Semi-Empiric Algorithm for Assessment of the Vehicle Mobility

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Abstract

The mobility of military vehicles plays a key role in operation. The ability to reach the desired area in war theatre represents the most important condition for a successful accomplishment of the mission for military vehicles. The off-road vehicles face a broad spectrum of terrains to cross. These terrains differ by geometry and the soil characteristics.

NATO References Mobility Model (NRMM) software is based on empirical relationship between the terrain characteristics, running conditions and vehicles design. The paper presents the main results of a comparative mobility analysis for M1 and HMMWV vehicles obtained using NRMM.

Keywords

Mobility; Soft Soils; Traction; Vehicle.

Introduction

There are numerous scientific attempts to describe the traction of vehicles on soft soils in direct correlation with the soils characteristics.

A large amount of papers have developed analytical approaches based on Bekker's equations [1]. The last developments of the analytical models deals with the detailed study of the design influence on traction characteristics [2, 3].

The complexity of the phenomena occurring within the terrain - vehicle interface leaved enough room for the development of empirical methods for evaluation of the vehicle

mobility. The first successful attempts includes the work of US Army specialized laboratories [4]. Considerable efforts were made in order to set up empirical relations who cover the current design diversity of the vehicle; finally, the mathematical relations were implemented into NATO Reference Mobility Modelling (NRMM) software [5, 6].

NRMM is a large scale digital simulation, which predicts the on-road and cross-country performance of a vehicle in a global sense. The measure of performance is speed-made-good and percent of an area denied due to immobilization.

NRMM is used in the development of requirements, cost-performance analyses, as an evaluation tool, in support of contract selections and to support other mobility studies.

NRMM is an engineering model (constructive type) which marries the engineering characterization of the vehicle (power train, running gear, suspension, mass and inertial properties and geometry) with the engineering characterization of the terrain (slopes, soil strength, obstacle geometry, surface roughness, and vegetation density). It is an analytical simulation model which predicts the vehicle's maximum attainable speed cross-country and on-road for a specified geographic region and environmental condition (wet season, rainfall, snow), and defines within the geographic region areas of immobilization and the reasons for such situation. Meanwhile, this model is based on empiric relations experimentally validated for al large variety of vehicles in terms of size, weight and running gear type.

The Mobility Index of the vehicle

The Mobility Index, (*MI*), represents a parameter that is related to the Vehicle Cone Index (*VCI*) performance of the vehicles running on fine-grained soils. It is composed of many traction parameters influencing vehicle characteristics. [6].

The calculation of Mobility Index (*MI*) is performed using design data specific to each vehicle by the following formulae [5]:

$$MI = \left(\frac{CPF \cdot WF}{TEF \cdot GF} + WLF + CF \right) \cdot EF \cdot TF \tag{1}$$

where: *CPF* – contact pressure factor:

- for tracked assemblies:

$$CPF = \frac{w}{n \cdot 1 \cdot b} \tag{2}$$

- for wheeled assemblies:

$$CPF = \frac{w}{0.5 \cdot n \cdot d \cdot b} \qquad (2)$$

- for wheeled assemblies:

$$CPF = \frac{w}{0.5 \cdot n \cdot d \cdot b} \qquad (3)$$

TEF = traction element factor done by:

- for tracked assemblies:

$$TEF = \frac{b}{100} \qquad (4)$$

- for wheeled assemblies:

$$TEF = \frac{100 + b}{100} \qquad (5)$$

WLF – wheel load factor:

- for tracked assemblies:

$$WLF = \frac{w}{10 \cdot Nr \cdot As} \qquad (6)$$

- for wheeled assemblies:

$$WLF = \frac{w}{2000} \qquad (7)$$

WF – weight factor, *GF* – grouser factor, *EF* – engine factor, *TF* – transmission factor, adopted from tables [5].

