A review of mobility metrics for next generation vehicle mobility models

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Abstract

In the United States, the NATO Reference Mobility Model (NRMM) has been used for evaluating military ground vehicle mobility and the Vehicle Cone Index (*VCI*) has been selected as a mobility metric. *VCI* represents the minimum soil strength required for a vehicle to consistently make a specific number of passes, usually one or fifty passes. In the United Kingdom the Mean Maximum Pressure (*MMP*) has been adopted as a metric for assessing military vehicle cross-country mobility. *MMP* is the mean value of the maxima occurring under all the wheel stations of a vehicle. Both *VCI* and *MMP* are empirically based. They have inherent limitations, such as the uncertainty whether the empirical relations for estimating the values of *VCI* and *MMP* can be extrapolated beyond the test conditions upon which they were based. This paper presents a review of the issues related to the basis upon which *VCI* and *MMP* were developed, as well as their applications to evaluating vehicle mobility in practice. With the progress in terramechanics and in modelling and simulation techniques in recent years, there is a growing desire to develop physics-based mobility metrics for next generation vehicle mobility models. Based on the review, criteria for selecting physics-based mobility metrics are proposed. Following these criteria, metrics for characterizing military vehicle traction capability limits and traversability on a given operating area are recommended.

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Nomenclature

A_l	rigid area of track link as a proportion of the product of track pitch and width
b	track width or tire section width
CI	cone index
CI_x	excess cone index above VCI
D	outer road wheel diameter
D_{snom}	drawbar pull developed by the suspension assembly at nominal slip
d	tire undeflected diameter
E	engine factor
F	tractive effort, thrust, or gross traction
f_t	radial deflection of pneumatic road wheel under load
G	grouser factor
H	clearance factor
h	tire section height
i	tire or track slip
L	wheel or track load factor
l	total length of tire or track in contact with ground
MI	mobility index
MMP	mean maximum pressure
m	total number of axles on a vehicle
n	number of tires per axle
n_r	number of road wheel stations on one track
P	$P=(b+d)n$ for wheeled vehicles; $P= b+l$ for tracked vehicles
P_{FG}	contact pressure factor
RI	remolding index
RCI	rating cone index
RCI_x	excess soil strength (RCI-VCI)
R_{tex}	external motion resistance of track
R_{tin}	internal motion resistance of track
T	transmission factor

t_t	track pitch
V_{max}	speed-made-good (effective maximum possible vehicle straight-line running speed from one location to another under steady-state conditions)
V_t	vehicle theoretical speed
VCI	vehicle cone index
W	vehicle weight, weight beneath the suspension assembly, or weight factor
X	transmission factor
δ	tire deflection

1. Introduction

In the United States and some other NATO (North Atlantic Treaty Organization) countries, military ground vehicle mobility has been evaluated using the NATO Reference Mobility Model (NRMM), since its release in 1979. In the cross-country performance prediction module of the current version of NRMM (NRMM II), vehicle cone index (*VCI*) is used as a metric to evaluate the cross-country mobility of military ground vehicles on fine-grained soils and on muskeg (organic soils) (Ahlvin and Haley, 1992). *VCI* represents the minimum soil strength required for a vehicle to consistently make a specific number of passes, usually one pass or fifty passes. *VCI* is determined using empirical relations and is therefore an empirically based mobility metric.

In the United Kingdom and some other NATO countries, another empirically based mobility metric, known as the mean maximum pressure (*MMP*), has been used as a mobility metric (British Ministry of Defence, 2005). *MMP* is defined as the mean value of the maxima occurring under all the wheel stations of a vehicle (Rowland, 1972).

Empirically based mobility metrics have inherent limitations. These include the uncertainty whether the empirical relations used for estimating their values can be extrapolated beyond the conditions upon which they were derived. Consequently, it is by no means certain that either *VCI* or *MMP* can play a useful role in evaluating the mobility of military vehicles with design features or operating environments and conditions different from those that the empirical relations were based.

In the initial development of *VCI* or *MMP*, the understanding of the physical nature and techniques for analysis of vehicle-terrain interaction were such that it was considered more practical to follow the empirical approach. With the progress in the development of terramechanics and in modeling and simulation techniques in recent years, there is a growing desire to develop physics-based next generation vehicle mobility models and hence mobility metrics for evaluating military ground vehicle cross-country performance. Selection of appropriate mobility metrics is of significance, as it will have an impact on guiding the development of next generation vehicle mobility models.

In this paper, the empirically based *VCI* and *MMP* are reviewed from the following perspectives:

(A) types of terrain that the empirically based mobility metrics are applicable to;
(B) validity of the empirical relations used in estimating the mobility metrics;
(C) procedures for measuring the values of the mobility metrics in the field;
(D) methods for deriving vehicle performance parameters (such as vehicle drawbar pull coefficient and motion resistance coefficient) from mobility metrics.

