Annex N – CDT REVIEW AND PATH FORWARD

Note: This Annex appears in its original format.

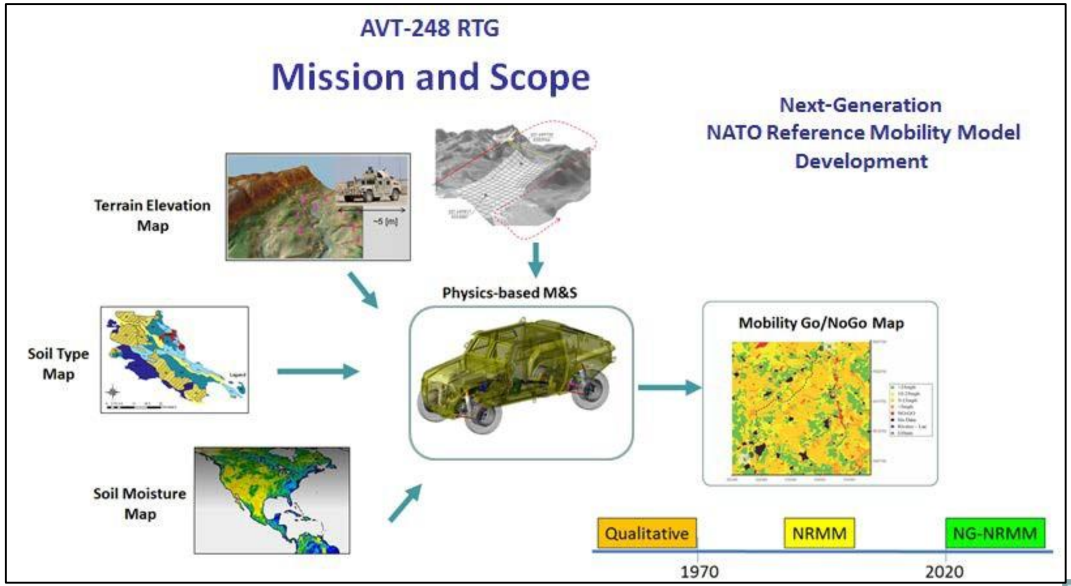
CDT Review and Path Forward

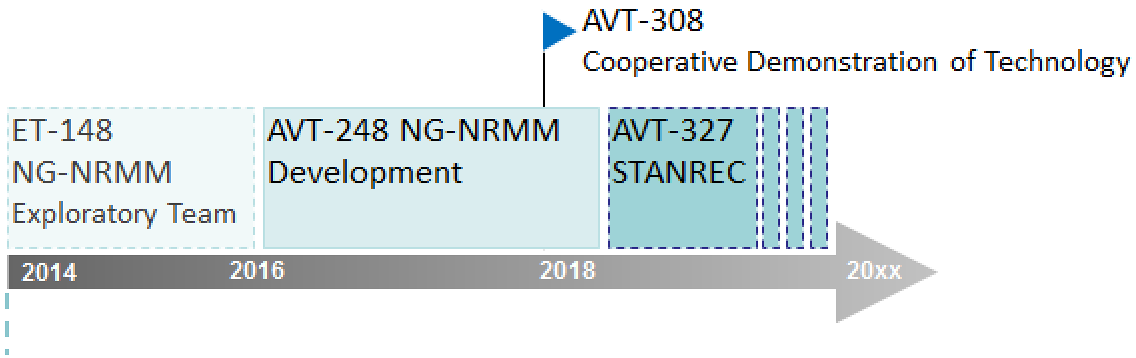
Presented by

Dr. Paramsothy Jayakumar

AVT-248 Task Group and CDT

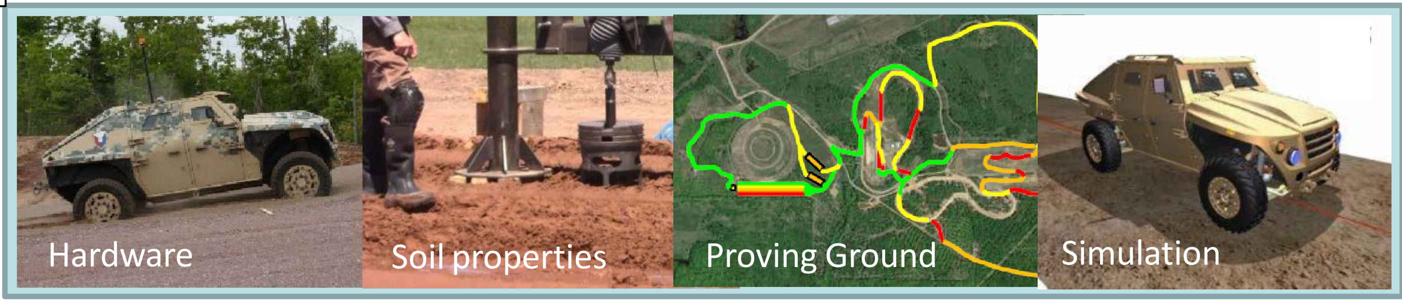
From basic research in **2014** to showcasing of technology in **2018**





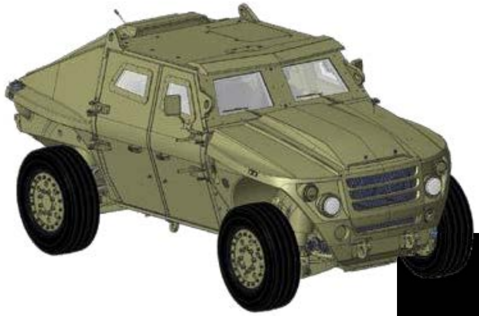
- ✓ Impact on **early stage vehicle designs** as well as **operational decision making**
- ✓ Increased **operational interoperability** and **safety** by predictive mission planning

CDT 2018 NG-NRMM

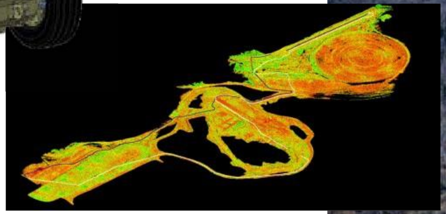


Physical Demonstration Plan

- **Vehicle Introduction (Why FED-A?)**
- **Vehicle Data Set**
  - General Physical Data
  - Ricardo Data Set
  - ATEC Test Report
- **Terrain Data Set**
  - Terrestrial LIDAR
  - High Resolution Aerial Imagery
  - Laboratory & In Situ Soil Strength Measurements
- **Vehicle Behavior Data Set**
  - As Tested Configuration
  - Data Acquisition / Instrumentation
  - 3D Model Calibration (General Automotive Tests)
  - Soft Soil Behavior Prediction (Sand Grade & Draw Bar)
  - Mobility Traverse (Speed Made Good Estimation)

