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Tool Development for Mobility Visualization and Routing Incorporating Vehicle Limitations and Terrain Modeling

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ABSTRACT

In this investigation, a prototype tool for visualizing vehicle mobility and planning routes across offroad terrain was developed and evaluated in the field. The tool uses detailed vehicle, soil, and terrain characteristics to plan routes and indicate vehicle limits, including go/no-go zones on the local terrain map. Consistent with NG-NRMM principles, the process uses Multi-Body system simulation and simple terramechanics soil models to characterize the vehicle capability and integrate this data within a geospatial application to visualize mobility over terrain and facilitate route planning. A tablet-based prototype was soldier-tested in the field to confirm operational utility and selected routes. The results indicate how the NG-NRMM approach and associated modeling strategies can positively impact operational planning and execution.

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1. INTRODUCTION

Every ground vehicle has unique performance limitations and it is currently difficult for the operator or mission planner to project these capabilities onto any specific operational scenario. However, advances in both vehicle and soil modelling, geospatial tools, and terrain data mean that the required information exists to resolve this difficulty. In this effort, a mobility visualization and routing tool is presented to demonstrate the effective combination of these inputs. Validation of this tool included in-vehicle field-testing and soldier participation. This effort involved several stages, which are documented herein:

- Define and populate representation of vehicle capabilities, as limited by terrain features such as roughness, longitudinal grade, lateral grade, and obstacles.
- Implement and automate an analysis process for populating this format for any specific combination of vehicle and terrain surface.

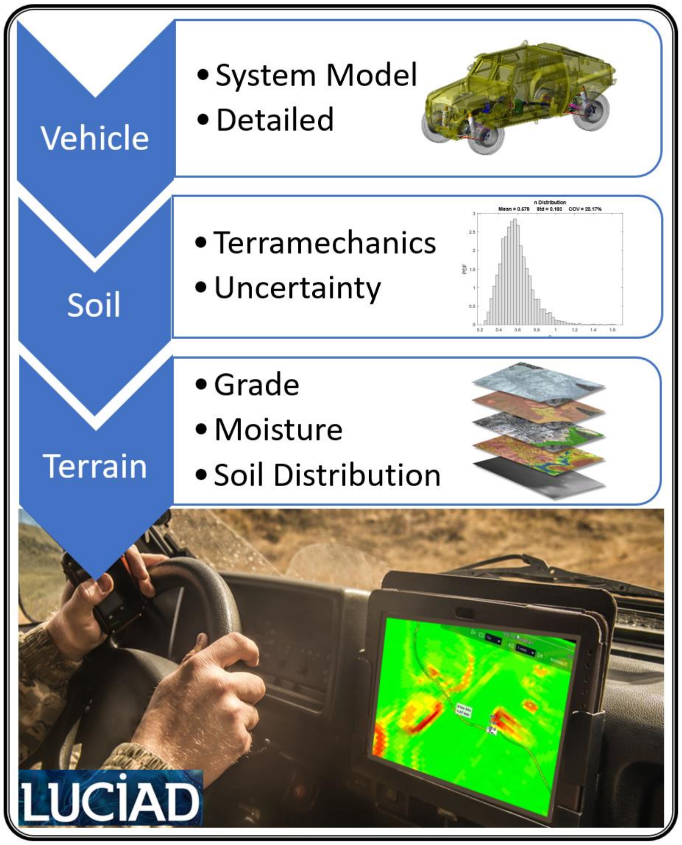


Figure 1: Tool development process overview.

- Customize an existing geospatial application to project vehicle characteristics onto a geospatial area, including visualization of the vehicle limitations, route planning, and adjustable environmental moisture settings.
- Validate this process with a hardware prototype using military personnel at the Keweenaw Research Center (KRC) and the FED-Alpha vehicle.

This effort serves as a substantial proof-step for the application of NG-NRMM methodologies in the generation of more accurate and informed tools. Such tools can improve acquisition assessments, tactical understanding, and operator effectiveness, while reducing risks to equipment, personnel, and mission objectives.

2. Vehicle Modelling and Characterization

For the process outlined here, it is necessary to have a vehicle model that will accurately reflect the design capabilities and limitations. Inaccuracies or simplifications that exist within the vehicle system model will necessarily be reflected in all downstream data derived from such a model. For this work, the intent has been to facilitate flexibility and extensibility in the underlying toolset, such that similar approaches can easily be developed using the most appropriate (or available) tools for capturing the vehicle and soil characteristics. In addition, through format standardization, the vehicle characterization approach implemented here has the additional benefit of facilitating comparisons between vehicles or analysis methods. For this effort, the Adams Car suite of tools for vehicle analysis are employed.

2.1. Vehicle Analysis Approach

Several specific analysis events were used to assess various limitations on the vehicle capability. Although intended to be broadly applicable, these events were implemented and tested using the FED-Alpha vehicle model developed previously as a part of the NG-NRMM NATO activities [1,2]. This model was adjusted to include a second tire option (the RoadX DT990 11R22.5), and to expand the available tire variations to include both 35 and 60 psi PAC2002 tire model options for both the original Goodyear and the new RoadX tires, as well as creating an FTire model of the RoadX tire at both 35 and 60 psi. The inclusion of this additional tire allows improved assessment of the tire selection on mobility. This vehicle was assessed using a matrix of configurations that included tire selection, tire pressure, and vehicle loading. Several events were used to assess the vehicle for later use in route development.