Based on the review, criteria for selecting mobility metrics for next generation vehicle mobility models are proposed. Following these criteria, physics-based mobility metrics for characterizing military ground vehicle traction capability limits and traversability on a given operating area are recommended.

2. Vehicle Cone Index (*VCI*)

As noted previously, in the current version of NRMM (NRMM II), *VCI* is used as a metric for evaluating military ground vehicle cross-country mobility on fine-grained soils and muskeg (organic soils). It should be pointed out, however, that *VCI* is not used for evaluating vehicle mobility on coarse-grained soils or on shallow snow on frozen ground (Ahlvin and Haley, 1992).

2.1 VCI for fine-grained soils

To determine *VCI* for a vehicle operating on fine-grained soils, the first step is to calculate the mobility index (*MI*). *MI* is a function of a group of vehicle design factors and is calculated using the following empirical equation (Ahlvin and Haley, 1992):

$$MI = \left[\frac{P_{FG}\, W}{T\, G} + L - H \right] E\, X \tag{2.1}$$

where E is engine factor; G is grouser factor; H is clearance factor; L is load factor (wheel or track); P_{FG} is contact pressure factor; T is traction element factor (wheel or track); W is weight factor; X is transmission factor.

2.1.1 One-pass vehicle cone index (VCI_1) *for fine-grained soils*

From *MI*, the one-pass VCI_1 is calculated using one of the following empirical equations, depending on the type of running gear (wheel or track) and the value of *MI* (Ahlvin and Haley, 1992):

(A) for tracked elements

$$VCI_1 = 7.0 + 0.2MI - \frac{39.2}{MI + 5.6} \tag{2.2}$$

(B) for all unpowered wheeled elements and powered wheeled elements for which *MI* ≤ 115.0 psi,

$$VCI_1 = 11.48 + 0.2\, MI - \frac{39.2}{MI + 3.74} \tag{2.3}$$

(C) For powered wheeled elements for which *MI* > 115.0 psi,

$$VCI_1 = 4.1\, MI^{0.446} \tag{2.4}$$

A tire deflection correction factor, which is expressed by $[0.15 / (\delta / h)]^{0.25}$, where δ is tire deflection and h is tire section height, has later been introduced to the calculation of VCI_1. The revised expressions for one-pass VCI_1 for wheeled elements are obtained by multiplying Equation (2.3) or (2.4) by the tire deflection correction factor for $MI \leq 115.0$ psi or $MI > 115.0$ psi, respectively.

2.1.2 Experimental evaluation of the empirical relations between VCI_1 and MI

Figure 2.1 shows a comparison of the measured and empirical relations between VCI_1 and MI for all tracked vehicles on fine-grained soils (Priddy, 1995). The empirical relation is based on Equation (2.2). A total of 20 measured data points were used for evaluating the correlation between the vehicle cone index (CI) and mobility index (MI) for tracked vehicles over the entire range examined, and for assessing the validity of empirical Equation (2.2).

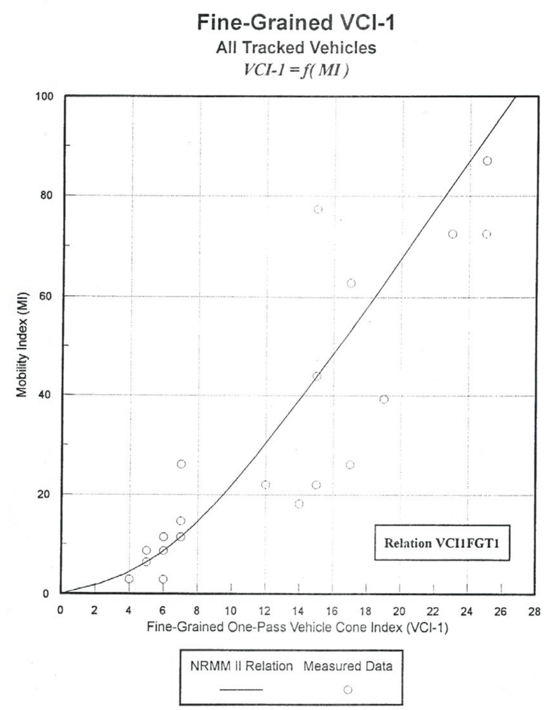

Figure 2.1 Comparison of measured and empirical relations between VCI_1 and MI for all tracked vehicles on fine-grained soils (Priddy, 1995).

Figure 2.2 shows a comparison of measured and empirical relations between VCI_1 and MI for all wheeled vehicles on fine-grained soils (Priddy, 1995). The empirical relation is based on Equation (2.3) or (2.4) multiplied by the tire deflection correction factor, dependent upon the value of MI. It is shown that more measured data points are in the range of *MI* below 200 than above 200 for evaluating the correlation between the vehicle cone index and mobility index for wheeled vehicles, and for assessing the validity of Equation (2.3) or (2.4) multiplied by the tire deflection correction factor.

