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Journal of Terramechanics xxx (2004) xxx–xxx

Journal of Terramechanics

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Overview of cold regions mobility modeling at CRREL

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Abstract

Over the last several decades, the Cold Regions Research and Engineering Laboratory (CRREL) has extensively tested and analyzed issues related to vehicle performance in winter. Using this knowledge and the experimental database, models were developed to capture the important elements for cold regions mobility performance. These models span a range of resolutions and fidelities and include three-dimensional finite element models of tire–terrain interaction, vehicle dynamics models of vehicles on winter surfaces, semi-empirical cold regions algorithms for winter performance within the NATO reference mobility model (NRMM), all-season vehicle performance in force-on-force war-gaming simulations, and vehicle–surface interaction for real-time vehicle simulators. Each of these types of models is presented along with examples of their application.

Keywords: Vehicle; Terrain; Winter; NATO reference mobility model; Snow; Ice; Soil; Freeze; Frost; Thaw

1. Introduction

Vehicle performance in winter conditions is largely determined by the low friction and deformable surface material that affects vehicle traction, motion resistance, handling, and maneuvers. The Cold Regions Research and Engineering Laboratory

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0022-4898/$20.00 © 2004 Published by Elsevier Ltd on behalf of ISTVS.
doi:10.1016/j.jterra.2004.08.004

(CRREL) has been studying the impact of winter on vehicle mobility for many years. Within the last decade, a concerted effort has gone into translating this knowledge base into computer models to help predict vehicle mobility in cold regions. Several types of models have been developed and are briefly presented:

1. Tire–terrain finite element modeling for cold regions terrains.
2. Variable friction tire model for vehicle dynamics simulations.
3. High-fidelity tracked and wheeled vehicle dynamics modeling for seismic signature simulations.
4. Algorithms for cold regions mobility performance within the NATO reference mobility model (NRMM).
5. Vehicle speeds under winter conditions in war-gaming simulations.
6. All-season, cross-country mobility for real-time vehicle simulators.

2. Finite element tire–terrain modeling

Tire performance in winter is important for passenger vehicles operating on snowy roads, as well as to the many industrial (agriculture, forestry, mining, construction), military, and recreational vehicles that are used for off-road operations in all weather conditions. The desire to incorporate theoretical mechanics into off-road vehicle performance prediction has generated great interest in applying numerical modeling techniques to simulate the interaction of the tire and terrain. Therefore, a full three-dimensional model simulating a tire rolling over deformable terrain was developed. The project consisted of three major tasks [1,2]:

- Evaluating tire modeling techniques that would be suitable for use in simulating a tire rolling on deformable terrain.
- Generating constitutive models for snow and other terrain materials for cold regions.
- Developing a complete three-dimensional model that combines the tire model with a model of deformable terrain.

2.1. Tire models

To apply a tire model to deformable terrain, a model is needed that is efficient yet accurately portrays the tire's structural behavior. Specifically, an accurate model of the contact patch is critical for simulating the impact of deformable terrain on tire performance. Models commonly used for designing tires predict deformation of the complete tire, including the interaction of the internal components. However, as our concern is only the deformation as it relates to the contact region and the tire's ability to roll across a deformable surface, simpler tire models can be employed for better computational efficiency. To this purpose, four types of tire models were evaluated for suitability to rolling on deformable terrain:

1. A rigid tire model.
2. A simplified tire model using methodology developed by Darnell [3] for use in vehicle dynamics models.
3. A tire model of the type used for vibration modal analysis, with a smooth tread.
4. A tire model similar to model 3, with a longitudinal, ribbed tread.

Each of these modeling techniques was applied to build models of tires used in an experimental test program. Comparison to measured tire behavior in terms of deflection, contact area, deflected sidewall profile, contact stress distribution, and performance on deformable terrain (snow and soil) is given in Shoop [1,4] to illustrate the strengths or weaknesses of each of these tire modeling techniques though their ability (or inability) to accurately duplicate the measured response.

2.2. Terrain models (snow, thawing soil)

Snow is an extremely complex material, undergoing constant change with time, temperature gradients, and applied load. Therefore, material (constitutive) model parameters were estimated using test data from snow of similar characteristics (density, age, snow type, and location). The type modeled was a fresh snow with an initial density of 200–250 kg/m^3 at moderate temperatures (between −10 and −1 °C). Test data were gathered from the field and from the literature to match this snow type as closely as possible. A finite element model simulating uniaxial confined compression tests was used to verify and improve the material model. The initial model parameters were then applied to simulations of plate sinkage tests for snow of similar age and density. The force–displacement curves for the plate moving into the snow matched the field and laboratory test data well [1].

A finite element model (FEM) of soft soil was generated in an effort to simulate the deformation behavior of thawing soil under vehicle loading on paved and unpaved roads. Freeze–thaw action produces a loose, wet soil that undergoes large deformation when subjected to vehicle loads. The soil modeled is a frost-susceptible fine sand, which was used in full-scale tests of paved and unpaved road sections in CRREL's frost effects research facility (FERF) [4]. The soil was subjected to a full suite of saturated and unsaturated triaxial testing under conditions similar to those experienced during the freeze–thaw testing in the FERF to generate a constitutive model representative of a frost-susceptible soil during thaw [6,7].

3. Applications of tire–terrain finite element modeling

3.1. Motion resistance in snow

The tire–snow finite element model was created to simulate one wheel of the CRREL instrumented vehicle (CIV) moving through a range of shallow (5 cm) to deep (50 cm) fresh snow covers with a density of 200 kg/m^3 (Fig. 1). The first model

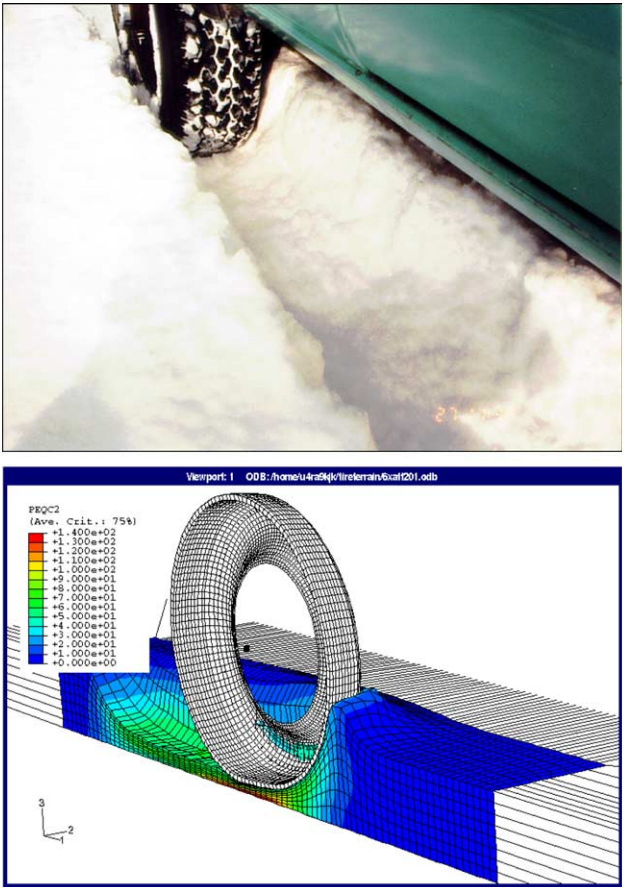

Fig. 1. The CRREL instrumented vehicle tire rolling on 20 cm of fresh snow, showing contours of plastic strain (bottom).

generated was that of a rigid wheel rolling in snow [8]. In fresh snow, the performance of the rigid wheel and the deformable tire models compare favorably because of the highly deformable nature of the terrain being the dominant factor controlling motion resistance. The tire–snow model simulates a towed wheel and duplicates the procedure of a rolling resistance test using our instrumented vehicle. Results were compared to field measurement of tire forces made with the CIV and to rolling resistance and sinkage predictions based on the algorithms used in the NRMM II, as shown in Fig. 2 [1,9]. The FEM traces the upper limit of the data, as desirable for a conservative prediction.

