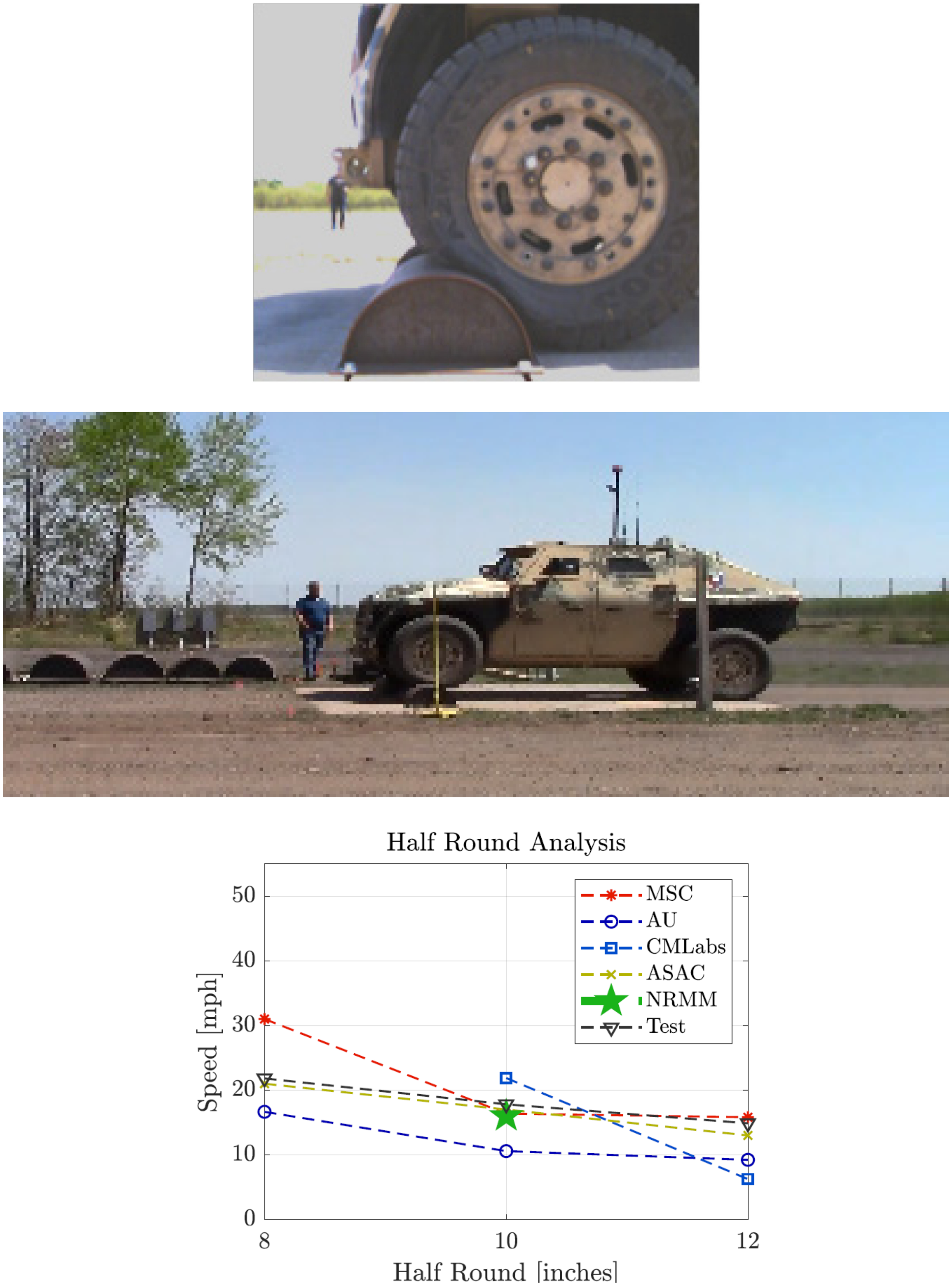
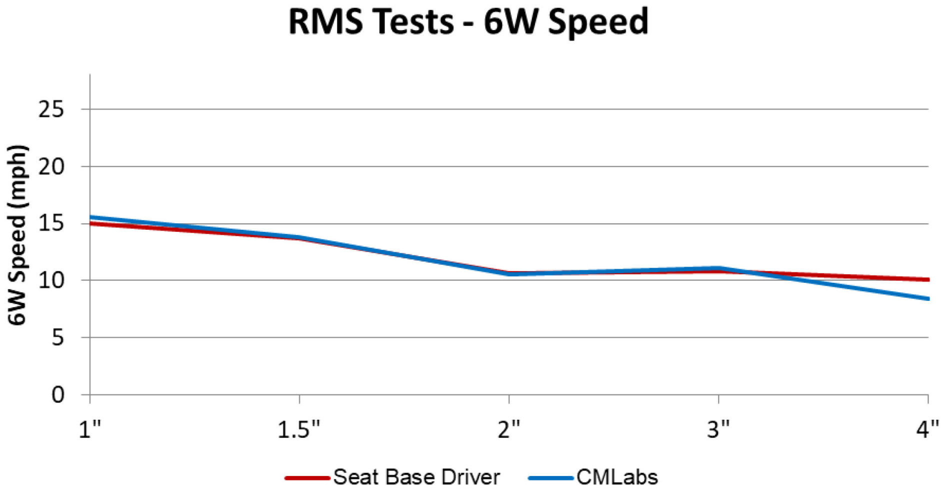


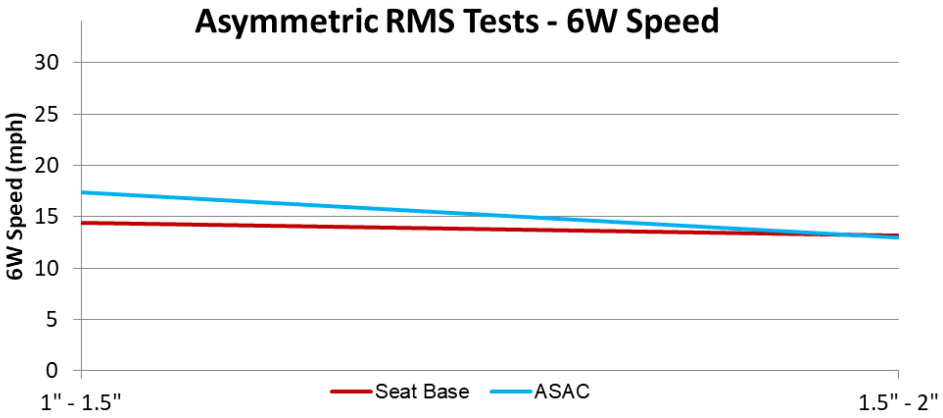
Figure 2-15: Half-Round 2.5 g Limiting Speeds, Test and Simulation Results.

2.4.4.9 RMS Symmetric and Asymmetric: 6 Watt Absorbed Power Limiting Speed

The driver comfort is the speed limiting factor on rough roads. Five symmetric Root Mean Square (RMS) courses were constructed at MTU/KRC. The RMS values were 1”, 1.5”, 2”, 3” and 4”. The vehicle was driven across each course at speed increments of 2 mph up through the 6 watt absorbed power speed according to TOP 1-1-014 [10]. The results for 2 of the software developers are presented in Figure 2-16 for symmetric and asymmetric RMS courses respectively.



(a) Symmetric RMS Courses, 1”, 1.5”, 2”, 3” and 4”.



(b) Asymmetric RMS Tracks: 1” – 1.5” and 1.5” – 2”.

Figure 2-16: Symmetric and Asymmetric 6 Watt Absorbed Power Speeds (mph).

2.4.4.10 Automotive Performance Conclusions

A summary of the results for the automotive test events is presented in Table 2-8 in comparison to NRMM. Comments are provided describing the shortcomings in NRMM as compared to the 3D physics-based simulation results as presented by the participating software developers.

Table 2-8: Summary of Automotive Test Events.

Test	NRMM	NG-NRMM	Comments
Wall To Wall	✗	✓	No 3D Steering Mechanism in NRMM
Steady State Cornering	✗	✓	No Steering, Load Transfer Capability in NRMM
Straight Line Acceleration	✗	✓	NRMM over-predicts acceleration performance
V-Ditch	✓	✓	
Step Incline (12”,18”,24”)	✓	✓	
Double Lane Change (Paved and Gravel)	✗	✓	No Steering, Roll and Lateral Dynamics in NRMM
Side Slope Obstacle Avoidance	✗	✓	No Steering and Lateral Load Transfer in NRMM
60 % Grade Paved	✓	✓	
Half Round (4”, 8”, 10”, 12”)	✓	✓	
Symmetric RMS (1”,1.5”,2”,3”,4”)	✓	✓	
Asymmetric RMS (1”-1.5”, 1.5”-2”)	✗	✓	No Roll Dynamics in NRMM

As expected, all events requiring 3D maneuvering renders NG-NRMM simulation software superior in comparison to NRMM results. In fact, for five of the tests NRMM cannot produce any results as they are dynamic events or steady state events requiring 3D modeling to capture the response. These events are:

- Wall to Wall;
- Steady State Cornering;
- Double Lane Change;
- Side Slope Stability; and
- Asymmetric RMS.

In addition, the obstacle events Test Operations Procedure calls for an angled approach to the V-Ditch and Vertical Climb in case of unsuccessful result at the 90 degree approach angle [7]. This was not exercised in the CDT but is an example of where existing tests performed in NRMM cannot fulfill the requirements of the Test Operations Procedure due to the lack of 3D simulation ability.

2.4.5 Soft Soil Tests

The software industry capabilities for 3D vehicle performance simulation on a hard surface is at a mature stage [11]. Taking the vehicle simulations off-road offer a number of challenges. The major challenges are in the uncertainty related to the spatial variation and the soil’s physical parameters such as soil type, density, moisture content, plastic and liquid limits, cohesion, friction angle, pressure sinkage relations, shear modulus, etc. A number of geotechnical tests were done in situ and in the lab at MTU/KRC to obtain these parameters, and make them available to the software developers.

This section is a documentation of the efforts done within the CDT to verify and in some cases validate the simulation model's ability to predict vehicle performance on soft soil. It should be noted that soft soil performance prediction is influenced by larger variation in soil constituents and conditions than hard surface tests [12]. Therefore, larger deviations from test to simulation predicted performance is expected than for the automotive events.

Two tests are considered:

- Drawbar Pull
  - Three types of soil conditions were used for the drawbar pull:
    - Fine Grain Sand Dry (FGS-Dry);
    - Fine Grain Sand Wet (FGS-Wet); and
    - Coarse Grain Sand Dry (CGS-Dry).
- Soft Soil Gradeability
  - A slightly different soil was used on the soft soil gradeability test:
    - Coarse Grain Soil Dry (this soil had some silt as compared to CGS-Dry.

2.4.5.1 Drawbar Pull

The purpose of the drawbar pull test is to measure the towing capacity of a vehicle while operating on a given soil. The test follows the guidelines set forth in the Test Operations Procedure 2-2-604 [13]. The vehicle under test is towing another larger vehicle capable of restricting the motion of the test vehicle as the wheel slip is increased by adding engine torque. The drawbar pull is defined as the measured force in the tow wire. The results presented here are drawbar pull coefficient vs. slip. The drawbar coefficient is the drawbar force divided by the vehicle weight. The wheel slip is defined as the difference between forward speed and peripheral wheel speed divided by peripheral wheel speed. By using this definition 100%, slip means that the vehicle is immobilized and 0% means no drawbar pull and no rolling resistance. The drawbar test indicates the ability to negotiate inclines for a given soil or provide towing force for a towed item. The location of the tow point is important for the results of the test and was provided to the software developers. As some software developers used Bekker-Wong equations, pressure sinkage and shear slip data were provided based on Ref. [14] or cone penetrometer measurements. The bevameter and Cone Index (CI) apparatus and data are shown in Table 2-9 and Figure 2-17. It should be noted that some unsteady behavior was observed in the original test data from MTU/KRC. An inertial correction using the measured acceleration and weight of the vehicle was performed on the test data before plotting the drawbar results.

Table 2-9: Cone Index Measurements.

SOIL TYPE	CI
Fine Grain Soil Dry	255 - 298
Fine Grain Soil Wet	06 - 30
Coarse Grain Sand Dry	126 - 300

In the following figures and sections, the results from the participating vendors are presented. CT represents a Discrete Elements Method simulation approach to terramechanics modeling and ST (or if nothing stated), is a

Bekker-Wong or Cone Index type approach to the terramechanics modeling. For specifics on software developer's implementation, the reader is directed to the individual software developers CDT reporting. KRC provided the drawbar pull coefficient vs. slip data. There has been some discussion regarding the rolling radius. For the test results, the rolling radius used by KRC was the distance travelled for one revolution of the tire divided by 2 pi as stated in the procedure [13]. It can be argued that the undeformed radius should be used. This would only slightly shift the plots in the horizontal direction and not change the overall shape of the results.

(a) KRC Bevameter. **(b) Cone Penetrometer.**

(c) Drawbar Pull Test.

Figure 2-17: Bevameter, Cone Index (CI) Apparatus and Drawbar Pull Test.

2.4.5.2 Fine Grain Soil, Dry

The FGS-Dry drawbar pull test and simulations are in good agreement across all vendors and for soft soil results can be considered validated by visual inspection of the results in Figure 2-18. One Vendor, MSC, has not produced results above 60% slip which can be due to the detail of how MSC implemented the simulation. For a specific gear ratio and RPM limit of the engine, it is only possible to achieve a certain amount of slip.

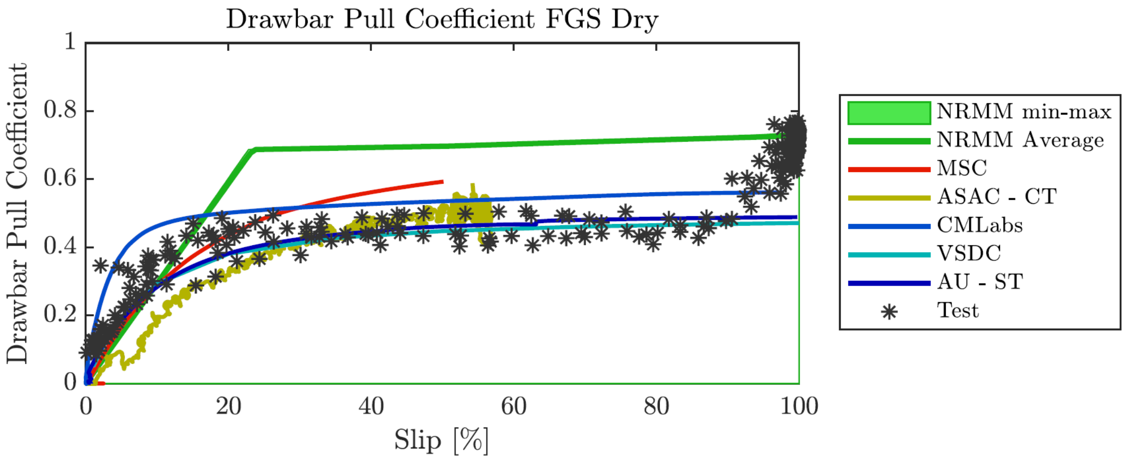


Figure 2-18: Fine Grain Sand – Dry Drawbar Pull Test and Simulation Results.