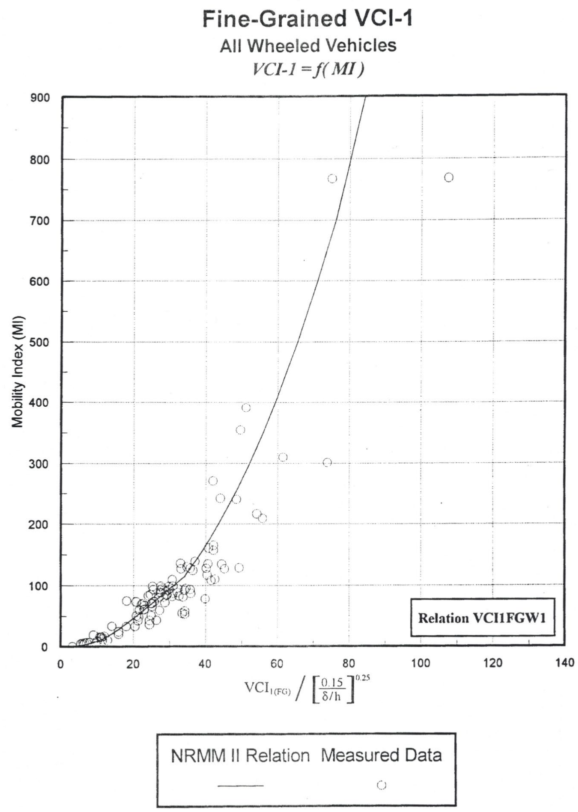

Figure 2.2 Comparison of measured and empirical relations between VCI_1 and *MI* for all wheeled vehicles on fine-grained soils (Priddy, 1995).

2.1.3 Procedures for measuring the one-pass vehicle cone index (VCI_1) on fine-grained soils

The procedures for measuring the one-pass vehicle cone index (VCI_1) for vehicle acquisition purposes have been recommended by the U.S. Army Corps of Engineers, Engineer Research Development Center (Stevens et al., 2013). The procedures were based on vehicles operating on high plasticity clay soil type CH in the Unified Soil Classification System, as it is considered to be the worst case for trafficability in fine-grained soils and remoldable sands. The procedures specify the requirements for vehicle parameters, site selection, test lane procedure, soil data collection, data analysis, and VCI_1 determination.

(A) Site selection

For VCI_1 tests, naturally occurring off-road lanes must be used. The lanes should be located on flat, level, soft-soil terrain that provides a range of rating cone index (*RCI*), which is the product of cone index (*CI*) and remolding index (*RI*), near the expected VCI_1 magnitude. The lane should be a minimum of two vehicle lengths long, relatively straight and level, and of relatively uniform consistency at the point of immobilization. Lanes should be in a natural state shaped only by sedimentary processes.

(B) Test lane procedure

The standard technique used to measure VCI_1 is through inference from zero- and multi-pass test data. For these tests, the self-propelled test vehicle will be driven at slow, steady speed making one or more passes in the same tracks through the test lane until immobilization occurs. For zero-pass immobilization tests, the vehicle will be operated in its lowest gears at a slow, steady speed (2-3 mph) in a straight line through the identified test area. Steady throttle will be applied until the vehicle becomes immobilized – defined as complete loss of forward movement. The vehicle will then be placed in reverse, and an attempt will be made to back out. If the vehicle does not move, this is the zero-pass immobilization point. For the multi-pass tests, the vehicle will make passes through the lane in its lowest gear at a slow, steady speed as for the zero-pass tests. The vehicle will move forward through the lane for the first pass and travel backward, in reverse, for the second pass. Forward and backward passes are continued until the vehicle becomes immobilized. If a vehicle makes eight good passes and becomes immobilized during the ninth pass, this would be considered as an 8-pass run.

(C) Soil data collection

The soil strength of the test lanes is characterized in terms of rating cone index (*RCI*). The locations of the soil measurements of *CI* and *RI* should be made near the point of immobilization but outside of the influence (disturbed) zone generated by the vehicle running gear. Figure 2.3 shows the spatial locations (plan view) for soil measurements.

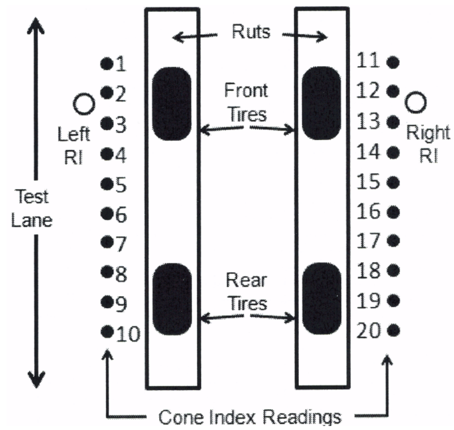

Figure 2.3 Spatial locations (plan view) for soil measurements (Stevens et al., 2013).

Figure 2.4 shows the locations of soil layers under the vehicle for soil measurements.

