Next Generation NATO Reference Mobility Model Development and Demonstration

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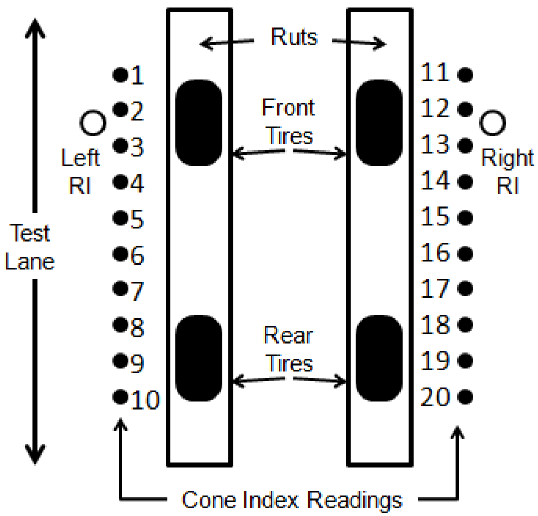
Dr. Richard Gerth, Deputy Chief Scientist

18 June 2018

Off-Road Mobility Challenges

Empirical Approach: NATO Reference Mobility Model

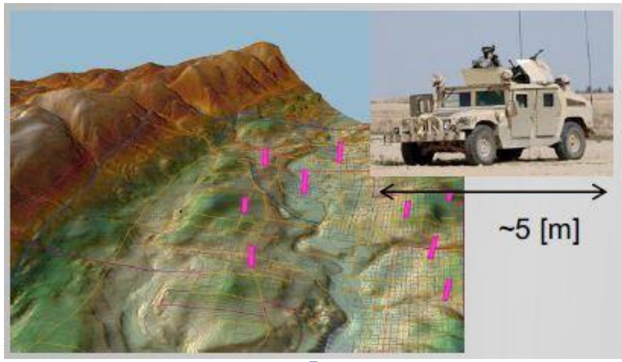


NATO Reference Mobility Model (NRMM)

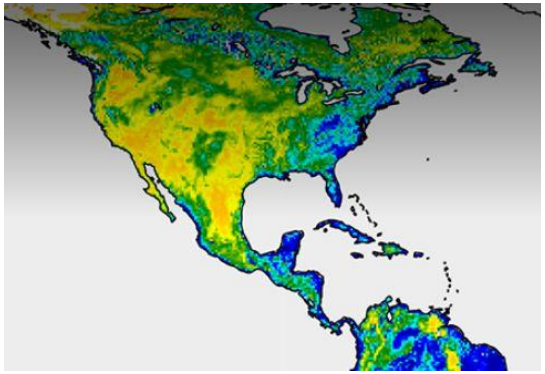
- Dr. M. G. Bekker of TARDEC is the "Father of Terrain-Vehicle Systems"
- NRMM was developed in 1960-70 by TARDEC and ERDC
- Worked towards NATO standardization in 1977-78
- Methodology relied on empirical relationships and **not** physics-based
- Does **not** extrapolate to contemporary vehicle designs and technologies
- Does **not** benefit from advances in simulation and computational capabilities

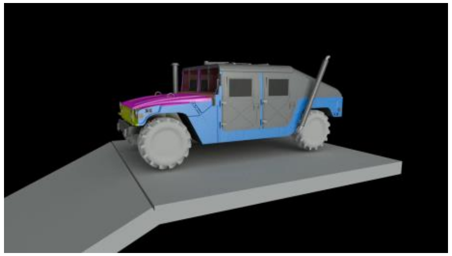
NATO AVT-248 Objective:
NextGen NATO Reference Mobility Model

Terrain Elevation Map



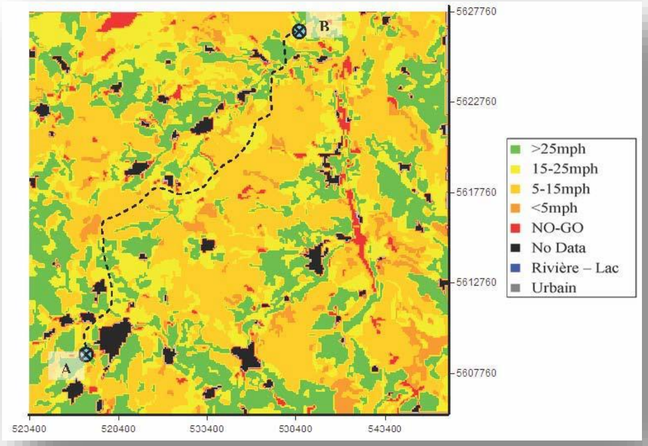
Soil Moisture Map

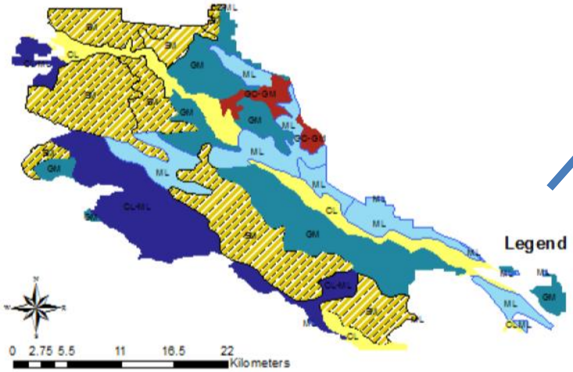




Physics-Based M&S

Mobility Go/NoGo Map





Soil Type

Qualitative | NRMM | NG-NRMM

1970 | 2020

NATO S&T Organization Applied Vehicle Technology Panel

- approved Exploratory Team from April 2014 - December 2015
- approved Research Task Group from Jan. 2016 – Dec. 2018
- 70 members from 15 nations participating

Goals

- Develop and demonstrate NG-NRMM process & technologies
- Incorporate NG-NRMM as a NATO Standard

Co-Lead

- Dr. Paramsothy Jayakumar (U.S. Army TARDEC)
- Dr. Michael Hoenlinger (KMW GmbH, Germany)

Research Thrusts

NATO Research Task Group 248 carries forward six research thrusts:

1. GIS Terrain and Mobility Map

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

2. Simple Terramechanics

   Identify most promising existing terramechanics methods supporting NG-NRMM requirements that provides possible means of correlating the requisite terrain characteristics to remotely sensed GIS data.

3. Complex Terramechanics

   Establish a vision for the long term terramechanics approaches that overcome the limitations of existing models.

Research Thrusts (continued)

4. Intelligent Vehicle Mobility

Identify unique mobility metrics and M&S methods necessary for mobility assessments of intelligent vehicles over a sliding scale of data and control system resolutions.

5. Uncertainty Treatment

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

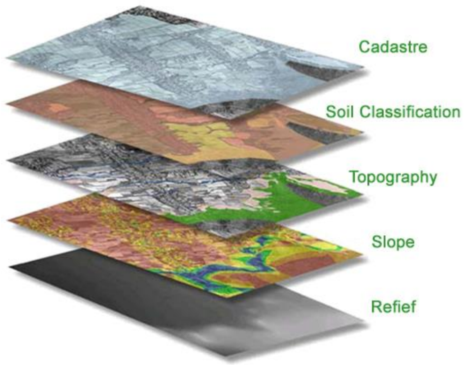
6. Verification & Validation (V&V)

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

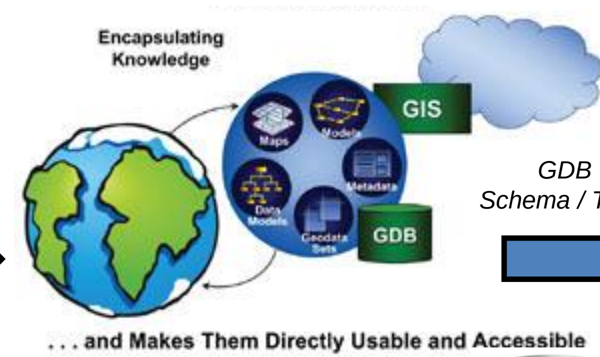
NATO AVT-248-Research Task Group Structure

Thrust	Lead	Organization
GIS Terrain and Mobility Map	Wojtysiak / Funk	AMSAA / ESRI
Simple Terramechanics	McCullough	BAE
Complex Terramechanics	Wasfy	ASA Corp.
Intelligent Vehicles	Jain	NASA JPL
Uncertainty Treatment	Choi	U Iowa / RAMDO Solutions
Verification & Validation	Balling	Aarhus Univ, Denmark
Data Gaps & Operational Readiness	Bradbury	DSTL, MOD, UK
Coop. Demonstration of Technology	Mayda / Gerth	NRC, Canada / TARDEC
NATO Standardization	Hoenlinger / McCullough	KMW GmbH, Germany / BAE

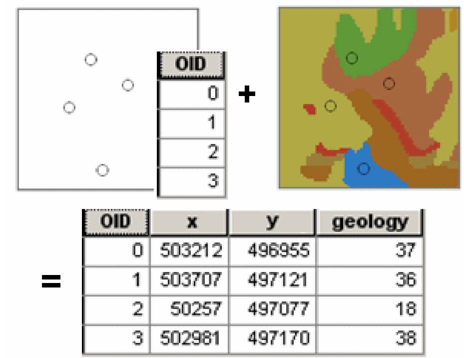
Thrust Area 1: GIS Terrain and Mobility Map



GIS Tools / Stds



GDB Schema / Tools



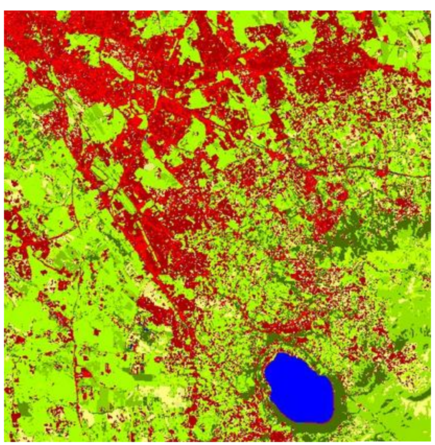
OID	x	y	geology
0	503212	496955	37
1	503707	497121	36
2	50257	497077	18
3	502981	497170	38

GIS Terrain Data Layers

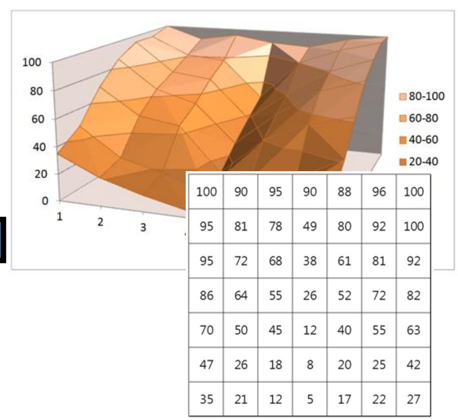
Geodatabase

NG-NRMM Terrain Dataset

(x, y, z, parameters 1…n)

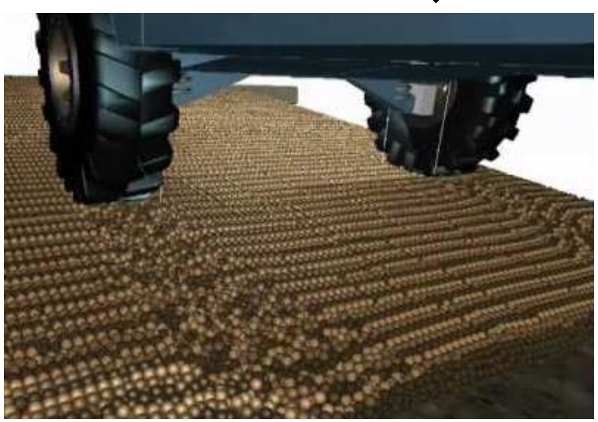


GIS Tools / Stds



100	90	95	90	88	96	100
95	81	78	49	80	92	100
95	72	68	38	61	81	92
86	64	55	26	52	72	82
70	50	45	12	40	55	63
47	26	18	8	20	25	42
35	21	12	5	17	22	27