To immobilize the vehicle to get 100% slip it is necessary that the test vehicle be slowed down. This violates the desire for steady state conditions, which then needs to be accounted for by subtracting the inertial force in the drawbar pull results. It was left to the software developers to implement the test and report the results correctly. NRMM shows the range of results using the variations in Cone Index measures shown in Table 2-9.

2.4.5.3 Fine Grain Soil, Wet

In FGS-Wet, as seen in Figure 2-19, it appears from the test data that significant amount of slip is needed to overcome motion resistance. Complex Terramechanics models are seen to predict the drawbar pull coefficient at low slip. However, at large slip above 20%, CT over-predicts the drawbar pull coefficient. Simple Terramechanics models over predict the drawbar coefficient throughout the entire slip range, while NRMM over-predicts at low slip and under predicts with its average value at large slip. All simulations have difficulties capturing the test results with reasonable accuracy throughout the entire slip range. It should be noted that the NRMM average is toward the bottom of the green area in the figure.

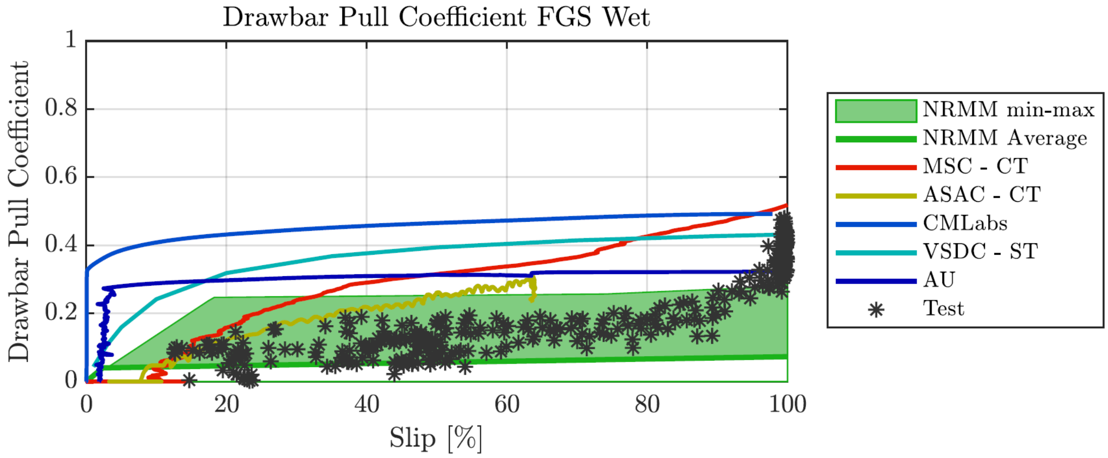


Figure 2-19: Fine Grain Sand – Wet Drawbar Pull Test and Simulation Results.

2.4.5.4 Coarse Grain Soil, Dry

In CGS-Dry as seen in Figure 2-20, it appears that the Complex Terramechanics models have difficulty in achieving the drawbar pull coefficient at low slip, and then over predict at higher slip values.

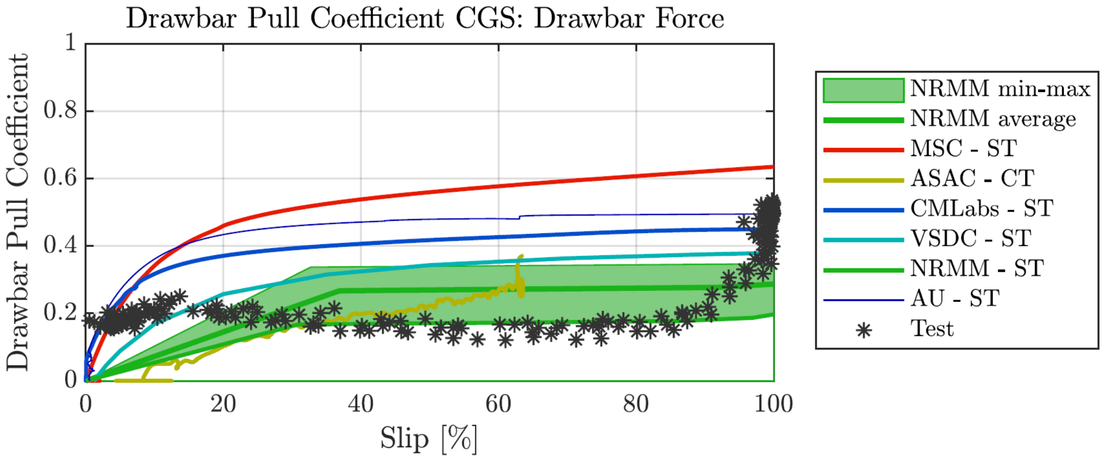


Figure 2-20: Coarse Grain Sand – Dry Drawbar Pull Test and Simulation Results.

In general, Simple Terramechanics models over predict the coefficient at all slip values. VSDC is close to the test data but still over-predicts above 20% slip. All simulations have difficulties capturing the test results with reasonable accuracy throughout the entire slip range and, in particular, none of the models capture the drawbar pull coefficient minimum around 60% slip.

It should be noted that the test results at low slip seem to indicate that there is very limited motion resistance in this soil as there are drawbar pull coefficient above 0 at very low slip values. This observation caused an investigation into the motion resistance coefficient and in particular thrust coefficient by purely looking at axle torque divided by wheel radius and again normalized by the vehicle weight. The results of this investigation were inconclusive. Concern was raised regarding the non-steady state behavior of the test. This led to another test being performed at MTU/KRC with the intent of keeping slip constant for longer periods of time to ensure steady state behavior. The results of this test and that of the software developer VSDC with the new data for both FGS-Wet and CGS-Dry are shown in Figure 2-21. It is clear to see the segments of test data with similar slip values for the CGS-Dry test. It should also be pointed out that in the 0 – 5 % slip there are data points indicating the significant motion resistance present in this soil.

This result led to a comparison of rut depth. Only VSDC had recorded this for the submissions and the results are presented for the original drawbar pull data in Table 2-10 indicating reasonable agreement except for the coarse grain pit.

In conclusion, the coarse grain soil appears to be outside of the capabilities of the simulation models. None of the models capture the drawbar pull coefficient minimum around 60% slip. Also, as shown in the test results in Table 2-10, this soil exhibits large soil deformation. Many factors can be contributing to the large over prediction by the Simple Terramechanics methods, such as large soil deformation laterally, soil transport fore to aft of the tire, etc. Furthermore, there is a question about why the test does not show motion resistance for this soil.

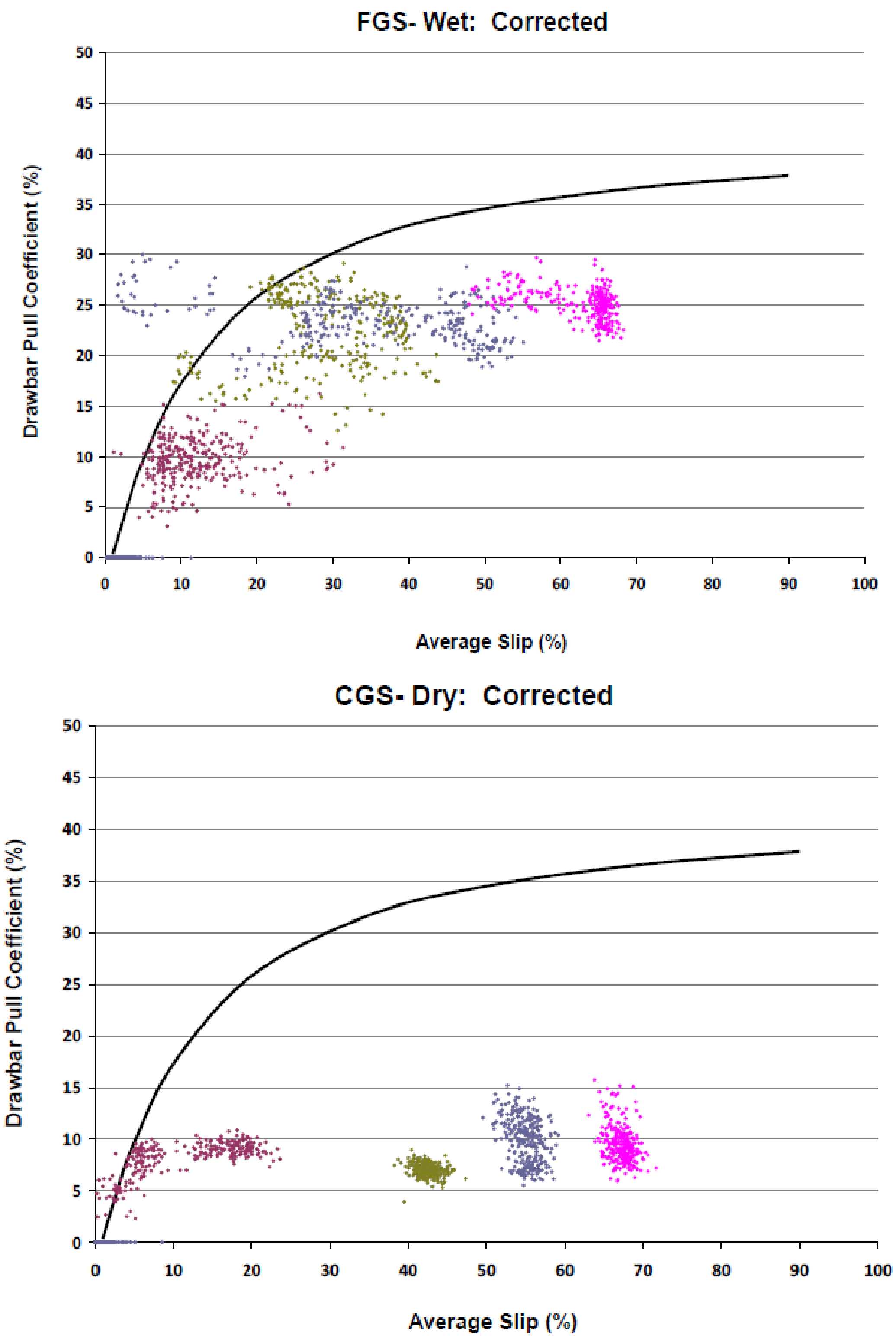


Figure 2-21: Steady State Drawbar Pull Tests FGS-Wet and CGS-Dry.

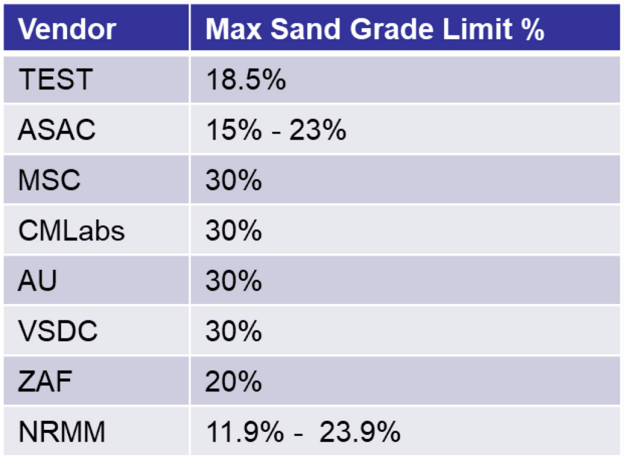
Table 2-10: Rut Depth Comparison, Test and VSDC.

Date	Soil	Test	Average Rut Depth Range (cm)	VSDC Predicted Rut Depth Range (cm)
5-June-18	Coarse-Pit	Drawbar	[9 , 10]	3.7
5-June-18	Fine Grain Wet	Drawbar	[14 , 15]	[14.7 , 15.8]
5-June-18	Fine Grain Dry	Drawbar	[3 , 4]	[5.2 , 6]

2.4.5.5 Variable Grade Sand Slope

The grade on coarse grain soil slope test is made by running the vehicle up the slope at slow speed with differentials locked. The slope design is made by 5% grade increments. The test vehicle was stuck with the front wheels on 10% grade and rear wheel on 15% grade. The vehicle on the slope, scan of wheel tracks, slip vs. slope and a table with all results are shown in Table 2-11 and Figure 2-22.

Table 2-11: Vehicle on Variable Grade, All Results.



Vendor	Max Sand Grade Limit %
TEST	18.5%
ASAC	15% - 23%
MSC	30%
CMLabs	30%
AU	30%
VSDC	30%
ZAF	20%
NRMM	11.9% - 23.9%

ZAF and ASAC were able to predict reasonably well the slope limit. However, from the slip vs. slope plot Complex Terramechanics results from ASAC show very large wheel slip as compared to test data. On the other hand, Simple Terramechanics shows too small wheel slip. These observations are in agreement with the drawbar pull coefficient predictions by CT and ST respectively on Coarse Grain Soil Dry. CT could obtain high drawbar pull coefficients with enough slip, and ST over predicted the coefficient and thereby required excess force to climb the hill without problems beyond the 30% slope. NRMM showed very large spread from min to max. slope and therefore was not considered a good solution.