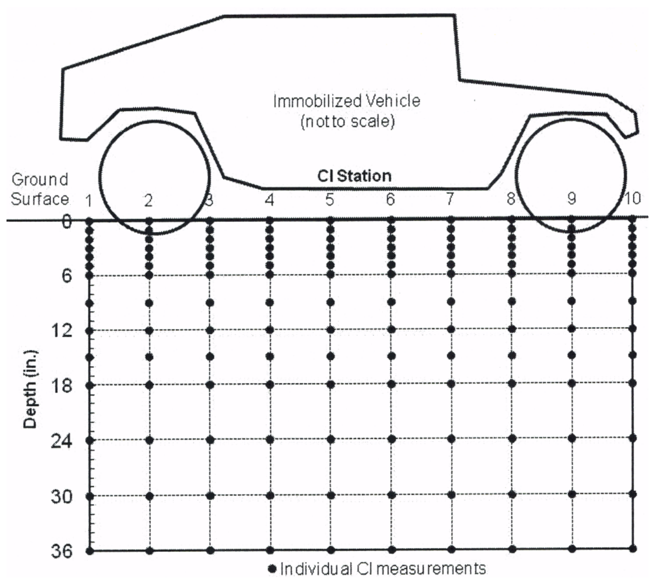

Figure 2.4 Locations of soil layers under the vehicle for soil measurements (Stevens et al., 2013).

For the plans shown in Figures 2.3 and 2.4, there are more than 280 locations where soil measurements have to be taken.

(D) Selecting the critical layer for determining VCI_1

After all the data have been collected, the next step toward determining VCI_1 is to determine the critical layer. The critical layer is the soil layer that has greatest influence on the VCI_1, and the soil strength value within the critical layer represents the VCI_1. Intuitively, it may appear that the critical layer is the layer on which the vehicle is resting when it becomes immobilized. This is not the case (Stevens et al., 2013). Although rut depth (permanent deformation) and sinkage (instantaneous deformation) are related to both soil strength and vehicle characteristics, the methodology for determining the critical layer does not use rut depth or sinkage measurements. This is because in a normal soil profile used for *VCI* testing, the vehicle will typically sink down through the critical layer.

It is stated that location of the critical layer is more closely related to the critical depth of the sinkage mobilizing stress that occurs within the soil beneath the center of the running gear ground contact at the initiation of downward sinkage movement (Stevens et al., 2013). However, the meaning of "the critical depth of the sinkage mobilizing stress that occurs within the soil beneath the center of the running gear ground contact at the initiation of downward sinkage movement" is not clearly defined, nor how "the critical depth of the sinkage mobilizing stress" can be measured or determined. In Appendix A of the Reference (Stevens et al., 2013), it is acknowledged that "Experience and judgement must be applied when deciding on the critical layer to apply for *VCI* measurements." This would seem to indicate that while elaborate procedures have been recommended, the determination of the critical layer and the associated *VCI* still relies on the experience and subjective judgement of an individual investigator (user). Consequently, it is uncertain that the recommended procedures would lead to objective determination of the critical layer and associated *VCI*.

In summary, the experimental determination of *VCI* for a given vehicle through testing is a complex process that requires considerable effort and time, as well as subjective judgement in determining the critical layer. Perhaps, the most demanding issue is to locate or to find a natural terrain (such as the high plasticity clay soil type CH) on which the properties and conditions would allow a given vehicle to traverse once or make fifty passes before becoming immobilised, in order to meet the requirement for or the definition of VCI_1 or VCI_{50}.

2.1.4 Estimating vehicle performance metrics based on VCI

It should be pointed out that while *VCI* is a mobility metric, it is not a physical and readily measurable vehicle performance metric, such as drawbar pull coefficient (ratio of vehicle drawbar pull to vehicle weight) or motion resistance coefficient (ratio of vehicle motion resistance to vehicle weight). For fine-grained soils, the procedures for estimating vehicle drawbar pull coefficient using the mobility index (*MI*) and vehicle cone index (*VCI*) may be illustrated by Figure 2.5.

