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August 2020

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Final report

Approved for public release; distribution is unlimited.

Prepared for Assistant Secretary for Army Acquisitions, Logistics & Technology
Washington, DC 20314

Under Project 471941, "Remote assessment of Snow Mechanical Properties" and
"Mobility in Peat and Northern Soils"

Preface

This study was conducted for the Assistant Secretary of the Army, Acquisition, Logistics and Technology under Project Number 471941, Task 48. The technical monitor was John Rushing.

The work was performed by the Terrestrial and Cryospheric Sciences Branch and by the Force Projection and Sustainment Branch of the Research and Engineering Division, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL).

At the time of publication, Dr. John Weatherly was Chief, Terrestrial and Cryospheric Sciences Branch; Mr. Justin Putnam was Acting Chief, Force Projection and Sustainment Branch; Mr. Jimmy Horne was Division Chief and Dr. Bert Davis, was the Technical Director for Geospatial Research and Engineering/Military Engineering. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

This paper was originally published as a proceeding of the ISTVS 15th European-African Regional Conference, Prague, Czech Republic, September 9-11, 2019 and funded under the Entry and Sustainment in Complex Contested Environments Project, Mobility in Peat and Northern Soils project under the 6.2 T40 ASTMIS.

The Commander of ERDC was COL Teresa A. Schlosser and the Director was Dr. David W. Pittman.

Recent Improvements to Snow Mobility Algorithms

Abstract

Northern environments cause unique terrain conditions for vehicle mobility, the most common of which are snow, ice and freezing or thawing ground. The cold regions mobility algorithms in NRMM (NATO Reference Mobility Model) were developed and implemented in the early 1990s. Meanwhile, vehicle technology has changed considerably and antilock braking, traction control, independent suspension, stability control and other drivetrain and suspension improvements are now common. Recently, we evaluated the legacy NRMM algorithms for 1) validation using modern vehicles; 2) updating sinkage algorithms for snow; 3) updating motion resistance calculations for snow; and 4) incorporating the use of chains or other traction multipliers for traction improvements on snow and ice. This paper presents recent work on validation and enhancements to the NRMM vehicle mobility model for snow and ice and the needs for future improvements.

1. Background

Northern environments cause unique conditions for vehicle mobility. Nearly two-thirds of the northern hemisphere is subjected to cold temperatures for prolonged periods during winter months, leaving both pavements and ground covered by snow and/or ice. Beneath the snow, the terrain can be frozen or in some combination of frost and thaw. Even the southern portion of the United States is occasionally covered by snow and ice or subjected to freeze/thaw cycles. Meanwhile, Arctic regions can be snow and ice covered for over six months.

During the late 1980s and early 1990s, CRREL developed the cold regions mobility models now currently within the NRMM (Richmond, et al., 1995). These models were based on several years of military and instrumented vehicle testing in snow covered environments (Blaisdell et al., 1990 and Richmond et al., 1990). Subsequently, military interests have shifted to desert environments and these models stagnated.

Recently, there is more interest in cold regions mobility and the models were re-evaluated for applicability using validation data from new vehicles and new vehicle technology. This paper documents the first steps at improving the calculations for snow sinkage, motion resistance, and traction. During the validation phase, the traction calculations gave reasonable estimates, but there was no method within NRMM to account for improvements due to traction aids such as chains and studs on snow and ice, so those were added. The motion resistance needed more significant improvement to better predict for a wide range of wheeled and tracked vehicles. To do this, both the snow sinkage and the motion resistance models were redone using a simple terramechanics approach (McCullough et al., 2017). More importantly, these new models relate to more readily available snow properties of depth and density.