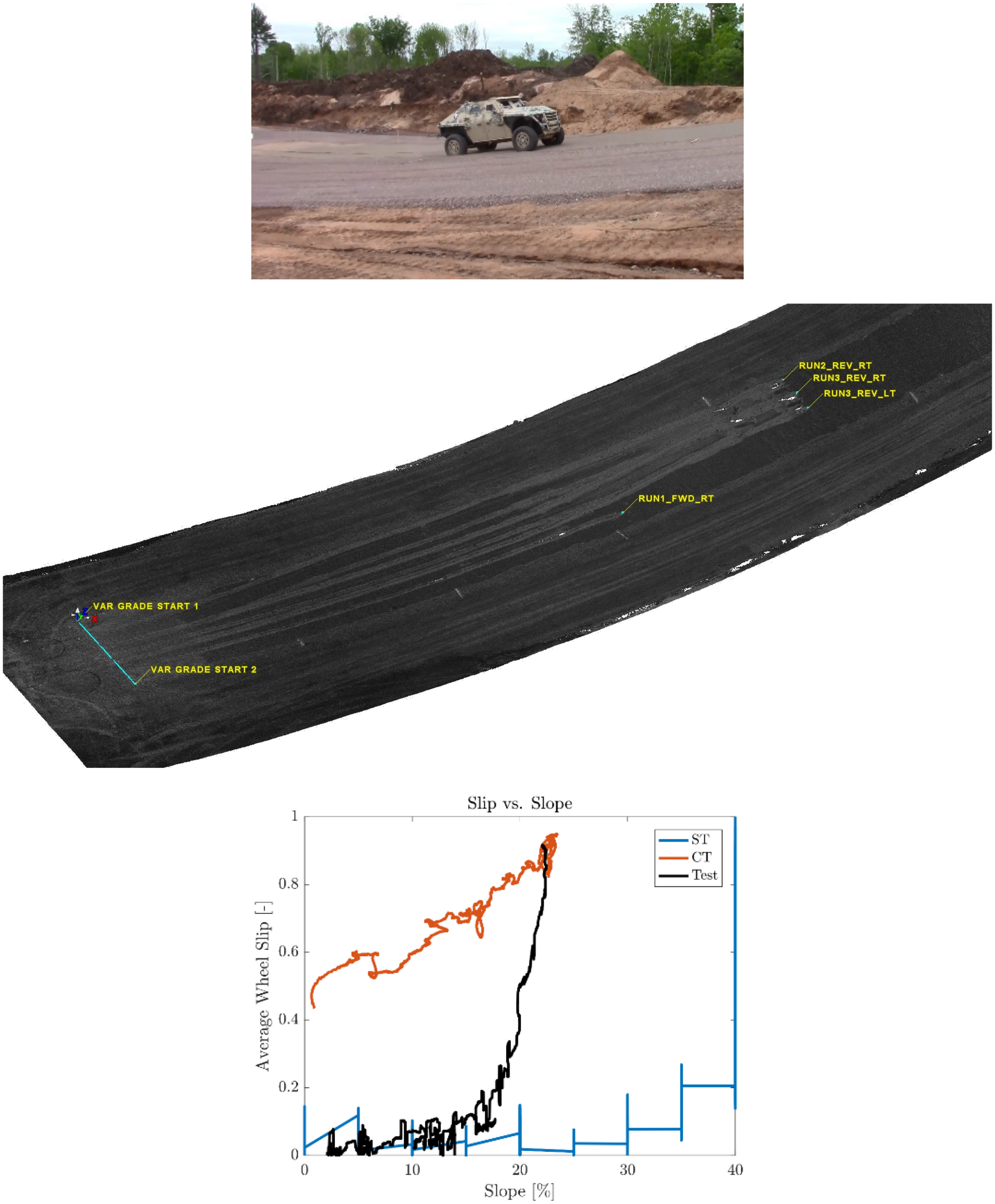


Figure 2-22: Vehicle on Variable Grade, Scan of Wheel Tracks, Slip vs. Slope.

2.4.5.6 Soft Soil Performance Summary

A summary of the conclusions for the soft soil performance is presented in Table 2-12. With reference to the performance on drawbar pull and slope on sand grade, NG-NRMM shows promising results while there is still work to be done in improved modeling and investigation of the soft soil test for the CGS-Dry case. This affects also the slip vs. slope performance on the sand grade test.

Table 2-12: Soft Soil Performance Conclusions.

Test	NRMM	NG-NRMM	Comments
Drawbar Pull, Fine Grain Soil – Dry	✗	✓	NRMM Over-Predicted
Drawbar Pull, Fine Grain Soil – Wet	✓	✓	
Drawbar Pull, Coarse Grain Soil - Dry	✗	✗	ST and CT Performed Reasonable NRMM Performed Reasonable
Variable Grade Sand Slope, 2NS - Dry	✗	✓	CT – Slip high NRMM Large Variation on Min Max

2.4.6 Mobility Traverse

In addition to the automotive and soft soil tests, the CDT exposed the software developers to a mission profile type test and simulation event. This was done by selecting two traverses on the MTU/KRC terrain, a yellow and a blue traverse as depicted in Figure 2-23.

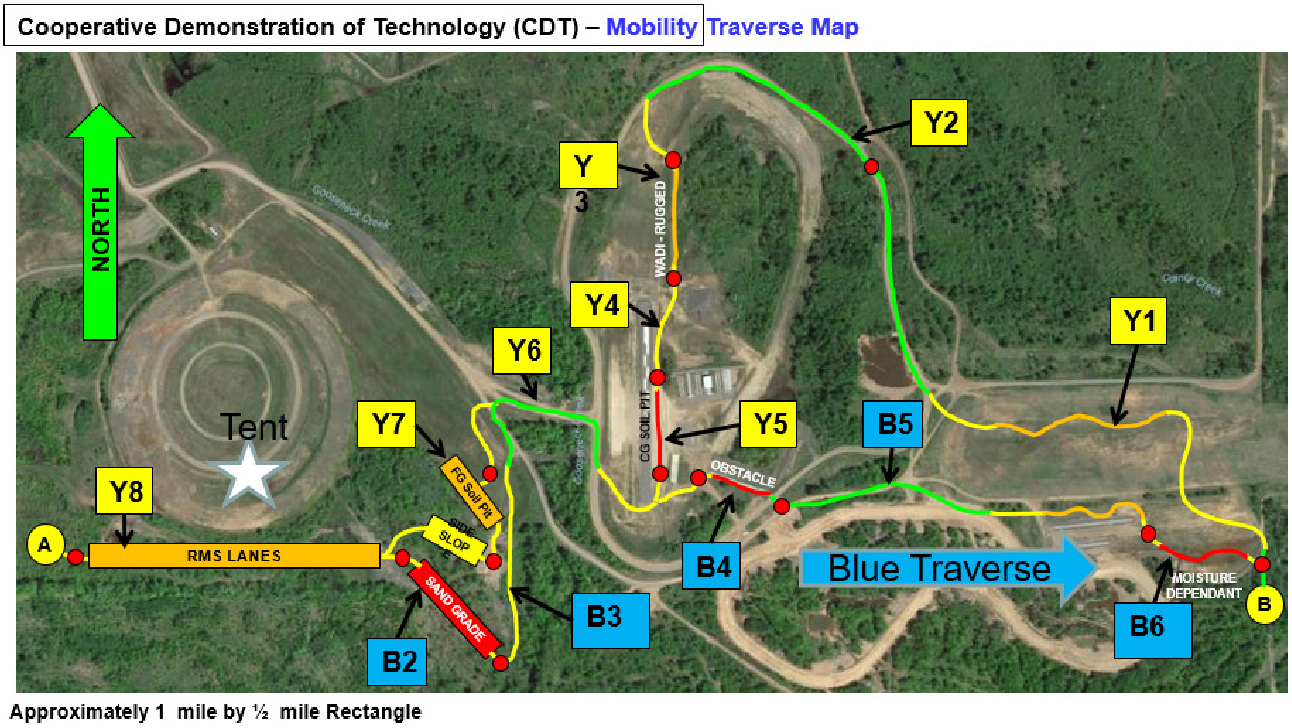


Figure 2-23: Yellow Y1-Y8 and Blue B1-B6 Mobility Traverses on the KRC Terrain.

The path of the MTU/KRC test vehicle was recorded as a GPS trace and made available to the software developers. An example of the GPS trace loaded into a software developer vehicle simulation model on MTU/KRC terrain and with GPS waypoints overlaid is shown in Figure 2-24.

Figure 2-24: AU/JPL ROAMS Software Showing FED-A Vehicle on KRC Terrain with GPS Waypoints.

2.4.6.1 Mobility Traverse Test and Simulation Results

The traverse segments contained elements from the automotive and soft soil tests such as RMS courses and slalom in soft soil pits. A description of the Traverse Segments is shown in Table 2-13. The intention of the mobility traverse was to compare NRMM predicted speeds with MTU/KRC test driver and software developers speed predictions. In the plots that follow, the individual traverses are illustrated as speed vs. distance travelled. The MTU/KRC driver drove each segment three times with the instruction to go as fast as possible without any risk of damaging the vehicle. NRMM based its speed predictions on speed-made-good calculation for the terrain units available in each segment. NRMM defines a terrain unit as an area with near constant properties. If the slopes changes, another terrain unit is defined, similar for RMS values, etc. In comparing the distance travelled for NRMM and the MTU/KRC drives, a significant difference was found on a number of NRMM traverse runs. This is seen in the traverse plots that NRMM at times is offset in the distance. The software developers were asked to go as fast as possible without losing control of the vehicle and keeping in mind the test results for 6 watt absorbed power on the RMS courses. CT or ST modeling is indicated in the plot legends. Speed comparisons are presented along with two additional metrics recorded from the software developer in the following plots, Figure 2-25 to Figure 2-38. In some cases the additional metrics were not available and plots appears blank.

Table 2-13: Section Descriptions and Vehicle Settings.

Traverse Section	Description
Y1	Stability Field Traverse with Sinusoidal Side SlopeLoop 2 with Panic Stop, High Range / No Differential Lock
Y2	Loop 2 with Rink Field Traverse and Setup for Wadi, High Range / No Differential Lock
Y3	Wadi, Low Range / With Differential Locked
Y4	Rink Field Traverse with Setup for Coarse Grain Pit, Low Range / With Differential Locked
Y5	Sinusoidal Coarse Grain Pit, Low Range / With Differential Locked
Y6	Rink Field Traverse with Loop 2 and Access Road to VDA 2, Field Traverse and Setup for Fine Grain Soil Pit, High Range / No Differential Lock
Y7	Fine Grain Soil Pit – Up slope into pit then 90 degree, Low Range / With Differential Locked
Y8	Construction Site Road to Side Slope, Obstacle avoidance on Side Slope, then RMS 2.0, High Range / No Differential Lock
B1	RMS 1.0 with Exit onto Gravel Pad, High Range / No Differential Lock
B2	Up Slope on Gravel Pad with Down Slope through 2NS , Sand Grade, Low Range / With Differential Locked
B3	Construction Site Road to Gravel Access Road and Loop 2, Rink Field Traverse with setup for OEF, High Range / No Differential Lock
B4	OEF Trail, Low Range / With Differential Locked
B5	Gravel Road to Stability Side Trail, Sinusoidal Side, Slope with Setup for Moisture Dependant Area, High Range / No Differential Lock
B6	Moisture Dependent Area, Low Range / With Differential Locked

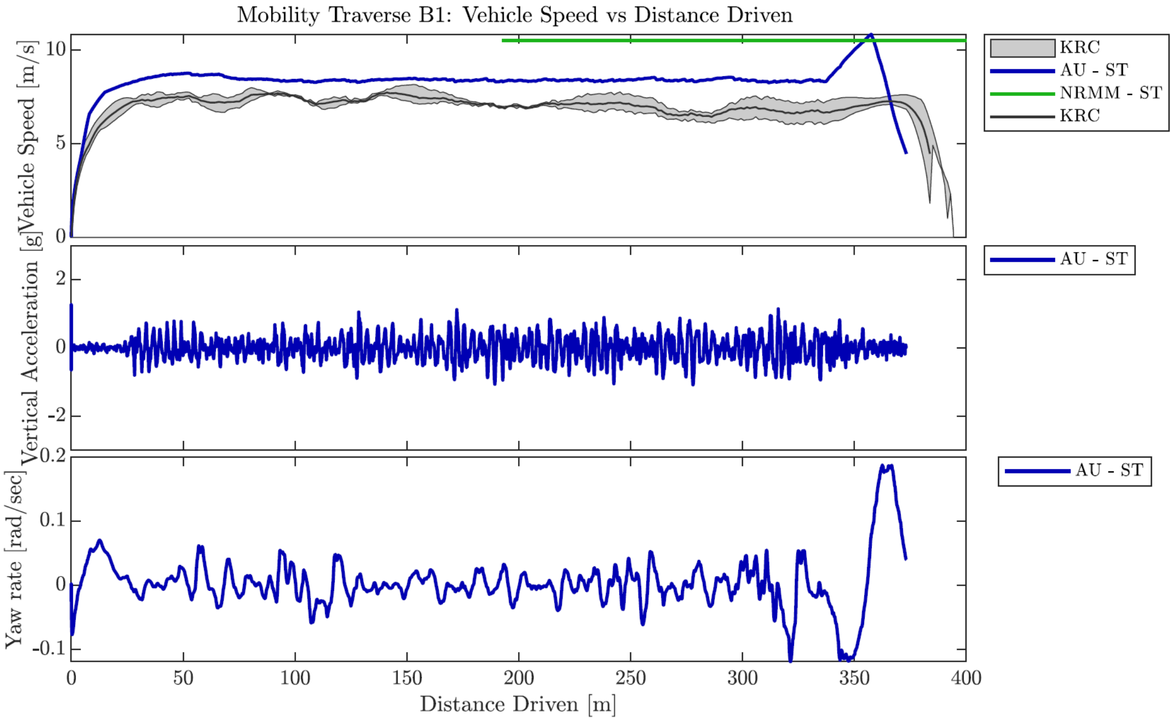


Figure 2-25: Section B1, RMS Lane, AU.

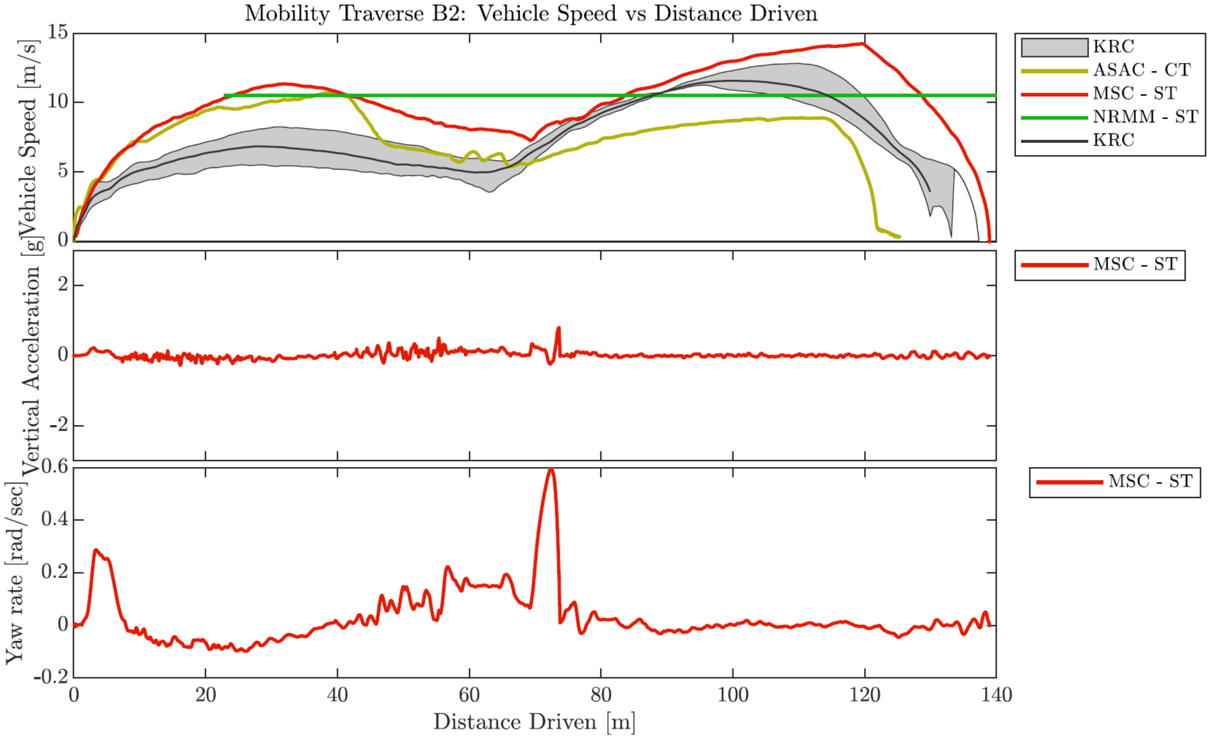


Figure 2-26: Section B2: Up Slope Gravel, Down Slope 2NS Sand, ASAC, MSC.