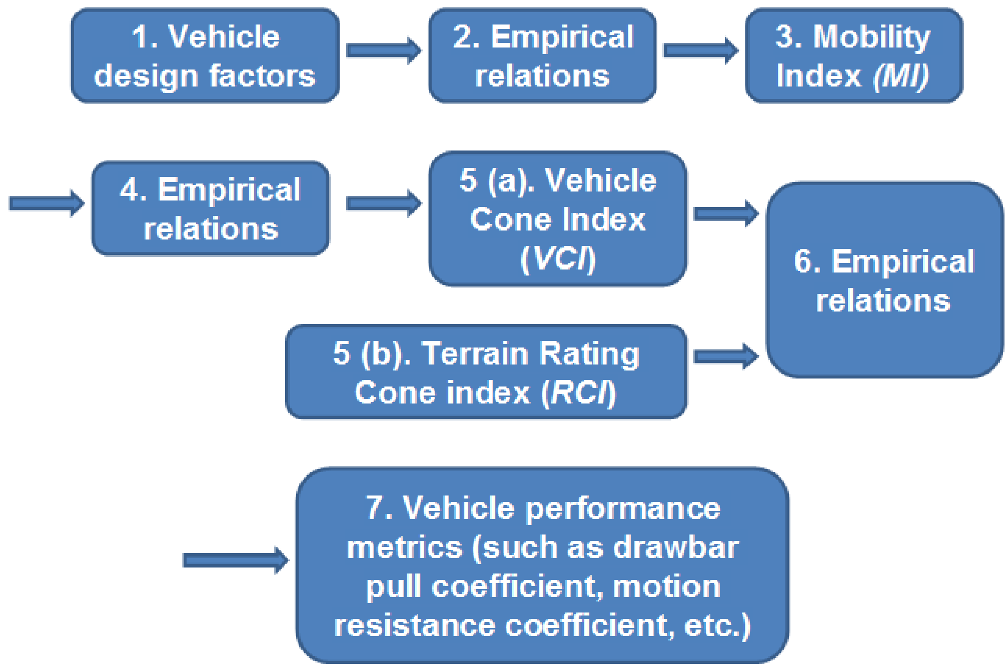

Figure 2.5 Procedures of NRMM for estimating vehicle performance metrics on fine-grained soils based on *VCI*.

It can be seen that the procedures involve three steps that are based on empirical relations, as described below:

(A) deriving *MI* from vehicle design factors;

(B) deriving *VCI* from *MI*;

(C) estimating vehicle performance metrics from the difference between *VCI* and the rating cone index (*RCI*) of the terrain on which the vehicle operates. The difference between *RCI* and *VCI* is usually referred to as the excess soil strength (RCI_x) (Ahlvin and Haley, 1992; Priddy, 1995).

The three empirical steps in the procedures for estimating vehicle performance metrics using *VCI* are in striking contrast to the physics-based models, such as NTVPM for tracked vehicles and NWVPM for wheeled vehicles (Wong, 2008, 2010), which use vehicle design and terrain parameters as input for directly predicting vehicle performance metrics, such as drawbar pull coefficient, motion resistance coefficient, etc.

As an example, in NRMM II for fine-grained soils, the drawbar pull coefficient at nominal slip D_{snom}/W for the suspension assembly is calculated as follows, for $RCI_x \geq 0$ (Ahlvin and Haley, 1992):

$$D_{snom}/W = A + \frac{B}{RCI_x + C} + D \tag{2.5}$$

where D_{snom} is the drawbar pull developed by the suspension assembly; W is the weight of the suspension assembly; A, B, C, and D are empirical constants, dependent upon the types of running gear (wheel or track) and terrain; RCI_x is the excess soil strength under the suspension assembly.

2.2 VCI for Muskeg (Organic Soils)

2.2.1 One-pass vehicle cone index (VCI_1) for muskeg

(A) For tracked suspension assemblies

$VCI_{1(MK)}$ is given by (Ahlvin and Haley, 1992)

$$VCI_{1(MK)} = 13 + 0.0625\left(\frac{W}{b+l}\right) \tag{2.6}$$

where W is weight beneath the suspension assembly, lb; b is track width, in.; and l is length of track on the ground, in.

(B) For wheeled suspension assemblies

$VCI_{1(MK)}$ is given by

$$VCI_{1\ (MK)} = 13 + 0.535\left(\frac{W}{(b+d)\,n}\right) \tag{2.7}$$

where W is weight beneath the suspension assembly, lb; b is tire section width, in.; d is tire undeflected diameter (at highway inflation pressure), in., and n is the number of tires on the suspension assembly.

2.2.2 *Experimental evaluation of the empirical relation between VCI_1 and vehicle design factors on muskeg*

Figure 2.6 shows a comparison of the measured and empirical relations between $VCI_{1(MK)}$ and W/P (i.e., $W/(b+l)$, where W is weight beneath the suspension assembly; b is track width; and l is track length on the ground), for all tracked vehicles on muskeg (organic soils) (Priddy, 1995). The empirical relation is based on the Equation (2.6). There are a total of 26 measured data points for evaluating the validity of empirical Equation (2.6) over the entire range examined, including 10 measured $VCI_{1(MK)}$ points and 16 measured lowest GO points.