2. Recent Snow Model Improvements

2.1 Snow Sinkage Prediction

A conservation of mass method is used by the legacy NRMM to determine vehicle sinkage in snow (Richmond et al., 1995). This method requires only inputs of snow depth, snow density, and maximum vehicle ground contact pressure to predict sinkage into snow. The required input parameters are easily measured or estimated allowing vehicle sinkage to be predicted in various winter scenarios or snow conditions. The method equates the snow mass before and after vehicle compaction for shallow snow conditions as indicated in Fig. 1.

$$m = \rho_o Ah = \rho_f A(h - z) \quad 1$$

$$z = h \left[1 - \frac{\rho_o}{\rho_f} \right] \quad 2$$

Where m is the snow mass (kg), h is the initial snow depth (m), z is the predicted sinkage (m), ρ_o is the initial snow density (kg/m³), ρ_f is the final snow density (kg/m³), and A (m²) is the tire contact area.

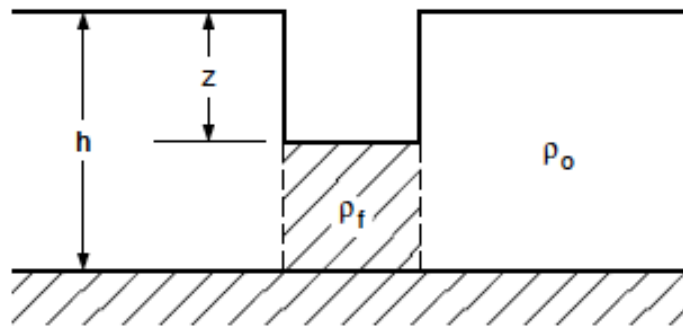


Figure 1 Vehicle sinkage for shallow snow as used in legacy NRMM (Richmond, et al., 1995).

The final snow density, ρ_f , is a function of the vehicle's maximum ground pressure, P_{max} (kPa). For wheeled vehicles it is defined as

$$\rho_f = \min(0.917, 0.519 + 0.0023P_{max}) 1000 \quad 3$$

while for tracked vehicles five categories are used to determine ρ_f :

$P_{max} > 700$ kPa (101.5 psi)	$\rho_f = 650$ kg/m ³
$P_{max} > 350$ kPa (50.8 psi)	$\rho_f = 600$ kg/m ³
$P_{max} > 210$ kPa (30.5 psi)	$\rho_f = 550$ kg/m ³
$P_{max} \leq 210$ kPa (30.5 psi)	$\rho_f = 500$ kg/m ³

Most tracked vehicles fall into the lowest ground pressure category (≤ 210 kPa) resulting in a final density of 500 kg/m³. However, over-snow tracked vehicles can have ground pressures below 15 kPa while battle tanks can have ground pressures greater than 100 kPa. Using the above final density algorithm for tracked vehicles means that all vehicles with maximum ground pressures lower than 210 kPa have the same sinkage.

One objective of the current work is to update the NRMM snow sinkage prediction algorithm to distinguish between tracked vehicles with differing ground pressures as is done for wheeled vehicles. Specifically, this must include the ability to predict mobility of lighter tracked vehicles traveling on deep snow, or “over snow” vehicles.

Another approach to predicting vehicle sinkage is to employ the Wong, Graber, and Preston-Thomas equation (Wong et al., 1984; and Wong and Preston-Thomas, 1987 and 1988). The equation describes the snow pressure sinkage characteristics and is given by,

$$P_c = P_w \left[-\ln \left(1 - \frac{z}{z_w} \right) \right] \quad 4$$

Where P_c (kPa) is the normal pressure, z (m) is the sinkage, and P_w (kPa) and z_w (m) are regression parameters determined from experimental data obtained using a Bevameter (Bodin, 2000). Rearranging Eqn. 4 to solve for sinkage,

$$z = z_w \left[1 - e^{-\left(\frac{P_c}{P_w}\right)} \right] \quad 5$$

The regression parameters can be further expanded to include size effects on the pressure-sinkage curve.

$$P_w = k_{p1} + b k_{p2} \quad 6$$

$$z_w = k_{z1} + \frac{k_{z2}}{c} \quad 7$$

Where k_{p1} , k_{p2} , k_{z1} , and k_{z2} are regression constants and c (m) is the radius of a circular sinkage plate or the smaller side of a rectangular sinkage plate. For a wheeled vehicle c is defined as the radius of the tire contact area, and for a tracked vehicle it is the width of the track. Bodin (2000) provides regression coefficients for pressure-sinkage curves for a snow depth of 70-80 cm.