Raster Output



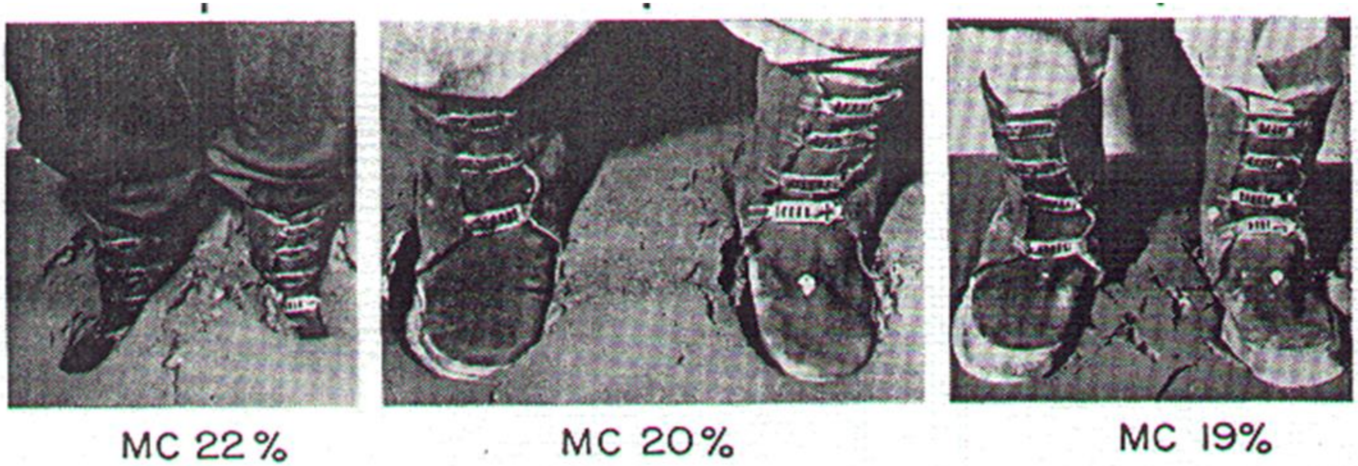
Geodatabase / Map Product

(x, y, z, t, parameters 1…n)

MBD Results Raster

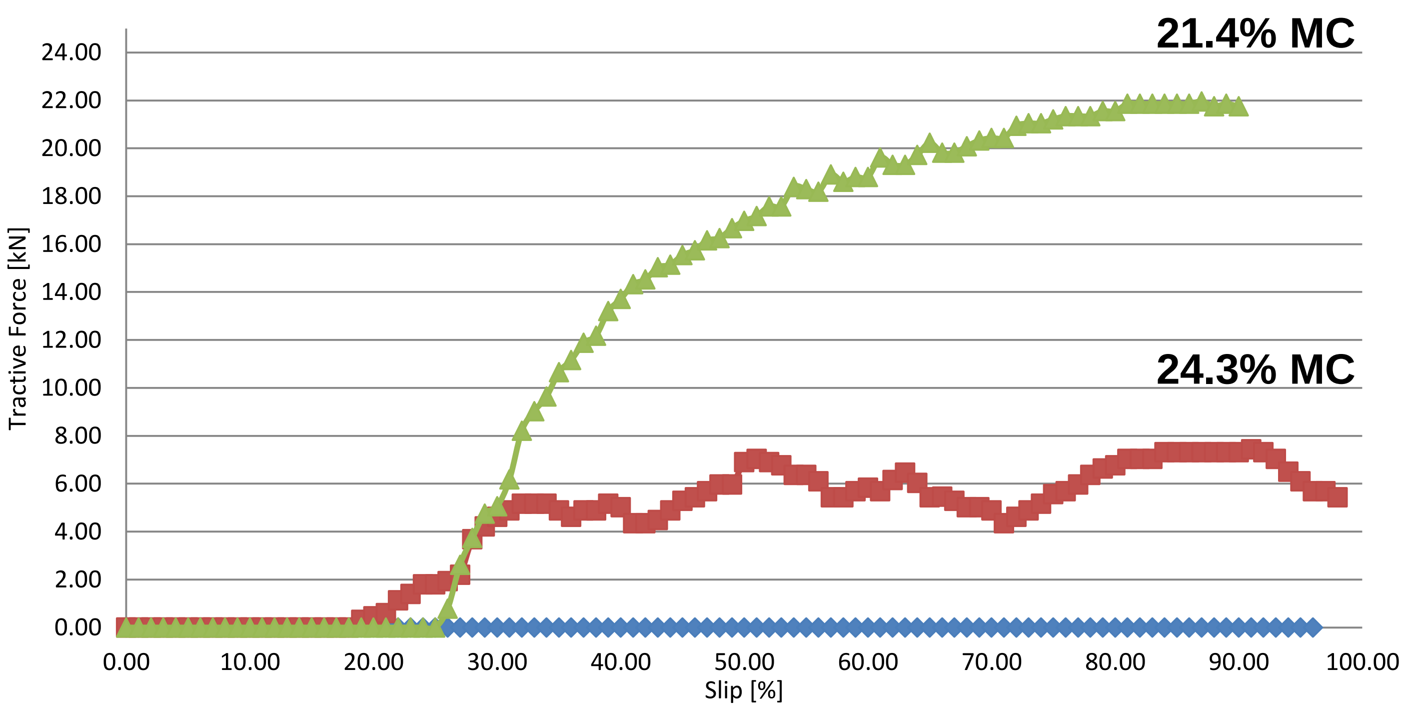
Raster Dataset in MBD Model

Moisture Content Effect



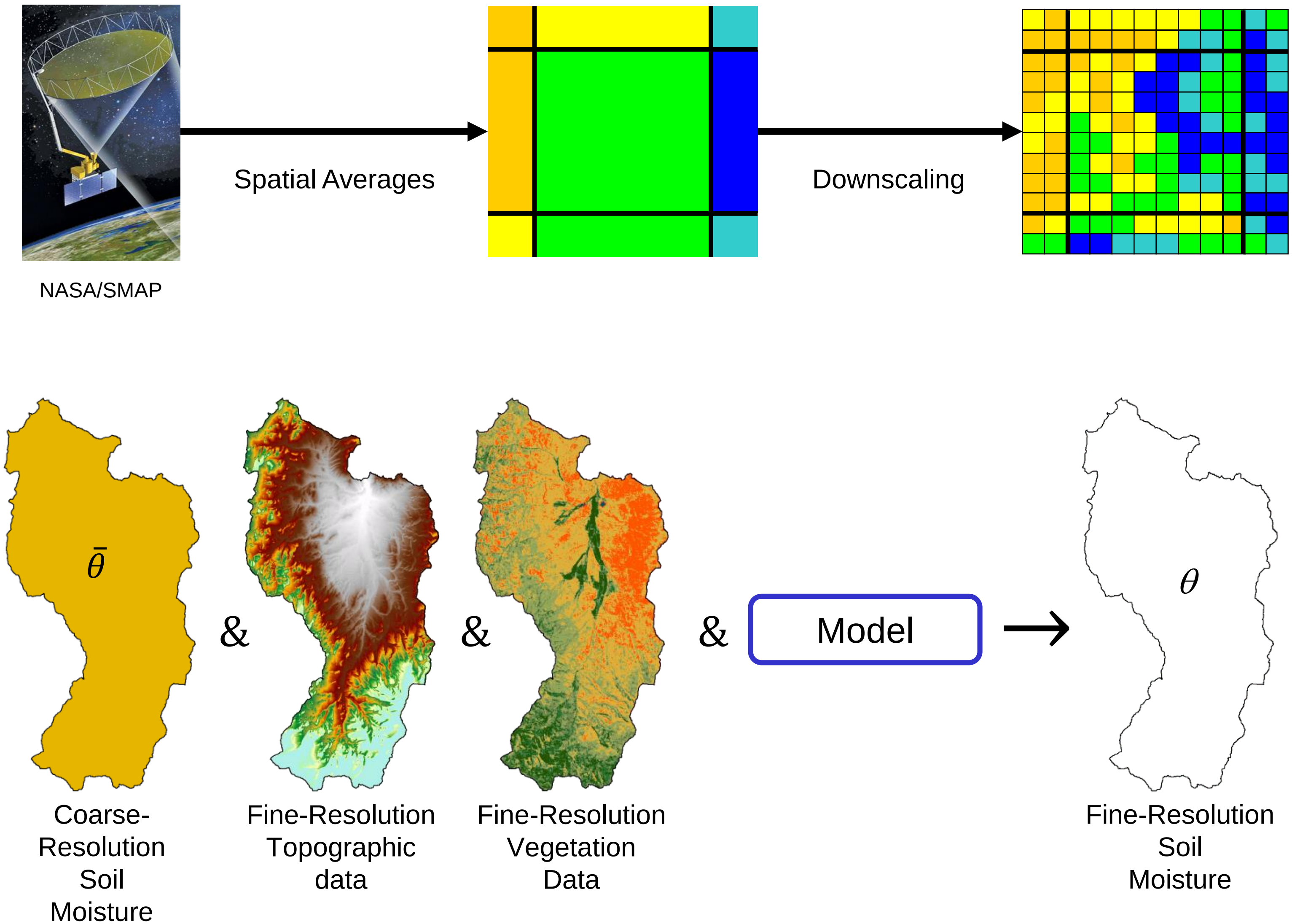
Bekker, M. G., “Off-the-Road Locomotion,” University of Michigan Press, 1960