Road Roughness: The vehicle was modelled driving in a straight line at a specified constant speed over a 3D mesh road surface representing the corresponding KRC RMS ride quality lane and the vertical absorbed power was calculated based on the acceleration observed at the passenger and driver ride meter locations. The analysis was repeated at multiple speeds to identify the maximum attainable vehicle speed for a given RMS road amplitude without exceeding 6 Watts of absorbed power. When repeated for several roads, the limiting relationship between RMS amplitude and vehicle speed can be identified.

Halfround Obstacles: The vehicle was modelled driving in a straight line at a specified constant speed over a 3D mesh road surface representing halfround obstacles of 4, 8, 10, and 12-inch heights. The peak vertical acceleration was identified based on the accelerations observed at the passenger and driver ride meter locations. The intent of the halfround event is to identify the maximum vehicle speed over each specified halfround size without exceeding 2.5 g's of vertical acceleration at the driver seat.

Longitudinal Grade: The longitudinal grade analysis was designed the asses the speed at which the vehicle can navigate a longitudinal slope, due to limitations in vehicle power or traction. The vehicle was driven in a straight line at 100% throttle on a flat soft soil or rigid road of interest. Once the vehicle had achieved steady-state velocity, the global gravity force was altered to affect a 5% increase in grade, and the simulation continued, still at 100% throttle, until steady-state velocity was again achieved. This was repeated, in 5% grade increments, until the vehicle failed to achieve a positive steady-state velocity. The steady-state speed was reported at each grade, producing a speed versus grade curve.

Lateral Grade: The lateral grade analysis was designed to identify a maximum safe operational speed for a given surface and lateral grade. The event replicates a scenario where a driver needs to maneuver to avoid an obstacle while driving on a lateral grade. The vehicle failure modes include both wheel lift and initiating an unrecoverable downward slide. The vehicle is driven in a straight line at 100% throttle on a flat soft soil or rigid surface at the lateral grade of interest. After steady-state velocity is achieved, a steer input of 180 degrees is applied, steering the vehicle in a downhill direction over the course of 0.6 seconds. The steering wheel angle is then rotated a relative 360 degrees in the uphill direction over the next 3 seconds. The vehicle is then given an additional 3 seconds to achieve an uphill velocity.

Surface	Map Key	Coefficient of Friction: dry	medium wet	wet	very wet
Pavement	PVMNT	1	0.9	0.85	0.8
Coarse Crushed Rock	CCR	0.9	0.8	0.7	0.6
Dirt Road	RN_VDA2 RNC STBC	0.85	0.7	0.55	0.4
Rock	ROCK	0.9	0.8	0.7	0.6

Table 1. Rigid Road Coefficients of Friction

If the vehicle has wheel lift-off or cannot achieve an uphill velocity in the specified time, the test is rerun with throttle decremented by 20%. Speed is reported as the steady-state speed at which the test was passed. If the vehicle fails at the lowest throttle (20%), the grade is considered a no-go.

2.2. Surface Representation

The methods outlined above were implemented on several specific surface representations, using the FED-A vehicle model. In support of the need for end-to-end

Application Display Name	Simple Name	KRC GIS Map Key	USCS Category	Soil Properties Used for Mobility Characterization — Application Environment Setting: Dry	Med Wet	Wet	Very Wet
Poorly Graded Sand	Sand	2NSR	SP	Dry Sand	Wet Sand	Wet Sand	Wet Sand
Poorly Graded Sand	Sand	SP	SP				
Coarse Sand	Sand	CGS	SP				
Stability	Silty Sand	STB	SW/SM				
Poorly Graded Sand	Sand	2NSS	SP				
Rink Natural	Silty Sand	RN	SM	Dry Fine Grain	Med Wet Fine Grain	Very Wet Fine Grain	Very Wet Fine Grain
Fine Grain Soil	Silt	FGS	ML				
Lab Tested Peat	Peat	PT	PT	Med Wet Peat	Med Wet Peat	Very Wet Peat	Very Wet Peat

Table 2: Designations of KRC deformable surfaces and corresponding soil properties used for analysis and mapping.

process validation and testing, the surfaces present in the KRC geospatial data set were used to define the requirements.

The surfaces defined in the soil-type layer of KRC's geospatial data set were grouped into "rigid" and "deformable" subsets. Within each group, different properties were defined to approximate four moisture settings: "dry," "medium wet," "wet," and "very wet." For the rigid roads, only the coefficient of friction was changed, as shown in Table 1. For this application, these friction characteristics were based on rough estimates of the surface properties.

The deformable KRC terrain includes quite a few distinct designations. Many of these are closely aligned with the soils recently tested by KRC and characterized for simple terramechanics modeling by Pesheck et al. [3]. Although the natural conditions found throughout the area will certainly introduce significant variations relative to the identified properties, the characterization is supported by validation and includes information about both moisture variation and statistical distribution. Hence, for this effort, the deformable soil definitions from KRC's geospatial dataset will be assigned to the characterized soils as shown in Table 2.