Table 1 Regression coefficients from Bodin (2000).

k_{p1}	7.35 kPa
k_{p2}	141.5 kPa/m
k_{z1}	0.51 m
k_{z2}	0.011 m ²

One limitation of the Wong, Graber, and Preston-Thomas equation is that the regression coefficients must be measured using a Bevameter for each snow condition. Therefore, each snow depth and density requires bevameter data to generate the equation's regression coefficients. In the proposed approach, the benefits of both approaches are employed allowing sinkage predictions using only easy to measure or estimate snow characteristics (snow depth and density), while differentiating sinkage for track pressures below 210 kPa. By recognizing that z_w in Eqn. 5 represents the maximum asymptotic sinkage, it is possible to employ the conservation of mass method to predict the maximum sinkage. In addition, size effects can be incorporated into the z_w coefficient. Physically, this represents the fact that the snow deformation is not confined to simply vertical compression, but that a portion of the snow mass will be displaced laterally, and that this portion depends on how the track or wheel size interacts with the snow including edge and depth effects (Blaisdell, et al., 1990). As with the Wong equation, the size effects are inversely proportional to the width of the track or wheel. Applying the conservation of mass for the vertical and laterally displaced snow results in,

$$\rho_o A h = \rho_f A (h - z_w) + \frac{b_s}{b} \rho_f A (h - z_w) \quad 8$$

Where b_s (m) is the size constant and b (m) is the tire or track width. The constant, b_s , and final density, ρ_f , are determined through a regression analysis, minimizing the error between the measured and predicted sinkage values. Solving Eqn. 8 for z_w results in the following,

$$z_w = h \left[1 - \frac{\rho_o}{\rho_f [1 + b_s/b]} \right] \quad 9$$

The maximum asymptotic sinkage, z_w , is then applied to Eqn. 5. In Eqn. 5 P_w represents snow strength, assuming a linear relationship between initial snow density and strength

$$P_w = C_r \rho_o \quad 10$$

hence

$$z = z_w \left[1 - e^{-\frac{P_c}{P_w}} \right] \quad 11$$

As with the determination of b_s and ρ_f a regression analysis is used to determine the value of C_r which minimizes the error between the measured and predicted sinkage values. The regression constants and the correlation to measured sinkage data is found in the Verification and Validation section.

2.2 Motion Resistance Model

The legacy NRMM version uses a regression equation relating motion resistance (MR) to snow density, track or wheel width, and contact length to determine vehicle MR in undisturbed snow. As with the NRMM sinkage equation, only easily obtained model inputs are required for the vehicle MR prediction. The MR (N) regression equation for the first wheel (MR_{1w}) or track (MR_{1t}) is given by Richmond, et al. (1995) and Richmond (1993) respectively as

$$MR_{1w} = 13.6041(\rho_o b a)^{1.26} \quad 12$$

$$MR_{1t} = 157.54(\rho_o b a)^{0.833} \quad 13$$

Where ρ_o is the initial snow density (kg/m^3), b is the track or tire width (m), and a is the length of track or tire in contact with the snow (m). The contact length for a tire is given by

$$a = r \arccos \left[\frac{(r - z)}{r} \right] \quad 14$$

Where r is the tire radius (m) and z is the sinkage (m). For a tracked vehicle the equation is given by

$$a = z / \sin(\theta) \quad 15$$

Where θ is the angle of the leading track edge relative to the ground surface, which we assumed to be 26° for all tracked vehicles.

Another method to determine a vehicle's MR is to equate the work required to compress the snow with the work associated with the moving the vehicle. Assuming a constant MR , the work associated with moving the vehicle is given by,

$$W_v = MRx \quad 16$$

where W_v is the vehicle work, MR is the motion resistance, and x is the distance traveled.