For the above relations, the following nomenclature applies: w = weight beneath assembly i, lbf; n = total number of elements (tracks) on assembly i; or total number of elements (tires) on assembly i; l = length of single element (track) in contact with ground, in.; b= width of single element (track) in contact with ground, in.; or single tire section width (undeflected and highway inflation pressure), in.; g = grouser height, in.; Nr = total number of road wheels on assembly i in contact with ground; As = area of one track shoe, in.; hc = minimum ground clearance of assembly i, in.; PWR = engine gross power to weight ratio, hp/ton; d = single tire outside diameter (undeflected and highway inflation pressure), in.; h = single tire section height (undeflected and highway inflation pressure), in.; δ = single tire hard surface deflection for scenario j, in.;

Soil characterization using the Cone Index

The Cone Index, (*CI*) characterises the in situ shear strength of a soil. It is obtained by the measurements performed using a specific device, the cone penetrometer. In fact, the Cone Index represents the force applied to a cone penetrometer with 0.5 sq in base area and 30 deg angle to penetrate 150 mm into the upper layer of the soil. The cone penetrometer realized by Military Technical Academy uses a strain gauge sensor for force measurement, the displacement being measured with a string potentiometer, as it is shown in Figure.

Figure 1. The cone penetrometer

Usually, several wheel assemblies act successively on the same soil area, so the repetitive loading has to be taken into consideration. The behaviour of the soil under repetitive loadings is described by the Rated Cone Index (*RCI*) which is measured using the same cone penetrometer but the soil is compacted by applying a defined number of blows.

The value of the rated cone index may be estimated using the following formula:

$$RCI = e^{a+b\ln(u)} \tag{8}$$

where *a* and *b* represents coefficients extracted from tables, and depend of the type of soils and its humidity *u*, in %.

For the soils described in the Unified Soil Classification System [6], the variation of the Rated Cone Index with the humidity was computed, the results being presented in Figure 2. The curves indicate a rapid decrease of the Rated Cone Index with the increase of the humidity for all types of soils.
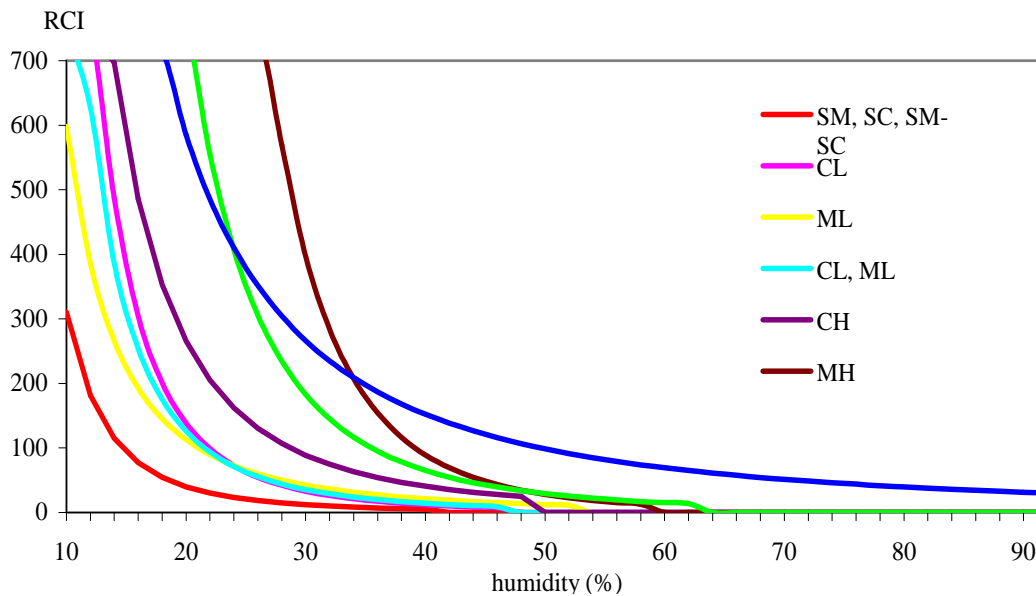

Figure 2. Variation of the Rated Cone Index versus soil humidity

Vehicle Cone Index

The Vehicle Cone Index, (*VCI*) represents the minimum soil strength in the critical layer, in terms of rating cone index for fine-grained soils or in cone index for coarse-grained soils and muskeg, required for a specific number of passes of a vehicle, such as one pass (*VCI*$_1$), or (usually) 50 passes (*VCI*$_{50}$).