Drawbar Pull

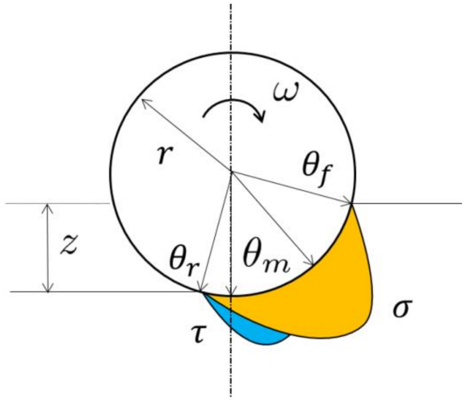


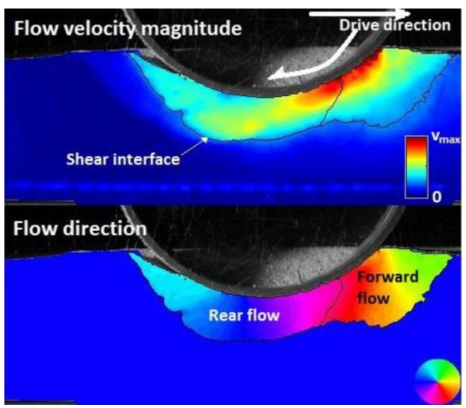
Tom Von Sturm
Bundeswehr, Germany

Downscaling Moisture Content



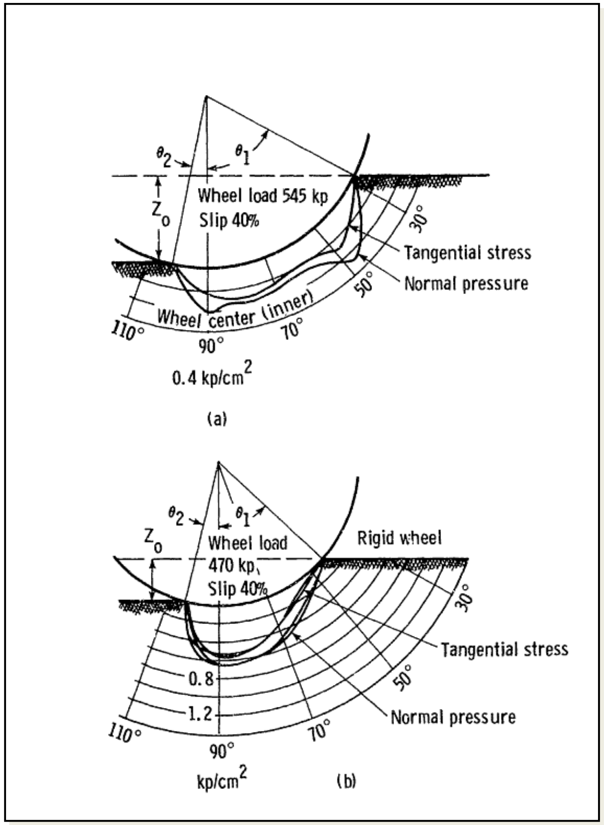
Bekker-Wong-Janosi Models



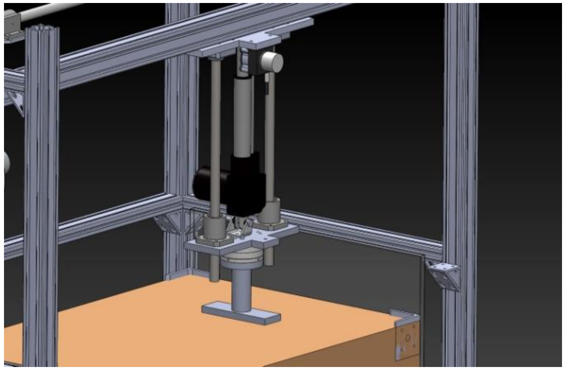


Particle Image Velocimetry

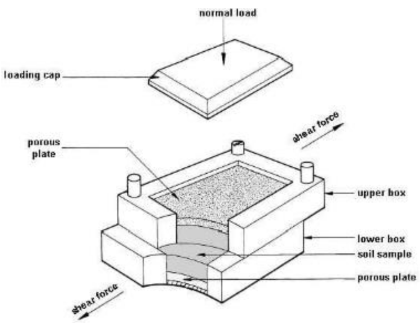
Stress Distribution



Laboratory Identification

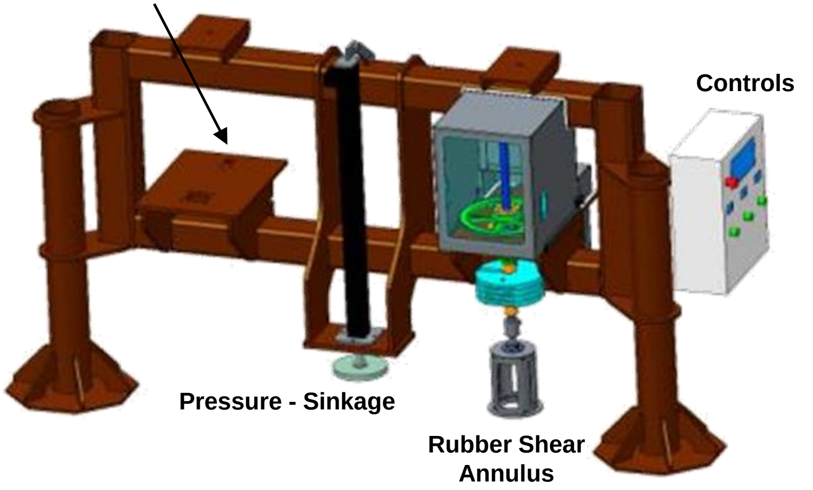


Pressure – Sinkage Test



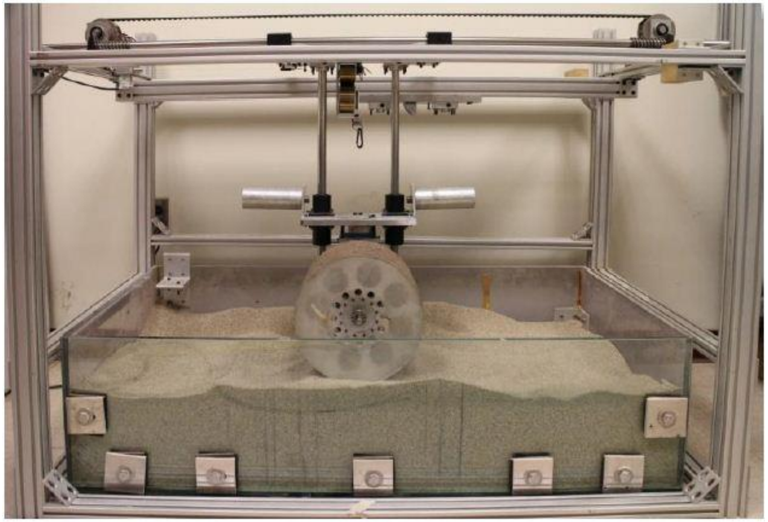
Direct Shear Test

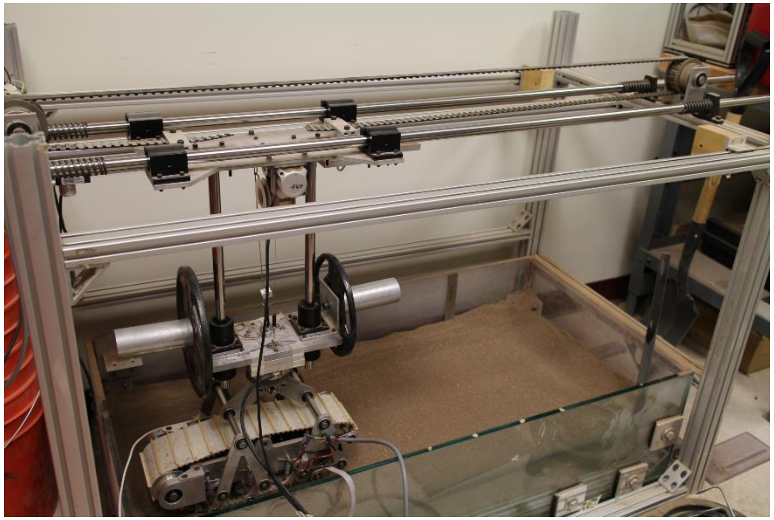
Soil Characterization Using Bevameter



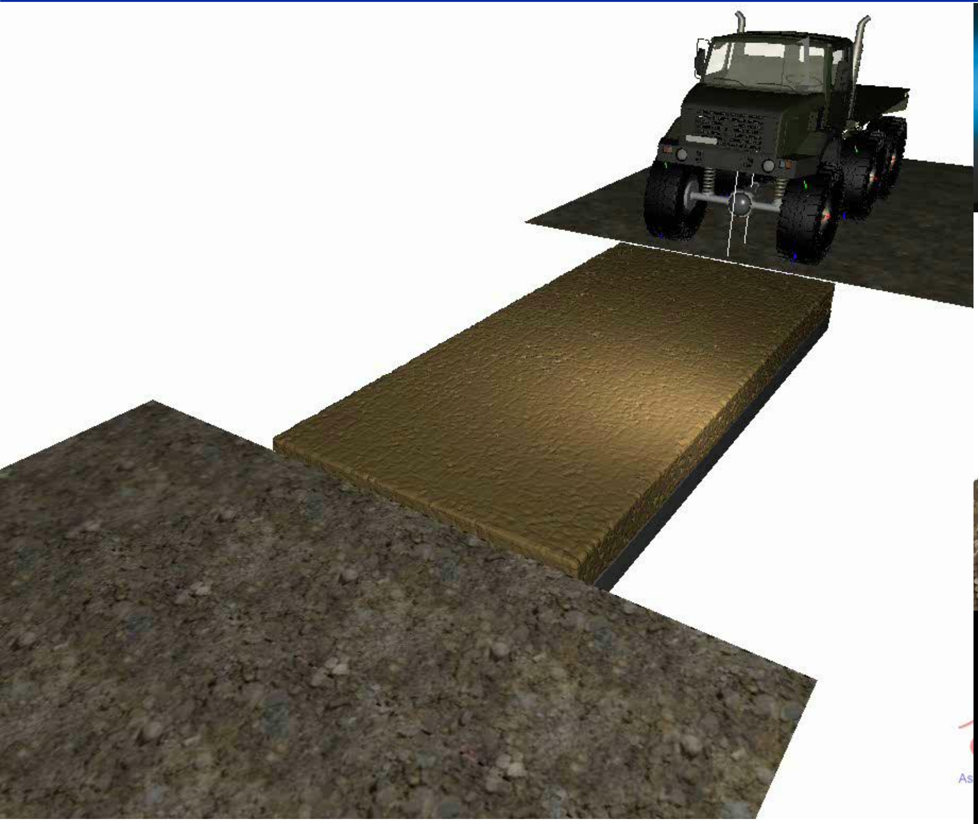
- B-W-J model calculates
  - draw bar pull
  - sinkage
  - motion resistance

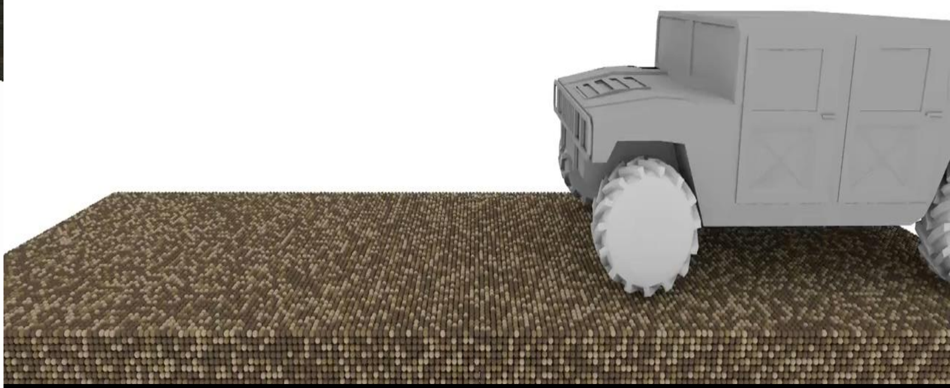
Experimentation Challenges: Relating Lab to Field

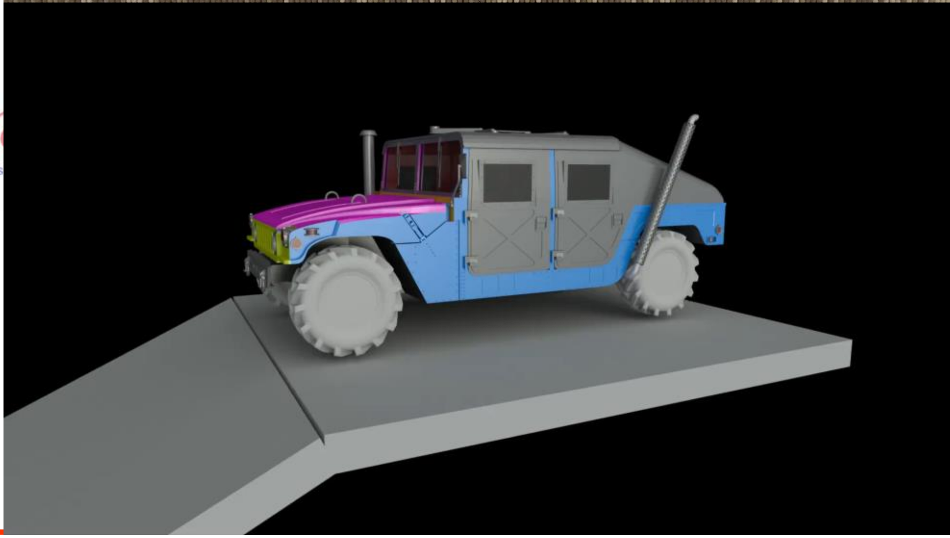




Thrust Area 3: Complex Terramechanics





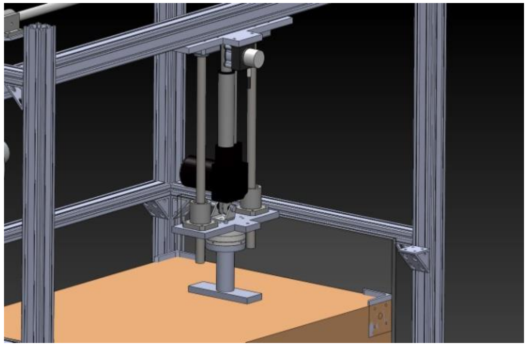


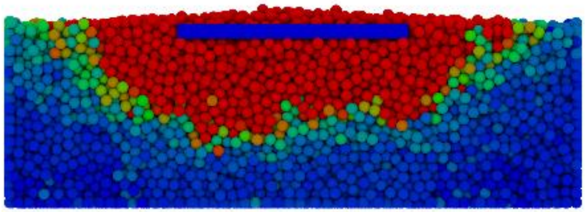
Computational Burden

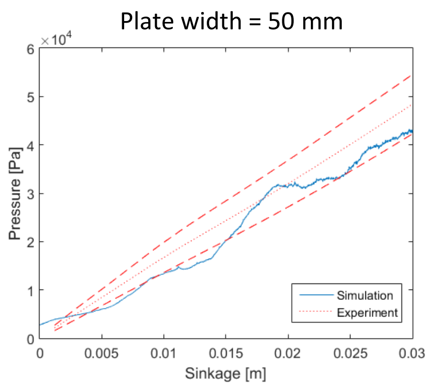
- **Hardware:** Cray XC40 32 cores
- **Software:** IVRESS; **Contact method:** DEM-P
- **Run time:** **14,000x slower than real time**
- **Model particle dia / Physical :** 30 mm **/** 0.002 mm
  = **15,000x bigger than real size**