3.2. Road rutting during spring thaw

Finite element simulations were used to study road distress formation on unsurfaced, secondary roads during springtime [10]. Separate models were used to evalu-

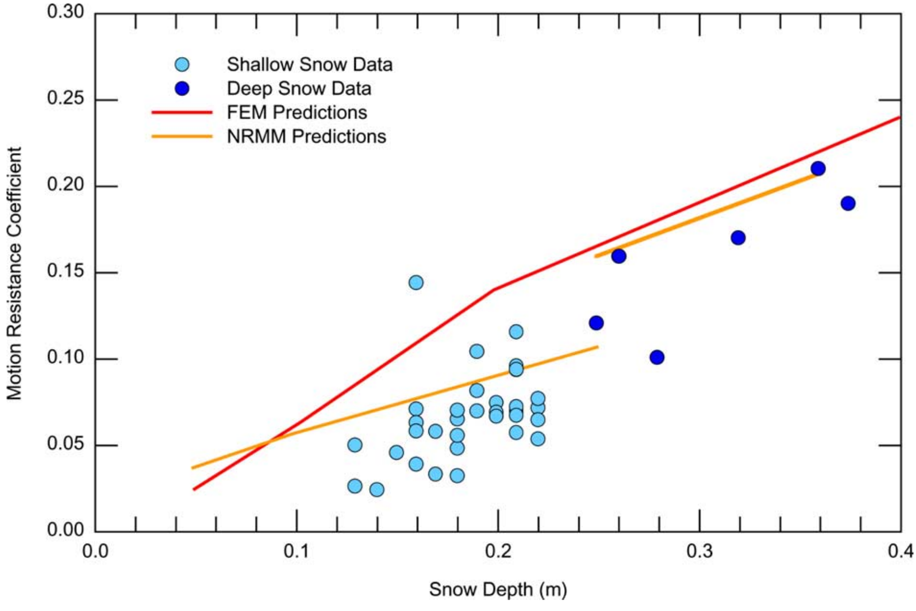

Fig. 2. Comparison of measured motion resistance data, NATO reference mobility model (NRMM) predictions, and finite element model (FEM) predictions, for a range of snow depths (density = 200 kg/m^3).

ate the formation of rutting during spring thaw and for washboard formation. The rutting model consisted of a wheel modeled as a rigid analytical surface with the geometry of the CIV tire. The thawing road was modeled as a thawed sandy soil overlying a rigid base (the frozen layer). Fig. 3 shows a comparison of the depth to which the tire sinks in the soil for various wheel slip values. The simulation time begins as the wheel is lowered onto the soil under gravity and allowed to equilibrate for 1 s of simulation time. During the next 1 s of simulation time, the wheel is accelerated from a longitudinal speed of 0–1 m/s. For the remainder of the simulations, the wheel axle is moved at a constant speed of 1 m/s. At zero slip, the wheel sinks only 2.2 cm into the thawed soil, and, as the slip increases, the tire sinks further into the soil until it sinks nearly through the full depth of the thawed soil at −100% (braking) slip. In general, the motion resistance coefficient steadily increases with increasing slip (and sinkage), with a maximum occurring between −80% and −100% slip. For the free-rolling tire, the slip varies freely throughout the simulation and final sinkage is similar to that of −100% slip.

3.3. Washboard formation on unsurfaced roads

The simulation used to study washboard formation was quite different owing to the dynamic nature of the problem. The model of the vehicle was a 1/4-car model, which included the suspension simulated using a spring and dashpot, as well as the sprung mass of the vehicle chassis. Also, because of the need to evaluate the effect

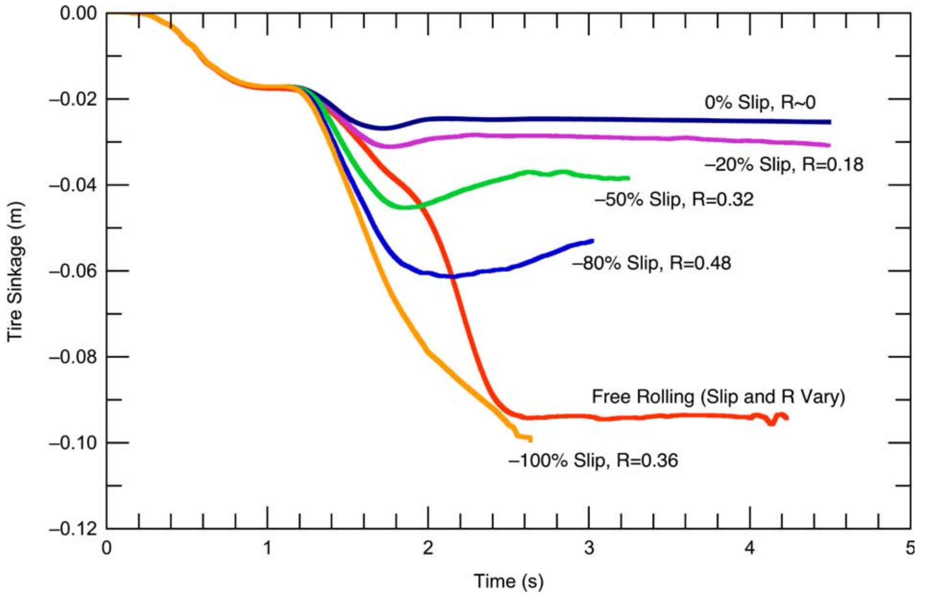

Fig. 3. Sinkage of the tire in the thawing soil, with motion resistance coefficient (R) labeled. Soil thaw depth is 0.1 m.

of the vehicle speed, and because higher speed would require a very long mesh of the road, the road model was changed to an adaptive Lagrangian–Eularian (ALE) formulation, where the mesh remains stationary, while the soil moves through the mesh beneath the rolling wheel at the speed of the vehicle. Monitoring the surface of the mesh at the edge of the simulation, after it is exposed to the vehicle loading, captures the deformed profile of the road. Several cases were modeled to study the effects of speed, wheel torque, slip, suspension, and impulse load. A spectral analysis of the soil deformation from the models identified several dominant frequencies; the lowest frequency identified ranged from 1.5 to 2 Hz, which is approximately the natural frequency of the suspension (1.59 Hz). The other predominant frequencies identified in the simulations correspond to wavelengths in the range of 55–65 cm, which fall within the range of washboard wavelengths measured in the field (25–84 cm [10]).

The deformation caused by a driven wheel is compared to that of a free-rolling towed wheel in Fig. 4. The amplitude of deformation caused by the driven wheel is up to three times greater than that of a free-rolling wheel, presumably because of the additional horizontal forces applied to the tire–soil interface.

4. Physics-based tire model for variable friction vehicle dynamics

Vehicle handling and maneuvering are controlled by the friction between the tire and the road surface, which can be extremely variable in winter conditions. A critical element in any wheeled vehicle dynamic model is the algorithm defining

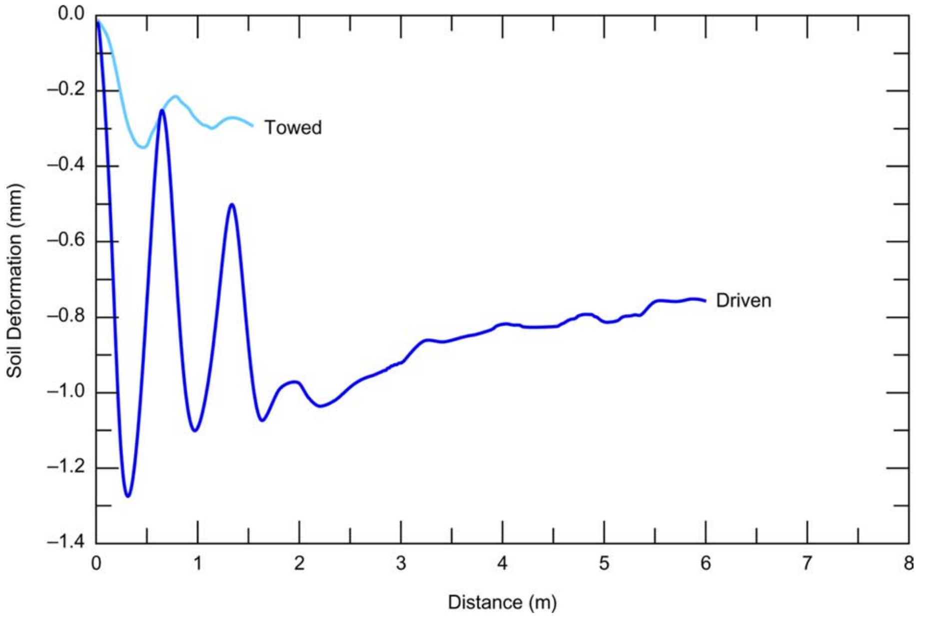

Fig. 4. Soil deformation (washboard formation) after simulating one pass of a driven wheel and a towed wheel.