The calculation of the Vehicle Cone Index for a single pass (*VCI*$_1$) is done by the following empirical formulae:

- for tracked vehicles:

$$\text{VCI}_1 = \left(7.0 + 0.2\text{MI} - \frac{39.2}{\text{MI} + 5.6} \right) \tag{9}$$

- for wheeled assemblies with MI<100 psi:

$$\text{VCI}_1 = \left(11.48 + 0.2\text{MI} - \frac{39.2}{\text{MI} + 3.74} \right) \cdot \left(\frac{0.15h}{\delta} \right)^{0.25} \tag{10}$$

- for powered wheeled assemblies with *MI*>100 psi:

$$VCI_1 = 4.1MI^{0.446} \cdot \left(\frac{0.15h}{\delta}\right)^{0.25} \tag{11}$$

For assessment of mobility of vehicles used according with the scenario which provides large units displacement, the trafficability is better described by the Vehicle Cone Index for 50 passes, which takes into consideration the degradation of the upper layer of the soil do to the passes of the previous vehicles. The formulae used in this situation are the following 1:

- for tracked vehicles:

$$VCI_{50} = \left(19.27 + 0.43MI - \frac{125.79}{MI + 7.08}\right) \tag{12}$$

- for wheeled assemblies with *MI*<100 psi:

$$VCI_1\left(28.23 + 0.43MI - \frac{92.67}{MI + 3.74}\right) \cdot \left(\frac{0.15h}{\delta}\right)^{0.25} \tag{13}$$

- for powered wheeled assemblies with *MI*>100 psi:

$$VCI_1 = 9MI^{0.446} \cdot \left(\frac{0.15h}{\delta}\right) \tag{14}$$

The results obtained using the above formulae for M1 tank and HMMWV wheeled vehicle are summarized in Figure 3.
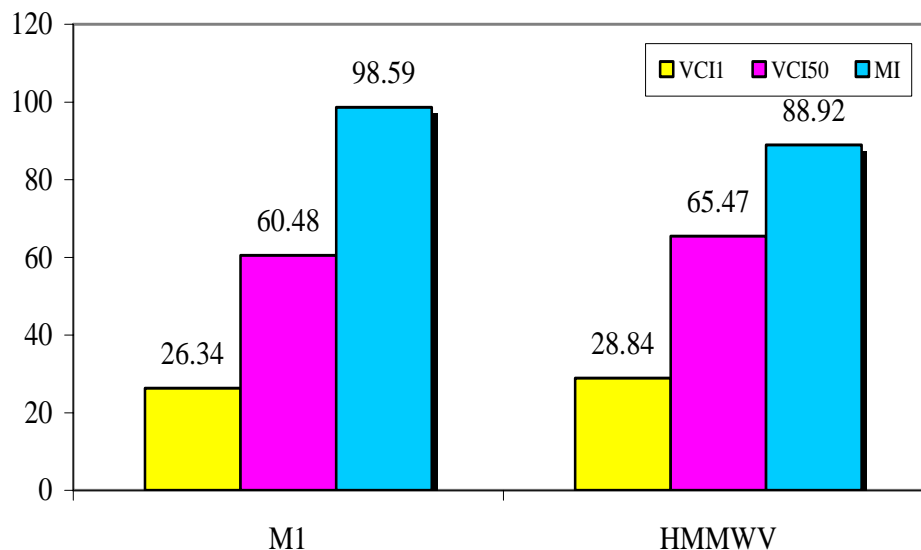

Figure 3. Vehicle Cone Index and Mobility Index for M1 tank and HMMWV wheeled vehicle

The data presented in Figure lead to the following conclusions:

1. The Mobility Index predicts the ability of the vehicle to cross obstacles and difficult terrains, in this case the tank being superior to the wheeled vehicle;

2. The grater values of VCI_1 and VCI_{50} respectively indicate the better behaviour of the wheeled vehicles for one pass and for multiple passes on soft soils.

The last conclusion is obvious if the total weight of the vehicles compared is considered. Nevertheless, the difference is not so great, and the tank keeps a high mobility despite the large effect of damage performed by the track on the upper surface of the soil.