Building Blocks: Scaled Experiments & Simulations

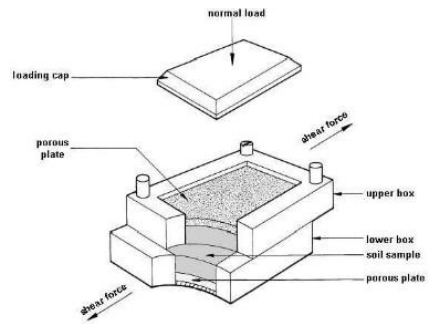
Pressure – Sinkage Test

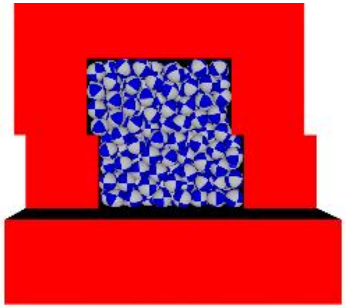


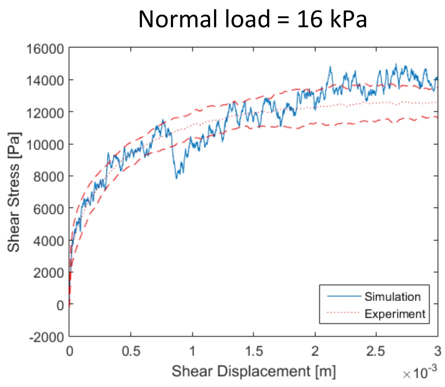




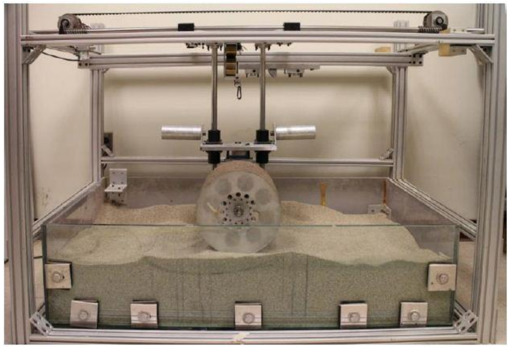
Direct Shear Test

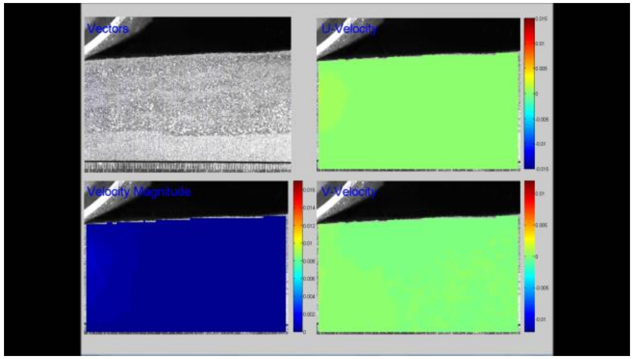


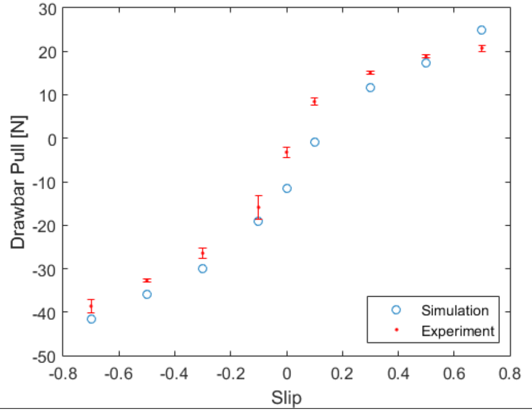




Single Wheel Test





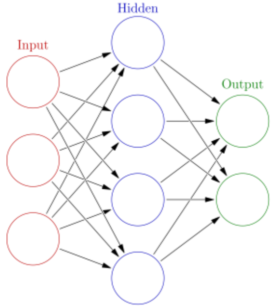


Performance Challenges: Algorithms & Hardware

High-Performance Computing

Multilayer Perceptron

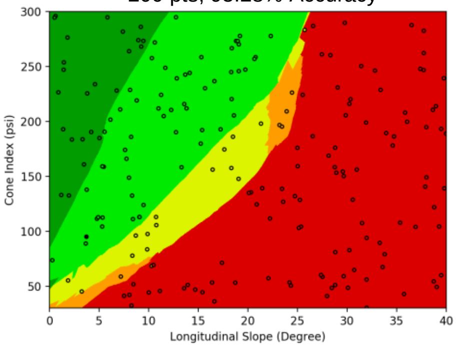
1 hidden layer with 100 nodes/layer



Random Sampling vs Active Learning

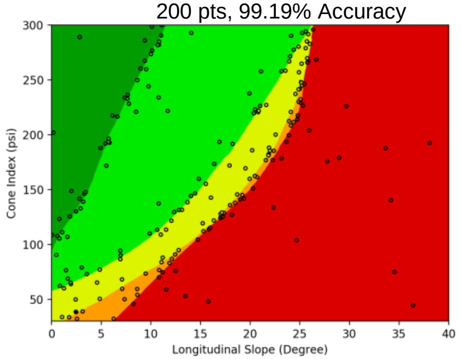
Random Sampling

Bootstrap Aggregating with 20 MLPs, 200 pts, 95.28% Accuracy

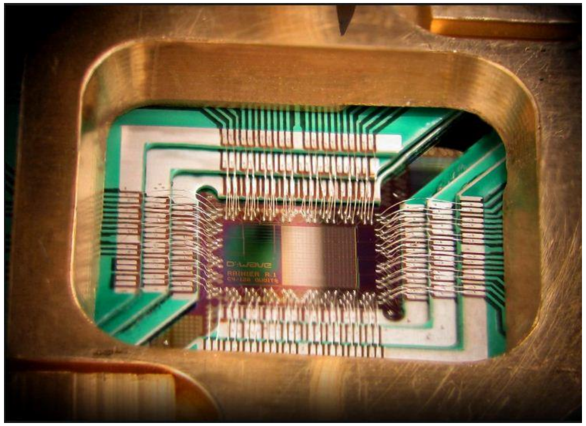


Active Learning

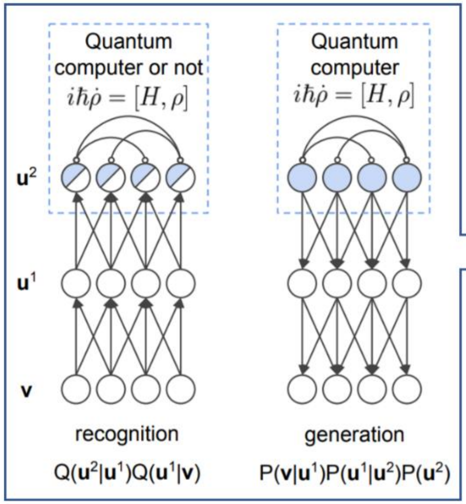
Bootstrap Aggregating with 20 MLPs, 200 pts, 99.19% Accuracy



Quantum Computing



Model



Data

$$\boldsymbol{s} = \{s_0, s_1, \dots s_n\}$$

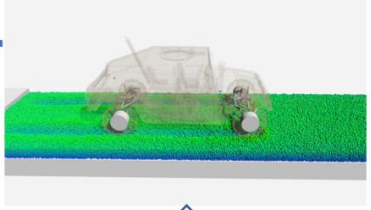
Quantum-Assisted Learning

Stochastic Gradient Descent

$$\frac{\partial \mathcal{G}}{\partial a_i^\ell} = \langle u_i^\ell \rangle_Q - \langle u_i^\ell \rangle_P$$

$$\frac{\partial \mathcal{R}}{\partial b_i^\ell} = \langle u_i^\ell \rangle_P - \langle u_i^\ell \rangle_Q$$

Simulation



Predictions

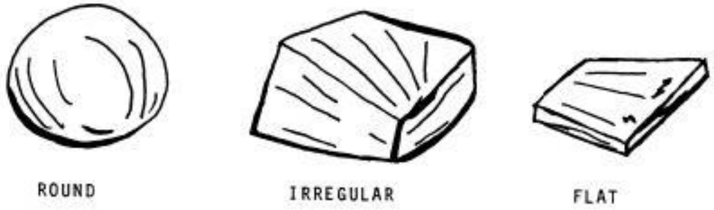
$$\mathbf{v} \sim \mathrm{P}(\mathbf{v}|\mathbf{u^1})\mathrm{P}(\mathbf{u^1}|\mathbf{u^2})\mathrm{Q}(\mathbf{u^2})$$

$$\mathbf{v} \sim \mathrm{P}(\mathbf{v}|\mathbf{u^1})\mathrm{P}(\mathbf{u^1}|\mathbf{u^2})\mathrm{P}(\mathbf{u^2})$$

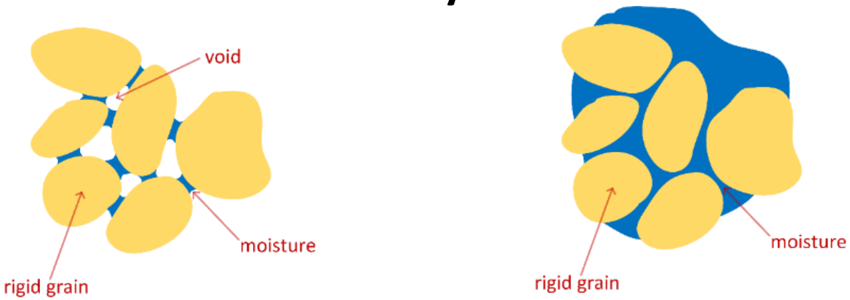
Challenging Nature of Off-Road Mobility

FY 2019 DOD MURI BAA: $6.25 mil. over 5 years, up to 6 PIs

Heterogeneity



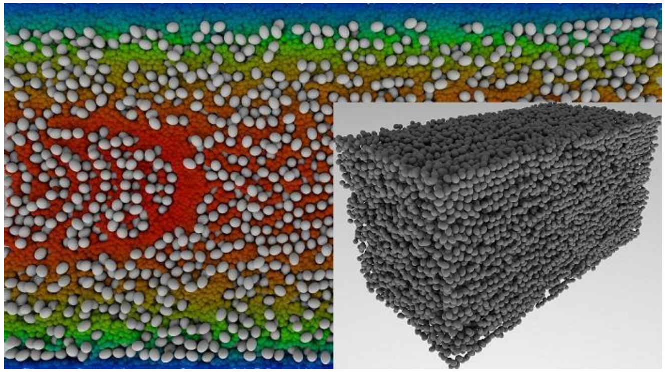
Multi-Physics



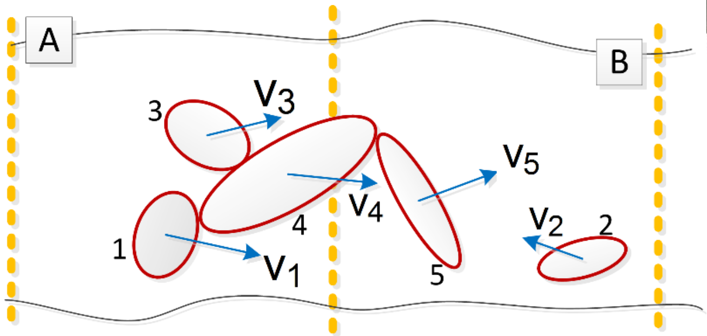
Low Saturation

High Saturation

Scalability



Dynamics



Multi-Scale

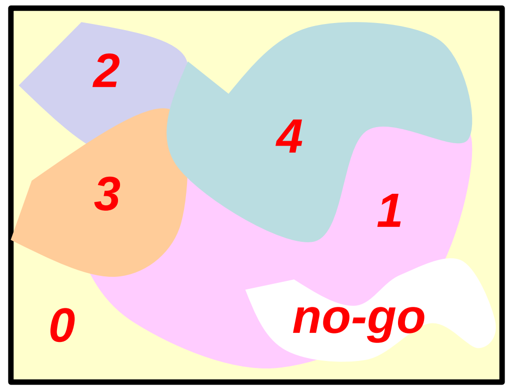
Environment

Scenario with metrics

NG-NRMM(I)