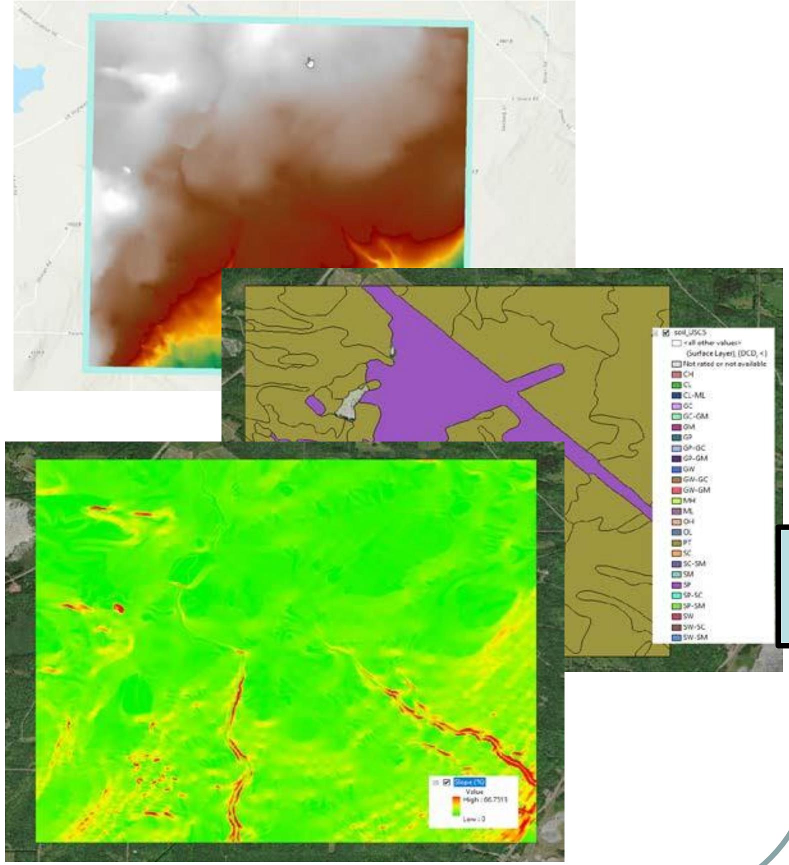


Fuel Efficiency Demonstrator (Alpha)



NG-NRMM – Analytical Component to Planning

Geospatial Inputs



Simple Terramechanics

Complex Terramechanics

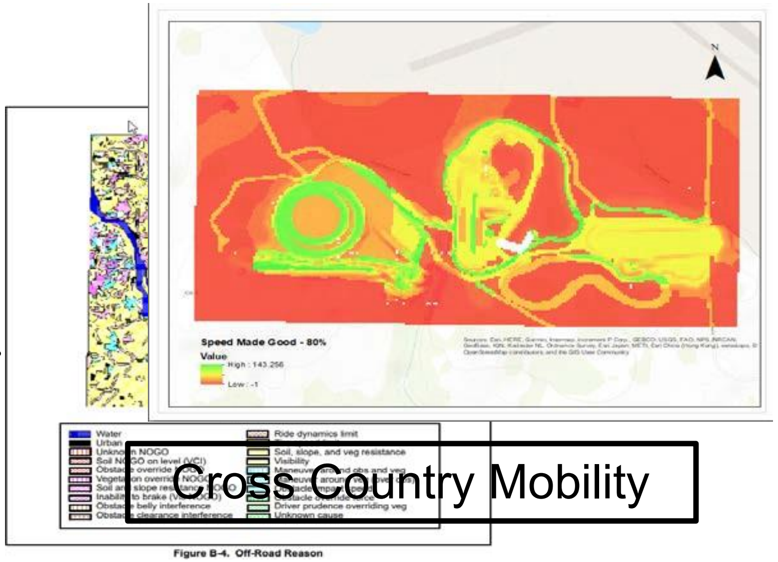
Uncertainty Quantification

NG-NRMM

Military Decision Making Process

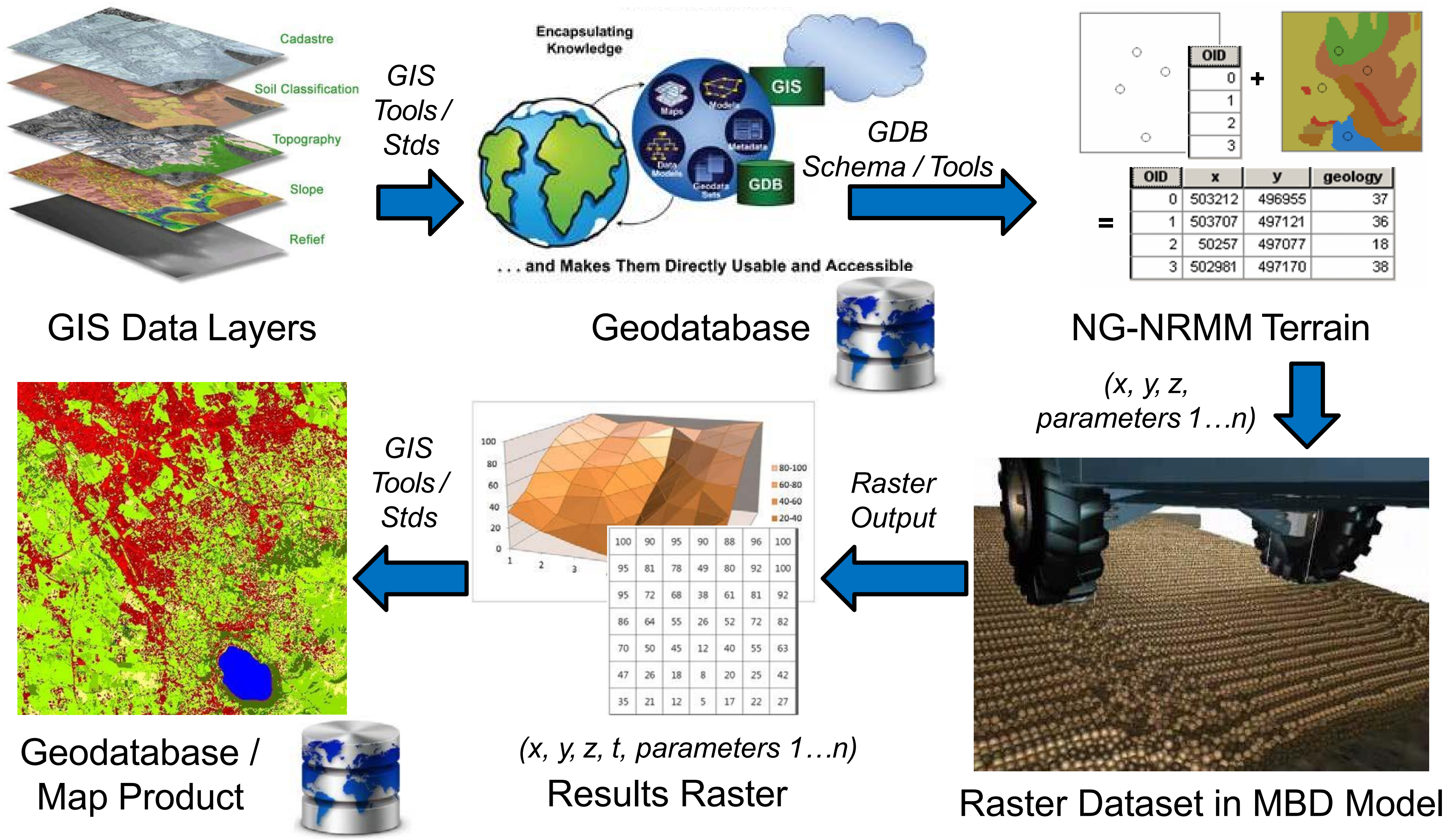
Intelligence Preparation of the Operational Environment