the interaction between tire and ground. A simple, physics-based analytical tire model, where surface friction is an independent variable, was developed at CRREL for use in vehicle dynamics simulations. Important features of the model include: (1) a set of required tire inputs that are easily determined using simple test equipment, and (2) an effective means for realistically adjusting tire–road frictional properties to represent dry pavement, ice-, and snow-covered surfaces. Longitudinal tire–road interactions in the CRREL tire model are represented by a simple one-dimensional quasi-static ''Brush'' mechanical analog, described by Dixon [11], and a nominal rolling resistance. The contact patch is divided into a forward ''static'' region and an aft ''slide'' region where sliding takes place between tire and road. The lateral behavior of a tire is nonlinear and is most often described using empirical and semi-empirical approaches (though some analytical models also exist). In the CRREL model, lateral forces are related to lateral tire patch deflections according to a beam-on-elastic foundation analog [9,12].

These formulations reduce required tire model input data to eight parameters that are relatively easy to measure using simple test equipment. Source code has been developed to incorporate the tire model into commercially available software – dynamic analysis design system (DADS). The tire model has been successfully demonstrated within a DADS simulation of a simple tire test device. Fig. 5 shows predicted longitudinal and lateral forces generated during combined cornering and braking on dry pavement compared to predictions for an unspecified radial tire (at the same vehicle speed and normal load) by Bakker et al. [13] using the well known ''magic'' model.

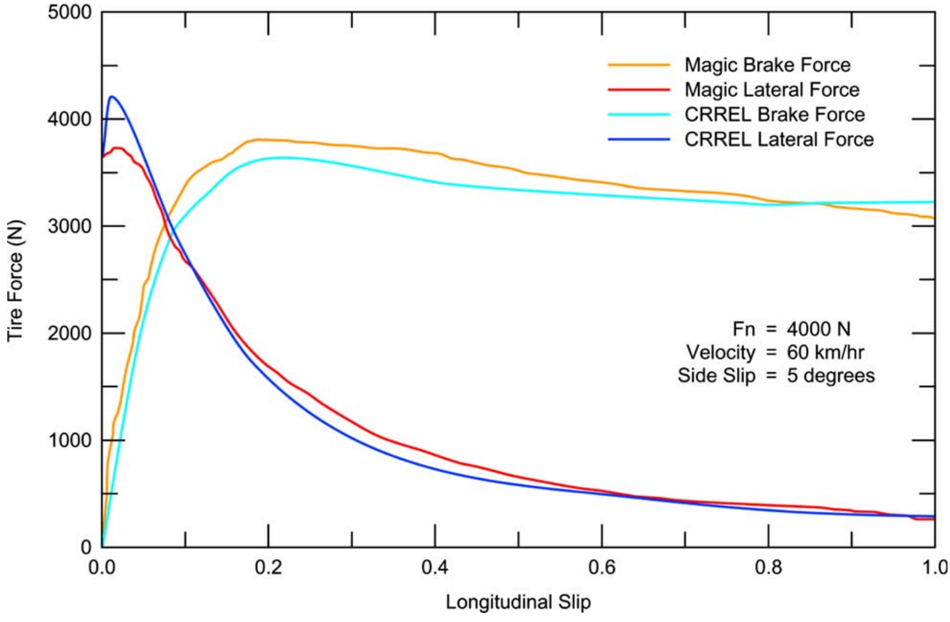

Fig. 5. Comparison of CRREL model and magic model tire forces on dry pavement (5° side slip).

4.1. Vehicle dynamics variable friction tire model applications

Tire model performance was evaluated by incorporating the model into a DADS model of the CIV and comparing simulation output against CIV measurements. The DADS CIV model used for this purpose is represented in Fig. 6. The CIV is instrumented to measure vertical, longitudinal, and lateral forces at the tire/surface interface, wheel speed at each wheel, true vehicle speed, and steering angles. It is designed as a research tool to perform various mobility tests (traction, resistance, and maneuverability) using different tires, traction aids, and vehicle configurations (of braking and driving wheels) on a range of terrain surfaces, including dry or wet conditions, snow, ice, and freezing or thawing ground. The data obtained from these tests are used to validate models and to develop algorithms to predict vehicle performance on cold-weather terrain. Fig. 7 shows lateral force predictions, along with field measurements, for a free rolling tire at different slip angles on compacted snow. The CRREL model predictions agree very well with the CIV measurements.

5. Tracked and wheeled vehicle modeling for vehicle dynamics

The military is interested in vehicle-generated seismic signatures as it seeks to deploy unattended seismic sensors to detect, track, and classify mobile targets. These sensors require accurate representations of vehicle-generated forces and high-fidelity

Fig. 6. CRREL instrumented vehicle (CIV) accurately measures tire forces at the surface interface and was simulated for use in the CRREL tire model validation.

computer models are being used to cost-effectively generate both vehicle seismic signatures and vehicle mobility predictions.

To streamline creation of military tracked vehicle models, a customized DADS utility with graphical user interface (GUI) was developed [14]. Details related to the vehicle track and suspension are emphasized in the models developed using this utility. The rest of the vehicle (i.e., hull, and vehicle contents) is represented as a single sprung mass with user-specified mass, center of gravity, and principal moments and products of inertia. Suspension layout information is specified in the GUI, along with dimensional, inertial, stiffness, and damping properties of individual suspension elements (road wheels, road arms, idlers, sprockets, support rollers, and track blocks), as seen in Fig. 8. Motion and forces at every body in the vehicle model are generated during a DADS dynamic simulation. This includes the ground forces acting at each track block, which are calculated using multiple DADS "point-ground" contact elements. The point-ground contact element includes a routine based on a modified set of Bekker [15] soil equations that is used to calculate normal ground forces. Tangential forces are calculated using a Mohr–Coulomb form of the

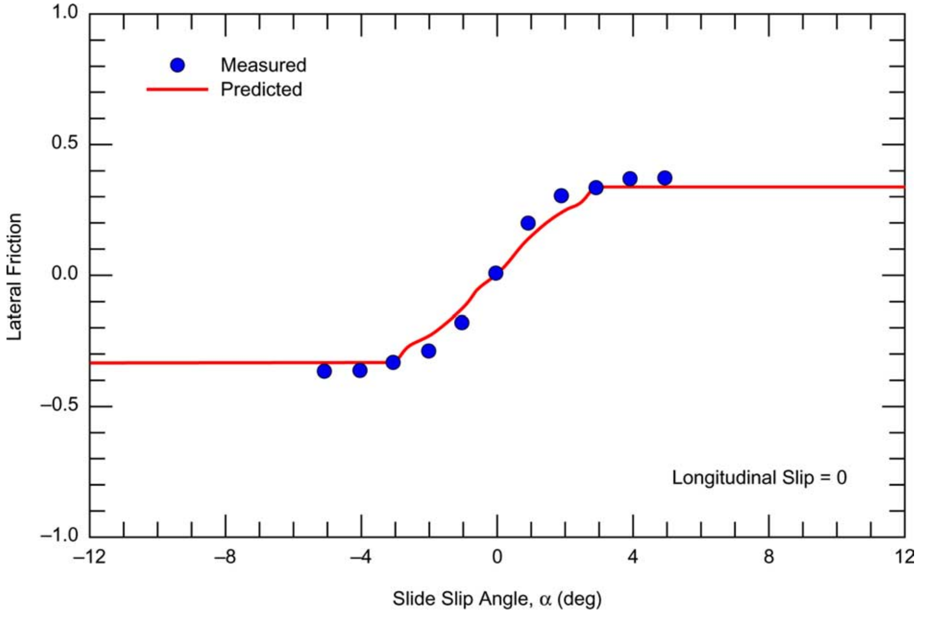

Fig. 7. Measured lateral force coefficient for packed snow compared with CRREL model predictions.

shear stress equation. As many as 11 such elements are currently employed per track block. Models of several vehicles were built and are being used to generate virtual ground force data for seismic propagation simulations. In addition to generating seismic data, these tracked vehicle models will be used to predict vehicle maneuverability on snow- and ice-covered surfaces.