Each tested soil includes only two or three moisture values. Hence, soil properties have been re-used for multiple different moistures, as shown, to fully populate the data set. Specific moisture measurements and Bekker-Wong parameters are documented in [3].

The vehicle events summarized in Section 2.1 were performed for the relevant surfaces for multiple vehicle configurations: light, nominal, and fully loaded, each with both 35 and 60 psi tires. This provides the essential information necessary to predict the vehicle capability over the terrain under various surface and vehicle conditions. Typical maximum speed versus grade results on different soils are shown for multiple tire options in Figure 2.

2.3. Incorporating Soil Uncertainty

In addition to identifying the vehicle behavior under typical soil conditions, it is of interest to understand the expected variation in vehicle performance that results from the variation in soil characteristics. As a part of the soil analyses conducted in [3], an uncertainty quantification process provided parameter distributions sufficient for creating a statistical sampling of for each soil based on the variations observed between tests.

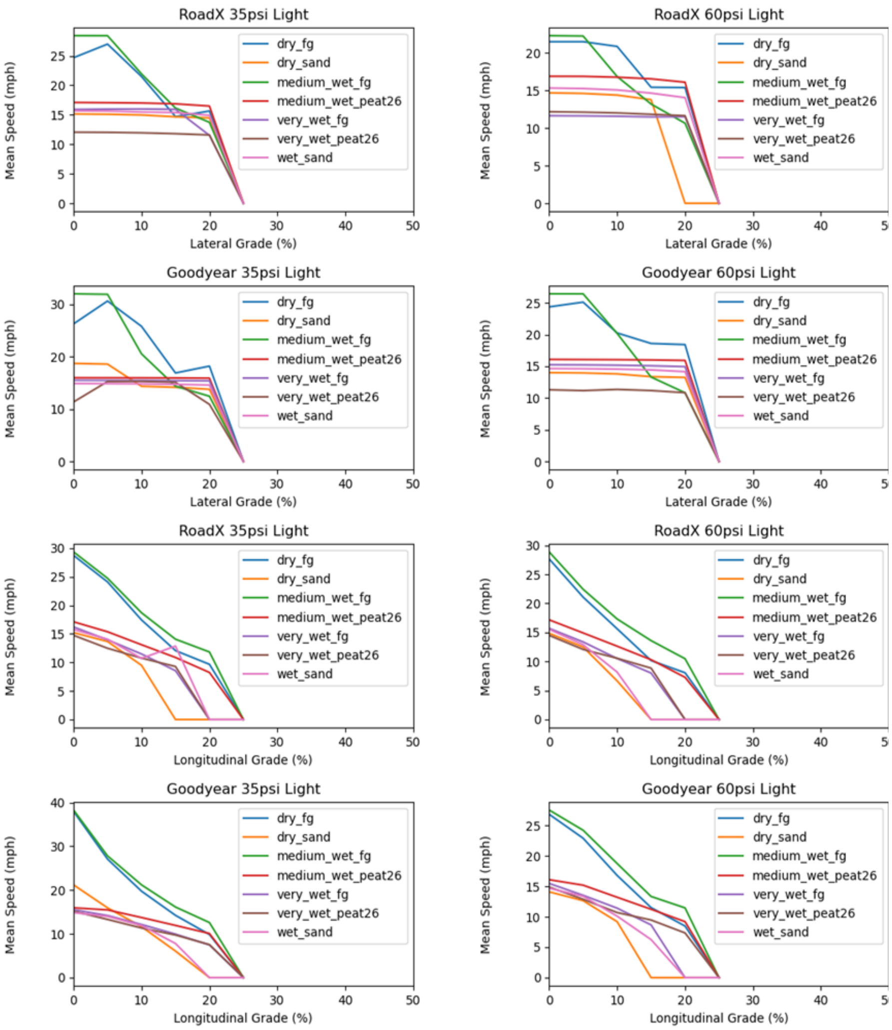


Figure 2: Mean Speed (mph) versus Lateral and Longitudinal Grade (%) for each Tire, Pressure and Soil for Curb Loaded Condition

For each of the seven soil-moisture combinations, the lateral and longitudinal grade performance was assessed for 100 variations. From these results, the maximum, minimum, 95th percentile, 5th percentile, mean, and +/- one standard deviation of attainable vehicle speed were retained for potential subsequent use in the geospatial toolset.

2.4. Vehicle Mobility Characteristics File

To encapsulate the performance of a particular vehicle in a specific operating condition, (tire, pressure, and loading) a file format was defined that could be easily parsed by different tools, streamlining both creation and ingestion operations. The JSON file structure was used for this purpose [4]. With this convention, the limiting factors for a given vehicle configuration are stored in a single standardized file structure. By design, this Vehicle Mobility Characteristics (VMC) file is not tied to any specific authoring tool or simulation toolset for either the vehicle or the soil.

2.5. Data Management

The approach proposed herein results in a compact representation of the vehicle limits and their anticipated statistical distribution for multiple configurations of the vehicle. However, thousands of simulations may be required to underpin this representation. In a production environment with many more vehicles, configurations, and terrain surfaces, a Simulation Process Data Management (SPDM) implementation is critical for systematically running the analyses required to create and update the VMC files and managing the associated input and output data streams. In this effort, a prototype SPDM instance was created and tested to validate the effectiveness of this approach and provide a foundation for potential follow-up activities.