Terrain Analysis



Cross Country Mobility

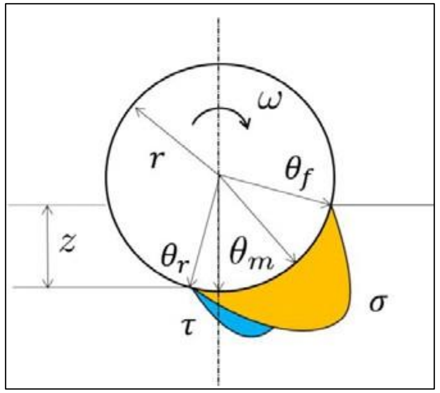
NG-NRMM TA-1 Workflow

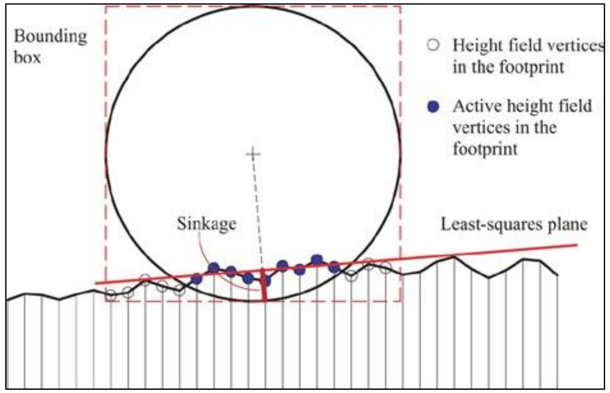


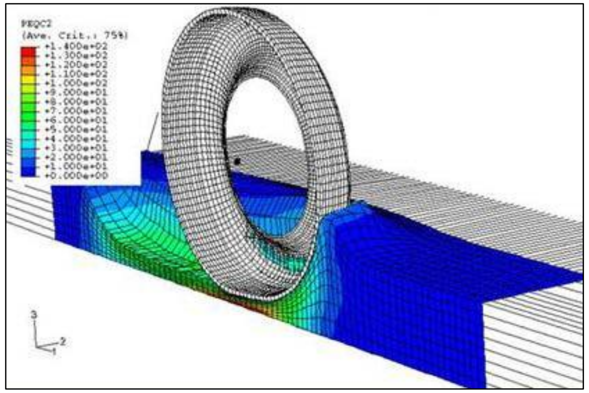
OID	x	y	geology
0	503212	496955	37
1	503707	497121	36
2	50257	497077	18
3	502981	497170	38

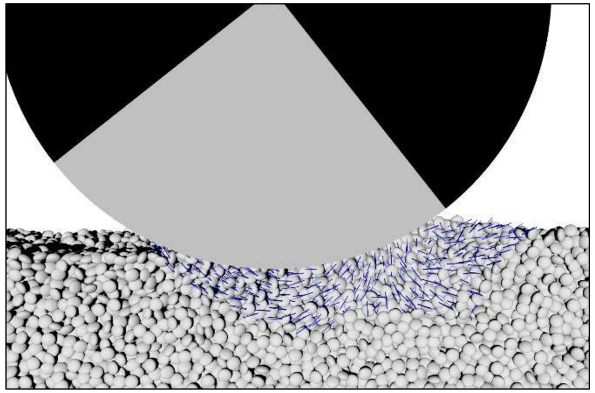
100	90	95	90	88	96	100
95	81	78	49	80	92	100
95	72	68	38	61	81	92
86	64	55	26	52	72	82
70	50	45	12	40	55	63
47	26	18	8	20	25	42
35	21	12	5	17	22	27

Terramechanics Numerical Models









ST: Pressure-sinkage models

Bekker-Wong normal stress
Janosi-Hanamoto shear equation

Integrate normal pressure and shear stress over contact patch

10^0 degrees of freedom

ST: Height field models

Soil vertical deformation tracked at grid points

Bekker-Wong type formulas applied at each point

10^3– 10^4 degrees of freedom

CT: Finite element models

Soil deformation captured by motion of FE nodes

Use elasto-visco-plastic soil material constitutive models (e.g., Drucker-Prager cap)

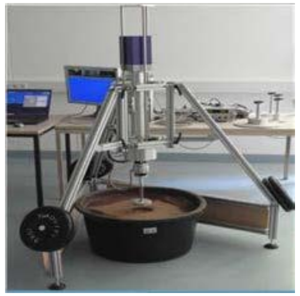
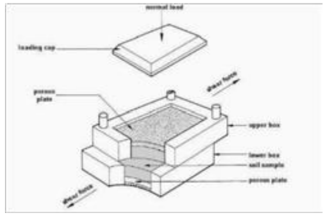
10^6 – 10^7 degrees of freedom

CT: Discrete element models

Soil modeled as collection of discrete virtual particles interacting through contact, friction, cohesion.