Lower-fidelity two-dimensional DADS models of wheeled vehicles have recently been developed that contain many fewer bodies, contact elements, and degrees-of-freedom (DOF) than the previously discussed tracked vehicle models. The reduced

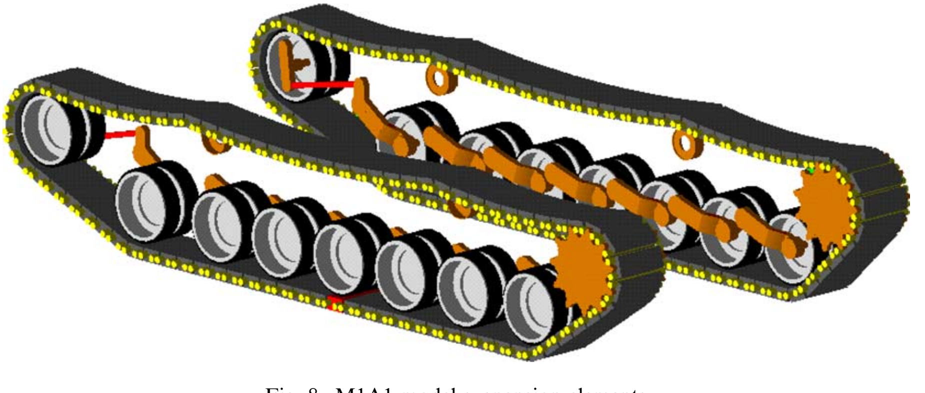

Fig. 8. M1A1 model suspension elements.

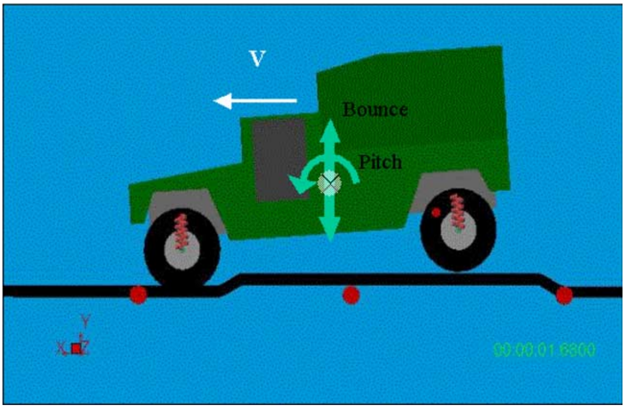

Fig. 9. Two-dimensional M998 HMMWV model for seismic analyses.

complexity of these two-dimensional models results in much shorter simulation run times, making them much more useful for conducting rapid parametric studies. Although not as precise as the three-dimensional vehicle models, the two-dimensional models, nonetheless, produce ground force outputs suitable for analyses of vehicle seismic signatures. Two-dimensional seismic models for an M998 HMMWV and light commercial truck have been developed to date. The HMMWV model is shown in Fig. 9.

5.1. Tracked vehicle dynamics for seismic signal generation

The development of unattended battlefield sensor systems is currently being supported by the creation of high-fidelity simulations of the seismic signals that propagate from moving tracked armored vehicles. These simulations require realistic representations of the force distributions applied to the ground at the vehicle track, which are determined by the vehicle sprung and unsprung mechanical properties, track suspension configuration, soil type, and vehicle motion (speed, acceleration, turning rate, etc.). Detailed three-dimensional mechanical models that account for these factors are needed to accurately define the dynamic interaction (and resulting forces) between track and ground.

This modeling capability was initially applied to an M1 tank, T72 tank, and BMP-2 armored personnel carrier. Simulations conducted include constant and variable speed driving and cornering on high and low-friction surfaces. Fig. 10 shows a plot of a short segment of modeled ground force data for a single track block on an M1A1 moving at 28 km/h. A “positive” vertical force acts into the ground while a “positive” shear force acts in the direction opposite to vehicle forward motion. The passage of each of the seven vehicle road wheels is clearly discernable. It is interesting to note that the shear force alternates between positive and negative values as each road wheel passes. The magnitudes of this sign reversal are great enough during

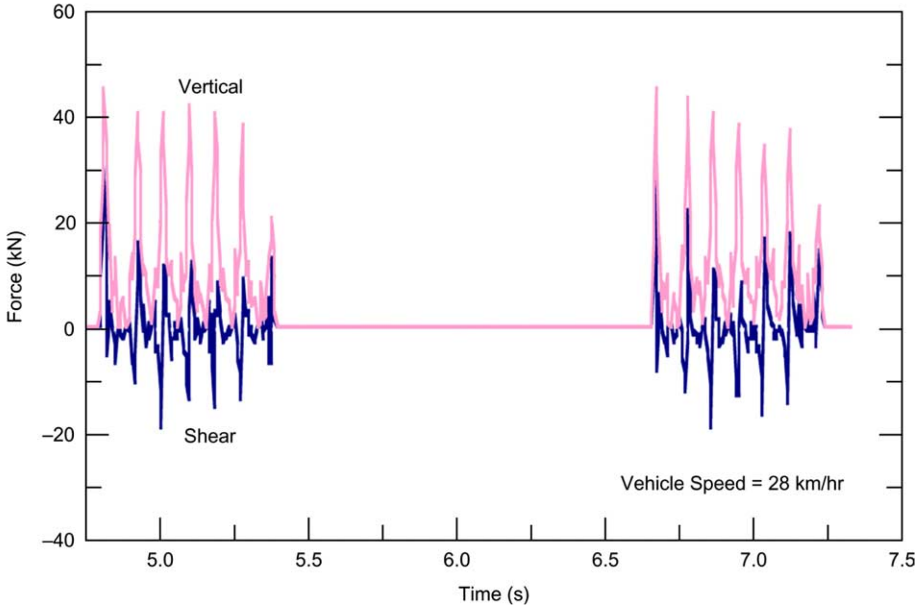

Fig. 10. Sample of modeled ground forces generated by an M1A1 track block.

passage of some of the inner road wheels (numbers 2–6) to result in a net resistive, rather than tractive, force during passage of a road wheel. This type of analysis may be useful for investigating track design. The Bekker soil parameters used in this simulation characterize a firm sandy loam.

Results from these high-fidelity vehicle dynamics models were used to generate seismic signatures in Lacombe et al. [16]. Analyzing the simulated seismic signature data in conjunction with the spectral features associated with the vibrations of specific vehicle sprung and un-sprung components, enables associating seismic signal features with suspension elements, offering valuable insight into target classification. In Fig. 11, a synthetic vertical seismic spectrum is displayed, associated with the vehicle mechanical model moving across simulated terrain. Results demonstrate signal magnitudes that are in general agreement with field data reported in Moran et al. [17]. Seismic spectrograms in the 20–60 Hz band clearly demonstrate harmonics associated with the fundamental track-block passage rate. The lower frequency seismic signal spectral peaks (below 5 Hz) are believed to be associated with the vertical and pitch motions of the vehicle sprung mass (hull and turret).