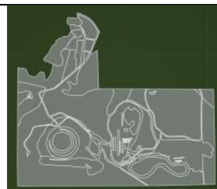
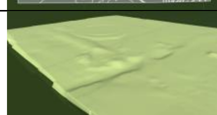
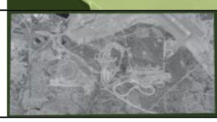
Layer	Format	Image	Notes
Soil	Vector (SHP)		• Sixteen soil types
Vegetation	Vector (SHP)		• Eight layers (S1–S8) • Stem spacing • Stem thickness
RMS	Vector (SHP)		• Roughness values of 0.1 to 4 • Values < 0.5 treated as flat surface
Elevation	Raster (GeoTIFF)		• 8.5m resolution
Imagery	Raster (JPEG2000)		• 25cm resolution

Table 3: Provided KRC Terrain Data

3. DMS Mobility and Routing Application

The Defense Mobility System (DMS) tool was designed with the intent of projecting the vehicle performance characteristics onto a geospatial domain and then leveraging the combination of vehicle and terrain characteristics to predict attainable performance and optimal vehicle routes.

3.1. DMS Platform

The DMS application was developed as a customization of the Luciad geospatial application suite from Hexagon. This COTS toolset includes existing functionality for building geospatial applications incorporating multiple disparate data sources, performing analytic processing on the loaded data including geodetic calculations, spatial queries, customizable pathfinding algorithms, etc., and providing a real-time visualization engine and application framework for accelerating geospatial applications. These capabilities minimize the need to develop new content for many visualization and interface options, significantly reducing application development time by focusing efforts on the interface and methods requirements that are specific to this effort.

3.2. Geospatial Source Data

A Geospatial data package for the KRC operational area was obtained, consisting of the layers and formats indicated in Table 3.

3.3. Pre-Processing Vehicle Capability

Given the geospatial data set and a specific vehicle configuration (VMC) file, the required information is available for computing vehicle speeds and resultant routes. However, the operations associated with route optimization require many repeated evaluations of the achievable vehicle speed at different map points and along different travel directions. Given the complexity of the VMC data and the fidelity of the map, routing performance suffered when these speed calculations were performed within the routing routines. In addition, much of this effort would be repeated for any subsequent route calculations. As a result, a pre-processing analysis step was implemented. When the application is initialized, it pre-processes the requested area-vehicle combination to determine the attainable speed throughout the map in multiple directions of travel.

The attainable vehicle speed, also known as "speed made good," is the minimum speed when the limitations imposed by each relevant map layer are assessed. For the KRC area, limitations from vegetation were most significant, followed by surface grade and lastly surface roughness (RMS). The pre-processing was performed at an interval of 3m to ensure that smaller features, like roads and ditches were captured. Furthermore, the speed was calculated for travel-direction vectors at 15-degree increments, as the limitations imposed by lateral and longitudinal grade are somewhat independent. The longitudinal and lateral grade (ground plane pitch and roll) along each potential direction was assessed by sampling the map elevation data surrounding each calculation point. As the vehicle characteristics are only specified for

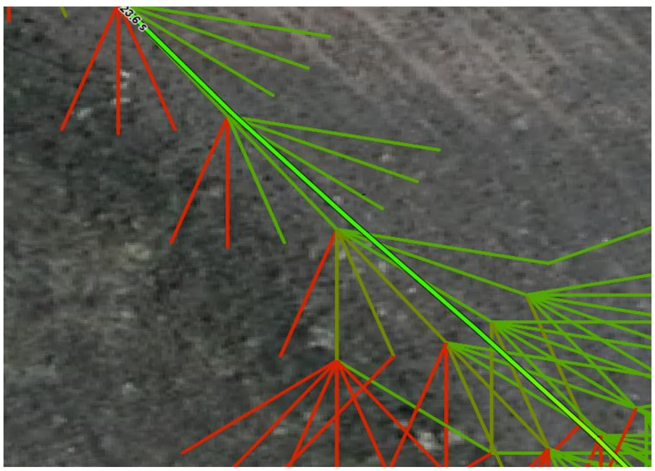


Figure 3: Evaluation of Route Variations

longitudinal-only and lateral-only, but not combined grades, the algorithm assesses the limitations imposed individually by the longitudinal and lateral components of the local grade, and then returns the minimum speed from these two cases. For example, if a specific vehicle, soil, travel direction combination will result in a 20% lateral grade (18 mph max) while climbing a 5% grade (21 mph max), the 20% lateral grade speed would be more limiting than the 5% longitudinal grade speed and 18 mph would be used as the limit.

This pre-processing was repeated for each of the four pre-set environmental moisture settings. This eliminates the need to repeat pre-processing due to moisture adjustments during active application use. This pre-processing was also repeated for both the 95% and 5% performance speeds estimated via the UQ process. Consequently, for each 3m sampling point, 216 speeds are cached: 24 directions for 3 moistures for 3 performance probabilities.