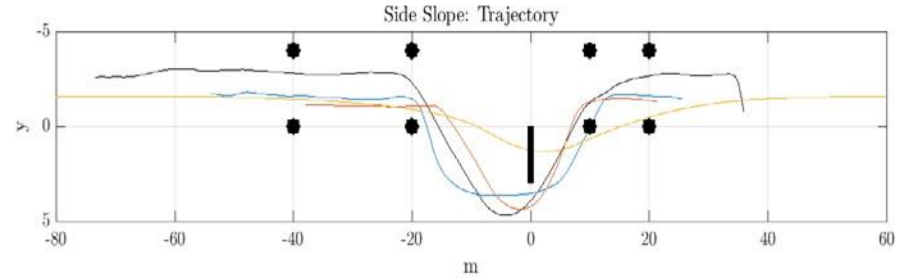
10^6 – 10^7 degrees of freedom

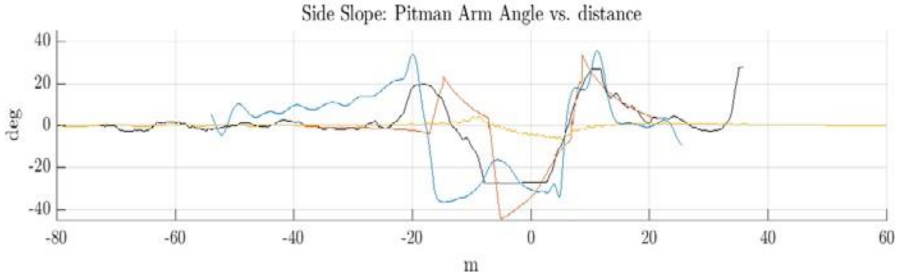
Terramechanics Results


NATO
AMSP-06

Correlated Test and Modeling Standards with Foundational Database



Benchmark Models Validated

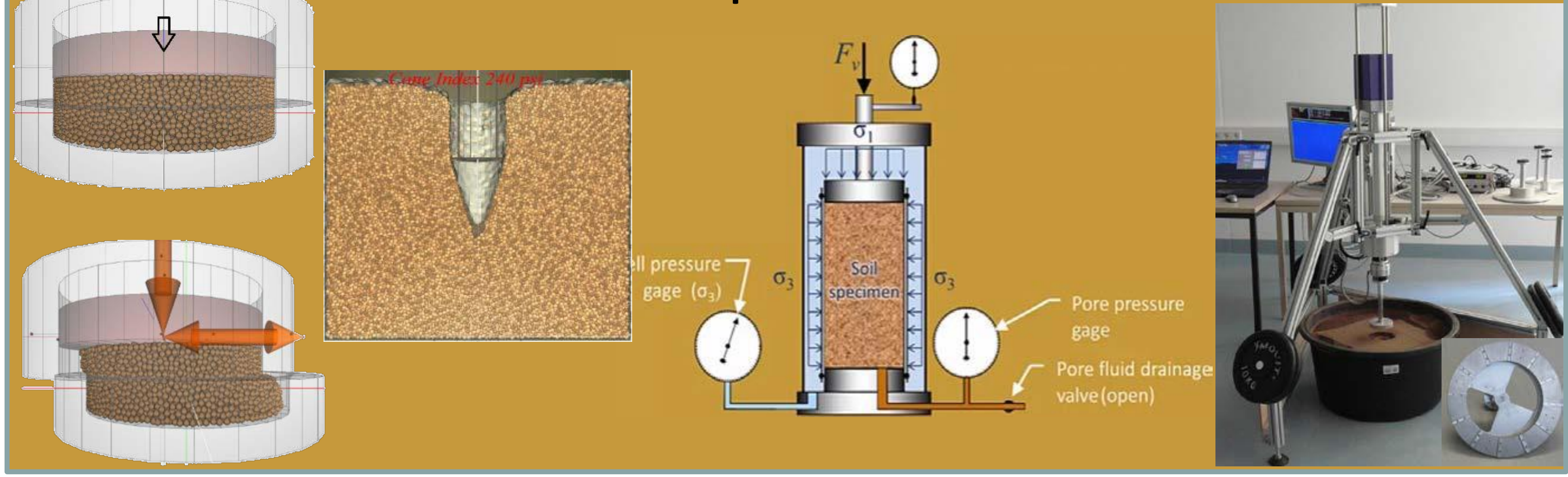

Vision for Future Automated Data Capture and Development

Complex Terramechanics

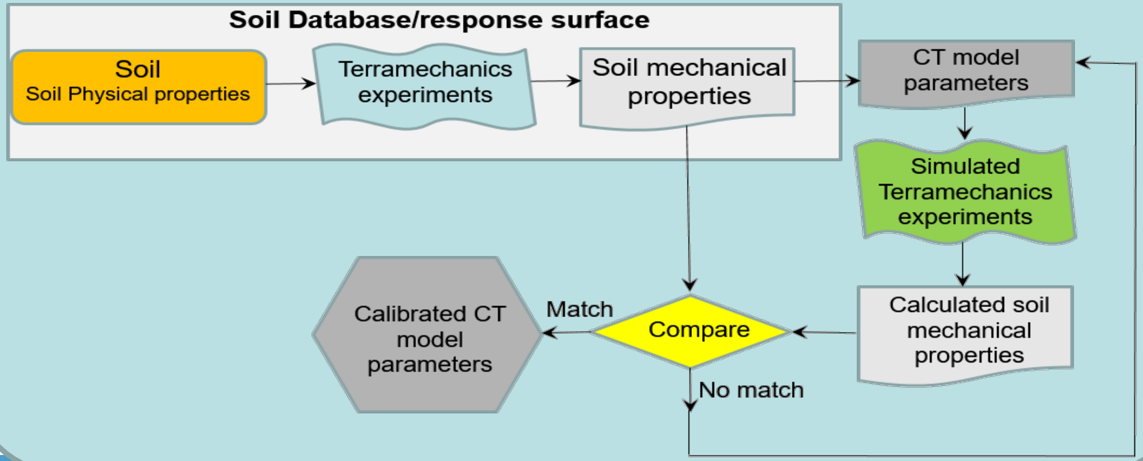
Definition: NG-NRMM CT models are those that given any **3D soil loading condition** by a vehicle surface can accurately predict the **3D reaction forces** on the vehicle surface and the **3D soil flow/deformation** including permanent deformation.

Rut depth/width/shape	Rut side wall height
Soil bulldozing	Soil separation/reattachment

Terramechanics Experiments for Model Calibration



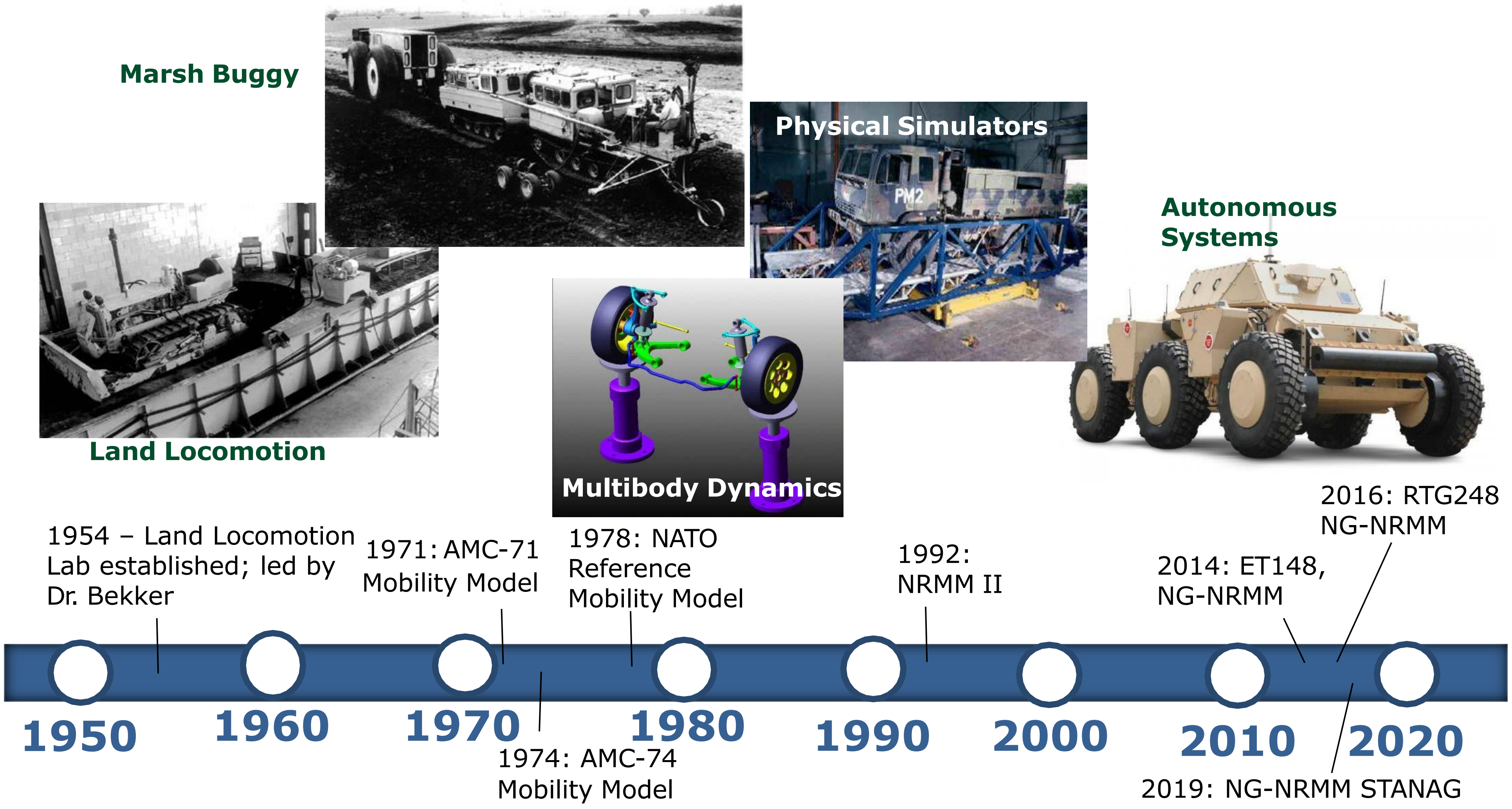
Calibration Process



Complex Terramechanics Path Forward

- Validate of the CT soil models for all soil types.
- Develop a database of calibrated CT soil models, including effects of moisture and temperature.
- Fundamental research of micro-scale soil models.
- Investigate/develop a soil classification system designed for vehicle mobility applications.
- Develop terramechanics experiment to measure soil damping, viscosity, and dilation.
- Improve the parallel scalability of the CT models.
- Develop models for:
  - Multi-layer terrains.
  - Water covered soft soil terrains.
  - Heterogeneous terrain.
  - Vegetation.
  - Urban obstacles.
- Validation/calibration of high-fidelity finite Element tire – DEM soil models.