The excess rating cone index, (RCI_x) is related to a vehicle's traction performance on fine-grained soils and is computed as:

$$RCI_x = RCI - VCI \qquad (15)$$

Greater the excess cone index, better mobility characteristics the vehicle has. To increase the value of the excess rating cone index, for the same soil (same RCI value) it is mandatory to decrease the vehicle cone index (VCI) value by specific design.

Traction performances

Computing traction performances relied to the drawbar at nominal slip, SLIP at "Maximum" Soil Strength, and Motion Resistance calculation using empirical relationship derived from experimental research for various types of soils according to USCS, slippery and non-slippery surfaces and different degrees of humidity.

As an example, in

Table there are presented the relationships for the drawbar coefficient at nominal slip for fine-grained soils. Similar structure of relationships exists in the case of motion resistance too.

The main variable of the above prediction equations is the Rated Cone Index of the soil. For a homogenous soil, the results of the computation are compared with the vehicle's capabilities in terms of maximum traction force. If the traction force is high enough to overcome the motion resistance, a maximum speed for given soil conditions is computed taking into consideration the engine power. The final results may be:

▪ NO GO situation when the drawbar pull is bellow to traction effort developed by the vehicle,

▪ otherwise, maximum speed for given soil conditions.

For the real terrains, the soil characteristics are not homogenous. The method used for mobility assessment consists of the spilling the area of the terrain into rectangular areas, small enough that the Rated Cone Index is constant. Then the computations are performed for each rectangular small area.

Table 1. Prediction equations for the drawbar coefficient at nominal slip for fine-grained soils

Relationship description		Prediction Equation
Criteria	Soil	
Wheeled CPF>4 psi w/out Tire Chains	SM	$\dfrac{D^{RCI}}{W_{Nom}} = 0.5200142 - \dfrac{4.5585}{RCI_x + 8.117059} + 0.374746007$
	SC, ML, CL, CH	$\dfrac{D^{RCI}}{W_{Nom}} = 0.6152356 - \dfrac{6.183363}{RCI_x + 9.258565} + 0.05261765$
CPF< 4 psi w/out Tire Chains	CH	$\dfrac{D^{RCI}}{W_{Nom}} = 0.6152356 - \dfrac{6.183363}{RCI_x + 9.258565} + 0.05261765$
w/Tire Chains		$\dfrac{D^{RCI}}{W_{Nom}} = 0.6452267 - \dfrac{5.036329}{RCI_x + 7.35047} + 0.03994437$
Tracked CPF>4 psi	ML, CL,SM	$\dfrac{D^{RCI}}{W_{Nom}} = 0.6612633 - \dfrac{4.90683}{RCI_x + 7.285463} + 0.02224646$
	SC, CH	$\dfrac{D^{RCI}}{W_{Nom}} = 0.6969994 - \dfrac{5.131209}{RCI_x + 6.99228} + 0.03483978$
CPF< 4 psi		$\dfrac{D^{RCI}}{W_{Nom}} = 0.7241738 - \dfrac{4.838035}{RCI_x + 6.301396} + 0.0435981$

The final results of the mobility assessment may be presented in following manners:

- as graphics presenting the maximum achievable speed on the percentage of the total terrain considered (Figure4);
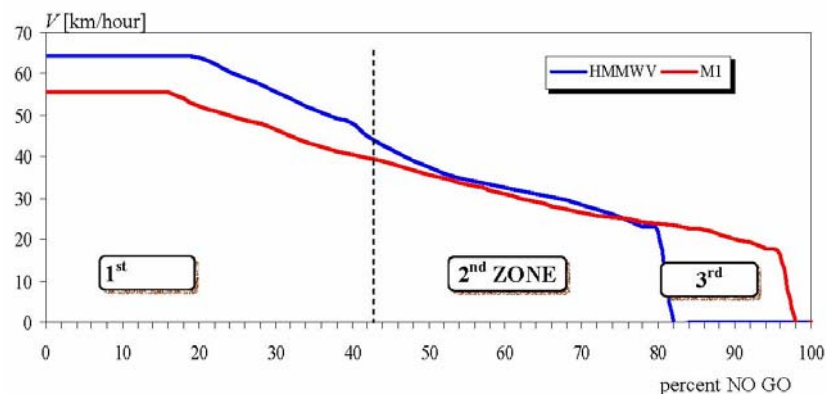- as maps for which the colours code indicates the maximum achievable speed.