5.2. Wheeled-vehicle dynamics for seismic signature analyses

A two-dimensional vehicle model has been developed to predict low frequency ground forces from light wheeled vehicles [18]. The computational efficiency of the

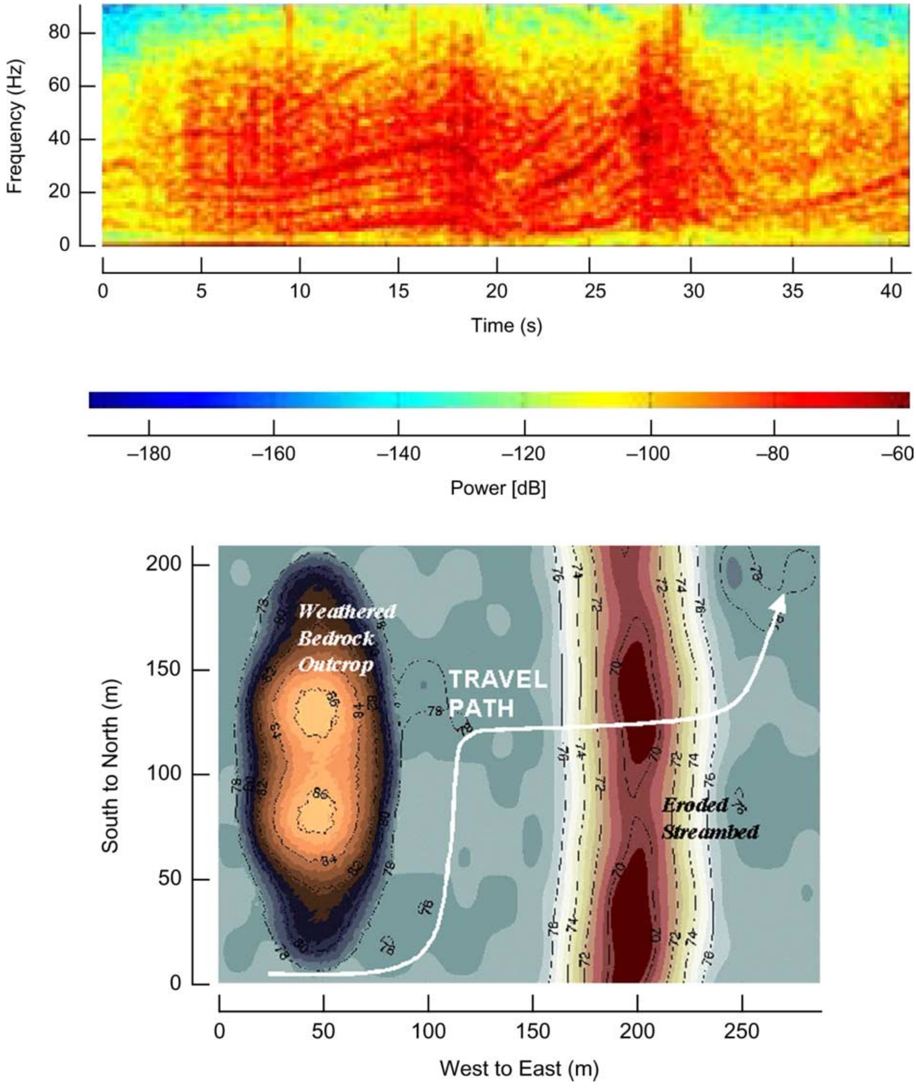

Fig. 11. Synthetic seismic signature (top) from tank model traversing simulated terrain (bottom).

model permits rapid investigations of vehicle behavior that is important to seismic signature generation. The model was adapted to represent an M998 variant of the US Army's HMMWV. The HMMWV model was used to simulate vehicle travel over smooth and rough road surfaces, as well as vehicle excitation by a vibrating test apparatus. Simulation results reveal how wheelbase, wheel rotation rate, vehicle speed, road roughness, and suspension and chassis resonance frequencies contribute to the seismic signature of a wheeled vehicle. Simple mathematical relationships

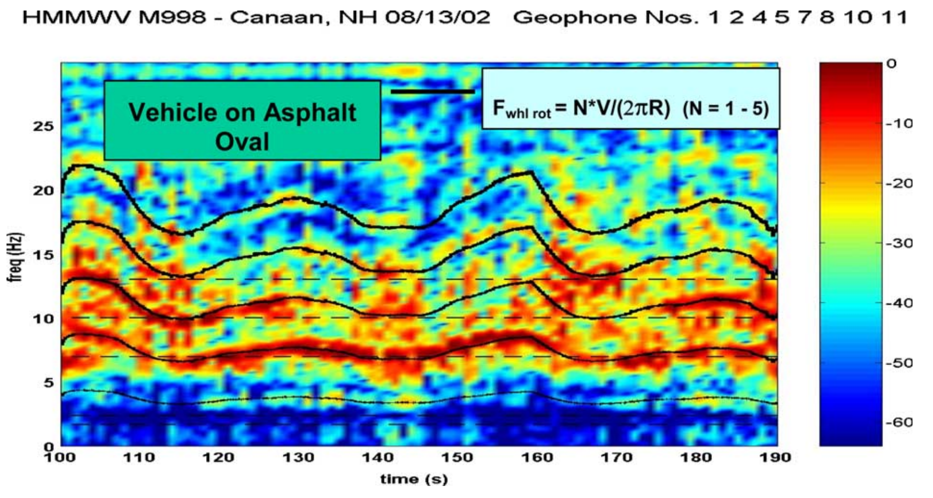

Fig. 12. Measured seismic spectra vs. predicted location of spectral banding for known vehicle velocity V and rolling radius R for travel over a smooth asphalt road surface.

derived from the HMMWV model relate speed, wheelbase, and tire rolling radius to important seismic spectral features.

Analyses of vehicle vibration and speed and ground vibration data collected during a field test in New Hampshire in August 2002 confirm predicted contributions of vehicle speed V, tire rolling radius R, and suspension response to vehicle seismic signatures for travel over a smooth asphalt road surface (Fig. 12). Test results also appear to verify predicted ‘‘scalloping’’ of seismic spectra due to wheelbase filtering of wheel excitation by rough unpaved road surfaces (Fig. 13).

6. Winter and spring mobility algorithms for cross-country movement in the NATO reference mobility model

Semi-empirical winter mobility algorithms have been developed over the past decades by Blaisdell et al. [19], Richmond et al. [20,21], and Shoop [5,22]. These algorithms are compiled into a set of equations that predict maximum available traction and motion resistance on winter terrain, including shallow and deep snow, ice, and frozen and thawing ground [23]. The winter terrain is described as a layered system, consisting of a surface cover (snow), a surface condition (normal, slippery, ice covered, etc.), a depth of ground frost, and a depth of ground thaw. Deep snow is defined as snow conditions for which vehicle sinkage is greater than the minimum ground clearance of the vehicle. The terrain parameter requirements are snow depth and density, soil type, soil cone index or soil moisture content, frozen soil depth, and thawed layer depth. These algorithms have been implemented in the NRMM II [24], to predict vehicle speed performance for operations on roads, trails, and cross-country, in all weather conditions, including terrain conditions associated with winter.

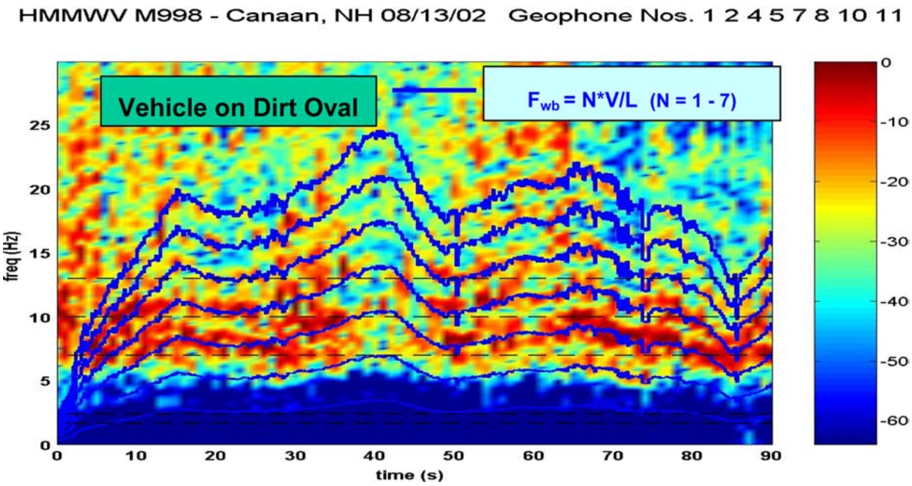

Fig. 13. Measured seismic spectra vs. predicted location of spectral banding due to wheelbase filtering of rough road surface excitation for known vehicle velocity V and wheelbase length L.

The primary factor calculated by the model is the available traction and the motion resistance caused by operation on soft surfaces. A traction versus wheel slip curve, in conjunction with power train capabilities, is used to generate an overall maximum traction versus speed prediction. The motion resistance is used in combination with other resisting forces (e.g., vegetation, slope) to determine the maximum possible force and consequent speed [25]. Model outputs are vehicle speed traveling up- and down-slope, average speed, and a code related to the "speed controlling condition" within each terrain unit.