The work associated with the compaction of the snow, W_s , is given by,

$$W_s = \int_0^{z_f} 2F_c(z) dz \quad 17$$

where $F_c(z)$ is the force required to compact the snow, which is a function of the compaction depth (z), and z_f is the final compaction depth. The snow compaction force can be expressed in terms of the snow stress which depends on the compaction depth and the area of the vehicle rut, or

$$F_c(z) = \sigma(z)Area = \sigma(z)bx \quad 18$$

where $\sigma(z)$ is the normal stress applied to the snow during compaction, and b is the rut width. Substituting Eqn. 14 into Eqn. 17 and noting that b and x are independent of compaction depth results in,

$$W_s = 2bx \int_0^{z_f} \sigma(z)dz \quad 19$$

In equating the vehicle and snow compaction work, the distance traveled is cancelled resulting in,

$$MR = 2b \int_0^{z_f} \sigma(z)dz \quad 20$$

If Eqn. 4 is used to define the normal stress, Eqn. 20 becomes,

$$MR = 2b \int_0^{z_f} P_w \left[-\ln \left(1 - \frac{z}{z_w} \right) \right] dz \quad 21$$

$$MR = 2bz_w P_w \left[\left(1 - \frac{z_f}{z_w} \right) \ln \left(1 - \frac{z_f}{z_w} \right) - \left(1 - \frac{z_f}{z_w} \right) + 1 \right] \quad 22$$

The MR equation is now a function of the final sinkage (z_f), the track or tire width (b), the maximum asymptotic sinkage (z_w), and the snow strength (P_w). If the ratio of z_f/z_w , becomes close to one, which occurs for most wheeled vehicles with ground pressure greater than 138 kPa, the MR resistance equation (Eqn. 22) reduces to,

$$MR = 2bz_w P_w \quad 23$$

MR resistance Eqn.s 22 and 23 quantify the minimum possible snow compression work done by a vehicle, representing a perfectly efficient compaction machine. In an effort to incorporate less than ideal compaction efficiency, a regression constant, D_r , is added to Eqn. 23 and fit to measured MR values,

$$MR = 2bz_w P_w D_r \quad 24$$

The regression constant and the correlation to measured MR data is found in the Verification and Validation section.

2.3 Chains

One of the primary means for improving traction on snow and ice is by adding traction aids. The ability to account for enhanced traction does not exist in the legacy NRMM. Using recent data collected from vehicle testing with chains, the impact of chains on traction coefficient values and also on the shape of the traction-slip curves was studied. A rule of thumb for the impact of chains on snow is a 30% increase in traction but modern chains were found to improve traction by up to 80% on snow and up to 90% on ice. This is a considerable improvement for vehicle mobility in winter conditions. The most significant improvements were at high slip based on the change in shape of the traction-slip curves. Without chains, traction reaches a peak and then decreases with high-slip. With chains, the traction coefficient is higher and then remains nearly constant rather than decreasing. The impact of chains on the vehicle traction versus slip curve is illustrated in Fig. 2. Antilock Braking Systems (ABS) and Traction Control Systems (TCS) are designed to limit wheel slip to the peak or maximum traction values for on-road commercial vehicles, but many military vehicles do not have these control systems and/or they are not tuned for the harsh off-road winter conditions of interest to the military.

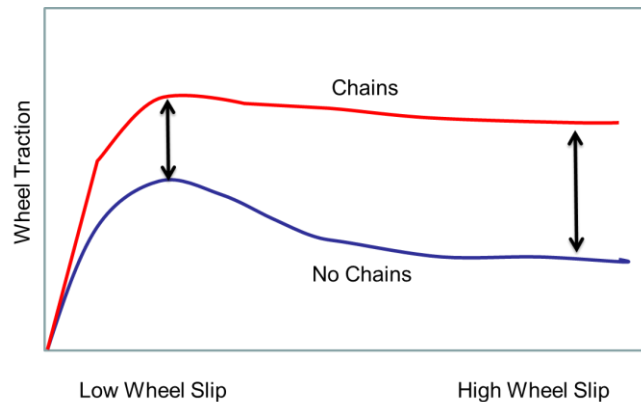


Figure 2. Idealized traction versus wheel slip curves for snow, with and without chains.