3.4. Routing Algorithm

The routing routines implemented in the DMS application leverage a pre-existing route planning toolset from the baseline LuciadLightspeed API. The pre-existing approach determines the shortest path between points using both geodetic distance and elevation change between evaluated segments with a cap on the maximum elevation change allowed. This approach is extensible, however, and has been modified here to include several additional features in the optimization process:

No roads: The routing operates without a road network, such that any point on the map can be queried as a potential point on the route path. The routing resolution is adjustable (typically 3 meters was used in testing and demonstrations), and the attainable speed is determined based on the closest pre-processed point on the map.

Travel Direction: The pre-processed directional information is used to adjust the attainable speed based on the travel direction vector.

Turning Radius: The approximate turning radius of the vehicle is accounted for to limit the path options available based on the local vehicle travel direction.

Route Duration: The cost function for the route is based on minimizing the estimated travel time along the route.

Culling Previously Traversed Segments: A mechanism was included to stop the current candidate route from evaluating any paths which have already been traversed within the active optimization.

3.5. Prototype Hardware

Although the application operates in Java and can therefore run as a desktop application, hardware was acquired to support field testing and demonstration of the tool. The hardware consisted of two ruggedized Windows 10 Durabook tablets with externally mountable GPS receivers.

3.6. Application Capabilities

The DMS application was implemented with operational use in mind. This use scenario necessitated streamlining the interface to reduce clutter and emphasize simplicity for users. User feedback from experienced US Army personnel was collected through two demonstration events and the corresponding suggestions were used to improve the tool interface and features. The DMS application can serve several roles in active use. As with a modern in-vehicle GPS system, the system may be used for route guidance, for gathering information about the surroundings, or simply for awareness of local features.

Visualization Modes: The system is configured to always display the photographic aerial view as a base layer for the display. Unlike a vehicle GPS system, roads are not identified as independent entities. When present in a map, they simply exist as harder, flatter ribbons of terrain. Atop the base visualization layer, several overlays are supported. All overlays correspond to the pre-processed data for the area and selected vehicle configuration (VMC) file. The environmental moisture level can be adjusted to reflect the existing or anticipated conditions during use. The options are simply "Dry", "Medium Wet", "Wet", and "Very Wet." Although the soil and vehicle performance data is calibrated to much more specific moisture content values, these settings are intended to reflect the information available to a typical operator without access to more precise sensor or environmental input.

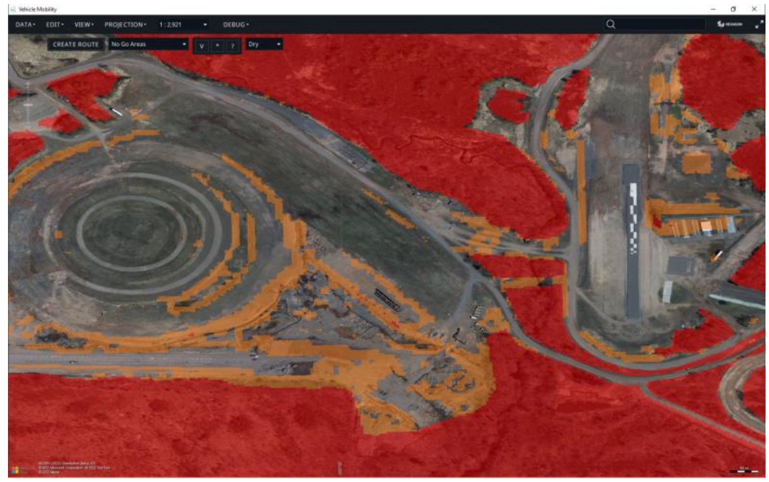


Figure 4: Default No-Go/Slow-Go map view.

The preferred overlay for operational use is shown in Figure 4. This overlay uses red and amber to demark the no-go (below 2 mph) and slow-go (below 10 mph) regions, respectively, but leaves the remaining areas "clear" (no overlay). This clearly indicates where travel risks are likely without obscuring the view of tractable areas.

Two different "Speed made good" overlays are included for the tool. These display the

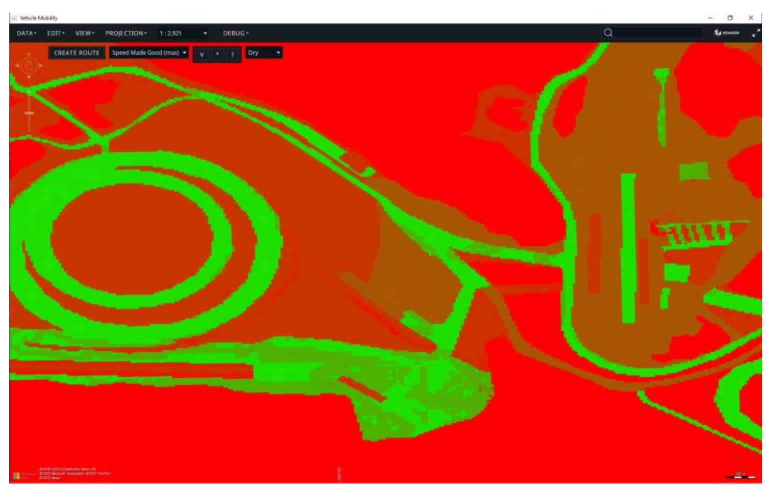


Figure 5: Speed Made Good (max)