Specific vehicle model & intelligence modes

Mobility plan (knob settings) for the region



"Autonomy Map"

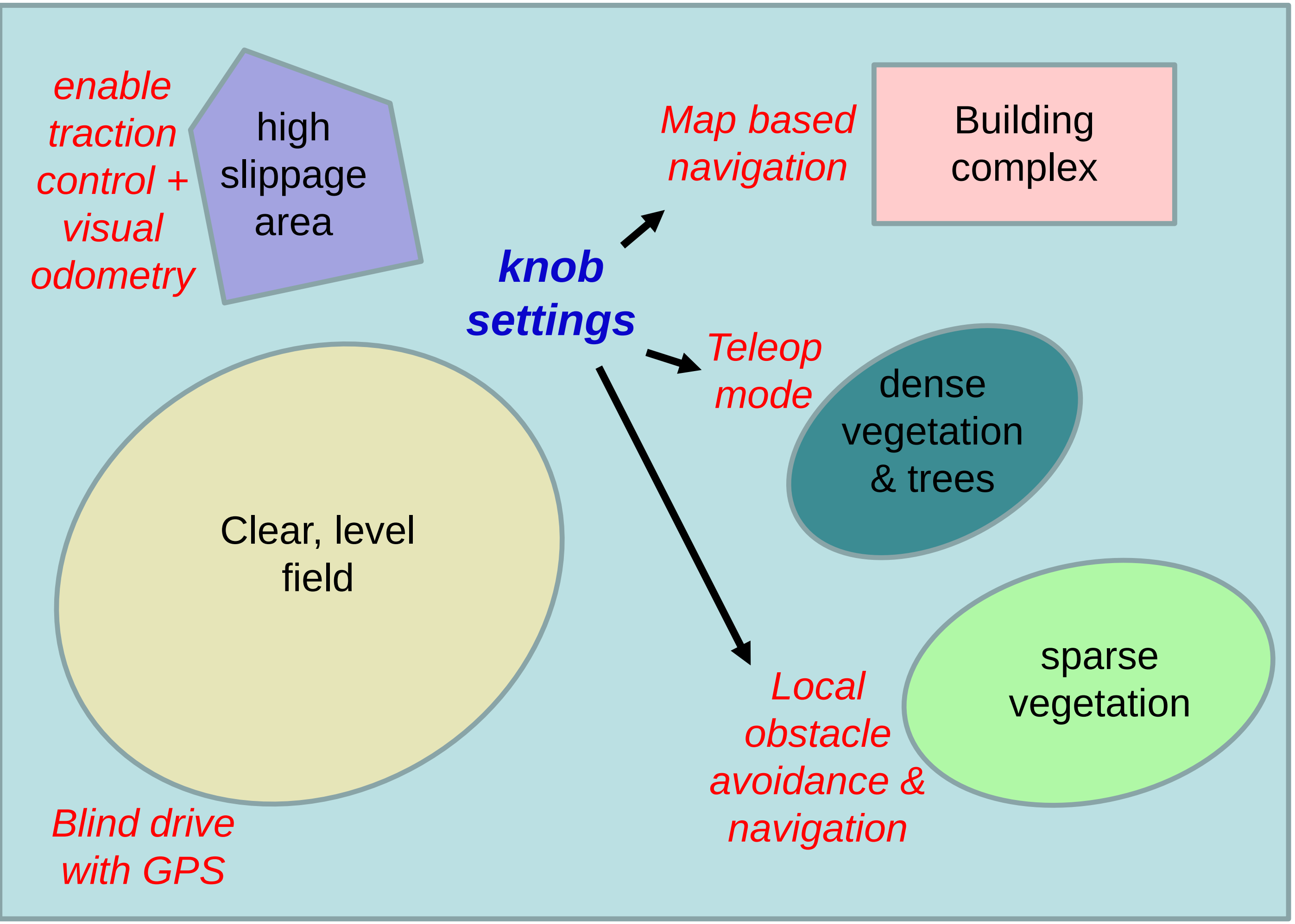
Component performance metric maps

Speed
Fuel consumption
Stability
Ride roughness
Slippage
Comm usage
…

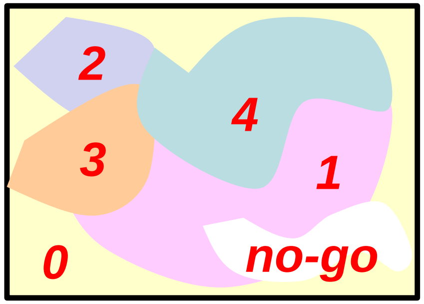
The knob settings recommendations from the **autonomy map** provide guidance for the proper operation of an intelligent vehicle across a region – and the generation of this map is the **primary responsibility** of NG-NRMM(I)

NG-NRMM standards will encompass the broader definitions of terrain and vehicle morphologies that are characteristic of intelligent vehicle applications.

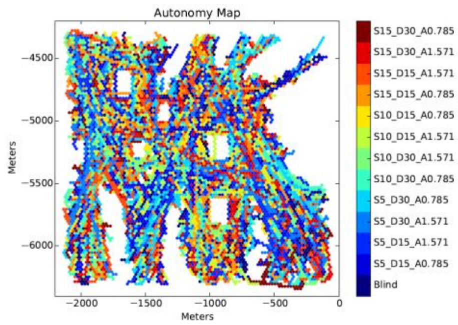
Variable Intelligence Modes

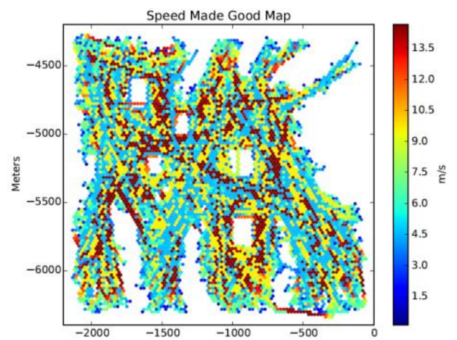


Autonomy Map (knob settings)



Autonomy and Speed Maps

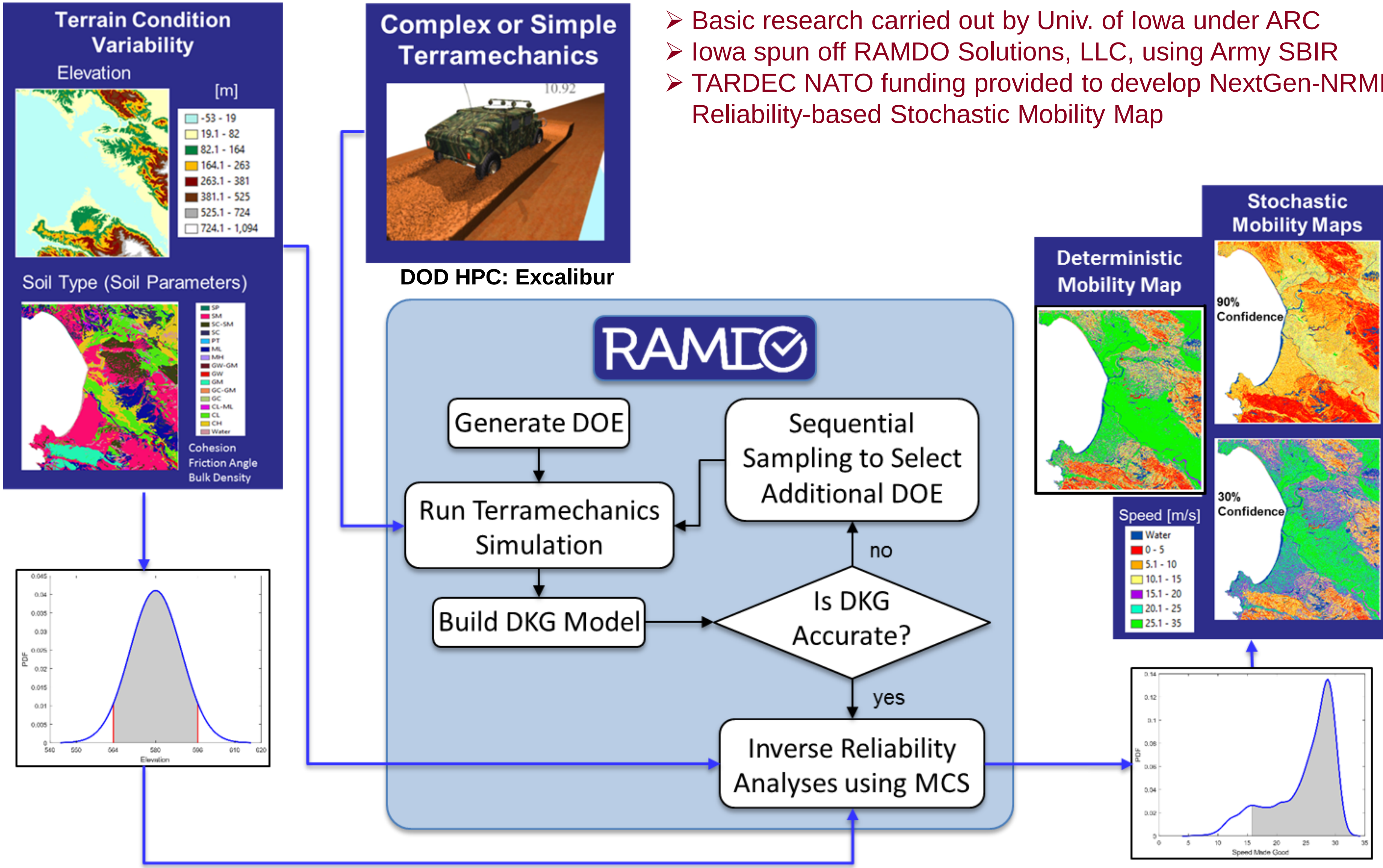




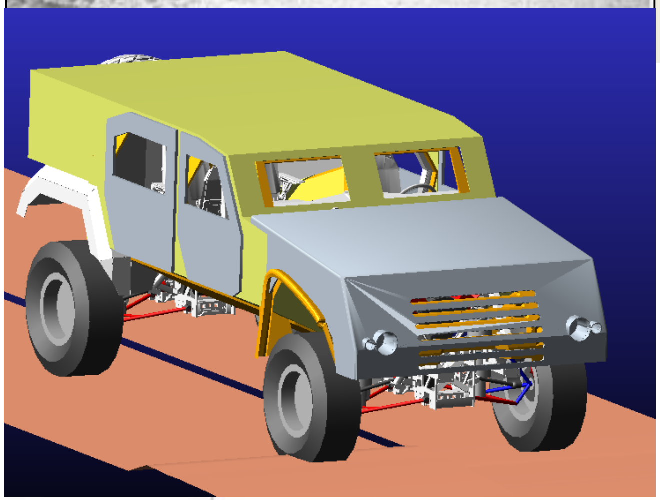
Need autonomy map to assign intelligence mode across the region in order to develop performance maps.

Thrust Area 5: UQ Stochastic Mobility Framework

- Basic research carried out by Univ. of Iowa under ARC
- Iowa spun off RAMDO Solutions, LLC, using Army SBIR
- TARDEC NATO funding provided to develop NextGen-NRMM Reliability-based Stochastic Mobility Map



Thrust Area 6: Verification and Validation



Participating Tool Developers

- United States
  - Advanced Science and Automation Corp.
  - MSC Software Corp.
  - University of Wisconsin – Madison
  - RAMDO Solutions
- Canada
  - CM Labs Simulations Inc.
  - Vehicle Systems Development Corp.
- South Korea
  - FunctionBay Inc. / MotionPort LLC
- South Africa
  - Council for Scientific and Industrial Research
- Denmark
  - Aarhus University

NG-NRMM Software Maturity Level

1. ***DEMONSTRATION:*** Demonstration of a correct implementation of a theoretically and conceptually consistent model.
2. ***PARAMETER SENSITIVITY DEMONSTRATION:*** Verification that performance change with a change in system parameter such as GVW or terrain deformability is consistent with theory and physics principles.
3. ***INDEPENDENT USER VERIFICATION:*** Independent user demonstration and correlation to vendor results
4. ***CROSS CODE VERIFICATION:*** Cross verification with another accepted mobility simulation code
5. ***CALIBRATION:*** Calibration to a real vehicle test data set
6. ***VALIDATION:*** Blind correlation to a real vehicle test data set
7. ***PARAMETER VARIATION VALIDATION:*** Blind correlation to a real vehicle test data set with a change in system parameter(s).