6.1. Winter performance analysis using NATO reference mobility model

The NRMM winter algorithms have recently been used for several winter mobility analyses, and two of these are mentioned here as representative of the type of analysis possible. The first of these was an analysis of towing forces (individual gear loads) as the Comanche helicopter is towed over deformable terrain surfaces [26]. The NRMM was used to estimate the longitudinal loads imposed on the landing gear to determine whether the helicopter can be moved with a HMMWV under the selected terrain surface conditions. The results showed the Comanche will have significant gear loads and a high resistance to towing on soft soils because of the high vertical load on each gear, which causes significant sinkage (deep ruts).

The bar chart in Fig. 14 presents the towing forces required for a variety of winter surfaces. Three soil types were modeled: a well-graded sand (SW) with a cone index (CI) of 50; a silty sand (SM) with CI = 80; and a silt (ML) with CI = 130. Each of these was modeled under "normal" (summer) conditions, with 60 cm of ground frost

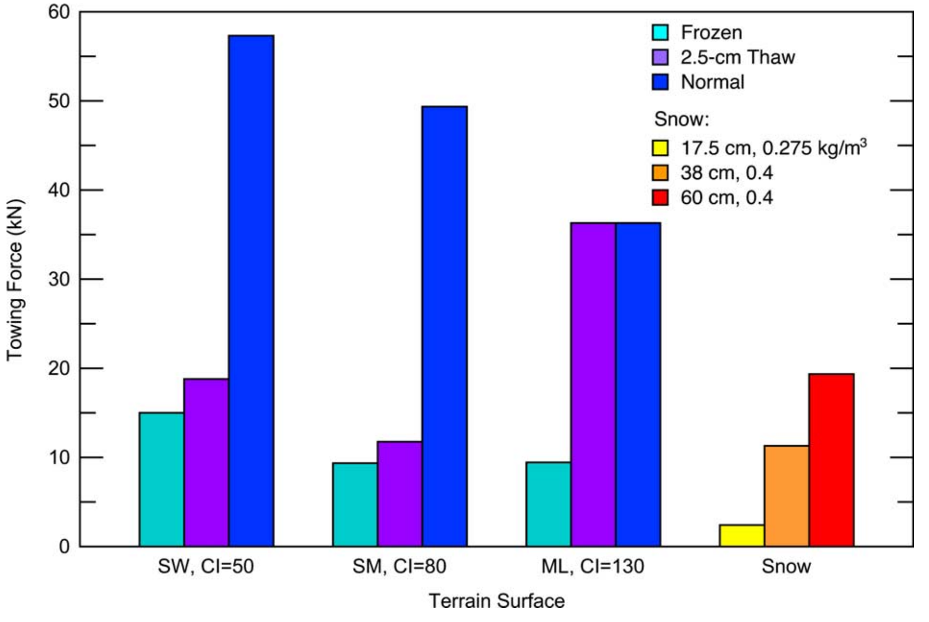

Fig. 14. Towing forces for the Comanche under normal (summer) soil conditions, frozen ground, thawing ground, and various snow covers.

(winter), and 60 cm frost with 2.5 cm surface thaw (early spring). The snow was also modeled in three conditions: 17.5 cm deep with 0.275-kg/m^3 density, 38 cm with 0.4-kg/m^3 density, and 60 cm with 0.4-kg/m^3 density.

The performance on thawed layers indicated no-go because of the high moisture condition of the soil – the soil was weak, resulting in high soil resistance and low traction. In most cases, frozen layers have significant soil strength available for vehicle mobility, reducing or eliminating sinkage. At 38 cm of snow, the HMMWV and Comanche exceed their ground clearance and begin to ‘‘belly drag,’’ significantly increasing the towing resistance. In this case, the gear loads also include the estimated effect of dragging the fuselage though the snow.

Another study involved the use of the NRMM combined with a column movement model [27] to apply speed predictions to a spatial framework and to extend these predictions to vehicle formation relevance. Spatial analysis of probable target locations can be merged with sensor performance layers for optimizing target acquisition. In terms of movable targets (i.e., vehicles and vehicle mounted equipment), spatial maps of vehicle routing, areas of no-go, and choke point areas where vehicles will accumulate, can make up spatial datasets to be used for optimizing sensor locations for the highest probability of finding mobile targets. Thus, a spatial map of cross-country mobility, mobility corridors, and mobility choke points will ‘‘value add’’ as additional intelligence to be synthesized with sensor performance templates. In addition, the seasonal effects on movable targets [28] (Fig. 15) are of particular interest for playing out scenarios through time, where even near-term weather effects can be critical.

Current efforts apply NRMM to predict terrain disturbance at Army training lands based on the seasonal state-of-the-ground [29,30].

7. Winter mobility in war-gaming simulations

Until recently, the US Army had no combat simulation in which to measure the effects of cold environments on the outcome of combat. To address that defi-

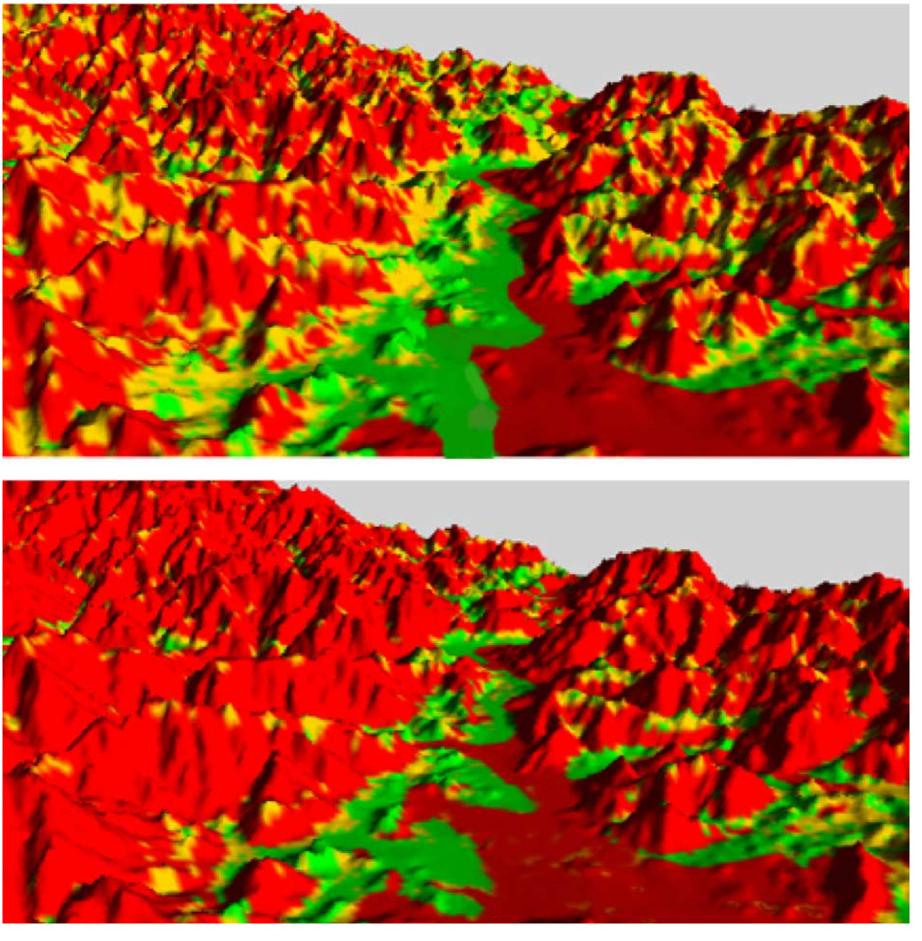

Fig. 15. Seasonal differences for vehicle pathways, go (light green) and no-go (dark red) areas in a northern climate with no snow (top) and with 18 cm of snow (bottom). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ciency, CRREL formed a partnership with the Simulation Lab of the Systems Engineering Department at the United States Military Academy in West Point, New York, to modify the JANUS simulation to handle selected winter environment effects [31]. In the first phase, mobility data were modified to reflect the effects of snow cover and frozen ground on the movement of vehicles. Simulations were conducted, assessing the mobility impacts of the snow and frozen ground on the outcome of the battle. The results showed a 70% increase in casualties for the friendly (attacking) forces as a result of 18 cm of low-density snow, largely attributable to decreased vehicle speeds and unreachable objectives. These results prompted subsequent work developing a Java based user interface to set up and conduct cold environment simulations accounting for weather impacts on both mobility and sensors [32,33].