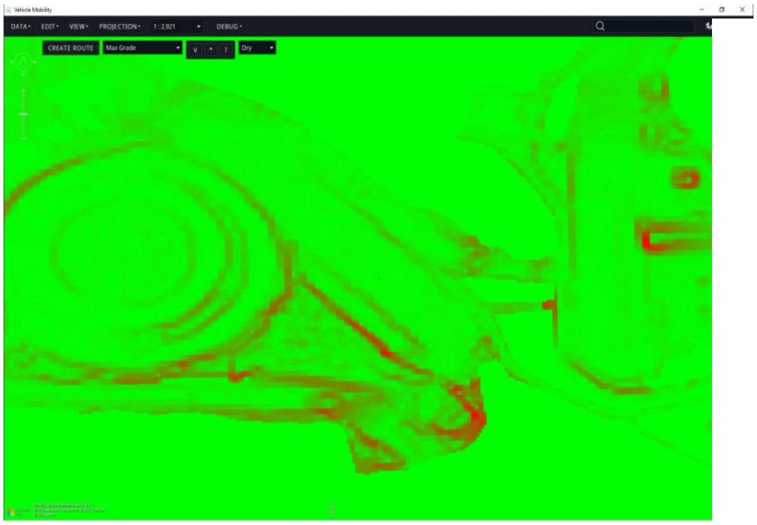


Figure 6: Application display of soils data layer for KRC

Figure 7: Application display of soils data layer for KRC

predicted attainable speed for each location on the map. The Speed Made Good (max) option (Figure 5) shows the expected maximum attainable speed for each location, in any direction. The Speed Made Good (min) view, not shown, represents the minimum max speed for any direction of travel. On flat ground, these two should match, but in complex terrain, there could be significant variation based on direction of travel. The KRC terrain is quite flat, so little difference is observed for this dataset.

In addition to the speed-based overlays, the terrain grade may also be shown, as in Figure 6. This may help to clarify aspects of the underlying terrain that contribute to the speed made good determinations.

While the above features have been implemented for easy use in the “operational mode” of the tablet. The application does retain the ability to revert to a more inclusive interface, with significantly more options for display of additional content, such as soil maps, vegetation, elevation, etc. The soil display is shown in Figure 7.

Route Creation and Modification: One of the primary features of the DMS tool is vehicle route development, and there are several features associated with this; many based on user feedback and in-field observations. Fundamentally, the route is comprised of waypoints connected by route segments. Route development proceeds through the following user actions:

Figure 8: Application display with example route creation.

Create Route: The user taps/clicks the Create Route button on the GUI and picks a starting point on the map. The start point is created.

Add Auto/Direct Route Point: The user selects if the route to the next waypoint should be optimized via the routing algorithm or use a straight point-to-point segment, and picks the next waypoint on the map. The new waypoint and the route segment are created.

Add Additional Waypoints and Route Segments: Repeat prior step, adding points until route is complete. An example route may be seen in Figure 8.

Once a route is created, it exists as a sequence of route segments and waypoints. These individual route elements can be modified through several actions:

Segment Type: Individual route segments can be selected and toggled between direct and auto segment types.

Insert Waypoint: When a segment is selected, it can be split by adding a new waypoint to the route. Once the waypoint is identified, the original route segment becomes two direct route segments connecting to the new waypoint. If desired, these can then be switched from direct to auto segments.

Delete Waypoint: Individual waypoints can be removed. If the waypoint connected existing route segments, a new direct segment is created connecting the remaining waypoints. If the end waypoint is removed, the corresponding end-segment is also removed.

In the event that a direct route segment passes through zero-speed areas or an auto-route solution cannot be found, that segment is displayed as a yellow dashed line. In addition, anticipated challenges along the route are also highlighted for operator awareness through route "decorations." Specific decorations have been implemented for locally steep grades, vegetation, and road roughness, as shown in Figure 9.

By default, each route segment also displays the calculated duration to traverse that portion of the route. In addition, the attainable vehicle speeds (mph) may also be displayed along the route, as shown.

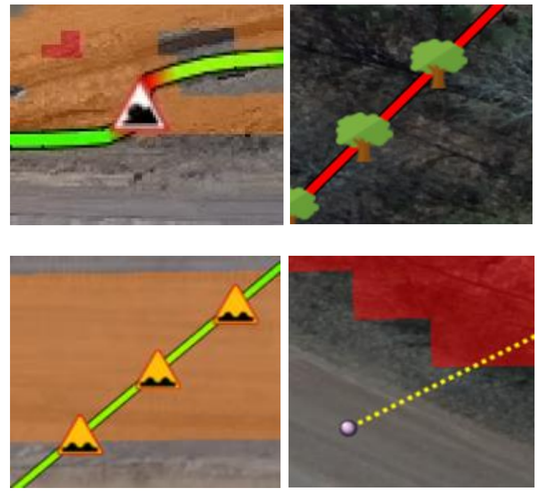


Figure 9: Route warning decorations (steep grade, vegetation, rough terrain, impassable route)

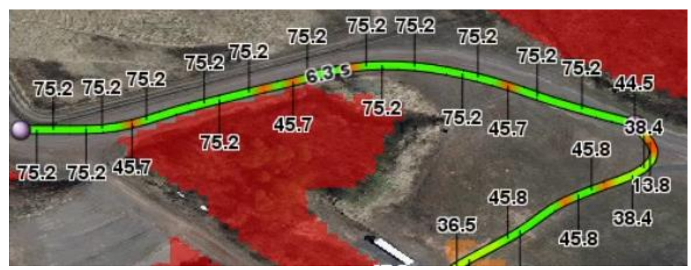


Figure 10: Attainable speeds displayed along route.