The impact of chains on vehicle traction was implemented in NRMM by applying a multiplication factor to the calculated snow traction. If the tire and chain combination and their multiplication factor is known, the factor can be included in the vehicle characteristics (vehicle file). Otherwise, the following default multiplication factors were chosen as a conservative estimate:

- 1.2 times increase in peak traction on snow
- 1.63 times increase in the traction at high slip on snow
- 1.3 times increase in peak traction on ice
- 1.25 times increase in the traction at high slip on ice (keeping in mind that high slip traction on ice is very low indeed!)

The additional motion resistance caused by the chains on packed snow or ice must also be accounted for by adding an additional resistance coefficient of 0.012 based on data measured by CRREL.

3. Verification and Validation

Model changes were first implemented in MATLAB and then migrated to NRMM. The new code was verified and designated as NRMM version 3.1 (not publically releasable). Validation was performed using data collected during the winter of 2018 and also using data from the literature (Richmond, et al., 1995 and Richmond, et al., 1990). In all, several wheeled and tracked vehicles were included in the validation data set as summarized below:

- Wheeled vehicles ranging from 2.4 to 36.3 metric tonnes for snow sinkage and motion resistance
- Tracked vehicles ranging from 6.6 to 57.6 metric tonnes for snow sinkage and motion resistance
- Wheeled vehicles ranging from 2.0 to 36.3 tonnes for data on chains on packed snow and ice.

The results of the verification and validation study are below.

3.1 Measured and Predicted Vehicle Snow Sinkage

The improvements to the sinkage equation were checked against data collected from the literature and test data collected during the winter of 2018 in West Yellowstone, Montana and in Bardafoss, Norway. Measured values represent a range of undisturbed snow depths from 3.5 to 64 cm, with sinkage values ranging from 2 to 51.5 cm. A comparison of the legacy and the new sinkage predictions are given in Fig. 3. The updated sinkage formulation represents the measured values with a correlation coefficient (R^2) of 0.95, and a slope of 0.996, which is closer to a perfect fit than the legacy formation with a correlation coefficient (R^2) of 0.87 and a slope of 0.90. A large portion of the improved fit can be attributed to the improved prediction of track vehicles.