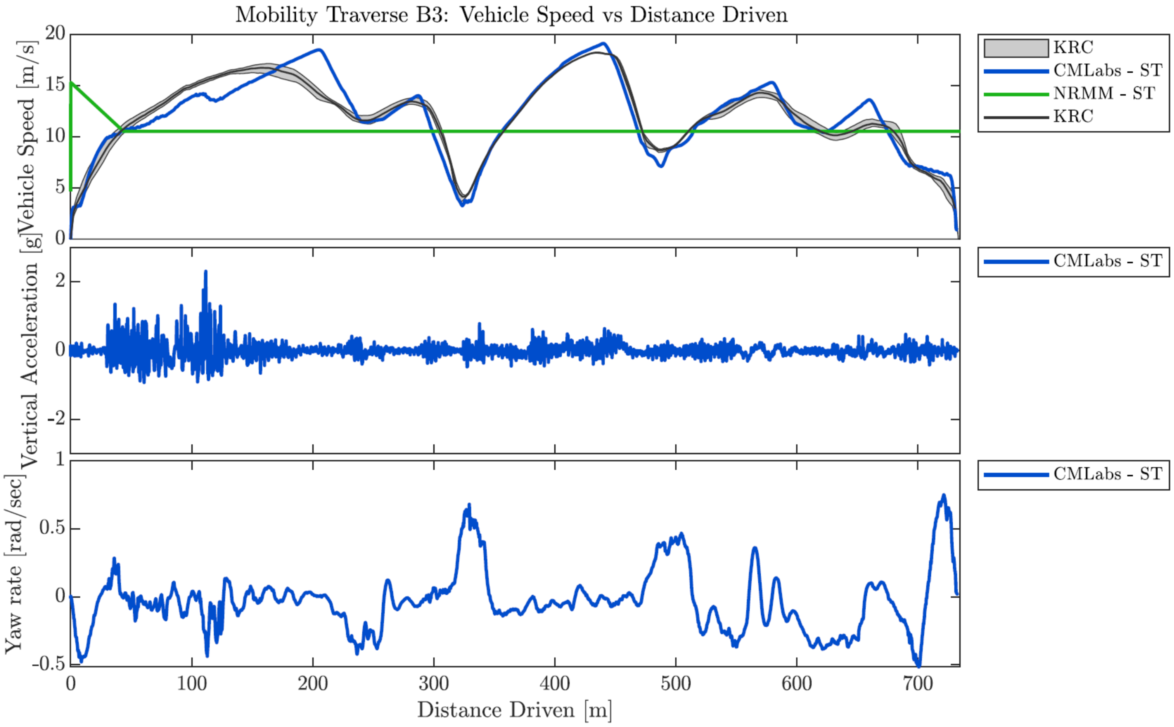


Figure 2-27: Section B3: Down Slope 2NS Sand, CM Labs.

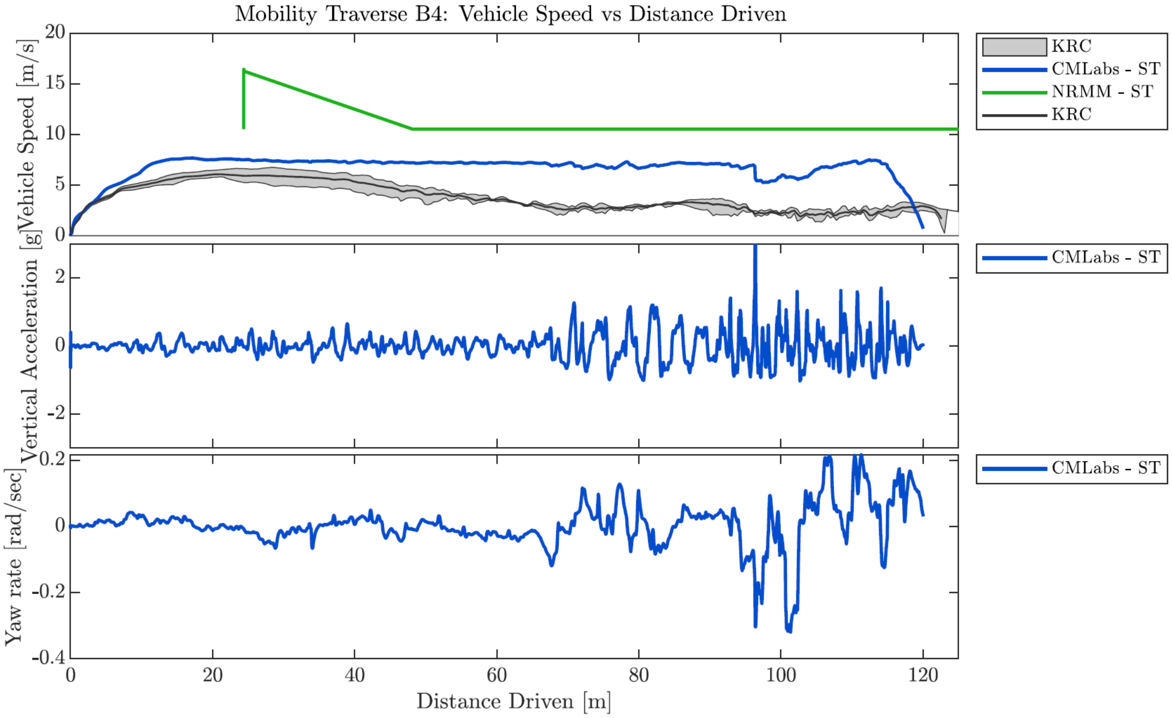


Figure 2-28: Section B4: OEF Trail, CM Labs.

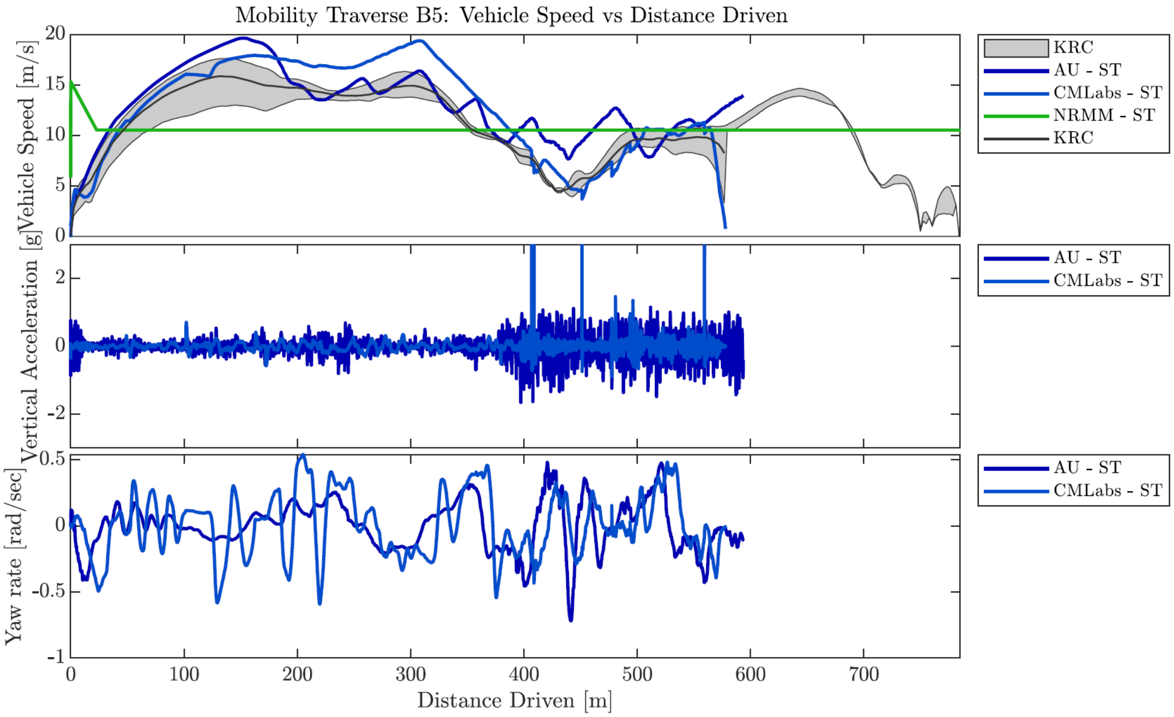


Figure 2-29: Section B5: Sinusoidal Side Slope, AU, CM Labs.

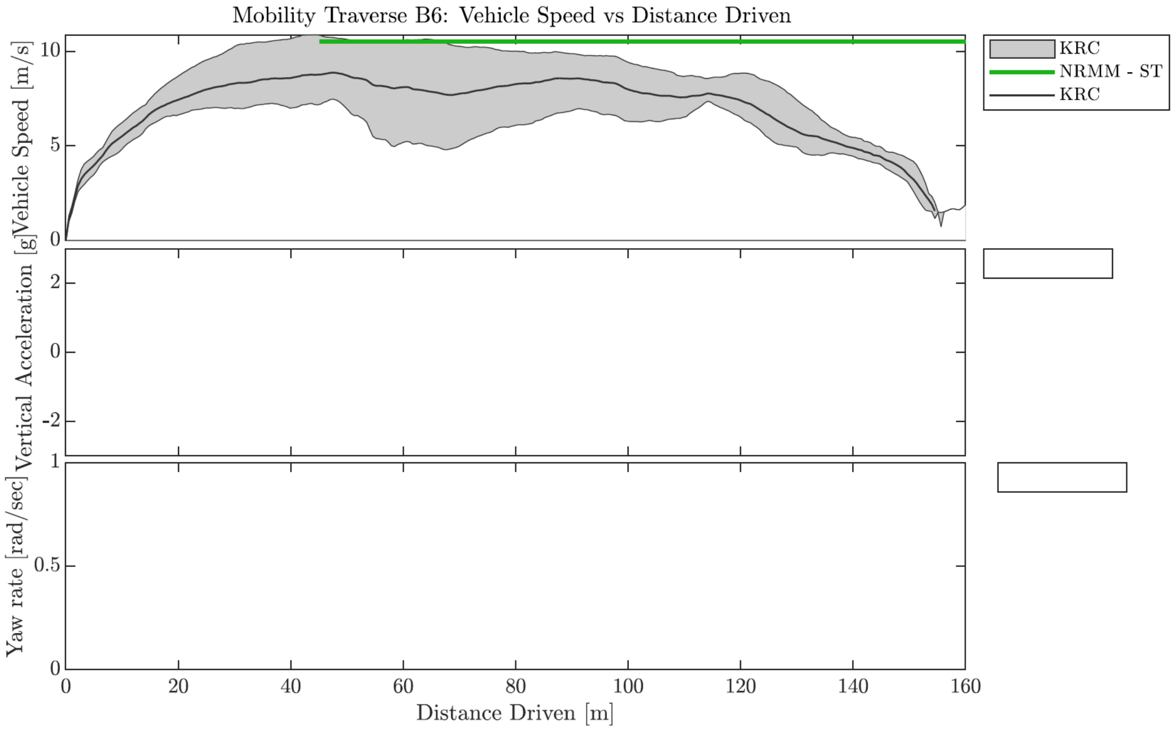


Figure 2-30: Section B6: Moisture Dependent Area, Only KRC and NRMM Results.

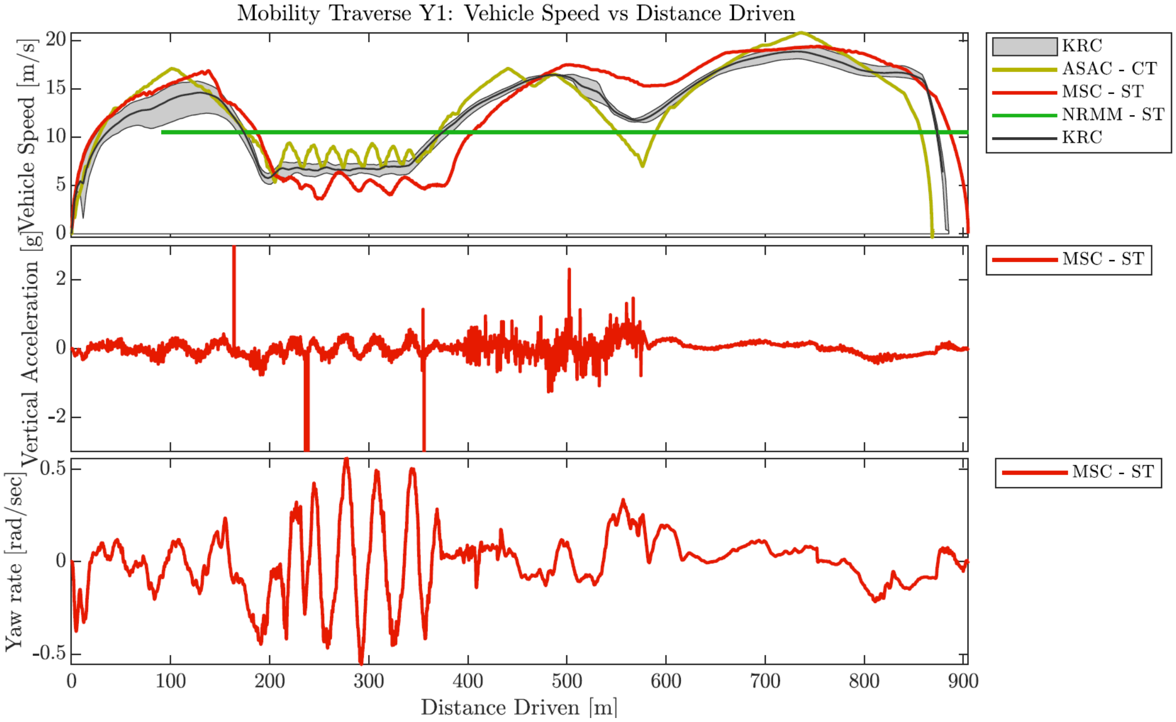


Figure 2-31: Section Y1: Stability Field Sinusoidal Side Slope, Panic Stop, ASAC, MSC.