In a separate program, as part of the US Army Defense Modeling and Simulation Office initiative to incorporate environmental impacts in military simulations, the NRMM was used to generate simulation parameters representing the impact of changing soil conditions (based on weather) on the plowing speed of a landmine clearing vehicle [34,35]. The output file contained parameters defining the tractive-force versus speed curves and motion resistance based on soil type and strength, and a table of plowing forces based on soil type, strength, and plow depth. Extending this concept to produce similar data files for additional vehicles was proposed for use in other US Army simulations. Subsequently, this implementation of NRMM predictions and the corresponding application files have become known as the standard mobility model (STNDMob) as presented in Baylot et al. [36].

The winter mobility algorithms (snow and ice) have been implemented within STNDMob in support of the US Army's OneSAF Objective System, OneSAF Test Bed Baseline, Joint Virtual Battlespace, and CombatXXI simulation programs. Snow density and depth, strength of underlying soil, and presence of an ice cover are the additional required winter parameters. Figs. 16 and 17 show the resulting estimates of motion resistance and speed for a high mobility tracked vehicle. The data for these figures were obtained by using NRMM with parametric terrain data; fitting hyperbolic equations to the tractive force-speed curves for given conditions, the equation is in the form

$$\text{Tractive force coefficient} = \frac{B(1)}{\text{Speed} + B(3)} + B(2).$$

The coefficients $B(1)$, $B(2)$, $B(3)$, plus the limiting values for the equation, and the corresponding terrain conditions are stored in an extensiable markup language (XML) data file. Resistances based on snow depth and density, calculated within NRMM, are also stored in this file. STNDMob has interpolation routines for conditions that fall between the parametric data.

Future efforts will add the freezing/thawing soil algorithms and investigate the use of STNDMob for route planning.

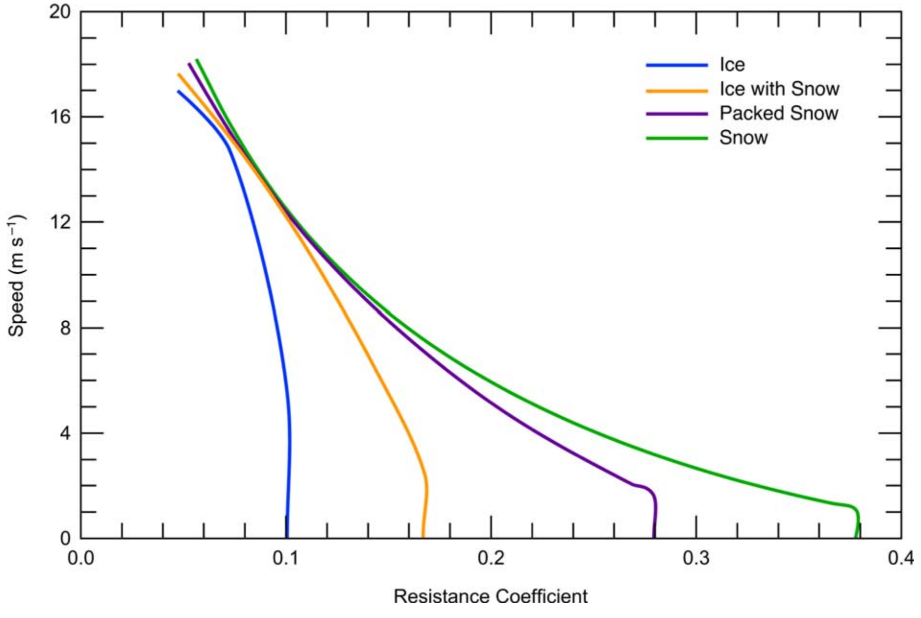

Fig. 16. Resistance force coefficient speed curve for a tracked vehicle in snow.

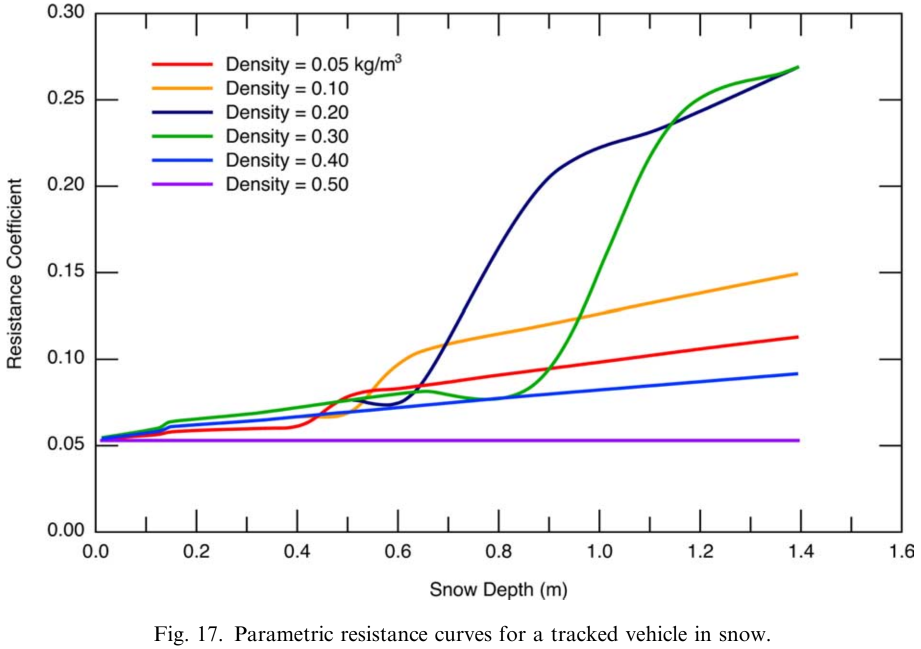

Fig. 17. Parametric resistance curves for a tracked vehicle in snow.

8. All-season terrain capabilities for real-time vehicle simulators

Until recently, real-time vehicle simulators did not account for the interaction of the tire and deformable terrain for cross-country mobility. The US Army science and technology objective (STO) strategy aims to remedy this technology gap through a joint research program among the US Army Corps of Engineers Research Labs (Geotechnical and Structures Laboratory, GSL, and Cold Regions Research and Engineering Laboratory, CRREL), the Tank and Automotive Research and Development Center (TARDEC), and the Army Research Laboratories (ARL). The objective of this program is to make significant advances in the state-of-the-art for off-road, all-season ground vehicle models, terrain mechanics, and vehicle–terrain interaction models. This effort includes three different levels of fidelity –"high-resolution," "real-time," and "hyper-real-time," with some consistency among them.

Simulation technologies developed and integrated through this joint research program include the development of general purpose, three-dimensional, physics-based, high-fidelity ground platform and terrain mechanics models and the interaction between them. The primary modeling and simulation technologies addressed include real-time simulation methods and vehicle–terrain interaction modeling, in addition to the development of standard vehicle interfaces, modeling of advanced suspension components, modeling of unconventional powertrain configurations, and flexible-body dynamics models. Of these, the real-time vehicle simulator serves as the showcase to demonstrate and evaluate the new simulation and vehicle technologies (Fig. 18).

8.1. The virtual evaluation suite and the real-time simulator

TARDEC has developed a cross-country real-time vehicle simulator to provide a framework within which to evaluate new simulation technologies and vehicle technologies. To provide a metric for vehicle performance, a suite of virtual test operating procedures is being implemented. This framework is called the virtual evaluation suite (VES). It is applicable to the study of ground vehicle stability, handling, ride, mobility, and durability over all terrains under all weather conditions [37]. The VES reflects a joint effort to develop software to build high-fidelity models of future Army vehicles and their corresponding terrains using a physics-based approach.

The VES consists of a standard vehicle interface definition, a driver model that implements a set of virtual test operating procedures, and a set of terrains that include seasonal effects, trafficking effects, and dynamic objects. The VES is being designed to subject detailed vehicle models to a standard set of tests, but is completely applicable to models of any resolution that meet the standard interface. The VES can be used to evaluate the vehicle modeling technologies in either manned or unmanned ground vehicles – the difference being the implementation of the driver model.

Evaluation suites currently planned for the VES include:

- Interface verification.
- Dynamic stability and handling.

Fig. 18. Virtual, solider-in-the-loop simulation using high performance motion simulators at the TACOM-TARDEC Ground Vehicle Simulation Laboratory (GVSL).

- Ride and shock quality.
- Mobility and Durability.
- Human Factors.