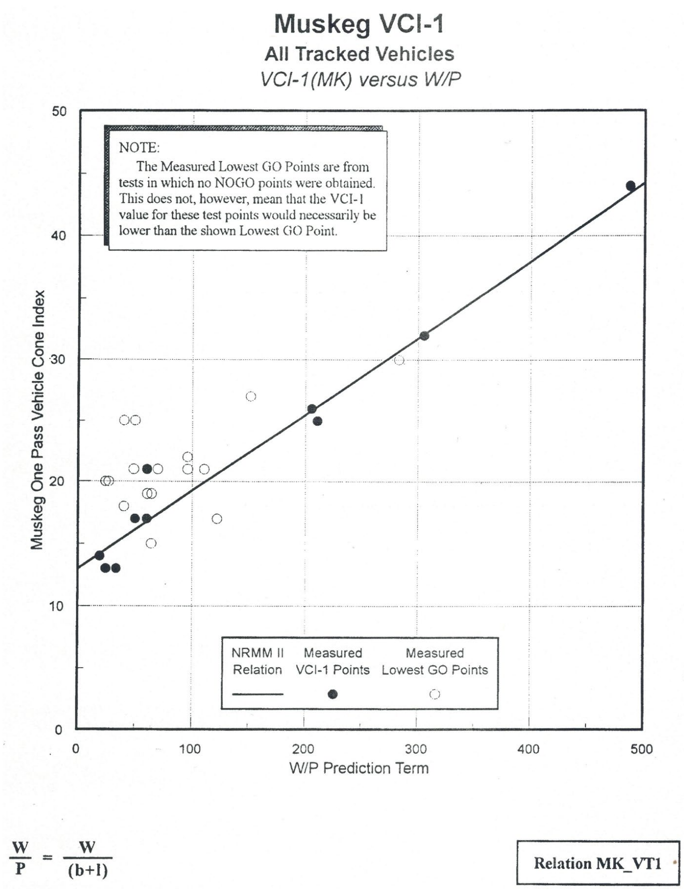

Figure 2.6 Comparison of measured and empirical relations between $VCI_{1(MK)}$ and *W/P* (i.e., *W/*(*b*+*l*)) for all tracked vehicles on muskeg (organic soils) (Priddy, 1995).

Figure 2.7 shows a comparison of the measured and empirical relations between $VCI_{1(MK)}$ and *W/P* (i.e., *W/* [(*b*+*d*)*n*], where *W* is weight beneath the suspension assembly; *b* is tire section width; *d* is tire undeflected diameter; and *n* is the number of tires on the suspension assembly) for all wheeled vehicles on muskeg (organic soils) (Priddy, 1995). The empirical relation is based on Equation (2.7). There are 6 measured data points for evaluating the validity of empirical Equation (2.7) over the entire range examined, including 3 measured $VCI_{1(MK)}$ points and 3 measured lowest GO points.

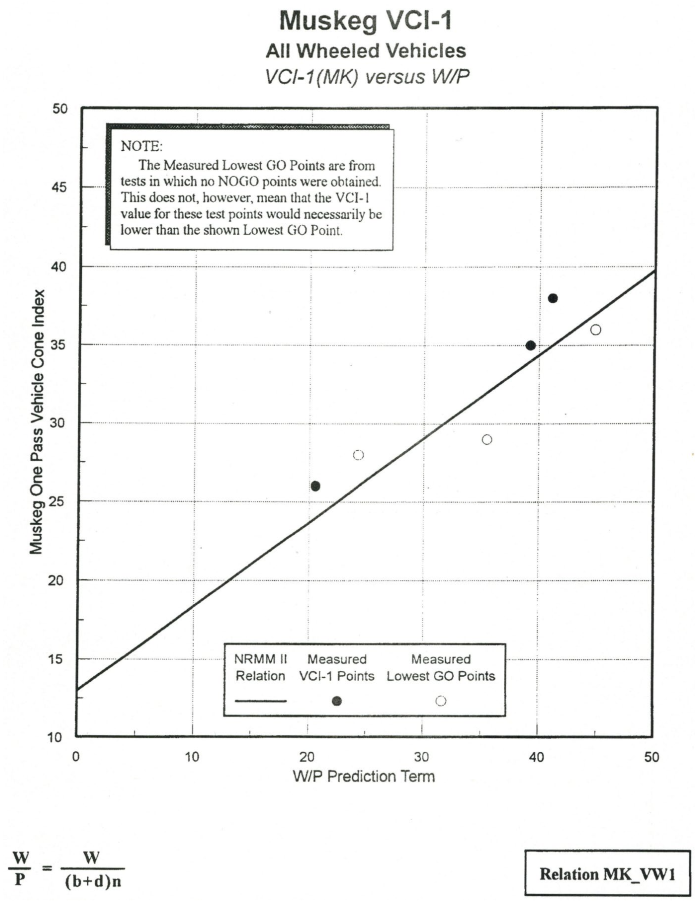

Figure 2.7 Comparison of measured and empirical relations between $VCI_{1\,(MK)}$ and W/P (i.e., $W/[(b+d)n]$) for all wheeled vehicles on muskeg (organic soils) (Priddy, 1995).

As shown in Figures 2.6 and 2.7, the number of measured data points is relatively few for evaluating the validity of the empirical relations between $VCI_{1(MK)}$ and the parameter W/P for all tracked and wheeled vehicles on muskeg (organic soils), given by Equation (2.6) and Equation (2.7), respectively. For all tracked vehicles, there are only 10 measured $VCI_{1(MK)}$ points, and for all wheeled vehicles, there are only 3 measured $VCI_{1(MK)}$ points.