Test Matrix

Test Name	Terrain
1 Straight Line Acceleration and Braking (TOP 2-2-602)	Pavement
2 Wall to Wall Turn Circle Radius	Pavement
3 Steady State Cornering (30 m radius) (SAE J2181)	Pavement
4 NATO Double Lane Change (AVTP 03-160 W)	Pavement, Gravel
5 Max. Side Slope with Sinusoidal Steer & Obstacle Avoidance	Hard-Packed Crushed Mine Rock
6 Maximum Longitudinal Grade	Pavement, Coarse Grain Sand
7 Vertical Step: 12”, 18", 24"	Concrete
8 V-Ditch	Concrete
9 Half-Round Obstacle: 4", 8", 10", 12"	Pavement
10 Symmetric Random Roads: 1", 1.5”, 2", 3“, 4” RMS	Hard-Packed Crushed Mine Rock
11 Asymmetric Random Roads: 1", 1.5”, 2" RMS	Hard-Packed Crushed Mine Rock
12 Soft-Soil Mobility: Drawbar Pull	Course Grain Sand Fine Grain Organic/ Silty Sand: Dry & Wet
13 Mobility Traverse	Composite of Natural Terrain & Engineered Courses

Paved Grade 60%

Sand Grade – Variable up to 30%

5% Grade Change Every 33 ft

Going Up

Coming Down

Mobility Traverse Segments

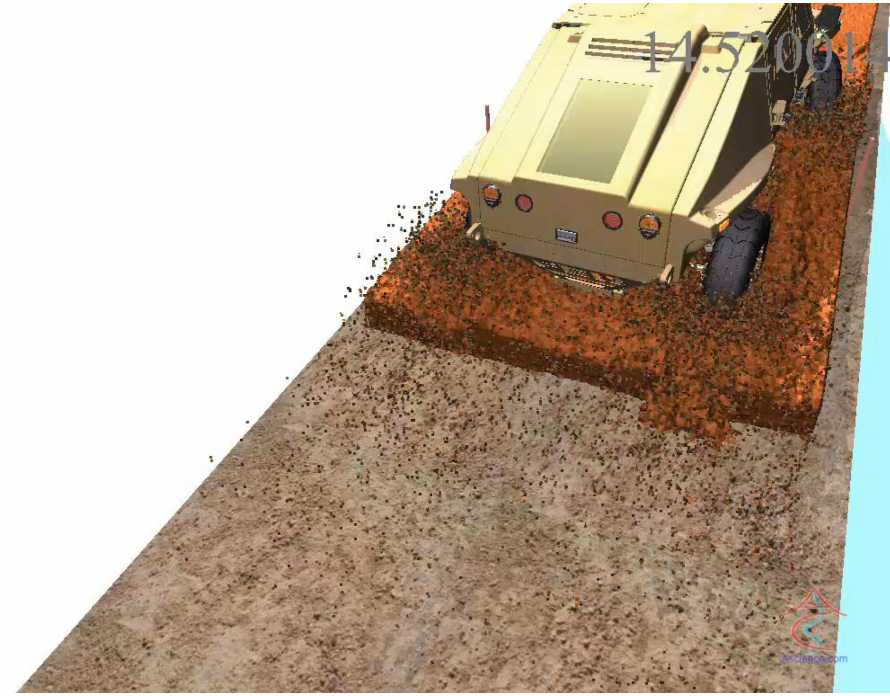
Sinusoidal on Coarse Grain Soil

WADI Crossing

Obstacle Avoidance on Side Slope

OEF Obstacle Course

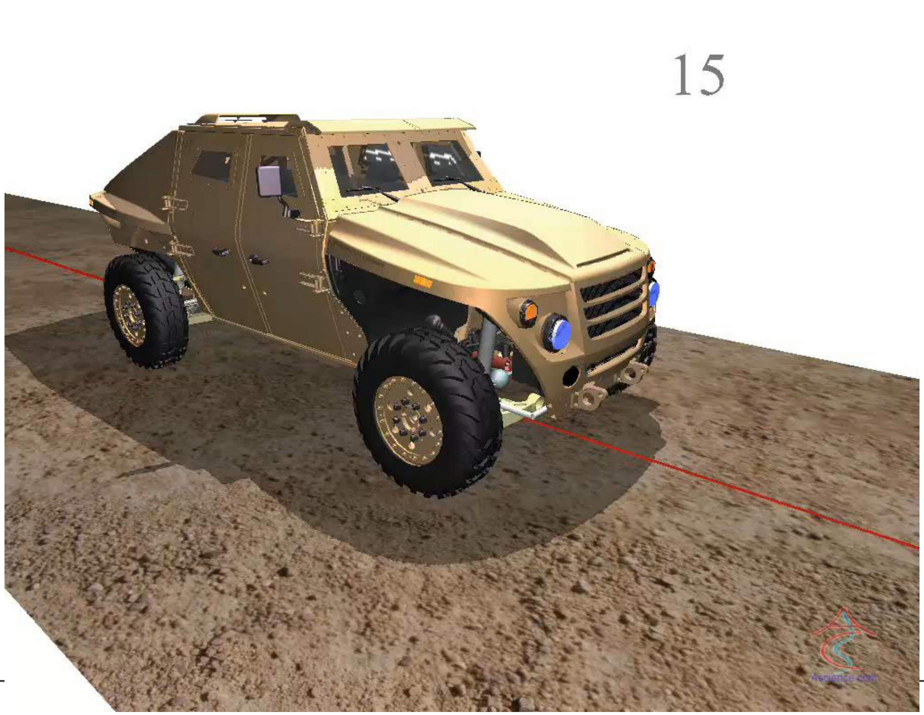
Soft Soil Mobility Demonstration



Ride Quality Demonstration

Symmetric Road: 3 in RMS

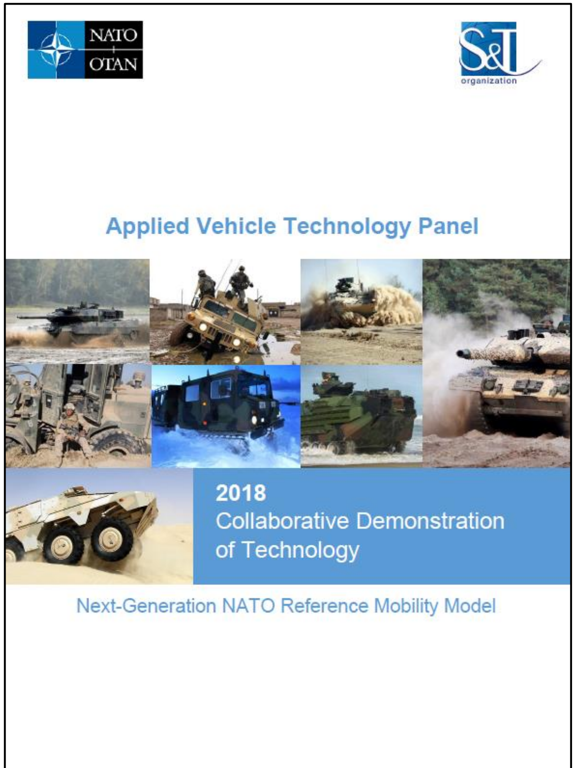
Asymmetric Road: 1.5 & 2.0 in RMS

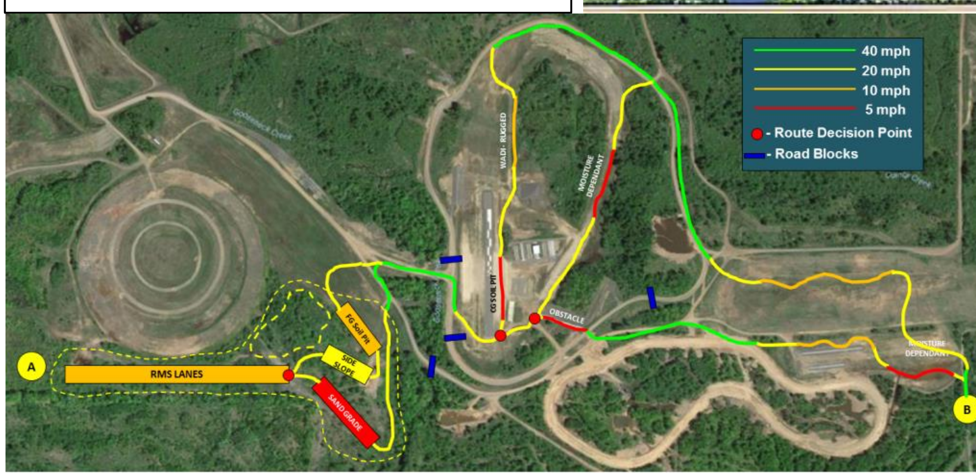


STANREC 4813: The STANREC guidance codifies results of the NG-NRMM effort and establishes an enduring artifact and path for NATO nations mobility modelling experts consensus of methods, benchmarks, and source databases that should be applied to physics based models and simulations of all operational land and amphibious mobility among the alliance.

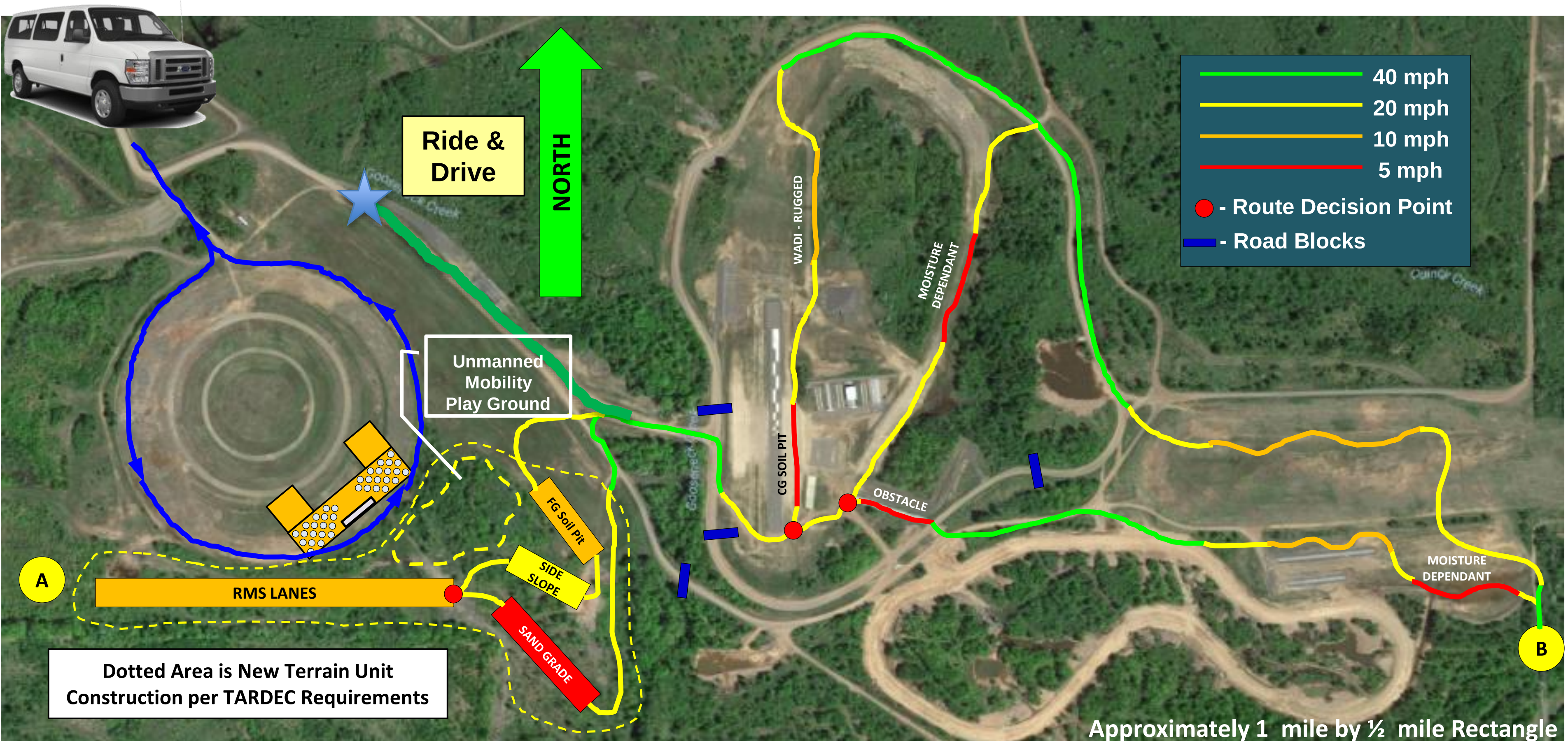
AMSP-06: Guidance for M&S Standards Applicable to the Development of Next Generation NATO Reference Mobility Model (NG-NRMM).