NATO Reference Mobility Model (NRMM)



What NRMM Can't Do

- Methodology not physics-based – relies on empirical, in-situ soil measurements
- Does not consider turning performance and lateral vehicle dynamics
- Does not support 3D models
- Does not extrapolate to contemporary vehicle designs and technologies
- Does not benefit from advances in simulation and computational capabilities
- Does not cover uncertainty, intelligent vehicles or data sets for urban areas
- Does not predict mobility for systems dissimilar to past systems (weight, power, suspension system, etc.)

Development of A Next Generation NRMM

NATO S&T Organization Applied Vehicle Technology Panel

- Project proposed at Copenhagen PBM April 2014
- Exploratory Team (ET-148) lasted from April 2014 - Dec. 2015
- Research Task Group (AVT-248) running from Jan. 2016 - Dec. 2018
- 70 members & participants from 15 nations

Goals

- Develop and demonstrate NG-NRMM process & technologies
- Incorporate NG-NRMM as a NATO Standard
- Conduct Verification and Validation benchmarking studies
- Demonstrate technology through a CDT

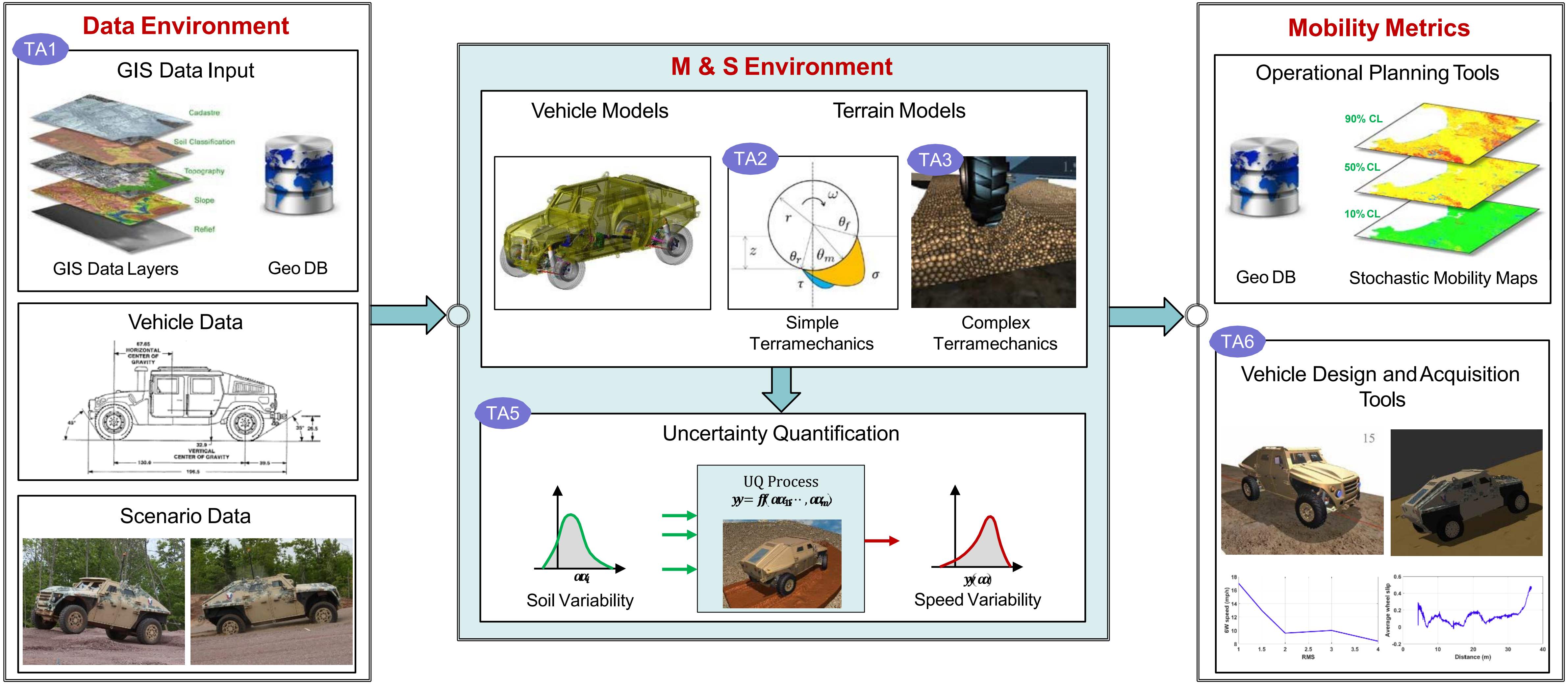
Co-Leads

- Dr. P. Jayakumar (TARDEC)
- Dr. M. Hoenlinger (KMW GmbH, Germany)

- Panel Member Sponsor: Dr. D. Gorsich

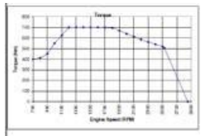
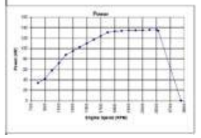
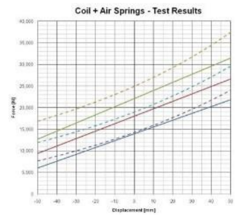