In summary, there are insufficient experimental data for evaluating the validity of the empirical relationships between one-pass vehicle cone index ($VCI_{1(MK)}$) and vehicle design parameters on muskeg, particularly for wheeled vehicles.

2.3 Evaluation of vehicle mobility on coarse-grained soils

As mentioned in the Introduction, in the current version of NRMM (NRMM II), the notion of a vehicle cone index is not applicable to coarse-grained soils. The Waterways Experiment Station (WES) coarse-grained soil numeric method with modifications is used for evaluating vehicle mobility. It replaces the coarse-grained soil vehicle cone index used in the previous edition of NRMM (NRMM I). In NRMM II, while a method for calculating the one-pass vehicle cone index VCI_1 for wheeled vehicles on coarse-grained soils is available, it is not used for performance predictions and is solely for comparative purposes (Ahlvin and Haley, 1992).

2.4 Evaluation of vehicle mobility on shallow snow on frozen ground

As also noted in the Introduction, in NRMM II vehicle cone index is not used as a metric for evaluating vehicle mobility on shallow snow on frozen ground (Ahlvin and Haley, 1992). In NRMM II, the prediction of wheeled vehicle mobility on shallow snow takes into account vehicle/tire design parameters, such as tire nominal section width, tire nominal diameter, tire nominal section height, tire characteristic length (a function of tire nominal diameter and deflection), number of tires on the axle, and tire normal load. The prediction of tracked vehicle mobility on shallow snow takes into account track characteristic length (track length) and normal load on the track. Snow density, cohesion, angle of friction, and depth are used for characterizing snow conditions for evaluating the cross-country performance of wheeled and tracked vehicles on shallow snow on frozen ground.

3. Mean Maximum Pressure (*MMP*)

Similar to the use of *VCI* as a mobility metric in the United States and some other NATO countries, another empirically based metric, known as the mean maximum pressure (*MMP*), is used for assessing military vehicle mobility in the United Kingdom. The *MMP,* which is defined as the mean value of the maxima occurring under all the wheel stations, was first proposed by Rowland as an indicator for tracked vehicle mobility (Rowland, 1972). Based on test data, Rowland developed empirical equations for estimating the values of *MMP* as a function of a handful of tracked vehicle design parameters. Later, the concept of *MMP* was extended to evaluating military wheeled vehicle mobility (Rowland, 1975; Larminie, 1992). It has been adopted by the British Ministry of Defence for classifying military vehicle mobility in its Defence Standard 23-6, as shown in Table 3.1 (British Ministry of Defence, 2005).

Table 3.1
Classification of mobility of light trucks (payload less than 4 tonne) in the British Defence Standard 23-6.

Criteria	Mobility Classes				
	High Mobility	Improved Medium Mobility	Medium Mobility	Improved Low Mobility	Low Mobility
MMP, kPa	Less than 280	280-350	350-550	550-700	Greater than 700

3.1 MMP for tracked vehicles

From test data obtained using pressure transducers buried in the soil beneath tracked vehicles, Rowland developed the following empirical formulas for predicting *MMP* of vehicles with different road wheel-track system designs (Rowland, 1975):
For link and belt tracks on rigid road wheels,

$$MMP = \frac{1.26\,W}{2n_r\,A_l\,b\sqrt{t_t\,D}} \quad kPa \tag{3.1}$$

and for belt tracks on pneumatic tired road wheels,

$$MMP = \frac{0.5\,W}{2n_r\,b\sqrt{D\,f_t}} \quad kPa \tag{3.2}$$

where A_l is the rigid area of link (or belt track cleat) as a proportion of bt_t; b is the track (or pneumatic tire) width in m; t_t is track pitch in m; D is the outer diameter of the road wheel or pneumatic tire in m; f_t is the radial deflection of the pneumatic tire under load in m; n_r is the number of wheel stations on one track; and W is the weight of the vehicle with two tracks in kN.

To evaluate whether a particular vehicle with a specific value of *MMP* will have adequate mobility over a given terrain, Rowland suggested a set of desired values of *MMP* for different types of terrain, as shown in Table 3.2 (Rowland, 1975).

Table 3.2
Desired values of *MMP* for various types of terrain.