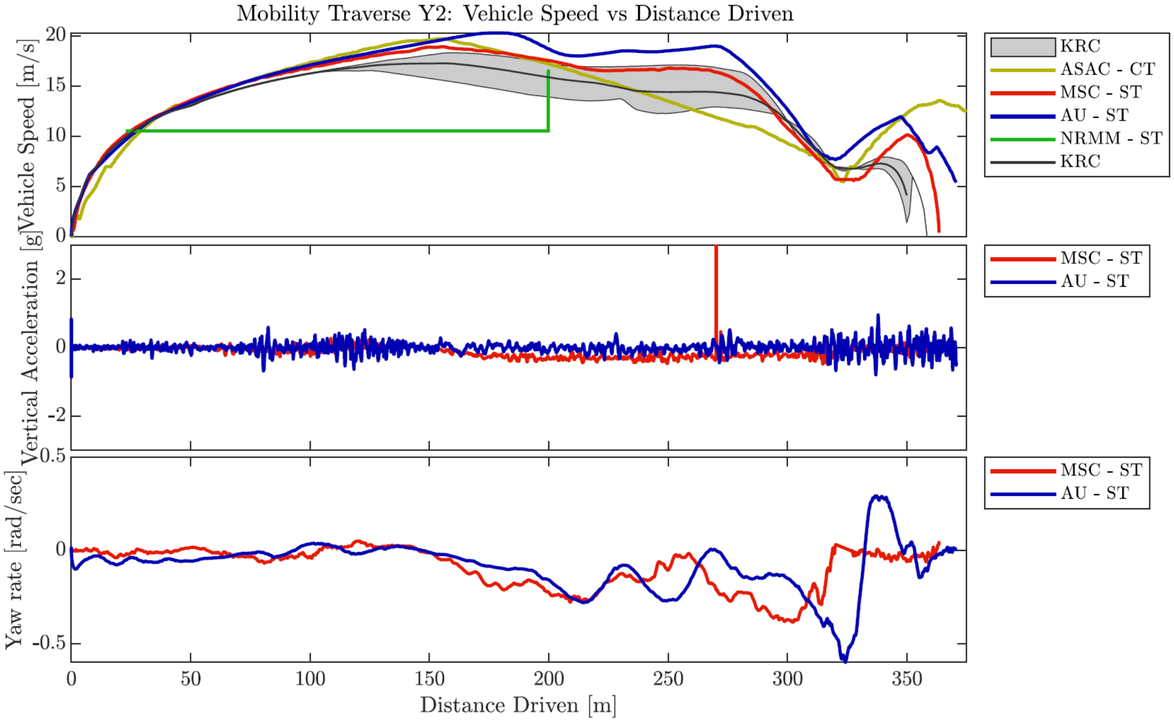


Figure 2-32: Section Y2: Rink Field Traverse, ASAC, MSC, AU.

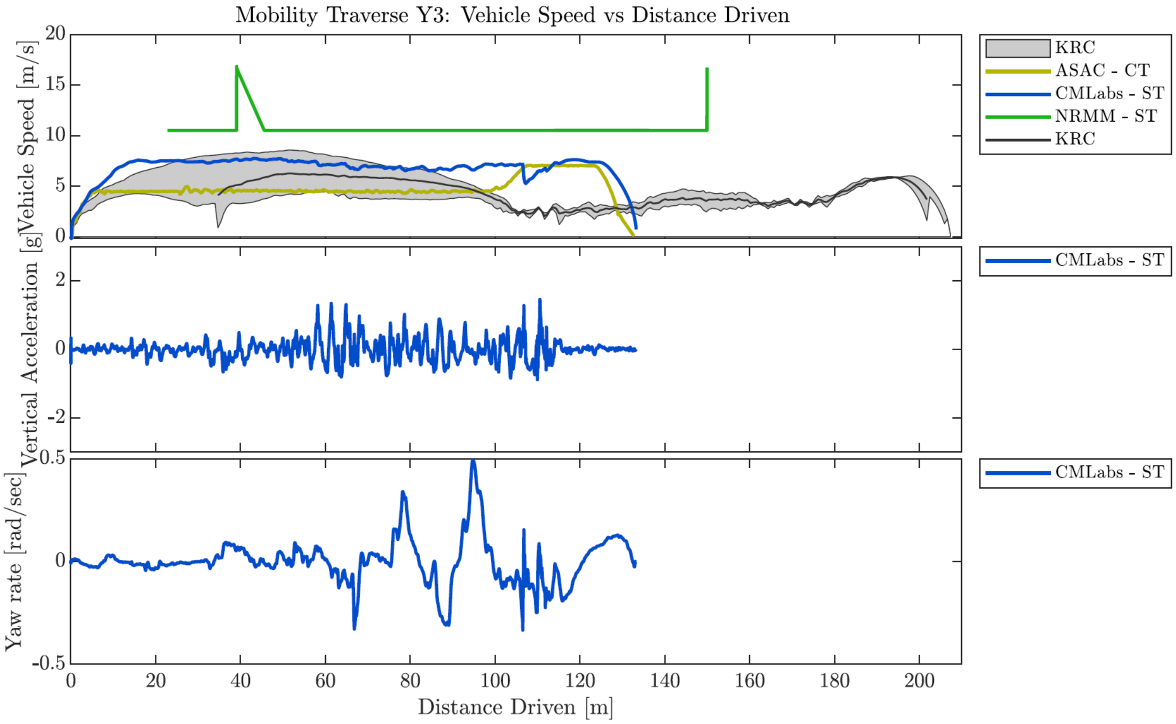


Figure 2-33: Section Y3: Wadi, ASAC, CM Labs.

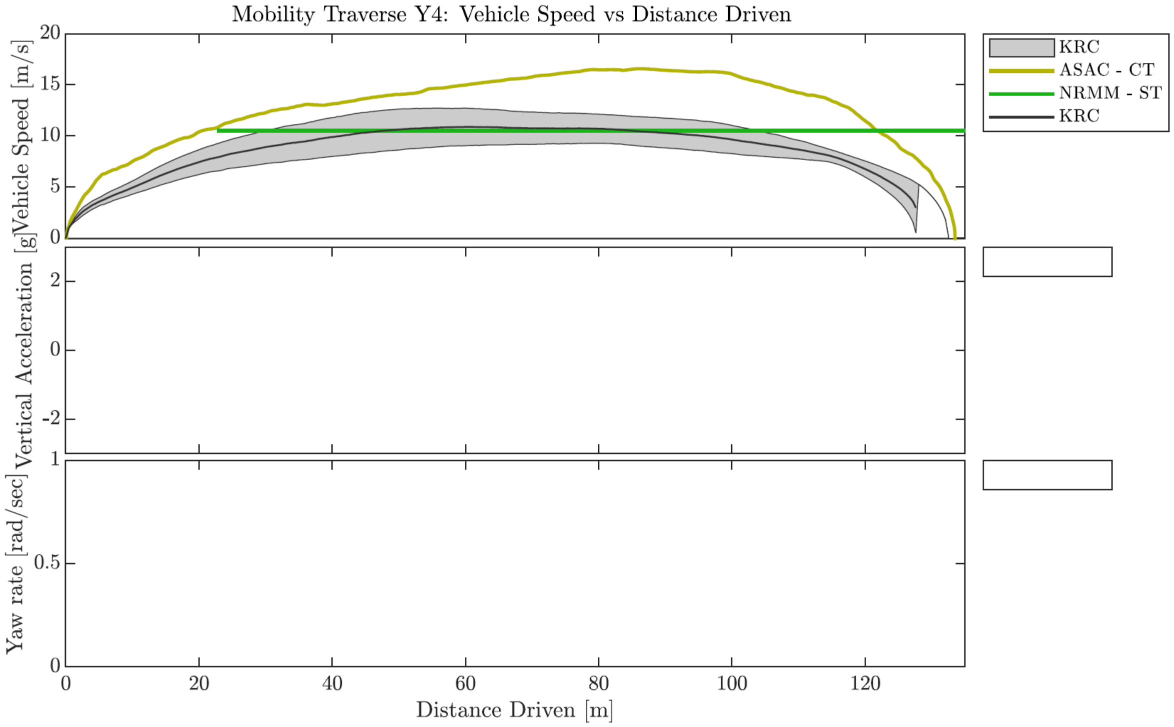


Figure 2-34: Section Y4: Rink Field, ASAC.

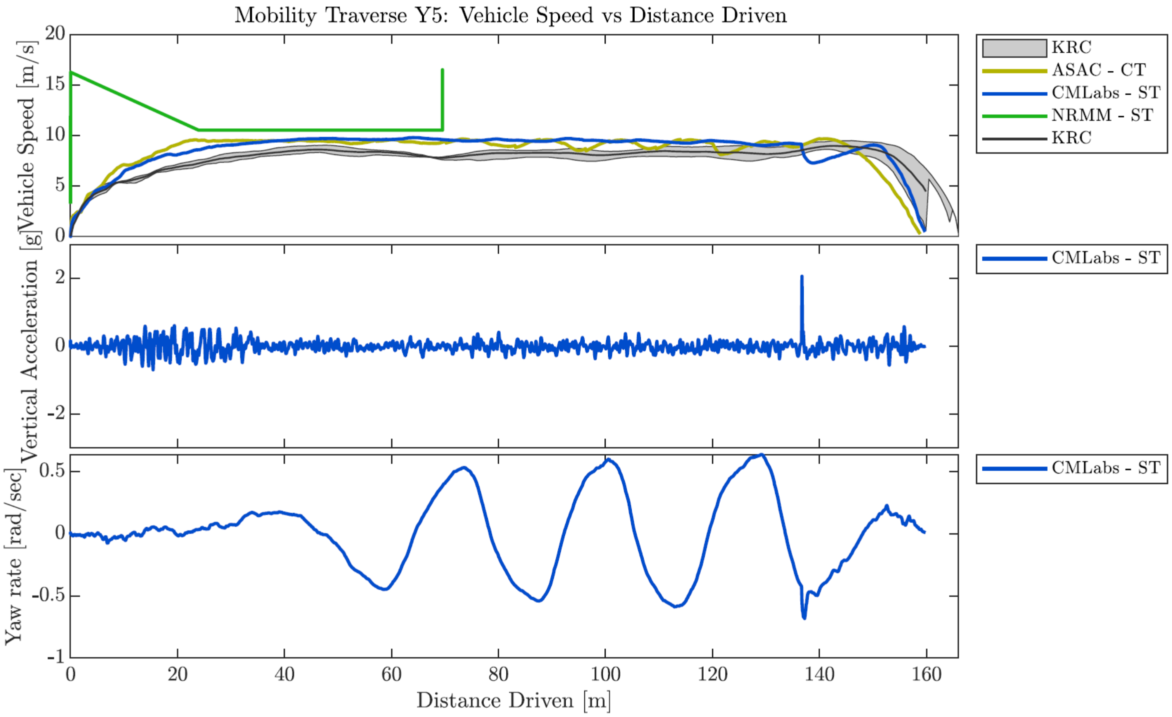


Figure 2-35: Section Y5: Sinusoidal Coarse Grain Pit, ASAC, CM Labs.

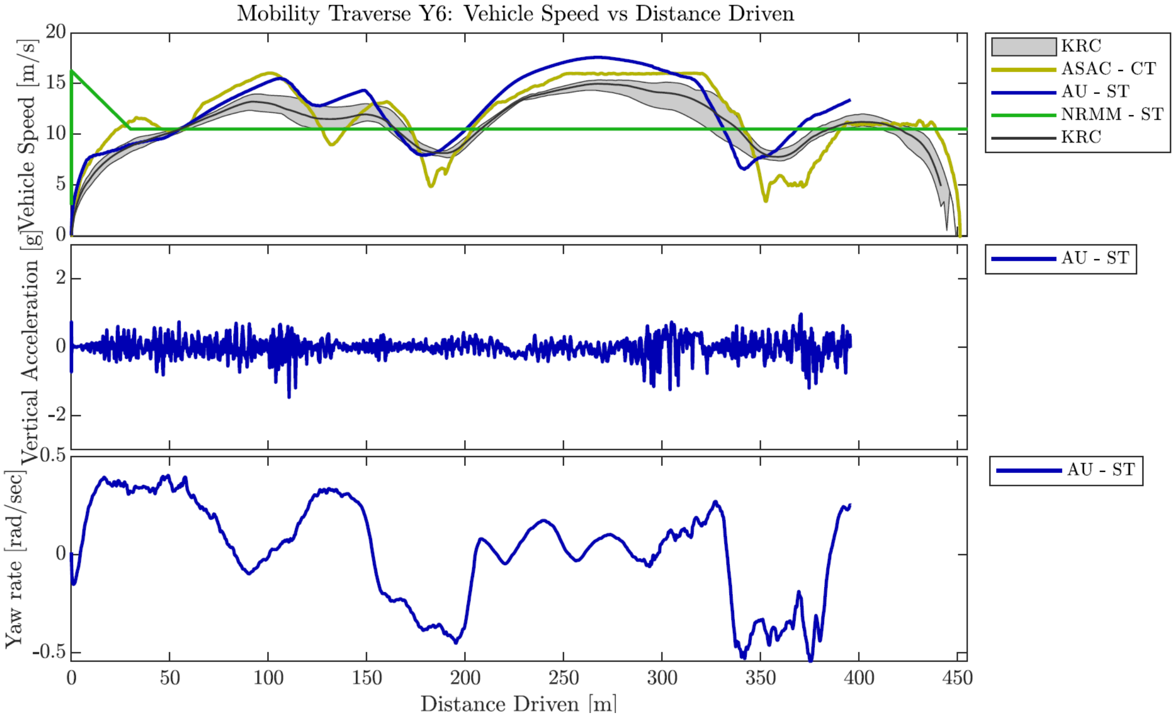


Figure 2-36: Section Y6: Field Traverse and Access Road, ASAC, AU.