AVT-248 on Estonia Field Trip

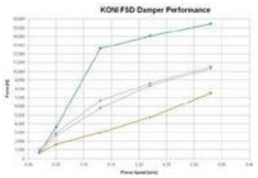
NG-NRMM Architecture

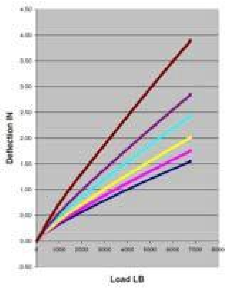


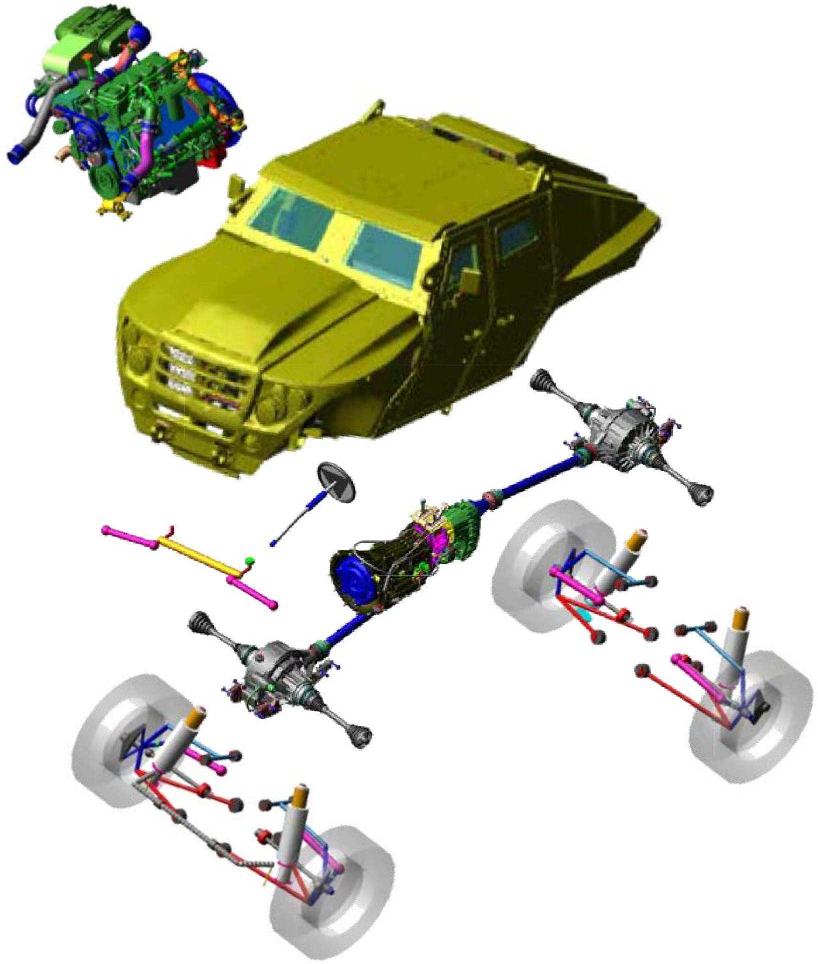
Vehicle Modeling

- **Vehicle system**
  - ➢ 3D multibody system
- **Suspension Systems**
  - ➢ Independent Multilink Suspension with Bushings, Coils and Air Springs
  - ➢ Mechanical or Hydraulic Roll Stabilizer Technology
- **Steering Systems**
  - ➢ Rack and Pinion or Parallelogram Steering
  - ➢ Multi Axle Steer and Steer by Wire Systems
- **Engine/Powertrain**
  - ➢ Throttle Dependent Torque and Fuel Maps
- **Tires**
  - ➢ Fiala, Pacejka, Ftire, Swift, etc.

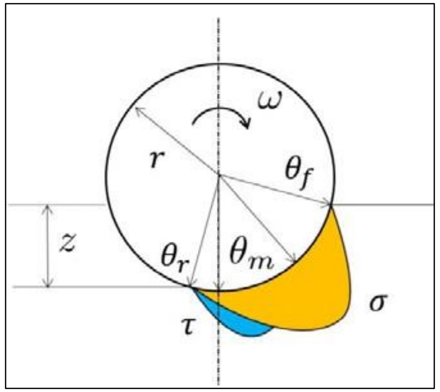






$10^1 – 10^2$ degrees of freedom

Terramechanics Numerical Models



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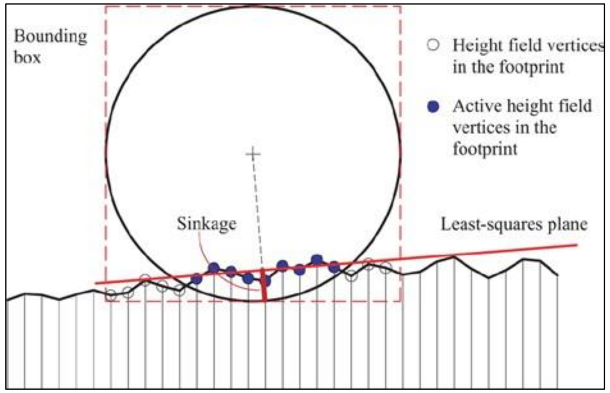

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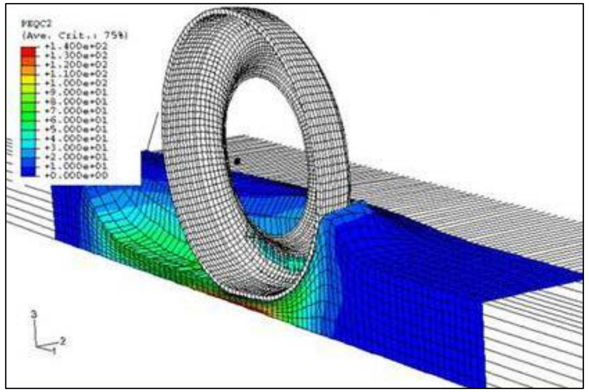

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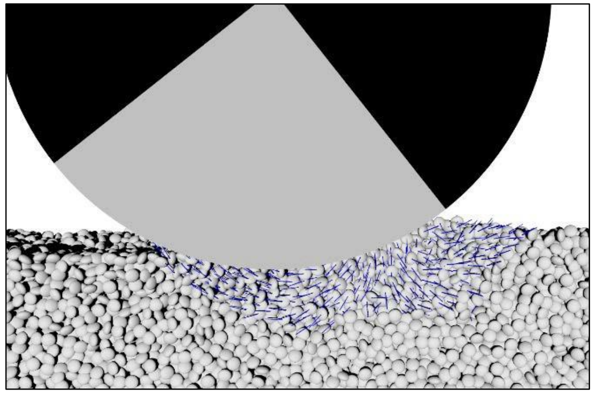

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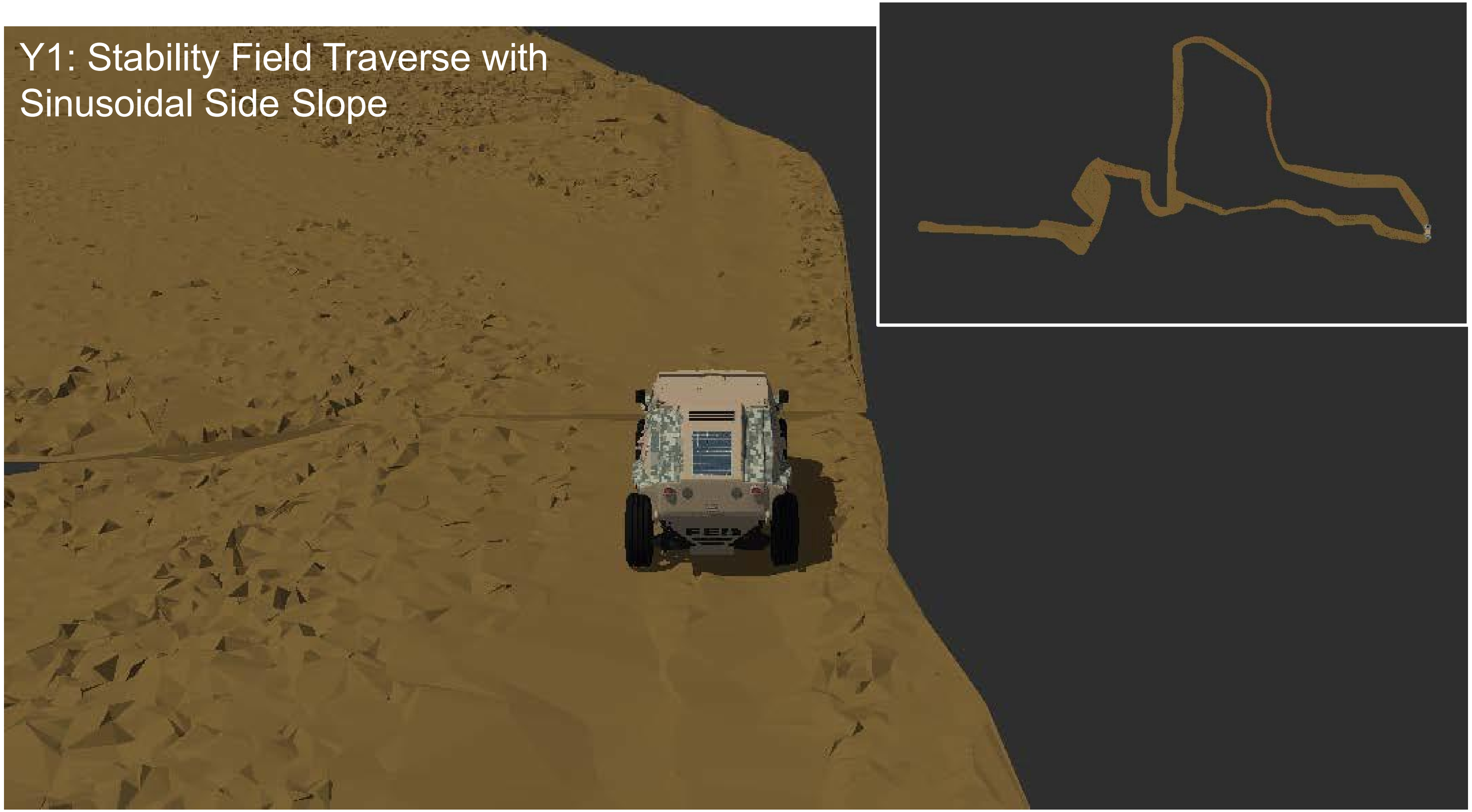
Mobility Traverse – Complete Path