The dynamic stability and handling test suite implements common tests (circle tests, lane changes, J-turns, test course laps, etc.). For the military, handling tests are also conducted cross-country and on test loops involving different terrain surfaces and all-season environments. The incorporation of these types of tests into the VES will result in a major advance in vehicle modeling and simulation. A minimal set of vehicle system states is also included – the vehicle's position and orientation, along with its translational and angular velocities and accelerations. Future work on the VES will include the development of standard instrumentation interfaces that will define and expose the internal states of the vehicle.

8.2. Virtual terrain and terramechanics

Realistic terrain representation is the key to successful physics-based simulations of all-terrain, all-season vehicle performance. Terrain surface models include visual representations, elevation profiles, and terrain features that impede mobility. The terrain must also include soil types, terramechanical properties, and the

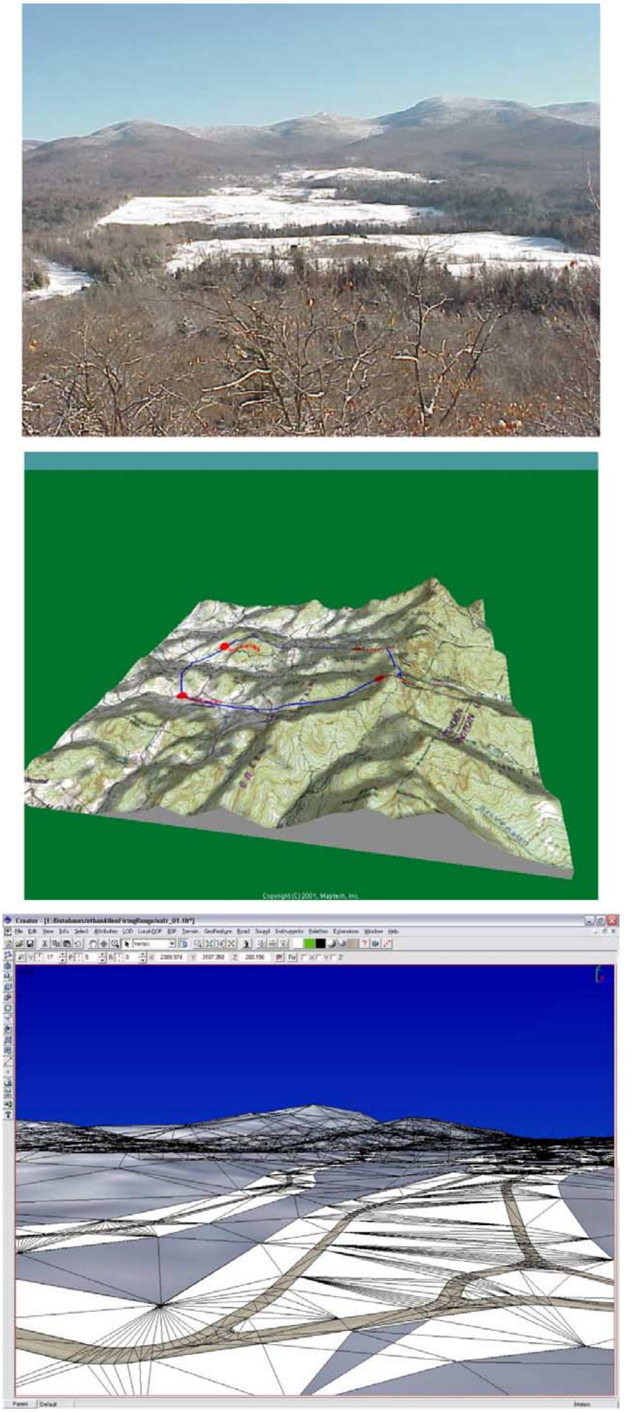

Fig. 19. Real and virtual all-season terrain for ride motion simulator.

state of the ground (wet, dry, frozen, thawed, snow or ice covered). These terrain and soil types must be correlated to the visual representation of the terrain (texture maps) (i.e., a soil that is soft sand must have a texture map that visually represents the soft sand). An all-season virtual terrain has been developed with the capabilities to spatially distributed soil and snow properties and to change these to reflect seasonal changes in the terrain [38]. The test terrain was the Ethan Allan Firing Range in northern Vermont, which consists of a wide range of terrains (mountains and valleys, forests, and fields) and soil types (Fig. 19). The methodology to incorporate terrain deformation and the consequent forces on the wheel or track due to variable terrain materials [39,40] will be applied to this virtual test site and validated against actual vehicle maneuvers using instrumented test vehicles.

Terrain mechanics modeling and simulation technologies addressed by the TARDEC–USACE project include the development of:

1. Methods to generate high-resolution terrain from lower resolution databases and statistical descriptions of the terrain.
2. Three-dimensional, all-season (soil, snow, ice) terrain mechanics models, including surface deformation, moisture, and temperature effects along with the generation of tractive forces.
3. Obstacle layers capable of accommodating high-resolution obstacle negation experiments.
4. Dynamic terrain models that allow for soil deformation memory and obstacles that change because of natural and man-made events.

9. Summary and conclusions

This paper presents an overview of some recent advances in cold regions mobility modeling to incorporate the effect of all-season terrain in vehicle performance modeling and simulations. The following modeling efforts and their application are highlighted:

1. A three-dimensional finite element model of a tire on cold regions terrains was developed. Material models for fresh snow and thawing soil were generated and validated using laboratory and field data. The finite element models agree favorably with both the measured data and the NRMM predictions for rolling resistance in snow, and has been used to study rutting and washboard formation on unsurfaced roads.
2. An analytical tire model was developed to simulate vehicle handling on variable friction surfaces. The CRREL DADS tire model contains eight parameters that are relatively easy to determine, and do not require sophisticated testing equipment. The model has been implemented in DADS and validated using data from the literature and from experiments using the CIV on snow.

3. Dynamic models of armored tracked vehicles containing detailed representations of track and suspension elements interacting with a deformable surface were developed, along with relatively simple two-dimensional models of light wheeled vehicles. Vehicle simulations were used to generate time histories of the absolute position and force vector (into the ground) of track blocks and tires. These data serve as the source signal for three-dimensional seismic propagation models and to evaluate the seismic signatures of different vehicles.
4. The incorporation of winter conditions into the NRMM has enabled relatively quick, semi-empirical estimations of vehicle mobility across a wide variety of terrain types, and assessments of seasonal impacts on vehicle performance.
5. The NRMM all-season capabilities provided the basis for incorporating winter impacts into force-on-force (war-gaming) simulations. The standard mobility model (StandMob) has been used to implement winter mobility into the one semi-automated force (OneSAF) and the joint virtual battlespace (JVB) war-gaming simulations.
6. A joint program between the US Army Corps of Engineers Research Labs (GSL and CRREL), the Tank and Automotive Research and Development Center (TARDEC), and the Army Research Laboratory (ARL) serves to advance the vehicle–terrain modeling and simulation capabilities for "high-resolution," "real-time," and "hyper-real-time." An all-season virtual model of terrain has been developed with the capabilities to spatially distributed soil and snow properties to realistically simulate seasonal effects, and an interface to incorporate terrain deformation and the consequent forces on the wheel or track on a variable strength terrain surface.

9.1. Future research needs

These modeling efforts represent a significant step forward in our understanding of winter mobility and have allowed incorporation of that knowledge into models and simulations for performance and design. However, a fundamental understanding of both the thermal and mechanical behavior of snow and freezing/thawing ground in terms of friction and its impact on traction is still difficult to quantify. In addition, simulation of other cold regions materials, such as trafficked snow and slush, and peat, which covers large portions of northern land masses are also needed. Adapting legacy empirical modeling to a three-dimensional framework, and validation of these models is a continuing effort, which is necessary for human-in-the-loop vehicle simulators and the incorporation of the full suite of cold weather impacts into war-gaming scenarios. Linking different fidelity models, such as finite element with real-time simulators, and maintaining consistency between the modeling resolutions and fidelities is an important issue for modeling and simulation programs. Of increasing importance is the understanding of mechanisms involved in the behaviors of autonomous and robotic vehicles, particularly those of very light weight and with non-traditional drive elements. These vehicles may engage the terrain in a manner quite different than human driven vehicles, although the issues are certainly not limited to cold regions.

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