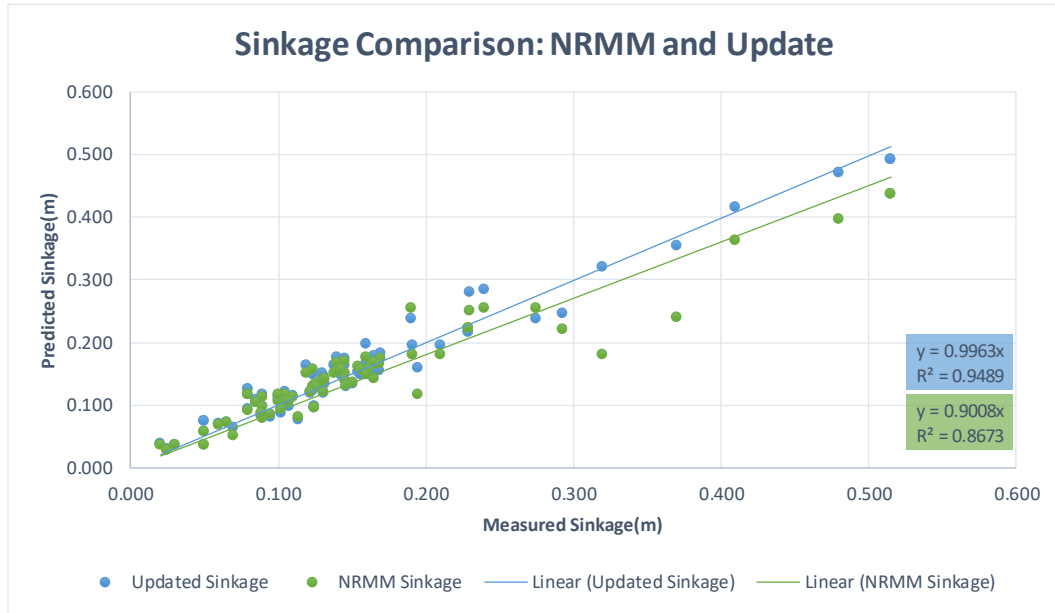


Figure 3. Legacy and updated snow sinkage predictions compared to measured data.

The regression coefficients were determined using the nonlinear least-squares freeware python script `scipy.optimize.curve_fit`. The coefficients from the regression analysis using Eqn.s 9 and 10 are: $b_s = 0.614817$ m, $\rho_f = 0.416604$ g/cm³, and $C_r = 48.36$ kPa/g/cm³. Sinkage measurements were taken with track or tire widths from 0.156 to 0.62 m, undisturbed snow densities from 0.090 to 0.410 g/cm³, undisturbed snow depths from 3.5 to 64 cm, and ground pressures from 13.3 to 413.7 kPa. The updated sinkage equation should not be applied outside of the ranges listed above.

3.2 Measured and Predicted Vehicle Motion Resistance

The improvements to the MR equation were checked against the data collected from the literature, Richmond (1990) and test data collected during the winter of 2018 in West Yellowstone, Montana and in Bardufoss, Norway. The data selected for the analysis were limited to fresh snow conditions with snow depths greater than 15 cm and below the vehicle ground clearances. The minimum snow depth requirement was selected such that other components affecting motion resistance, such as surface roughness, are negligible. The upper depth range was selected to limit confounding the MR data with snow plowing effects in front of the vehicle body. Measured values represent a range of undisturbed snow depths from 15 to 55.3 cm, with initial snow densities from 0.11 to 0.36 g/cm³, tire or track width from 0.254 to 0.62 m, and between 2 and 5 axles. The updated MR equation should not be applied outside of the ranges listed above.

As with Blaisdell et al. (1995) and Richmond (1990) it was found that the number of axles was statistically significant in predicting MR . To account for this, Eqn. 22 was modified to include the number of axles, N_a , as well as the regression constant, D_r , such that

$$MR = 2bz_w P_w \left[\left(1 - \frac{z_f}{z_w}\right) \ln \left(1 - \frac{z_f}{z_w}\right) - \left(1 - \frac{z_f}{z_w}\right) + 1 \right] N_a D_r \quad 25$$

As with the updated sinkage equation a regression analysis was conducted using the `scipy.optimize.curve_fit` routine. The regression analysis resulted in a D_r coefficient of 1.633. The updated MR formulation represents the measured

values with a correlation coefficient (R^2) of 0.55, and a slope of 0.94 (blue data in Fig. 4), which is closer to a perfect fit than the legacy formation with a correlation coefficient (R^2) of 0.0586 and a slope of 1.25 (green data in Fig. 4).