Figure 4. Mobility assessment output in terms of NO GO percentage of the total area

Comparing the same two vehicles, from Figure4, the main conclusions are detailed below.

Within the 1st zone, the speed of the wheeled vehicles is grater with about 10 km/hour than the speed of the tracked vehicle; this zone represents about 45% of the total area considered, and consists of firm soils for which wheeled vehicles develop grater speed and, consequently, they have grater mobility.

The 2nd zone, which represents about 40% of the total area, considered by this scenario, the speed of the two vehicles is almost the same. This zone corresponds to the typical soft soils of the usual battlefields.

For the 20% of the terrain, the wheeled vehicle is not capable to develop enough traction effort to keep moving, and get stuck. This zone corresponds to the difficult terrain within the area considered.

This representation relied to a statistical approach which cannot offer adequate answers for mobility assessment for a given itinerary of the vehicle's displacement.

A deeper analysis could be performed taking into consideration the specific soil characteristics in correlation with the area in which they occur. This type of analyse involves a mapping approach, illustrated in the figures below [7].

For the dry terrain, a terrain scenario was adopted for comparative simulation of the mobility. The results obtained are presented in Figure5 to Figure7.

The comparative analysis reveals the area of the terrain for which one vehicle may achieve better mobility characteristics with respect to speed or GO/NO GO situation.
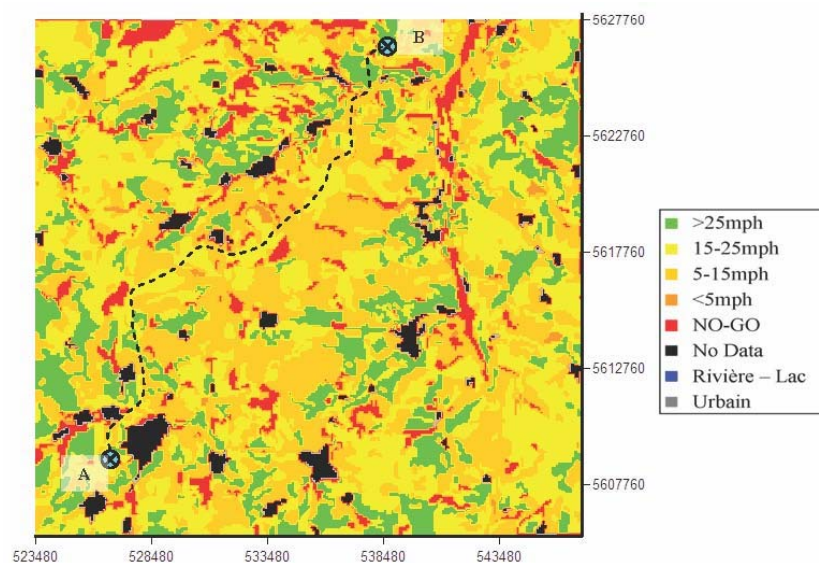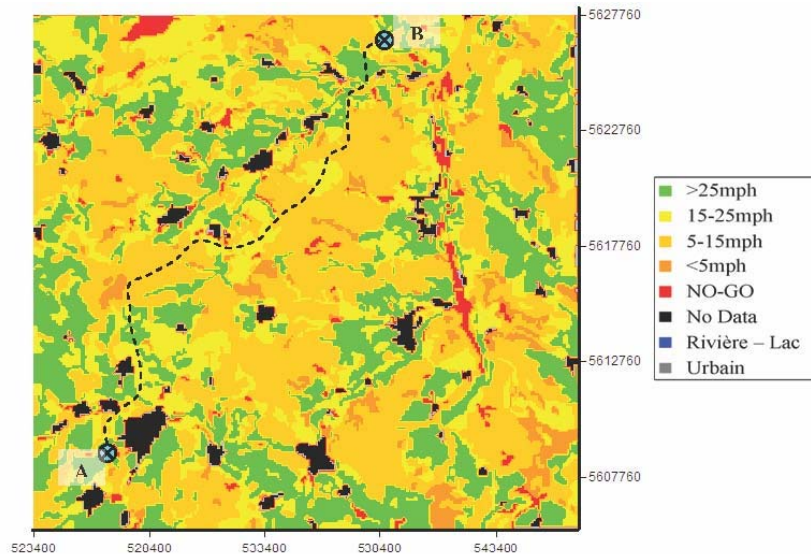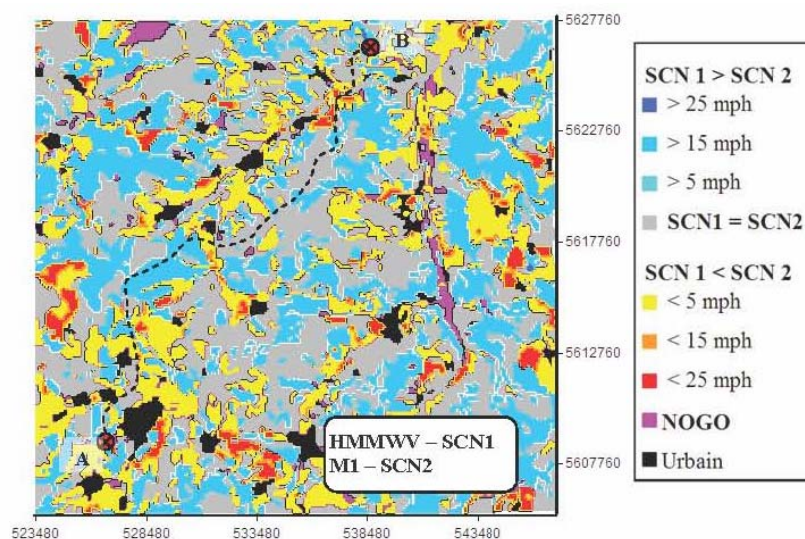
Figure 5. Mapping of HMMWV maximum speed on dry terrain