Note that the speeds and resultant durations reflect a predicted maximum attainable speed under steady conditions for each terrain location. Hence, with the current implementation, the calculated segment duration both assumes that the vehicle operator is at maximum speed and does not account for local transitions in speed or heading. This will tend to underpredict the timing for most operational scenarios. This is discussed further in the Validation Section below.

Figure 11: User-Defined Go/No-Go Overlays.

Additional Application Features: In addition to the features discussed above, several other features were implemented to improve the tool capability:

Go/No-Go Overlays: The operational environment is dynamic and conditions can easily differ from the static underlying datasets used to generate both the visualizations and routing calculations. As such, the DMS application provides a mechanism for users to create regions (polygons) on the display and set a corrected vehicle speed. This allows the users to update the application with real-time data which overrides the static data and produces a more accurate route based on current conditions. An example is illustrated in Figure 11 above, where an obstruction and a clearing have been added to override the nominal data.

Map Queries: While the dynamic speed/grade visualizations can be useful for both operators and planners, the toolset allows the user to query any point within the operational area and display information about the terrain characteristics at that location. This is useful for determining why certain areas are designated as slow or fast or why a route does not choose a certain path that seems passable based on the available imagery on the display. The streamlined "operator" and more detailed "planner" views both have slightly different information displayed, with the "planner" view having access to greater information. These views are displayed in Figure 12.

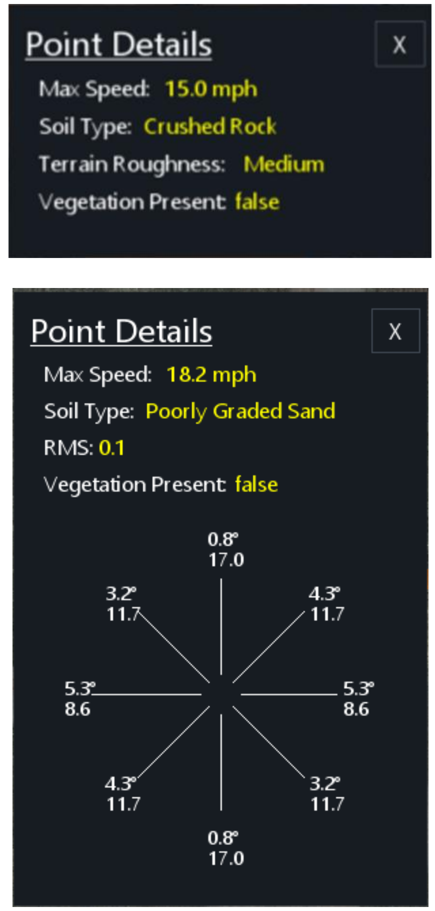


Figure 12: Point Detail display for both operator view (top) and planner view (bottom)

Note that the planner display includes directional speed data, plus a specific numerical value for the RMS, whereas the operator view is simplified for easier interpretation.

4. Validation

Several activities were performed with the goal of validating the DMS toolset. Ultimately, this validation reflects not only on the operational capabilities and stability of the application on the tablet, but also on effectiveness of the underlying modelling and simulation dataset that is populating the application. Two "Field Events" were conducted at the KRC facilities; an initial

"Beta test," and a subsequent assessment of the nearly final implementation. Both events included the participation of experienced Army soldiers. The soldiers indicated that the predicted mobility information would be very beneficial in the field, both for active missions and for operator training scenarios. In addition, they provided significant feedback for improving tool features, options, and usability.

For the second testing event, the predicted routes were found to be traversable by the test vehicles. In areas where the attainable speeds were predicted to be slower, the vehicle would encounter significant terrain characteristics impacting speed. The routes were well-aligned to operator expectations (improved surfaces preferred, steep slopes and soft terrain avoided). Occasional exceptions, such as routing through a field instead of a convenient road, were determined to stem from deficiencies in the data set such as missing off-road RMS surface roughness data (e.g. the algorithm prefers an apparently smooth field over a 1.2-inch RMS road). Improved GIS data or algorithm assumptions would reduce these exceptions.

As discussed in above, the speeds used for the routing calculation reflect the max attainable speed for the vehicle at any given location. During testing, the actual attained speeds were less, as the vehicle is rarely exercised to its limits. However, the predicted speed trends accurately corresponded to speed variations experienced in the field. Critically, the tool rarely identified true no-go areas as traversable.

In addition to the primary route-planning functionality, the accessibility of vehicle limits (slow-go and no-go areas) for the local terrain was found to provide valuable feedback for maintaining safe vehicle operation.

5. Development Opportunities

The DMS application that has been presented represents a functional prototype that incorporates several significant new developments. However, there remain opportunities for improvements, simply through the improved integration of existing information or methods.