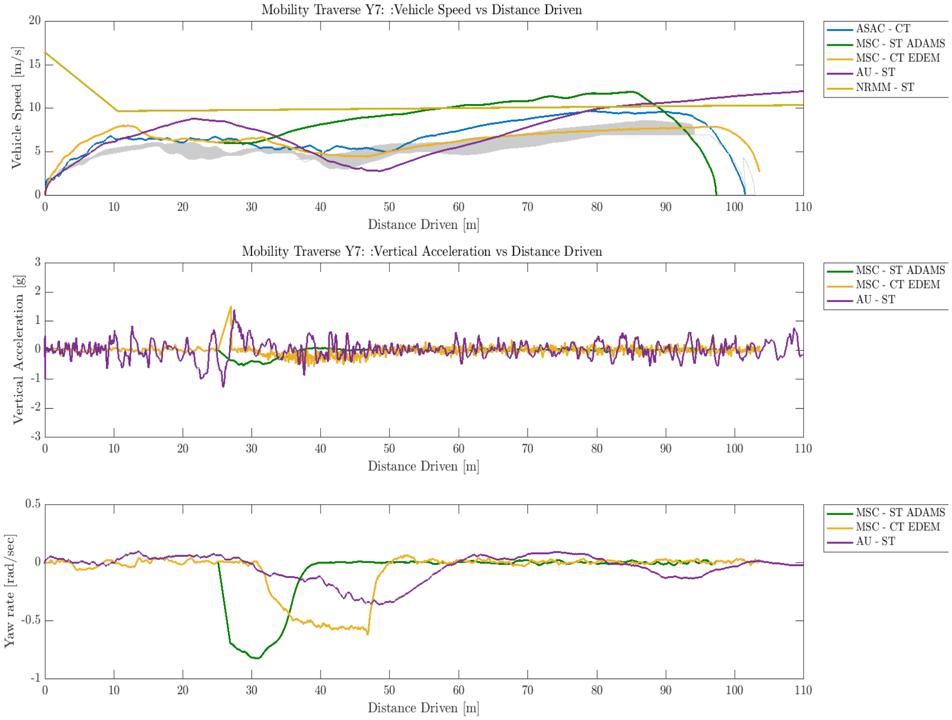


Figure 2-37: Section Y7: Fine Grain Soil Pit, 90 Degree Turn and Accelerate, ASAC, MSC, AU.

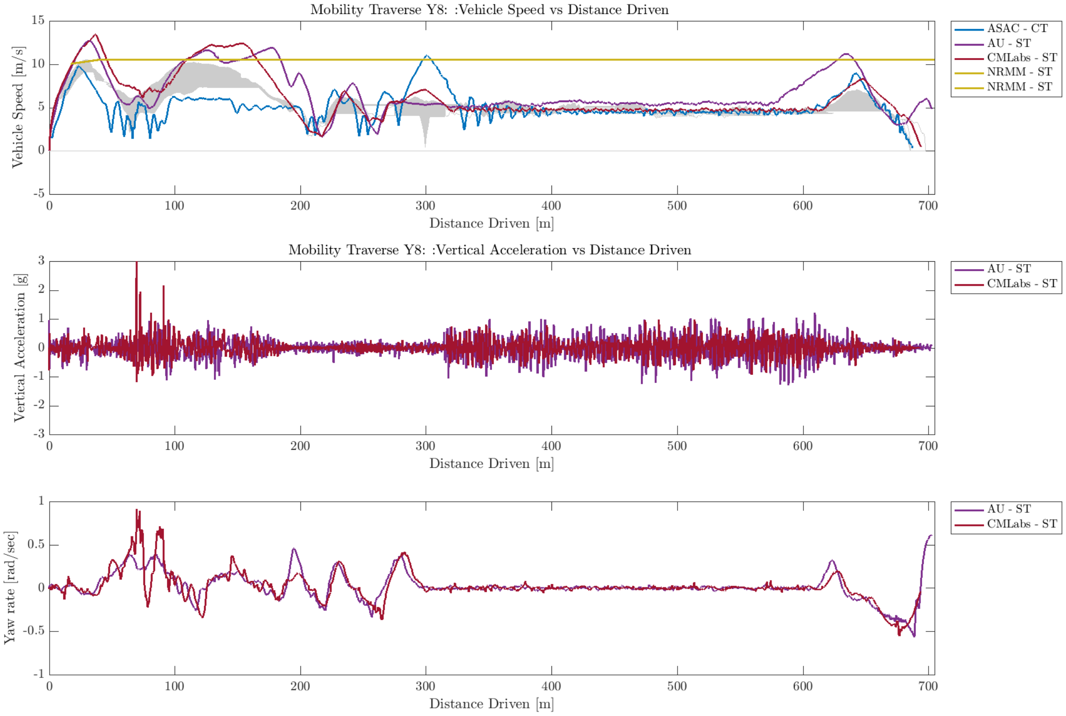


Figure 2-38: Section Y8: Side Slope Obstacle Avoidance and RMS 2", ASAC, AU, CM Labs.

2.4.6.2 Mobility Traverse NG-NRMM vs. NRMM Comparison and Conclusions

NRMM and NG-NRMM simulation performances are compared by looking at the speed maximum, and average reported in mph. A summary table is presented in Table 2-14 showing results for each segment: Segment length (m), maximum and average speed as well as time in each segment for NG-NRMM, Test and NRMM. Furthermore, maximum speed as well as average speed as percent deviation from the tests are listed as well. Representing Figure 2-38 as histograms for average and maximum speed deviations is shown in Figure 2-39.

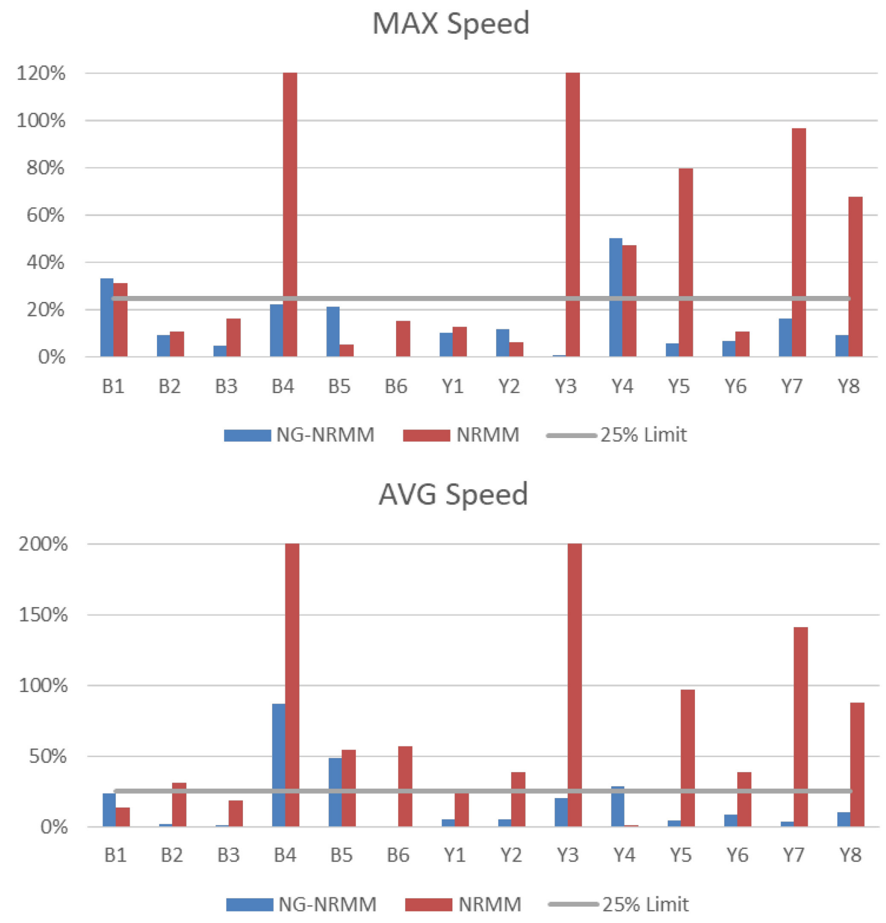


Figure 2-39: Max. and Avg. Speed Deviation from Test with 25% Deviation Indication.

Taking Section Y7 as an example, Y7 represents up slope driving with a 90 degree turn in a soft soil pit. NRMM over-predicts the speed significantly, as it does not slow down before the turn. Hence, NG-NRMM is in better agreement with the real test driver. Furthermore, from Figure 2-39, it is seen that the speed for Y7 is larger for NG-NRMM than the real test driver. This is because the NG-NRMM driver models do not have the same perceived speed limits as the test driver. From Figure 2-39, it is also seen that NG-NRMM is within 25% of the test speed in more than 75% of the traverse segments.

An overview of the individual segment performance in both average and maximum speed with comments on the reasoning is shown in Table 2-15 for the blue traverse and Table 2-16 for the yellow traverse.

Table 2-14: Traverse Segments Speed Results, NG-NRMM, Test, NRMM.

Speed (MAX and AVG) reported in mph			NG-NRMM*			Test			NRMM			MAX Speed		AVG Speed	
Section	Description	Traverse Length (m)	MAX	AVG	TIME (sec)	MAX	AVG	TIME (sec)	MAX	AVG	TIME (sec)	NG-NRMM	NRMM	NG-NRMM	NRMM
B1	RMS 1.0 with Exit onto Gravel Pad	385	24	18	48	18	15	60	24	17	52	33%	32%	23%	14%
B2	Up Slope on Gravel Pad with Down Slope through 2NS Sand Grade	131	24	13	22	27	13	23	24	17	17	-10%	-11%	2%	31%
B3	Construction Site Road to Gravel Access Road & Loop 2, Rink Field Traverse with setup for OEF	733	43	23	73	41	23	72	34	27	60	5%	-16%	-1%	19%
B4	OEF Trail	123	17	13	21	14	7	40	37	32	9	23%	162%	87%	353%
B5	Gravel Road to Stability Side Trail, Sinusoidal Side Slope with Setup for Moisture Dependant Area	580	44	27	48	36	18	89	34	28	47	22%	-5%	49%	54%
B6	Moisture Dependant Area	156	N/A	N/A	N/A	20	13	29	24	20	18	N/A	15%	N/A	57%
Y1	Stability Field Traverse with Sinusoidal Side Slope, Loop 2 with Panic Stop	882	47	23	86	42	24	82	37	31	64	10%	-13%	-5%	27%
Y2	Loop 2 with Rink Field Traverse & Setup for Wadi	356	44	26	31	39	24	33	37	34	24	12%	-6%	5%	39%
Y3	Wadi	205	16	7	70	16	8	53	38	30	15	-1%	137%	-20%	264%
Y4	Rink Field Traverse with Setup for Coarse Grain Pit	133	37	20	15	25	28	20	36	28	11	50%	47%	-29%	-1%
Y5	Sinusoidal Coarse Grain Pit	162	22	16	23	21	15	25	37	29	12	6%	80%	5%	97%
Y6	Rink Field Traverse with Loop 2 & Access Road to VDA 2 Field Traverse & Setup for Fine Grain Soil Pit	444	36	20	50	34	22	46	37	30	33	7%	11%	-9%	39%
Y7	Fine Grain Soil Pit - Up slope into pit then 90 degree turn in pit with accelerated exit	103	22	11	21	19	11	22	37	25	9	16%	97%	4%	141%
Y8	Construction Site Road to Side Slope, Obstacle avoidance on Side Slope, then RMS 2.0	713	25	10	161	23	11	141	38	21	77	9%	68%	-10%	88%

Table 2-15: Blue Traverse Comparison, Max. and Avg. Speed. NRMM and NG-NRMM.

Traverse		Max Speed		AVG Speed		Comments
		NRMM	NG-NRMM	NRMM	NG-NRMM	
B1	RMS 1.0 with Exit onto Gravel Pad	✗	✗	✓	✓	Test Driver Below 6W Speed
B2	Up Slope on Gravel Pad with Down Slope through 2NS Sand Grade	✓	✓	✗	✓	NRMM Low Avg Speed (Lacks Terrain Unit Transitions)
B3	Construction Site Road to Gravel Access Road & Loop 2, Rink Field Traverse with setup for OEF	✓	✓	✓	✓	
B4	OEF Trail	✗	✓	✗	✗	Asymmetric input, 6W Limits
B5	Gravel Road to Stability Side Trail, Sinusoidal Side Slope with Setup for Moisture Dependant Area	✓	✓	✗	✗	Driver Limits, 3D Maneuver
B6	Moisture Dependant Area	NA	NA	NA	NA	Test Did Not Go Through Water

Table 2-16: Yellow Traverse Comparison, Max. and Avg. Speed. NRMM and NG-NRMM.

Traverse		Max Speed		Average Speed		Comments
		NRMM	NG-NRMM	NRMM	NG-NRMM	
Y1	Stability Field Traverse with Sinusoidal Side Slope, Loop 2 with Panic Stop	✓	✓	✓	✓	
Y2	Loop 2 with Rink Field Traverse & Setup for Wadi	✓	✓	✓	✓	
Y3	Wadi	✗	✓	✗	✓	Short + Transitions
Y4	Rink Field Traverse with Setup for Coarse Grain Pit	✗	✗	✓	✗	Driver Limits
Y5	Sinusoidal Coarse Grain Pit	✗	✓	✗	✓	Steering
Y6	Rink Field Traverse with Loop 2 & Access Road to VDA 2 Field Traverse & Setup for Fine Grain Soil	✓	✓	✓	✓	
Y7	Fine Grain Soil Pit - Up slope into pit then 90 degree turn in pit with accelerated exit	✗	✓	✗	✓	Steering 90 deg, Acceleration
Y8	Construction Site Road to Side Slope, Obstacle avoidance on Side Slope, then RMS 2.0	✗	✓	✗	✓	Steering, Roll

2.5 PHASE 4 – CDT EVENT

The three day event was held at the MTU/KRC test facility, and was comprised of presentations and demonstrations of the latest technology developments in modeling and simulation of off-road mobility of ground vehicle systems. The CDT program is reproduced below.