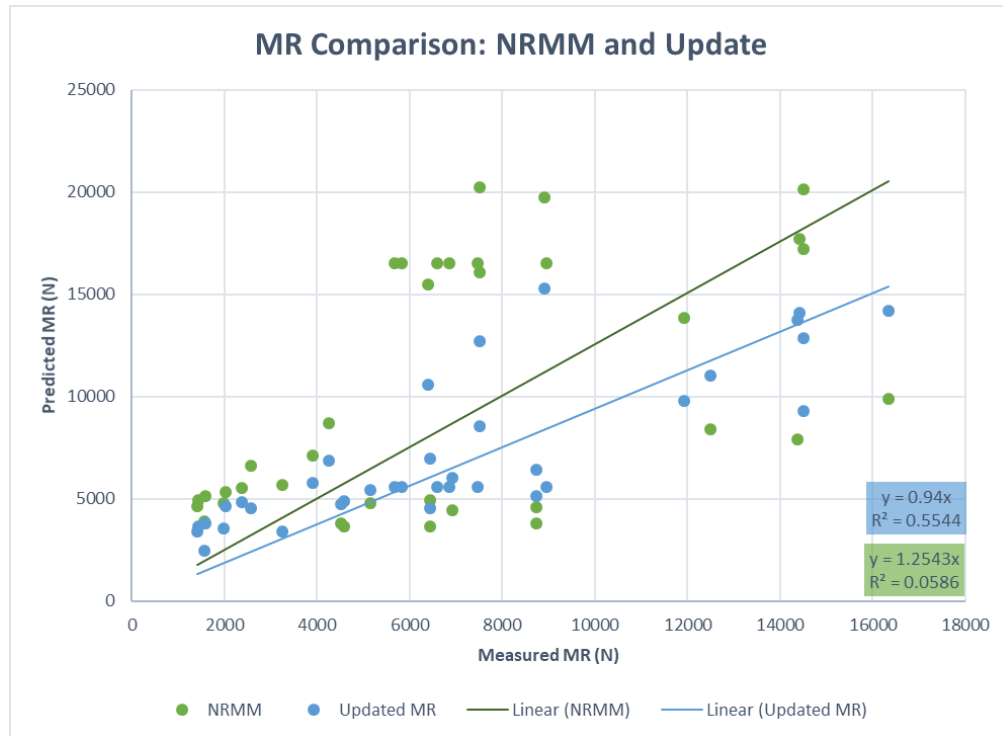


Figure 4 Legacy and updated motion resistance prediction compared to measured data.

Although the updated MR equation represents an improved fit to the measured data, the fit (R^2) of 0.55 is still rather poor. In addition, the number of axles appear to have a significant effect on MR which is not expected from equating snow compaction work to vehicle work. Also, the measured data from literature appears to have substantial variance. For instance, in one case where the only difference between two tests was a change in tire inflation pressure from 275 to 207 kPa a corresponding 48% change in MR occurred. This indicates that either there is considerable noise in the data or that a significant independent variable is missing from the prediction of MR . Additional work is required to fully understand vehicle MR in undisturbed snow, and also to account for the additional plowing resistance when sinkage is greater than the ground clearance.

3.3 Implementing Impact of Chains (Verification Only)

The implementation of the chain model within NRMM is ongoing. To date, only the original test data but no validation data exists. Therefore only verification results are presented. After implementation, the NRMM traction output and speed were checked for a variety of known vehicle combinations. Once the model was determined to provide adequate traction and speed results, the speed was then mapped across a terrain to illustrate the impact of chains on vehicle speed.

The impact of using chains for snow mobility can be directly observed by the decrease in the NOGO areas of a cross country speed map as shown in Fig. 5. In mapping the speed over the test area, the NOGO area, shown in red, decreased by 98%, which is considerable. While average speed for the area generally increased, it is primarily due to the reduction in the NOGO (or zero speed) areas.

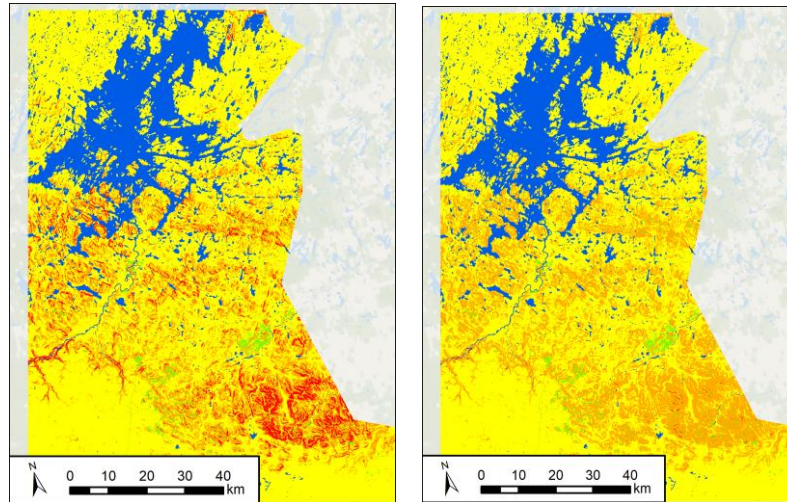


Figure 5. Comparison of speed maps for a heavy wheeled vehicle without chains (left) and with chains (right) showing reduction of NOGO areas (red) and a slight increase in overall speed (more orange and yellow).