5.1. Accuracy

The incorporation of several additional features could improve the accuracy of this type of application:

Baseline terrain moisture: The method employed here assumes that the entire terrain is at a shared moisture level. This does not account for pre-existing variation in the terrain (naturally wetter and dryer areas). The methods employed here could be revised to adjust moisture relative to this baseline setting.

Surface roughness methods: Enhance the GIS representation to estimate surface roughness more effectively in offroad areas. This will allow improved use of the RMS speed criteria for more accurate routes.

Improved vehicle route speed estimates: Maximum vehicle speed is not an ideal metric when estimating route timing or likely vehicle speed. Improved logic for likely operator behavior could improve route duration predictions.

Leverage UQ information for planning and visualization: Due to project time and budget constraints, the UQ data developed over the course of this project was not effectively leveraged for routing and map visualization. There are several ways that this data could be used to impact the tool effectiveness and the reliability of the routes it generates.

Combination grade: With additional analysis, improved performance limit estimates for combined longitudinal/lateral grade conditions could be integrated into the application.

Sensor integration for soil property updates and calibration: Though not currently accessible, future sensors that provide feedback on tire rut depth or moisture could be leveraged to dynamically update the terrain model for a better fit to current conditions.

5.2. Functionality

In addition to the accuracy, several tool enhancements could extend the capability of the DMS application.

Data and algorithm routing enhancements: The modified Dijkstra's search algorithm is suitable for smaller operational areas such as KRC. This can be extended to a larger region by combining it with other routing methodologies, potentially combining road network usage with the current offroad capabilities where road networks are not available.

Saving and sharing map features, such as go/no-go areas and planned routes: With the underlying geospatial data being relatively static, dynamic updates from both mission planners and vehicle operators could be used to provide a more up-to-date picture of the area.

Interactive route notifications: During vehicle operation, the application could provide feedback on route conditions, upcoming hazards, reduced speeds, or other information that could be useful to the vehicle operator.

Convoy, multi-vehicle display capability: Currently the DMS application is a single node system from either an operator's or planner's perspective. A natural extension would be for each vehicle's position and routing information to be connected and disseminated to create a common operational picture. This would provide situational awareness for the vehicle operators as well as a real-time picture of the area for mission oversight.

In addition to the display of multiple vehicles, this could be used during the planning phase to define a convoy consisting of multiple vehicle types moving in a group across the terrain. This would ensure that all vehicles would be able to traverse the planned route and find the optimal coordinated path.

Coordination outside of convoy movement is also possible with connected systems. In this manner, multiple vehicles operating in the area can plan movements to rendezvous, approach areas simultaneously from different vantage points to have overlapping/flanking fields of view, etc. Realtime situational updates could be used to reroute vehicles around obstacles discovered by a forward unit or to send assistance to a disabled vehicle.

Route preview based on point-cloud scans: Combining satellite imagery, point cloud data, and elevation, routes could be previewed and visualized from a first-person perspective from within the application.

Line of sight contributions to route planning: Given the surface elevation data, GIS tools can calculate line of sight for a given point or route. This can be used to determine visibility from or to the vehicle along the route or in planning to avoid areas of visibility from defined points or installations.

6. Conclusions

The analysis process and mobility application presented here illustrate that the required methods and technology components are available for the implementation of interactive tools for visualizing vehicle capabilities and planning corresponding routes in accordance with guidance from the NG-NRMM standards. Testing feedback on the DMS application prototype clearly indicates that the utility of such a tool could extend beyond the envisioned mission planning and mission execution scope into more uses, such as operator training and expanded situational awareness. With this additional vehicle-specific information available, operator safety and effectiveness in the field could be improved.

Broad implementation of this approach primarily requires advances in available data, not methods. The ongoing efforts to enhance and standardize geospatial formats and build up terrain databases will help to provide a foundation for future work in this area. In addition, a standardized representation of the vehicle capabilities, like the VCF file used herein, helps to integrate additional vehicle and terrain representations. This approach allows multiple soil and vehicle analysis methods (both legacy and emerging) to contribute vehicle representations for use within the tool. As the required vehicle analyses are well-defined, the architecture is well-suited to automated SPDM HPC implementations for managing a growing library of models and terrains. With a managed implementation, new methods or data may promptly be integrated into the tool. These methods could also support cloud-based computation for live updates to predicted performance based on field data from satellite, drone, or vehicle sensors.

While the tool shown here demonstrates capabilities well beyond those currently available to mission planners and vehicle operators, there are opportunities for enhancements. There are several specific tasks of clear value:

- The existing DMS capabilities could be augmented through the incorporation of additional vehicles and terrain properties, allowing assessment of the tool in an expanded variety of scenarios. A larger area of operation would clarify if methods improvements are necessary for routing performance at larger scales.
- Significant uncertainty data is available to the application but not currently exposed to the user. Enhancing the application to present this information could provide additional value to users.
- Emerging off-road autonomous vehicle development requires routes that account for both vehicle capability and uncertainty. The geospatial routes developed in the DMS system could be leveraged for autonomous guidance.
- Additional data, such as drone footage or point cloud scans may be leveraged to enhance the route visualization or preview the path.

These activities would guide development of the toolset and clarify its value for both in-vehicle and logistical planning. This information would inform planning for next-generation tools that are positioned to leverage both vehicle performance data and geospatial details for in-field use.

7. REFERENCES

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