CDT Program

Monday 24 September 2018, DAY 0		
1500-1800	Registration and Social	*Rozsa Center for the Performing Arts*
Tuesday, 25 September 2018, DAY 1		
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 and Data	Michael McCullough
1645 **	Thrust 3: Complex Terramechanics Model and Data	Tamer Wasfy
1730	Summary and Tomorrow's Preview	Paramsothy Jayakumar
1800	Transport to *KRC Main Building*	
Wednesday, 26 September 2018, DAY 2		**Theme: Operational Scenario**
0730	Registration and Transport to *Tent Site*	*KRC Main Building*
0830	Safety Brief	Jay Meldrum
0845	NATO Welcome	Steen Sondergaard and Christoph Mueller
0915	GVSC 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 *KRC Main Building*	
1800	Cocktail Hour	*Memorial Union Ballroom*
1900	Dinner Reception	
	After-Dinner Speaker	Richard Koubek, President, MTU
Thursday, 27 September 2018, Day 3		**Theme: Future**
0800	Registration and Transport to *Tent Site*	*KRC Main Building*
0900	Review of First Two Days and Plans for Today	Paramsothy Jayakumar
0930	Thrust 5: Uncertainty and 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 *Adams*: **Mobility and Beyond** – Eric Pescheck	
	CSIR	**South African** Mobility Prediction Software *MOBSIM* – David Reinecke	
	CM Labs	**Real-Time** Vehicle Simulation using *Vortex Studio* – Martin Hirschkorn	
	VSDC	Wheeled Vehicle Mobility Prediction using *NWVPM* – Joe Wong	
	AU	*ROAMS*, a Fast Running Mobility Simulator Utilizing **GeoTIFF Terrain Maps –** Louise Bendtsen	
	ASA	*DIS* – A **Complex Terramechanics** 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 *KRC Main Building*		
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			

Approximately 160 persons attended each day; the full, three day agenda is included in Section 2.5. All of the presentations were held in a specialized presentation space in an outdoor tent (Figure 2-40) that included a 9 x 12 foot screen in the front of the room with five additional 55-inch TV screens mirroring the main screen. Speakers were elevated at the podium with a clear view to a dedicated 55-inch TV used as a video prompter. Audience members were encouraged to participate in the presentations, which resulted in lively discussion and they also took advantage of breaks between presentations and evening programming for networking opportunities. The tent complex had other rooms housing both food and static exhibits of various vehicles. The exhibit room was deliberately sectioned off from the presentation room to keep noise levels down from socializing and networking by attendees during presentations.

The meeting was intended to be a critical peer review of the AVT-248 and AVT-308 committee's NG-NRMM's multi-year effort(s) as well as a showcase of the physical testing methods involved in collecting data for the project. Attendees were introduced to NG-NRMM technologies through the presentations described below.

Figure 2-40: NATO CDT Event in Houghton, MI, USA.

History, Motivation, and Goals for NG-NRMM (Annex B) – The presentation discussed the need and motivation for an updated NRMM model, the goals of the group, and then proceeds to describe the four year project starting with the NATO Exploratory Team (ET) that was proposed during the spring of 2014 to investigate an efficient simulation-based NG-NRMM and concluded in December 2015. The next steps, based on the results of the ET, was to form an RTG AVT-248 group to develop a NG-NRMM which was initiated in January 2016 and concluded in December 2018.

NATO Task Group and CDT Objective (Annex C) – The presentation describes the four objectives that were envisioned for AVT-248 as follows; to implement the development of a prototype NG-NRMM; to develop two prototype demonstrations, one in the area of ST and the second in the area of CT; to conduct a verification and validation exercise; and finally, to write a recommended standard, or STANREC to provide guidance for M&S standards that are applicable to the development of an NG-NRMM.

NG-NRMM Virtual and Physical Demonstration Plan (Annex D) – The presentation demonstrated the NG-NRMM process through M&S, vehicle testing and demonstration (illustrated through ride-alongs) and introduces NG-NRMM as the standard and recommendation for 3D Physics-based Mobility Prediction. Its split into two parts; the virtual and physical demonstration plan. The virtual plan focuses on virtual technologies such as data environment, sourcing of data, modeling and simulation technologies, and participating software vendors and collaboration between organizations. The physical demonstration plan discusses the vehicle platform, instrumentation, introduction to the acquisition of soil and terrain data (topology, soil, vegetation, water, etc.), and the vehicle behavior (automotive, soft soil and the mobility traverse). Finally, the resulting mobility prediction based on V&V and demonstrated in the mobility traverse is discussed.

Thrust 1- Geospatial Terrain and Mobility Mapping (Annex E) – The presentation described the thrust area's work on developing improved, standardized methodologies to transform high resolution satellite imagery / remotely sensed GIS data into accurate NG-NRMM terrain representations. It focused on contributions to the development of a NATO Standard Recommendation (STANREC) that will guide development of future NG-NRMM terrain generation tools and enable cartographic visualization of NG-NRMM output products are discussed. It also described efforts to develop an example suite of geospatial terrain construction tools to demonstrate capabilities required by NG-NRMM and the use of geoprocessing tools that ingest terrain data from various sources and resolutions to create a "standard" terrain file that can be utilized within NG-NRMM.

Thrust 2 – Simple Terramechanics (ST) Model and Data (Annex F) – The presentation discussed the thrust area's efforts to collect, describe, and codify existing deformable soil M&S approaches, along with their complementary supporting experimental methods that are based on pressure sinkage formulations of soft soil bearing pressure upon vehicle running gear along with their complementary traction-slip equations for traction stress response. Terramechanics effects are one of the primary attributes affecting vehicle mobility and have been judged by AVT-248 to be a foundational capability required in both the current NRMM and the NG-NRMM, and therefore one of the primary focus areas of the group. Specific areas discussed are defining the input and output parameters required for ST models, identifying and promoting prototype demonstrations of GIS-based end-to-end ST models and simulations and establishing an NG-NRMM ST database of valid ST parameter data sets.

Thrust 3 – Complex Terramechanics (CT) Model and Data (Annex G) – The presentation highlighted the thrust areas two main focus areas in CT. One area was to define a set of requirements which will guide development of CT software tools and associated calibration and validation experiments for NG-NRMM. Those software tools will be used to accurately predict the vehicle mobility measures on various worldwide terrains that are encountered in ground vehicle military applications, especially off-road soft soil terrains. Recommendations include: terramechanics models, experimental calibration of the terramechanics models, mechanics models of the interface between the soil and the vehicle surface (including tire models), and required CT data in GIS software tools. In addition, the thrust area presents CT prototype software tools that attempt to satisfy the requirements. The purpose of an NG-NRMM CT compliant software tool is to predict the mobility for any given ground vehicle, and terrain damage measures on any given terrain map which can include various terrain conditions.

NG-NRMM Virtual Demonstration (Annex H) – 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. The presentation describes 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.

Thrust 5 – Uncertainty and Stochastic Mobility Maps (Annex I) – This presentation described RAMDO Solution's work to develop a framework for a stochastic approach for vehicle mobility prediction over large regions using full stochastic knowledge of terrain properties and modern terramechanics M&S capabilities and to demonstrate the generation of reliability-based stochastic mobility maps. The framework is for carrying out Uncertainty Quantification (UQ) and reliability assessment for Speed-Made-Good and Go/No-Go decisions for the ground vehicle based on the input variability models of the terrain elevation and soil property parameters which are destined to be part of a suite of NG-NRMM tools. RAMDO discusses its work in carrying out UQ for the software vendors by creating and running the terramechanics simulations using a Dynamic Kriging (DKG) model of the terramechanics simulations to analyze the terrain and soil variability to generate the stochastic mobility maps. Figure 2-41 is an example of a Go/No-Go map of the MTU/KRC traverse terrain course(s) and RAMDO Solution's Final Report is included in Annex J.

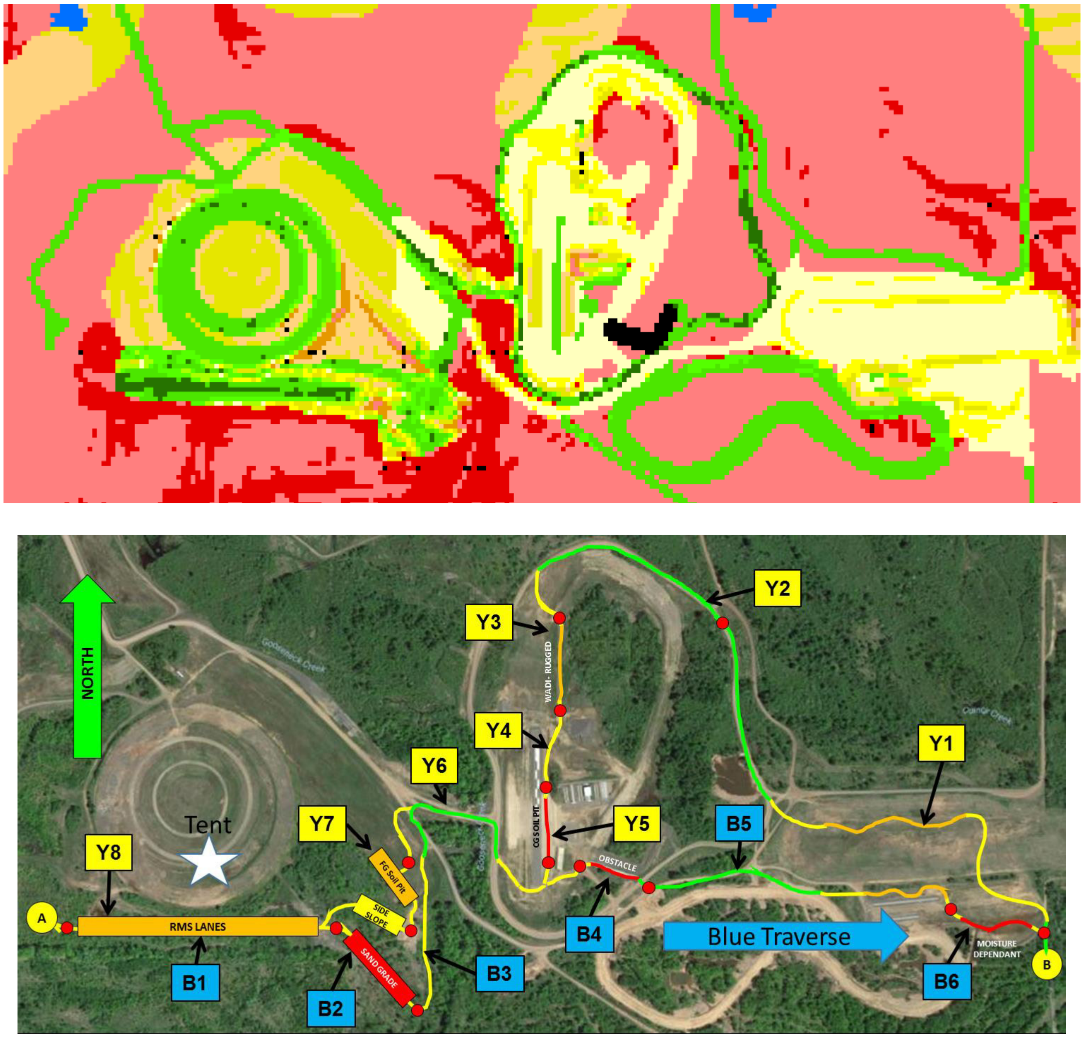


Figure 2-41: Sample Go/No-Go Map of MTU/KRC's Traverse Terrain Course.

Thrust 6 – NG-NRMM Verification and Validation (V&V) (Annex K) – The presentation described a framework for benchmarking the ability of M&S software solutions to predict mobility performance and validate against available test data and/or perform cross-code validation in case of lack of test data. It is an open-ended V&V effort since additional vehicle descriptive data and benchmarking tests can be added as they become available. It discusses the thrust area's efforts to demonstrate a process for a tracked and a wheeled vehicle and includes a number of software developers who were invited to participate in the benchmarks on a voluntary basis. A primary focus of the thrust area was to establish a reliable and comprehensive analysis process of the predictive capabilities of off-road vehicle simulation models and to establish a recommendation for software capability by means of modeling and simulation in connection with calibration, verification and validation with existing tests.

NG-NRMM Standard (Annex L) – This presentation described the STANREC that was constructed to describe the architecture, provide terrain data development guidance to ensure that terrain data products are interoperable between NATO and other alliance members, and that both the terrain data and NG-NRMM can be used by all NATO members. The recommendations provided align with the Defence Geospatial Information Working Group (DGIWG) – the multi-national body responsible for geospatial standardization for the defence organizations of member nations, to provide compatible geospatial information for joint operations. The STANREC defines the product specifications, encoding formats and application schemas for military geospatial data; and is built upon generic and abstract standards for geographic information defined by the International Organization for Standardization (ISO TC/211) and the Open Geospatial Consortium (OGC).

Thrust 7 – Gaps and Operational Readiness (Annex M) – The presentation seeks to identify gaps that will need to be addressed by future work in the pursuit of NG-NRMM, more specifically capability gaps and the challenges of implementing NG-NRMM. It also discussed an exercise to benchmark the group's views on how the emerging NG-NRMM will be used (to provide context to gaps and challenges identified). It describes and identifies gaps and challenges in work to date against the ET-148 and STANREC requirements and makes recommendations for NG-NRMM and the STANREC.

CDT Review and Path Forward (Annex N) – The presentation summarized the efforts of the NATO ET and the follow-on RTG to upgrade the NRMM M&S tool and the planned path forward toward implementing the recommendations of the group.

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 physical 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 talks described below.

MSC – Military Vehicle Simulation with Adams: Mobility and Beyond (Annex O) – MSC Software's presentation illustrated the capability of its' current commercial multi-body dynamics analysis tools for predicting military vehicle mobility in a wide variety of scenarios. MSC's Adams™ product suite was used to model the FED-Alpha vehicle, successfully validate this model, and then accurately predict the vehicle performance on both paved and deformable surfaces. MSC demonstrated a capability for incorporating either ST or CT terrain representations into the Adams™ analysis domain and evaluating the corresponding vehicle mobility characteristics. Additionally, MSC discussed its' capability to simulate the FED-Alpha model with Adams™ at real-time speeds, facilitating a variety of autonomous, driver-in-the-loop and hardware in the loop development scenarios.

Lastly, MSC highlighted its work with Luciad to demonstrate the capabilities of its geospatial toolset through the creation of a custom application that leveraged the Adams™ simulation results to visualize vehicle mobility characteristics across a specified terrain and predict an optimal cross-country path (Figure 2-42). MSC Software's final report is included in Annex P.

CSIR – South African Mobility Prediction Software MOBSIM (Annex Q) – This presentation from South Africa's Council for Scientific and Industrial Research (CSIR) described its' in-house developed Mobility Prediction Software (MOBSIM). Similar in scope to the NRMM, MOBSIM's internal modules are discussed as well as its' inputs, simulation environment, and outputs. The two-dimensional, template-based software was utilized during the CDT to model and simulate the test matrix, where applicable, for comparison purposes.

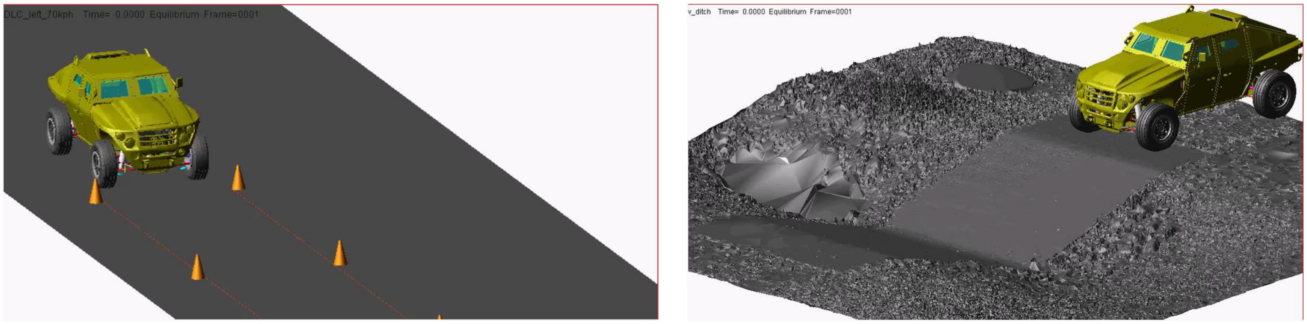


Figure 2-42: MSC Software NG-NRMM CDT FED-Alpha Simulations.