4. Summary and Conclusions

Recent interest in revitalizing cold regions capabilities instigated validation data collection and improvements to snow sinkage, motion resistance, and traction aid model capabilities. This study represents the first major change in the legacy NRMM cold regions mobility model since the early 1990s. The result is improved predictions for vehicle mobility in snow, and a step in moving from purely empirical relationships to a more mechanistic model through implementation of simple terramechanics and relating that to the more basic snow properties of depth and density. Future work will expand upon this mechanistic approach using snow mechanical properties that directly influence vehicle mobility and further exploring the full range of mechanisms that impact cold regions mobility.

Nomenclature

a	Track contact length	[m]
A	Contact area	[m ²]
B	Rut, tire or track width	[m]
c	Plate radius	[m]
d	diameter	[m]
D	diameter	[m]
E	energy	[kJ]
F	force	[N]
h	snow depth	[m]
m	mass	[kg]
MR	Motion resistance	[N]
N	Number of axles	
P	Pressure	[kPa]
ρ	Density	[kg/m ³]
r	Radius	[m]
σ	Normal stress	[kPa]
v	Velocity	[m/s]
W	Work	[N-m]
x	Travel distance	[m]
z	sinkage	[m]

Acknowledgements

This project was funded by the Entry and Sustainment in Complex, Contested Environment work package (project 468822) and the USMC maneuver study (project H6H482) and we gratefully acknowledge this support. We also appreciate the expertise provided by the US Marine Corps and the West Yellowstone staff of the Nevada Automotive Research Center.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE August 2020			2. REPORT TYPE Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Recent Improvements to Snow Mobility Algorithms					5a. CONTRACT NUMBER	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Sally Shoop, Mark Bodie, Susan Frankenstein, and Matthew Bigl					5d. PROJECT NUMBER 471941	
					5e. TASK NUMBER 48	
					5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Engineer Research and Development Center Cold Regions Research Laboratory 72 Lyme Road Hanover, NH 03755					8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CRREL MP-20-9	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Assistant Secretary of the Army/Acquisitions, Logistics & Technology 103 Pentagon Washington, DC 20314-1000					10. SPONSOR/MONITOR'S ACRONYM(S)	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.						
13. SUPPLEMENTARY NOTES Originally published in <i>Proceedings of the ISTVS 15th European-African Regional Conference, Prague, Czech Republic, September 9-11, 2019.</i>						
14. ABSTRACT Northern environments cause unique terrain conditions for vehicle mobility, the most common of which are snow, ice and freezing or thawing ground. The cold regions mobility algorithms in NRMM (NATO Reference Mobility Model) were developed and implemented in the early 1990s. Meanwhile, vehicle technology has changed considerably and antilock braking, traction control, independent suspension, stability control and other drivetrain and suspension improvements are now common. Recently, we evaluated the legacy NRMM algorithms for 1) validation using modern vehicles; 2) updating sinkage algorithms for snow; 3) updating motion resistance calculations for snow; and 4) incorporating the use of chains or other traction multipliers for traction improvements on snow and ice. This paper presents recent work on validation and enhancements to the NRMM vehicle mobility model for snow and ice and the needs for future improvements.						
15. SUBJECT TERMS Snow, mobility, NRMM, Validation, Sinkage, Chains, Motion resistance						
16. SECURITY CLASSIFICATION OF:				17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	19b. TELEPHONE NUMBER (include area code)			