Figure 6. Mapping of HMMWV maximum speed on dry terrain

Figure 7. Comparative analysis of mobility assessment o dry soil

In Figure5 an itinerary was marked from point A to point B. The same itinerary was marked on the map presented in Figure. If this itinerary represents to most probable course of action, the instantaneous speed of each type of vehicles may be evaluated. Consequently, the mission plan may be adjusted with respect to mobility factors, for instance limiting the speed of the hybrid column of vehicles or planning separate columns of vehicles in correlation with their mobility.

Conclusions

The mobility of vehicles running off road relies to the characteristics of soils to be crossed. These characteristics vary significantly with the type of soil (granulation, cohesive or sandy particles content, etc.) and with the humidity.

The characterisation of the soil with the respect to the vehicle's traction is done by a single parameter, the Cone Index. The measurement in situ of the Cone Index supposes simple procedures and hardware but, usually, the results of the measurements have a large variance due to the non-homogeneous soils. Consequently, this method relays mainly to a statistical approach than to a deterministic algorithm.

The relationship for Drawbar Pull coefficient at nominal slip, and the Motion Resistance Coefficient are simple in essence but are specific for each type of running gear (tracked or wheeled), and for each type of soil. More than that, the relationships are specific to the nature of the running surface (slippery or non-slippery). All the above mentioned aspects introduce severe difficulties in adopting the right formula to be applied due to the fact that the correct characterisation of the soil type supposes the existence of a high expertise. Nevertheless, the validation of the relationships used by NRMM through a large amount of experiments carried out on a large diversity of vehicles increase significantly the confidence on the final results.

The computing amount of work is low, so efficient mathematical algorithms may be used for a shorter time of computing. Consequently, this model may be implemented for real-time modelling in war game software.

The comparative analysis is useful for general mobility assessment, but few differences results between similar vehicles competing in acquisition programmes; so, a limited applicability of NRMM is expected for comparing two or more similar vehicles.

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