Traverse Loop Summary			
	Method		
AVG. Speed	NG-NRMM	TEST	NRMM
(m/s)	7.4	7	11.5
(Km/hr)	26.6	25.3	41.4
(Miles/hr)	16.5	15.7	25.7

- Average "Speed-Made-Good" across the complete Traverse Loop
- Of note, NG-NRMM tended to over predict S-M-G by 10%, while NRMM over predicted by 60%

Section	Description	Speed Variance (%)	
		NRMM	NG-NRMM
B1	RMS 1.0 with Exit onto Gravel Pad	14.0	23.4
B2	Up Slope on Gravel Pad with Down Slope through 2NS Sand Grade	31.3	1.9
B3	Construction Site Road to Gravel Access Road & Loop 2, Rink Field Traverse with setup for OEF	18.6	-1.4
B5	Gravel Road to Stability Side Trail, Sinusoidal Side Slope with Setup for Moisture Dependent Area	54.4	49.0
Y1	Stability Field Traverse with Sinusoidal Side Slope, Loop 2 with Panic Stop	26.9	-5.4
Y2	Loop 2 with Rink Field Traverse & Setup for Wadi	38.8	5.0
Y3	Wadi	264.9	-20.2
Y4	Rink Field Traverse with Setup For Coarse Grain Pit	85.9	32.8
Y5	Sinusoidal Coarse Grain Pit	97.2	4.7
Y6	Rink Field Traverse with Loop 2 & Access Road to VDA 2 Field Traverse & Setup for Fine Grain Soil Pit	38.5	-8.8
Y7	Fine Grain Soil Pit - Up slope into pit then 90 degree turn in pit with accelerated exit	142.2	3.8
Y8	Construction Site Road to Side Slope, Obstacle avoidance on Side Slope, then RMS 2.0	88.0	-10.1

NRMM

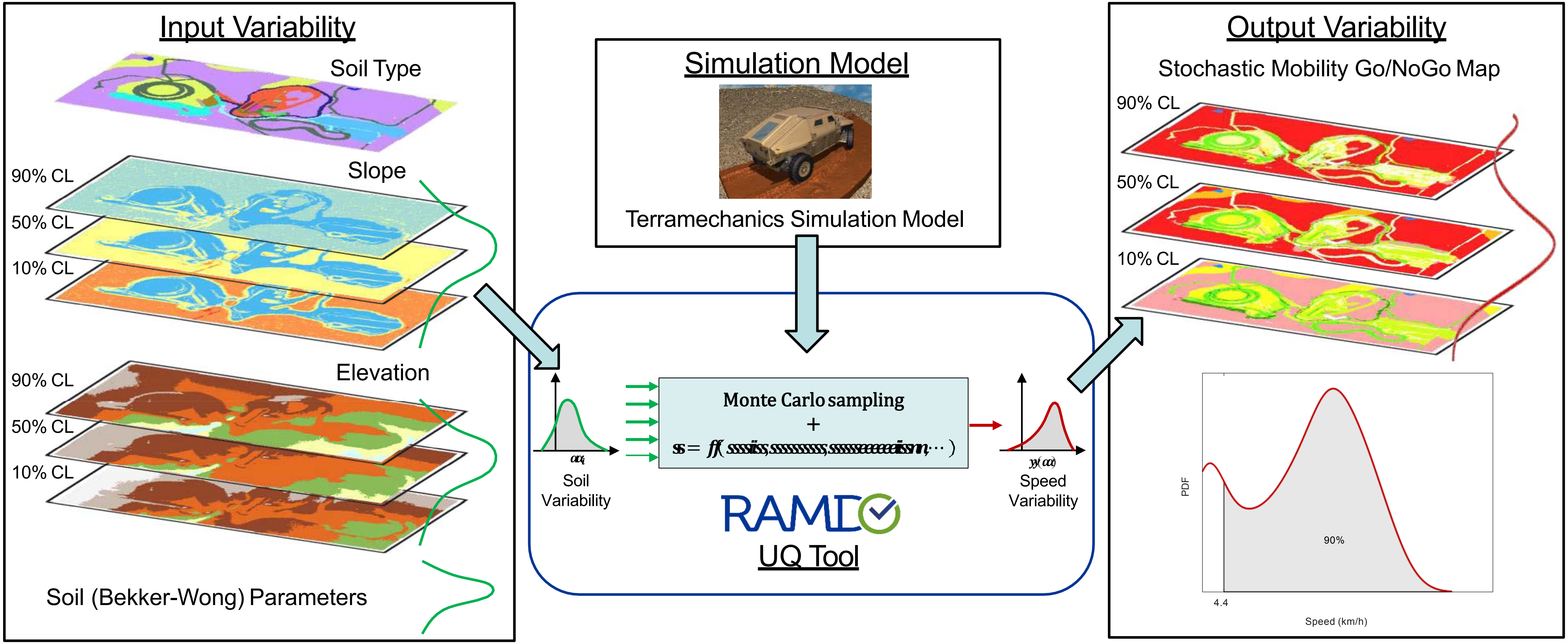
-Consistently over predicts Speed-Made-Good for ALL segments
-Over predictions range from 14.0% to 264.9%
-Average VALUE of over prediction error is 75.1%

NG-NRMM

-Both over and under predicts S-M-G.
-Over predictions range from 1.9% to 49.0%
-Under predictions range from -1.4% to -20.2%
-Average VALUE 6.2%

- **Modern methods, NG-NRMM, are available that can significantly improve our ability to make mobility predictions and assessments. These hold the promise of improving 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 High Fidelity solutions which are suitable for research and development work at the technology and procurement level.**
- **Statistics and confidence maps should be implemented**
- **There has been significant progress in NG-NRMM development, but investment is needed to make NG-NRMM the new standard.**
  - Invest in the generation of NEW and correlation of exiting data
  - Invest in Uncertainty Quantification
  - Invest in simple and complex terramechanics research
  - Support and promote the development of a NATO Stanag