Cooperative Demonstration of Technology (CDT)


NATO OTAN
S&T organization
Applied Vehicle Technology Panel
2018
Collaborative Demonstration of Technology
Next-Generation NATO Reference Mobility Model



CDT Venue



Ride & Drive
NORTH
Unmanned Mobility Play Ground
40 mph
20 mph
10 mph
5 mph
- Route Decision Point
- Road Blocks
WADI - RUGGED
MOISTURE DEPENDANT
CG SOIL PIT
OBSTACLE
MOISTURE DEPENDANT
A
B
RMS LANES
FG Soil Pit
SIDE SLOPE
SAND GRADE
Dotted Area is New Terrain Unit Construction per TARDEC Requirements
Approximately 1 mile by ½ mile Rectangle

CDT (25-27 SEP 2018) @ KRC

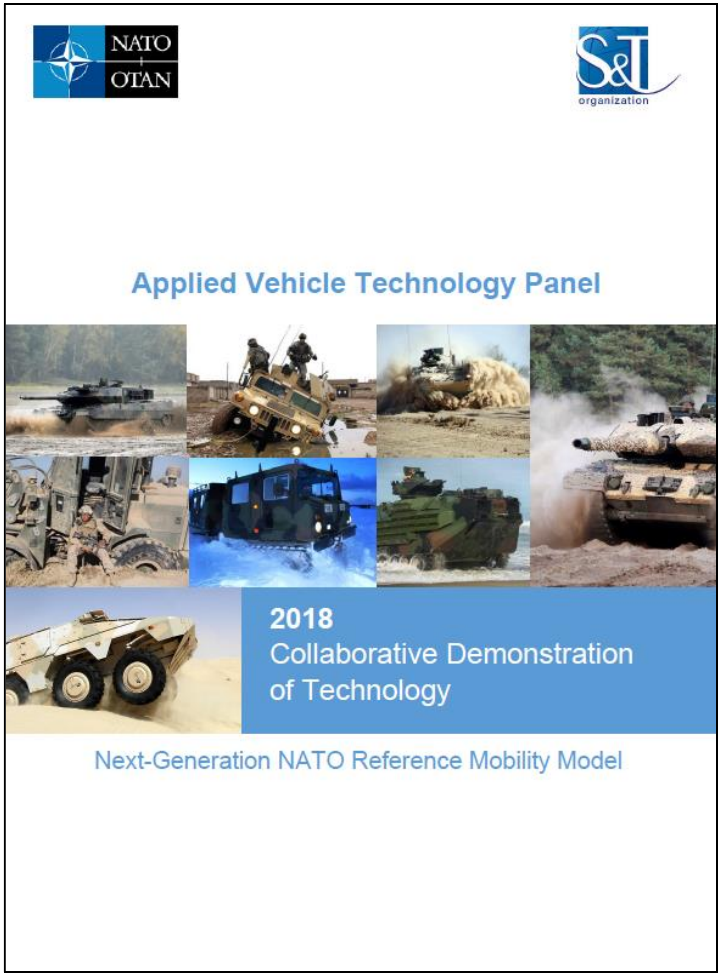
M: Day 0	Arrival and evening social
T: Day 1	Technical Day Highlighting Technical Accomplishments of AVT-248
W: Day 2	VIP Day Highlighting Operational Significance and End-to-End Demonstration of Technologies; Dinner
Th: Day 3	Technical Day Focusing on Assessment, Gaps, and Path Forward

- VIP Speakers: Dr. Rogers, Mr. Shaffer (NATO), Dr. Gorsich
- All presentations under tent on course
- Continuous Ride and Drives (30 minute loops) on Day 1 and 2
- Exhibitor Area and Static Vehicle Displays on course
- Rain contingency plan exists
- Creating Marketing Videos
  - Separate Videos highlighting NATO and TARDEC leadership
  - Documentary (10-15 min); YouTube (1-3 min); Facebook (45-60 sec);
  - Request Director Interview

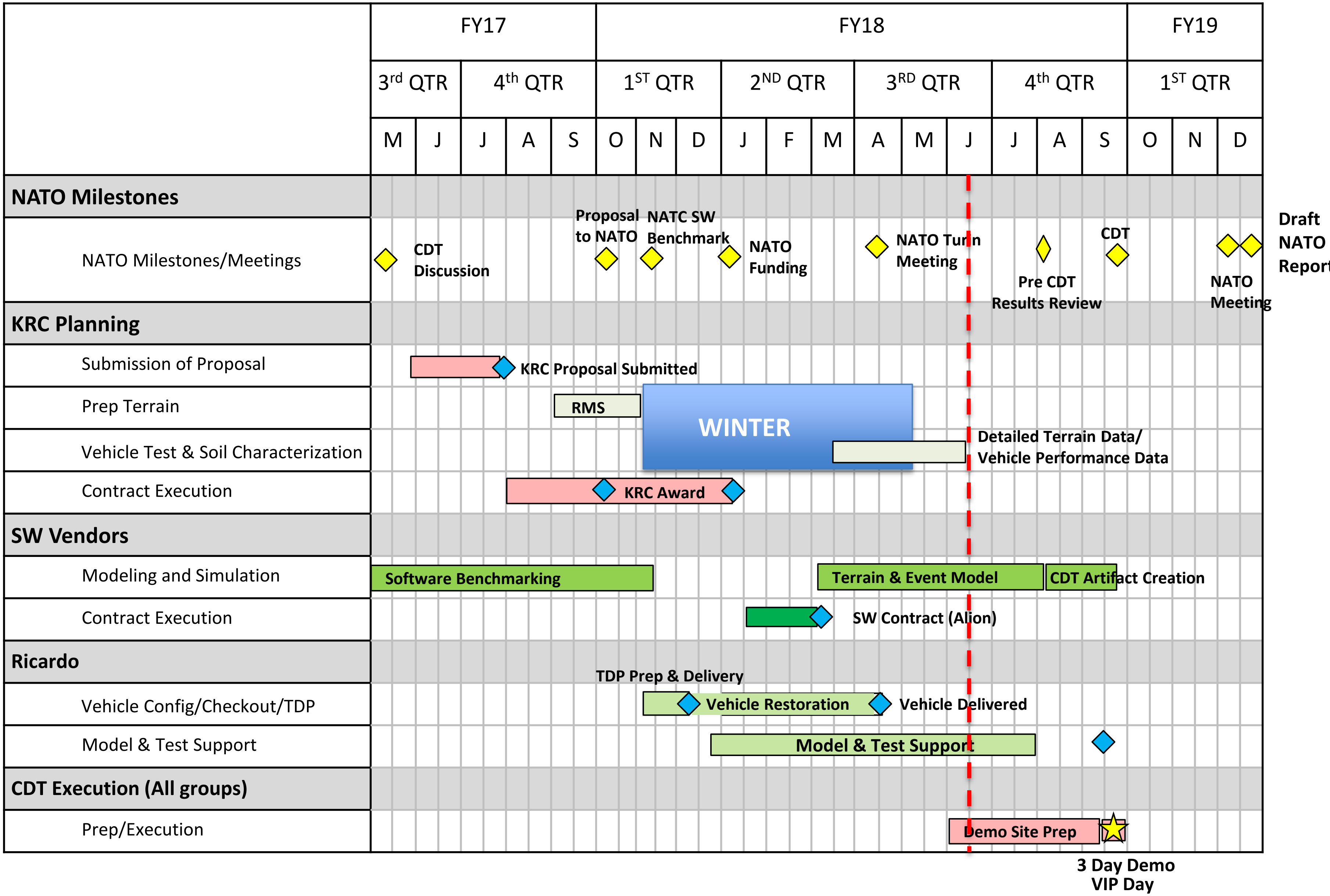
Invite and Registration Status

- Working with protocol office and EBO
  - Have received Dr. Rogers invite list
  - Updating with DXD input
  - Still working the industry list
  - NATO has own list
  - Committee members also sending invites
  - TARDEC tracking all
- All participants must register with NATO
  - NATO vets attendees
  - NATO keeps master registration list and will bring all badges
  - Monthly telecons will be weekly as we get closer
- If registration numbers are low, we will advertise at GVSETS
- Registration closes 31 AUG 2018
  - VIP exceptions usually possible

- Currently registered: 79
- Planning for up to 300 max.



CDT Schedule



Budget

Task	Performer	Total
Terrain Preparpation	KRC	$ 177,000
Test Preparation and Support	KRC	$ 341,500
CDT Event Hosting	KRC	$ 125,000
Vehicle Prep and Model Support	Ricardo	$ 94,529
Test Support	Ricardo	$ 44,238
CDT Event Support	Ricardo	$ 7,679
Simple/Complex Mobility Models	Software vendors	$ 575,000
NRMM Baseline	TARDEC Analytics	$ 100,000
Project Management	PST/Alion	$ 156,850
Total		**$ 1,621,796**

- NATO is contributing € 110K to support AVT-248 and AVT-308.
- Applying for ORF food funds.
- 8 Software Vendors are participating:
  - MSC Software Corp. (US)
  - CM Labs Simulations Inc. (Canada)
  - RAMDO Solutions (US)
  - Aarhus University (Denmark)
  - Advanced Science and Automation Corp. (US)
  - Vehicle Systems Development Corp. (Canada)
  - NRMM (TARDEC)
  - Council for Scientific and Industrial Research (SA)

BACKUP SLIDES

Military Challenges are Unique

AVT-248 USA Non-Government Members

Member	Organization
Wasfy, Tamer	Advanced Science and Automation Corp.
Dasch, Jean	Alion Science and Technology
Letherwood, Michael	Alion Science and Technology
McCullough, Michael	BAE Systems Land and Armaments
Shyu, Albert	BAE Systems Land and Armaments
McDonald, Eric	Desert Research Institute
Funk, Matthew	Environmental Systems Research Institute, Inc.
Alger, Russ	Keweenaw Research Center
Bradley, Scott	Keweenaw Research Center
Osborne, Mark	Keweenaw Research Center
Mengel, Dean	Lockheed-Martin Missiles and Fire Control
Perry, Kevin	Lockheed-Martin Missiles and Fire Control
Hodges, Henry	Nevada Automotive Test Center
Pulley, Reid	Nevada Automotive Test Center
Yang, Xiaobo	Oshkosh Corporation
Gaul, Nick	RAMDO Solutions
Froman, Bernard	Ricardo Defense Systems
Scharmen, Wesley	Ricardo Defense Systems
Cammarere, Mark	Technology Service Corp.
Vantsevich, Vladimir	University of Alabama, Birmingham
Niemann, Jeff	University, Colorado State
Jones, Andrew	University, Colorado State
Scalia, Joseph	University, Colorado State
Foster, Craig	University of Illinois at Chicago
Choi, KK	University of Iowa
Negrut, Dan	University of Wisconsin-Madison
Serban, Radu	University of Wisconsin-Madison

AVT-248 USA Government Members

Member	Organization
Jain, Abhinandan	NASA Jet Propulsion Laboratory
Schultz, Gregory	U.S. Army Aberdeen Test Center
Frankenstein, Susan	U.S. Army ERDC-Cold Regions Research & Engineering Lab
Shoop, Sally	U.S. Army ERDC-Cold Regions Research & Engineering Lab
Wojtysiak, Brian	U.S. Army Materiel Systems Analysis Activity
Ortega, Brian	U.S. Army Materiel Systems Analysis Activity
Gerth, Richard	U.S. Army Tank Automotive Research, Dev and Eng Ctr (TARDEC)
Gorsich, David	U.S. Army Tank Automotive Research, Dev and Eng Ctr (TARDEC)
Gunter, David	U.S. Army Tank Automotive Research, Dev and Eng Ctr (TARDEC)
Jayakumar, Paramsothy	U.S. Army Tank Automotive Research, Dev and Eng Ctr (TARDEC)
Morgan, Melissa	U.S. Army Tank Automotive Research, Dev and Eng Ctr (TARDEC)
Singh, Amandeep	U.S. Army Tank Automotive Research, Dev and Eng Ctr (TARDEC)
Thyagarajan, Ravi	U.S. Army Tank Automotive Research, Dev and Eng Ctr (TARDEC)