CML – Real-Time Vehicle Simulation using Vortex Studio (Annex R) – CM Labs presentation presented a high level overview of its' modeling of the FED-Alpha vehicle, performing the required tests, and then comparing results to actual MTU/KRC field test results. All modeling was done using CM Labs Simulations' Vortex Studio software (Figure 2-43), which is a unified simulation and visualization platform that allows you to create true-to-life simulations of land and sea equipment and environments, or integrate its components into other software. Vortex is also used in hardware in the loop simulations for design purposes and the soft ground modeling in Vortex Studio is based on the Bekker/Wong ST model. CM Labs' final report is included in Annex S.

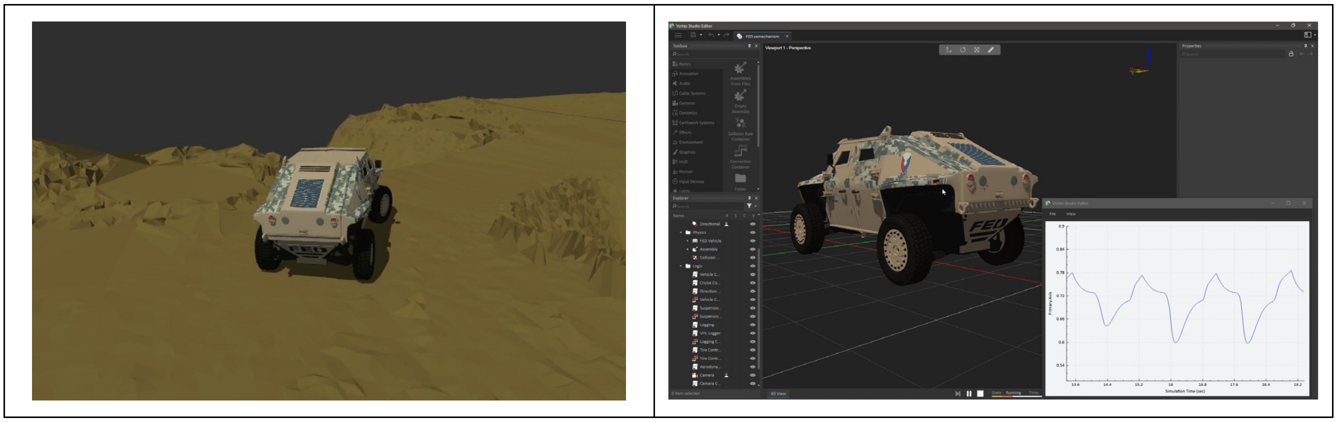


Figure 2-43: CM Labs NG-NRMM CDT FED-Alpha Simulations.

VSDC – Wheeled Vehicle Mobility Prediction Using NWVPM (Annex T) – This presentation highlighted Vehicle Systems Development Corporation's ground vehicle mobility simulation and analysis using the Nepean Wheeled Vehicle Performance Model (NWVPM) which utilizes a Bekker/Wong ST model. It identifies the input terrain and vehicle parameters required to model the vehicle, the tests conducted, and presents the comparison of the performance of the FED-Alpha vehicle predicted by the NWVPM, with the MTU/KRC test results. VSDC's final report is included in Annexes U1 and U2.

AU – ROAMS, Fast Running Mobility Simulator Utilizing GeoTIFF Terrain Maps (Annex V) – This presentation described Aarhus University's simulation analysis of the FED-Alpha using the Jet Propulsion Laboratory's (JPL) ROAMS (Rover Analysis, Modeling and Simulation) software utilizing a Bekker/Wong ST model. It discussed the vehicle simulation in ROAMS (Figure 2-44) as well as the methods and theories for the involved simulation aspects. It further discussed the simulation execution and results of the individual vehicle tests that includes details on the implementation using the vehicle and soil data from MTU/KRC and insights into how the virtual vehicle tests were conducted in ROAMS. AU’s final report is included in Annex W.

Figure 2-44: Aarhus University NG-NRMM CDT FED-Alpha Simulations.

ASA DIS/A CT Software Tool for Predicting Vehicle Mobility (Annex X) – This presentation summarizes Advanced Science and Automation Corp.’s (ASA) NG-NRMM CDT project results. It describes the vehicle model, the soil model, and ASA simulation results for each CDT test event using both a ST and CT models. Figure 2-45 illustrates ASA simulations and their final report is included in Annex Y.

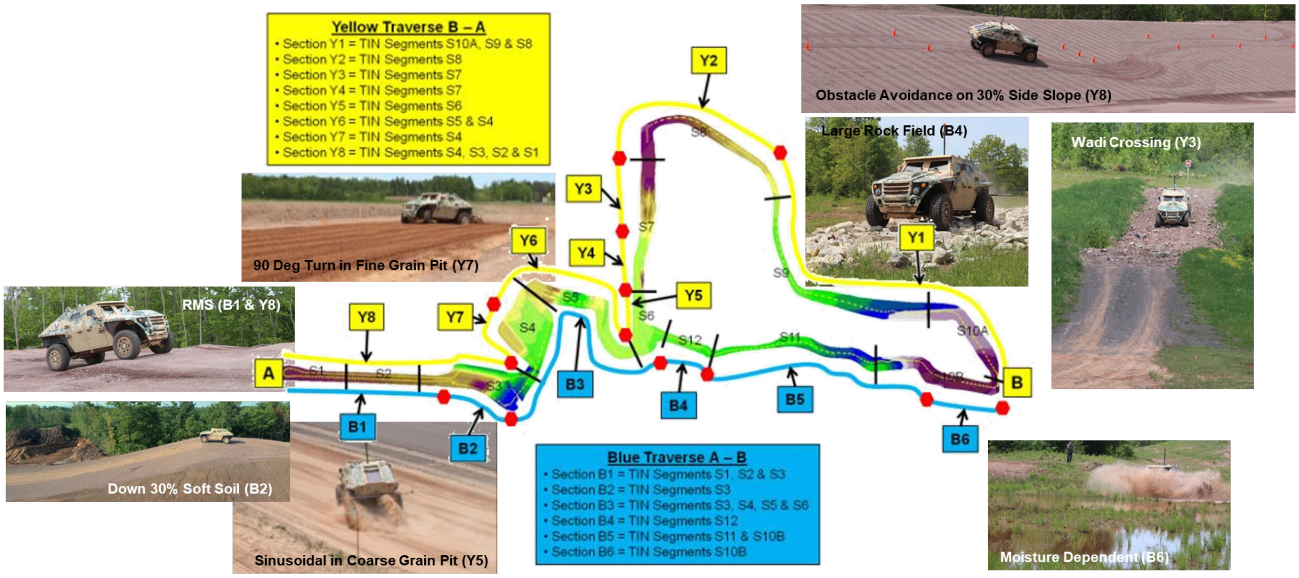
Other activities at the CDT were meant to keep attendees active, engaged, and as close as possible to the testing. On the first and second days of the CDT, participants were able to walk some of the courses and witness vehicle demonstrations of the vehicle traversing select terrains. Activities included ride-alongs, a soil data collection demonstration, driving simulators in the exhibit area, a large driving simulator brought by MSC located in the main MTU/KRC building, and two walk-around demonstrations meant to showcase the vehicle testing performed at the MTU/KRC test course. These demonstrations highlighted the RMS, Obstacle Avoidance on a Side Slope, Sand Grade, and a 90 Degree Turn in the Fine Grain Soil Pit tests that were used to collect data used in the NG-NRMM model refinement. These four tests were demonstrated twice, once with a wheeled FED-ALPHA and then with a tracked M113 A2/A3 Armored Personnel Carrier (Figure 2-46).

Figure 2-45: Advanced Science and Automation Corp.'s (ASA) NG-NRMM CDT FED-Alpha Simulations.

Figure 2-46: 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 (Figure 2-47) 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, 4 x 4, 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.



Yellow Traverse B – A
- Section Y1 = TIN Segments S10A, S9 & S8
- Section Y2 = TIN Segments S8
- Section Y3 = TIN Segments S7
- Section Y4 = TIN Segments S7
- Section Y5 = TIN Segments S6
- Section Y6 = TIN Segments S5 & S4
- Section Y7 = TIN Segments S4
- Section Y8 = TIN Segments S4, S3, S2 & S1

Blue Traverse A – B
- Section B1 = TIN Segments S1, S2 & S3
- Section B2 = TIN Segments S3
- Section B3 = TIN Segments S3, S4, S5 & S6
- Section B4 = TIN Segments S12
- Section B5 = TIN Segments S11 & S10B
- Section B6 = TIN Segments S10B

Figure 2-47: Mobility Traverse Course.

The event also featured software vendor booths as well as displays from other CDT participants. The static displays included nine vehicles displaying small, medium, and large variants of both wheeled and tracked vehicles and some additional robotic vehicles, including:

- M1 Abrams Main Battle Tank;
- Assault Amphibious Vehicle (AAV);
- M113 Armored Personnel Carrier (APC);
- RG 33L Panther Medium Mine-Protected Vehicle (MMPV);
- RG31 Mk5 4×4 Mine-Protected Personnel Carrier Vehicle (MPPCV);
- FED-Alpha;
- 6 wheel skid steer variant of the Lockheed-Martin Squad Mission Support System (SMSS);
- Tracked Howe and Howe Punisher Squad Multipurpose Equipment Transport Variant; and
- Polaris MRZR.

Many logistical challenges were met and solved by the MTU/KRC staff. Attendees registered through the NATO STO website and event communications was handled through an MTU/KRC website. This allowed the MTU/KRC staff to update the website with the latest information about housing at local hotels, transportation arrangements between those hotels and the MTU/KRC facility, flight arrangements, and meal accommodations. Lodging for over 400 people was arranged in local hotels. The presentation tent was built to accommodate and seat up to 200 people, hold 11 total exhibits, and have space for tables of food to be served. Shuttle services were also necessary to take all attendees out about 1.5 miles into the test course to get to the main event location. A fleet of five twelve-passenger vans ran continuously throughout the day to carry people to and from demonstration areas and the main event area. Finally, MTU/KRC staff provided security to prevent unwanted access into secured MTU/KRC areas. Feedback (Annex Z) from participant surveys revealed a unanimous agreement that the CDT was a success and that the event logistics were well handled by MTU/KRC. All events on the agenda, as tight as it was, ran as scheduled and all unforeseen occurrences were well handled and the agenda adjusted accordingly. The demonstrations of technology were greatly appreciated and provided valuable first-hand experience to those who participated, especially to those who had never seen a military vehicle or had not experienced riding in off-road vehicles.

Chapter 3 – RESULTS / LESSONS LEARNED

The entire CDT required enormous effort on a compressed time schedule. The software developers were constantly delivering on new sub-tasks: calibration, full tests and mobility traverses. There was limited time to perfect the simulation models, but it is believed that the CDT demonstrated the capability well. Additional time would allow for improved simulation results, but the overall goal of the CDT was demonstrated with the results presented in this report.

The overall conclusions on the verification and validation as well as the comparison between NRMM and NG-NRMM performance on the mobility traverses can be summarized as follows:

- Automotive tests:
  - NG-NRMM physics based 3D models are capable of predicting all tests; and
  - NRMM lacks 3D dynamics and therefore only performs straight line events.
- Soft Soil Tests:
  - NG-NRMM predicts all soft soil events except Coarse Grain Dry;
  - CT and ST software developers demonstrated multi-pass effects;
  - NRMM only predicts events on Fine Grain Soil Wet; and
  - NRMM showed large variation in slope prediction.
- Mobility Traverse:
  - NG-NRMM predicts within 25% of the test speed in more than 75% of the traverse segments;
  - NG-NRMM driver models do not have the same perceived speed limits compared to a test driver; and
  - NRMM over-predicts average speed compared to tests.

Overall NG-NRMM capable software was demonstrated to be in better agreement with tests as performed at KRC compared to NRMM. Several of the CDT tests were not possible for NRMM as they are 3D dynamic events. 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 coarse grain, dry. 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.

Chapter 4 – CAPABILITY GAPS / CHALLENGES

The AVT 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 a methodology on 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 Monterey and CDT data sets).

4) **Soft soil simulation – Test standards, lack of required improvements (e.g., drawbar pull test); relating model and physical parameters, CT using material point method (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, define 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; includes 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 recommend a 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.** TBD.
12) **Intelligent Mobility.** 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 and 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) have 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.

Chapter 5 – RECOMMENDATIONS / WAY FORWARD

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, remotely 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 were 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 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. 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 for the future, 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 terramechanics experiments to understand 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.

Chapter 6 – TAKEAWAYS / FOLLOW-ON ACTIVITIES

6.1 TAKEAWAYS

Modern methods, such as NG-NRMM, can significantly improve the ability to make more accurate mobility predictions and assessments which hold 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.

All of the data/information mentioned in this paper including raw test performance data, vehicle data, terrain and soil data, CDT event information, and promotional videos is Distribution Statement A – Unclassified – Distribution Unlimited and can be downloaded at ftp://ng-nrmm:thread$panel@nrmm.mtukrc.org for use. The entire site is currently set to read-only access and all information and media located on the site can used and distributed freely.

6.2 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 were released to the NMSG (NATO Modeling and Simulation Group) for review in December 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 hopefully, resolved by, NATO itself, individual participating nations, or related independent software developers.

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Verification and validation

14. Abstract

A NATO Research Task Group (RTG) committee was formed to develop a Next-Generation NATO Reference Mobility Model (NG-NRMM). A NATO Cooperative Demonstration of Technology (CDT) effort was held to demonstrate and validate the NG-NRMM and in September 2018, a 3-day CDT event took place to showcase the committee's work. The objective was to highlight key differences between legacy NRMM and next generation mobility prediction software by creating complex and simple terramechanics simulation models of a wheeled vehicle traversing actual terrain(s) and comparing the results to physical tests. An overview of the event, research, testing, and validation results are presented. The intent was to make the all the data available to the research community to use for further research in off-road mobility and autonomy and is Distribution Statement A – Unclassified – Distribution Unlimited and can be downloaded (details in report) for use.

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