Uncertainty Quantification Process

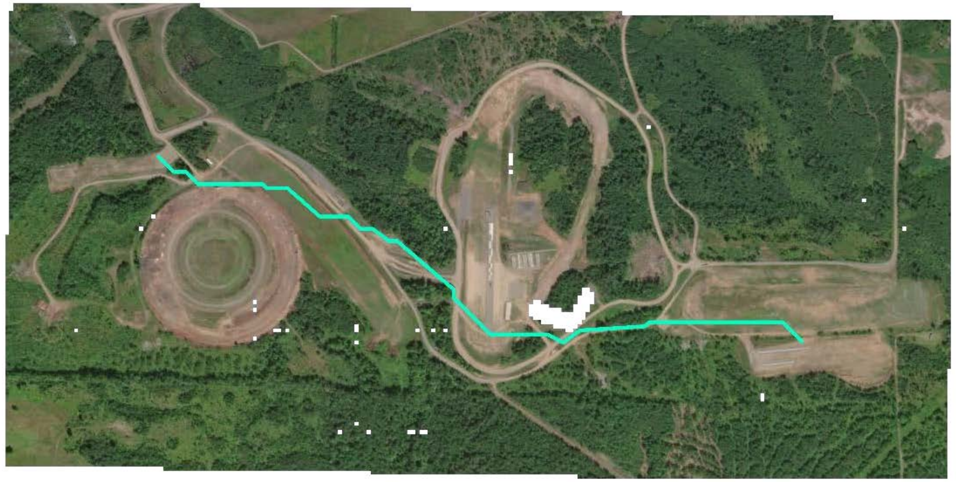


Path Planning on Stochastic Maps

90% Route

50% Route

10% Route



Deterministic Route

Conclusions Verification and Validation

- **3D Physics Based Simulations is Capable of Predicting Paved Surface Automotive 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
    - Step Incline

- **3D Physics Based Simulations is Capable of Performing Soft Soil Simulations**
- **Validation Possible on Certain Soils**
  - Drawbar Pull
    - Fine Grain Dry and Wet (ST and CT ✓)
    - Coarse Grain Dry ✗
  - Variable Sand Slope Grade (CT)
    - Does not reach 100% slip
  - Investigations into Coarse Grain Dry Drawbar Pull Test Performance based on Wheel Torque and Motion Resistance is In-conclusive.

Conclusions Verification and Validation

Notes:

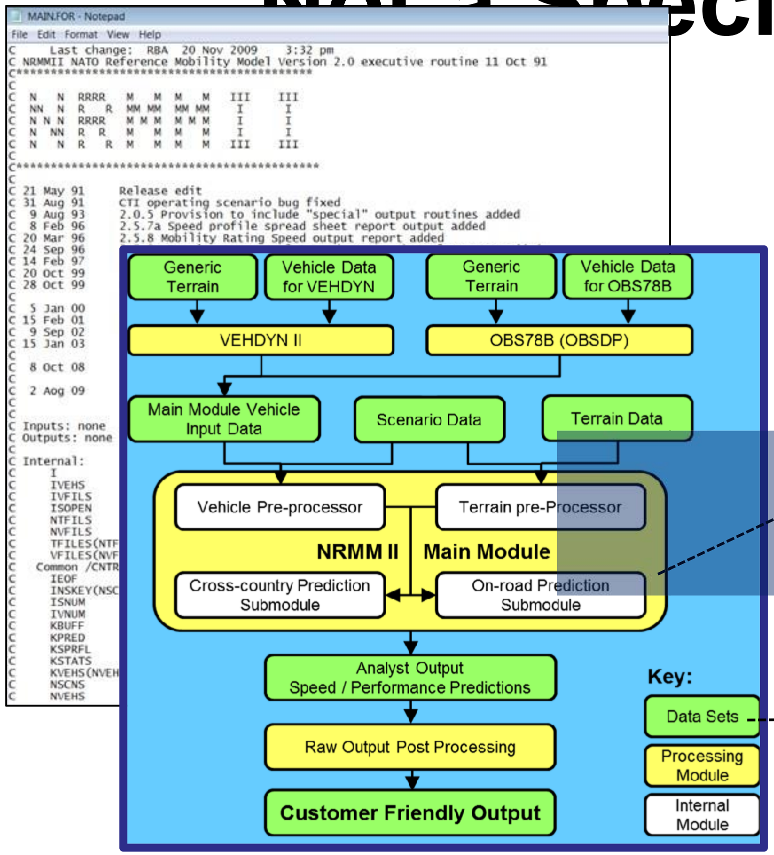
- It is well known that ST is challenged on sloped terrain. However, in the case of the CDT events, Coarse Grained Sand has proven to be difficult to predict accurate Drawbar Pull as well as Variable Sand Slope Grade.

- Complex Terramechanics was able predict Variable Sand Slope, however based on the Drawbar Pull Results a higher slope seems possible.

- Rut depth measures are disturbed by flowing sand. Few developers are currently tracking multi-pass effects.

Insert VSSG Pictures, of Test Simulation.

NG-NRMM Will Be Standards Not a Specific Computer Code



Next Generation NATO Reference Mobility Modeling Standards

GIS Based Input and Output

Mobility Metrics:
Speed Made Good
GO/NOGO
Fuel Economy

Terramechanics Models & Db
Uncertainty Quantification
Autonomous Vehicles

Legacy Terrain Files and
Updated Terrain Data Format

V&V Maturity Scale and Benchmarks

Existing Standards (AVT, ITOPS,GIS, etc)

NG NRMM STANREC Conclusions

- **AMSP-06 is an enduring artifact and development path for NATO nations mobility modelling methods, benchmarks and source databases that should be applied to physics based simulations of all operational land and amphibious mobility among the alliance.**
- **The initial release will occur in November 2018**
- **A new RTG, AVT327 will manage initial support**
- **An enduring forum and change process should be established for codifying future changes to NG-NRMM standards**

Thrust Area 7 - Summary

1. **How to identify the capability of any given implementation of NG-NRMM?**
   - Configuration Control method of Layers and Levels proposed
2. **Who will use NG-NRMM and what for?**
   - Group feedback stresses the fact it should not be assumed that all implementations of NG-NRMM will have the same aspirational end state
   - Divergent requirements and use cases will impact having a single solution
   - Simple NG-NRMM has the greatest potential for exploitation
   - There is still a case for a common, minimum NATO capability
3. **What are the perceived capability gaps and challenges?**
   - Gaps and challenges not just about terrain and soil data…..
     - E.g. obtaining and storing vehicle data, how to utilise NRMM2 legacy terrain files, bulldozing, water terrain ingress/egress
   - Different tools and approaches are likely to be required for novel solutions (e.g. walking vehicles) and small UGVs

Thrust Area 7 – Way Forward

1. **Decision required whether STANREC to adopt Layers and Levels method**
   - If adopted, work required to refine Layers, define Levels
   - If not adopted, alternative required

2. **Review and refine NG-NRMM (Key New) Requirements and STANREC based on AVT248 findings and lessons**
   - E.g. prioritise gaps and challenges
   - E.g. decision required whether modelling novel solutions (e.g. walking vehicles) and small UGVs should be held to the same requirement
   - E.g. ensure requirement for Diagnostic Data included in STANREC

With Appreciation

NATO Science & Technology Org.

AVT-248/308 Members

Keweenaw Research Center

U.S. Army TARDEC

Software Developers

CDT Speakers, Organizers, Attendees

Special Thanks for Funding to

U.S. Army TARDEC
NATO STO