AVT-248 Non-US Members

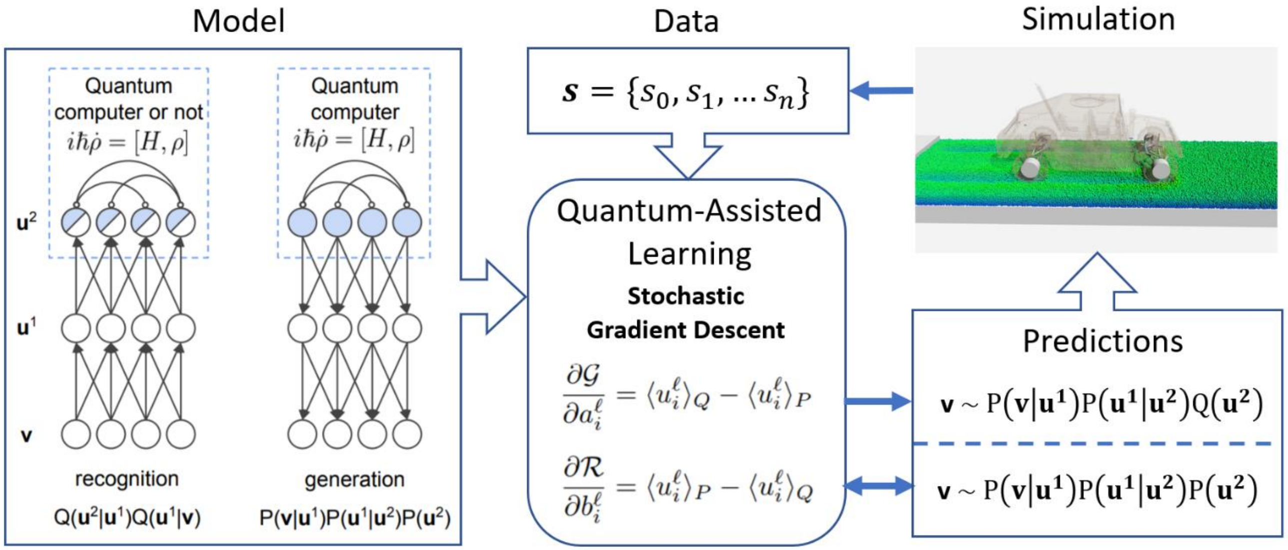
Member	Country	Organization
Mayda, William	Canada	National Research Council Canada
Preston-Thomas, Jon	Canada	National Research Council Canada
Hestera, Hrvoje	Croatia	Croatian Ministry of Defense
Zecevic, Marko	Croatia	Croatian Military Academy
Neumann, Vlastimil	Czech Republic	University of Defence
Rybansky, Marian	Czech Republic	University of Defence
Balling, Ole	Denmark	Aarhus University
Vennik, Kersti	Estonia	Estonian National Defence College
Becker, Andreas	Germany	Technical University of Kaiserslautern
Hoenlinger, Michael	Germany	Krauss-Maffei Wegmann GmbH&Co,KG
Von Sturm, Tom	Germany	Wehrtechnische Dienststelle 41 (WTD-41)
Zieger, Petra	Germany	BGIC Bundeswehr Geoinformation Center
Corso, Francesco	Italy	Secretariat General of Defence and National Armaments Directorate
Sgherri, Roberto Guido	Italy	EMI Scarl
De Klerk, Wim	Netherlands	TNO Defence Safety and Security
Jendraszczak, Eugeniusz	Poland	National Defence University
Walentynowicz, Jerzy	Poland	Military University of Technology
Wrona, Jozef	Poland	Industrial Research Institute for Automation and Measurements PIAP
Glowka, Jakub	Poland	Industrial Research Institute for Automation and Measurements PIAP
Ciobotaru, Ticusor	Romania	Military Technical Academy
Petru, Rosca	Romania	Military Equipment and Technology Research Agency
Kuffova, Mariana	Slovakia	Armed Forces Academy of General M.R. Stefanik
Modungwa, Dithoto	South Africa	Council for Scientific and Industrial Research (CSIR)
Nkosi, Phumlane	South Africa	Armaments Corporation of South Africa SOC Ltd (ARMSCOR)
Reinecke, David	South Africa	Council for Scientific and Industrial Research (CSIR)
Akalin, Ozgen	Turkey	Istanbul Technical University
Bradbury, Mike	United Kingdom	Defence Science & Technology Laboratory (DSTL)
Bruce, Jonathan	United Kingdom	Defence Science & Technology Laboratory (DSTL)
Hameed, Amer	United Kingdom	Cranfield University at the Defence Academy of the UK
Suttie, William	United Kingdom	Defence Science & Technology Laboratory (DSTL)

Field Identification Using a Bevameter

- B-W-J model calculates
  - draw bar pull
  - sinkage
  - motion resistance

GO/No-GO Maps via Quantum Machine Learning

Sequential Hybrid Pipeline

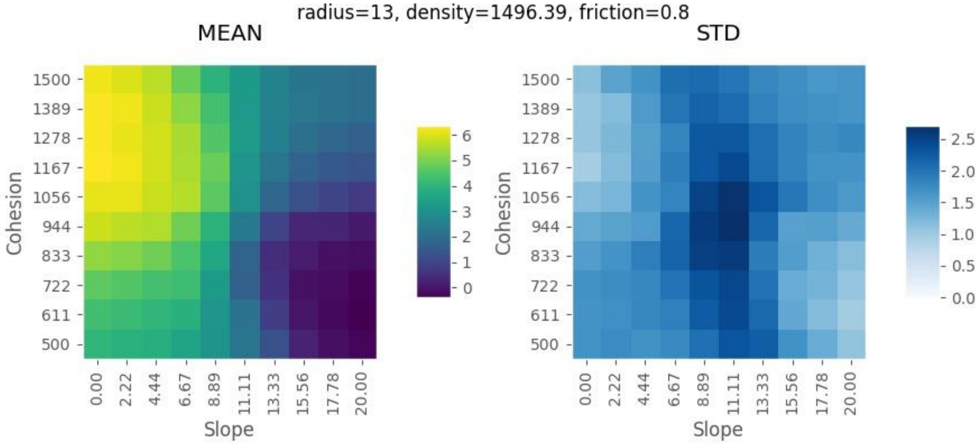


DOD HPC: Lightning

Simulation

D-Wave 2000Q

Prediction Example



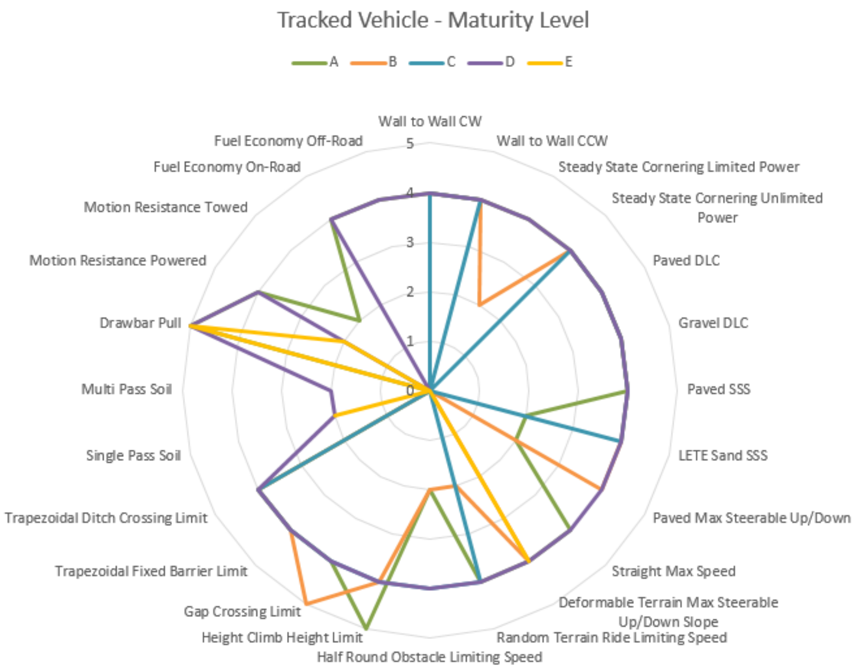
Ground Vehicle on Granular Terrain

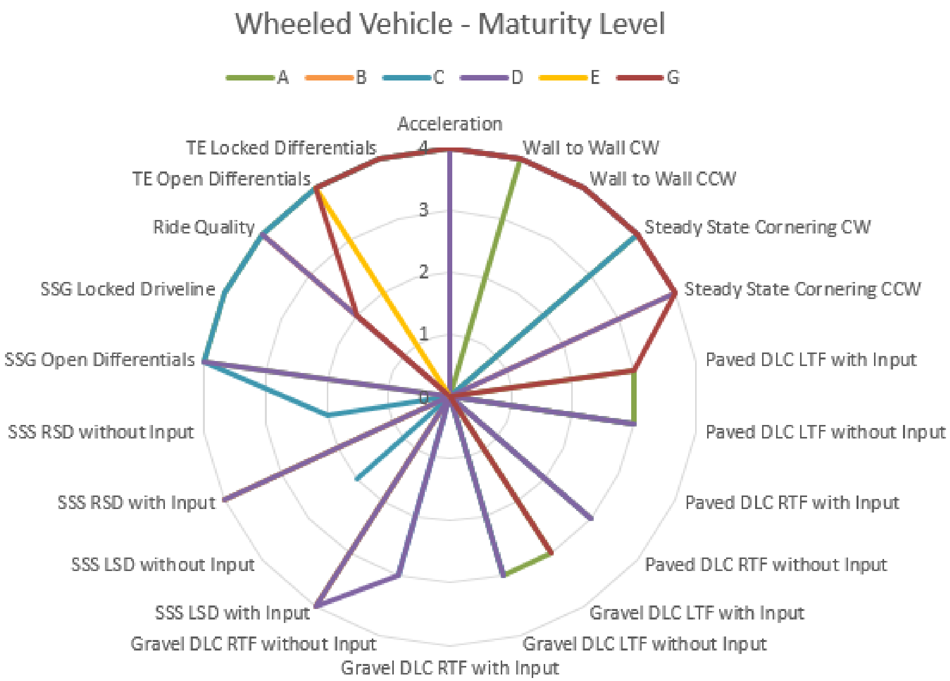
- Full MBS vehicle model
- Complementarity-based approach for cohesive frictional contact
- Multi-core, OpenMP-based parallelization

QML Algorithm Setup

- 2 hidden layers with 12 nodes/layer
- Learning rate: 0.01
- Regularization parameter: 0.0001

NG-NRMM Software Maturity Level





1. ***DEMONSTRATION:*** Demonstration of a correct implementation of a theoretically and conceptually consistent model.
2. ***PARAMETER SENSITIVITY DEMONSTRATION:*** Verification that performance change with a change in system parameter such as GVW or terrain deformability is consistent with theory and physics principles.
3. ***INDEPENDENT USER VERIFICATION:*** Independent user demonstration and correlation to vendor results
4. ***CROSS CODE VERIFICATION:*** Cross verification with another accepted mobility simulation code
5. ***CALIBRATION:*** Calibration to a real vehicle test data set
6. ***VALIDATION:*** Blind correlation to a real vehicle test data set
7. ***PARAMETER VARIATION VALIDATION:*** Blind correlation to a real vehicle test data set with a change in system parameter(s).

A: ASA

B: MotionPort

C: MSC

D: U. Wisconsin

E: VSDC

G: CM Labs

Pre-CDT Agenda (Day 2 GVSETS)

Purpose

- Review results and determine what will be presented at CDT and how
- Agree on message
- Agree on agenda / speakers/ visuals / CDT presentation materials
- Plan and agree on path forward to CDT

AGENDA

0800	Opening Remarks
0830	Performance Results
1000	Break
1030	Performance Results
1200	Lunch
1300	CDT Messaging
1340	Draft CDT Agenda
1400	NG-NRMM Demo
1500	Break
1530	Final Agenda / Message
1730	Adjourn