Terrain	Mean maximum pressure, kPa		
	Ideal (Multi-pass operation or good gradeability)	Satisfactory	Maximum acceptable (Mostly trafficable at single-pass level)
Wet fine-grained soils - Temperate - Tropical	 150 90	 200 140	 300 240
Muskeg Floating mat and European bogs	30 5	50 10	60 15
Snow	10	25-30	40

Issues of using *MMP* as a mobility metric for military tracked vehicles have been examined in detail (Wong, 1994; Wong, Jayakumar, Toma, and Preston-Thomas 2018; Wong, Jayakumar and Preston-Thomas, 2018). The major findings are summarized below:

(A) In estimating the value of *MMP*, the empirical equations proposed by Rowland do not take into account terrain characteristics. Experimental evidence has shown that the pressure distribution under road wheels on a track, hence *MMP*, is greatly influenced by terrain properties. Table 3.3 shows a comparison of the values of *MMP* of an armoured personnel carrier with rigid road wheels (having rubber rims) and link tracks on various types of terrain calculated using Equation (3.1) with those measured (Wong, Jayakumar, Toma, and Preston-Thomas, 2018; Wong, Jayakumar and Preston-Thomas, 2018). Average values of *MMP* predicted by NTVPM are also shown in the table. It can be seen that the value of *MMP* for the vehicle calculated using Rowland's empirical formula is the same for all types of terrain, while those measured vary significantly with terrain types. This indicates that the empirical formula proposed by Rowland is not consistent with the physical nature of vehicle-terrain interaction. The table also shows that the average values of *MMP* on various types of terrain predicted using NTVPM are generally closer to the measured values than that calculated by Rowland's empirical equation.

Table 3.3
Comparison of the value of *MMP* calculated by Rowland's empirical formula of an armoured personnel carrier on various types of terrain with that measured and that predicted by NTVPM.

Terrain type	Calculated *MMP* by Rowland's formula kPa	Average measured *MMP* kPa	Average predicted *MMP* by *NTVPM* kPa	Calculated *MMP* by Rowland's formula/ Average measured *MMP, %*	Average predicted *MMP* by *NTVPM/* Average measured *MMP, %*
LETE Sand	100.3	391.7	310.5	25.6	79.3
Petawawa Muskeg A	100.3	94.1	78.2	106.6	83.1
Petawawa Snow A	100.3	260.8	248.8	38.5	95.4
Petawawa Snow B	100.3	278.2	286.6	36.1	103

(B) The empirical equations for estimating the value of *MMP* of tracked vehicles, proposed by Rowland, only takes into account a limited number of vehicle design factors, as shown in Equations (3.1) and (3.2). A number of vehicle design features that have been shown to have a significantly impact on *MMP* and vehicle cross-country performance, such as road wheel suspension characteristics and initial track tension, have not been taken into account in the empirical equations.

(C) Field test data have demonstrated that there are significant discrepancies between the values of *MMP* calculated using the empirical equations and that measured on many types of terrain.

(D) It should be pointed out that *MMP*, similar to *VCI*, can only be used for evaluating vehicle mobility on a GO/NO GO basis. It cannot be used for quantitatively assessing vehicle mobility, like drawbar pull coefficient.

3.2 MMP for wheeled vehicles

As noted previously, the application of the concept of mean maximum pressure for tracked vehicles has been later extended to evaluating wheeled vehicle mobility. An empirical formula for estimating the value of *MMP* for wheeled vehicles has been proposed by Maclaurin (Priddy and Willoughby, 2006). It is derived from the soil-tire numeric developed by the Waterways Experiment Station and is given by:

$$MMP = \frac{W}{nmb^{0.8}d^{0.8}\delta^{0.4}} \tag{3.3}$$

where b is tire section width (inflated; unloaded), in.; d is tire outside diameter (inflated; unloaded), in.; m is total number of axles; n is number of tires per axle; W is gross vehicle weight, lb; δ is average hard-surface tire deflection, in.

It is found that for wheeled vehicles, one-pass vehicle cone index (VCI_1) may be related to *MMP* as follows (Priddy and Willoughby, 2006):

$$VCI_1 = 2.53 + 1.35\,MMP \tag{3.4}$$

Similar to using *MMP* as a mobility metric for tracked vehicles, the validity of using *MMP* to evaluate wheeled vehicle mobility is uncertain. In general, the use of *MMP* as a mobility metric is questioned for the following reasons [Wong, 1994; Hetherington, 2001; Hetherington and White, 2002):

(A) The empirical equations for estimating the value of *MMP* are solely a function of a handful of vehicle design parameters and are independent of terrain characteristics. Experimental evidence shows that the value of *MMP* is greatly influenced by terrain behaviour. This indicates that the *MMP* methodology is inconsistent with the physical nature of vehicle-terrain interaction.

(B) There is an insufficient level of confidence in the empirical equations for estimating the value of *MMP.*

(C) Using specific values of *MMP* for classifying vehicle mobility is not necessarily appropriate, as this may encourage vehicle designers/manufacturers to manipulate a handful of vehicle parameters in the empirical equations for *MMP* to meet a somewhat arbitrarily defined value, instead of stimulating the designers to explore innovative ways of improving vehicle mobility in the field.

4. Proposed physics-based mobility metrics for next generation vehicle mobility models

Based on the review of currently used mobility metrics, *VCI and MMP,* it is proposed that a mobility metric for next generation vehicle mobility models for military ground vehicles be:

(A) physics-based, instead of empirically based;

(B) capable of assessing vehicle cross-country performance on a quantitative basis, instead of on a GO/ NO GO basis;

(C) applicable to all types of terrain;

(D) readily measurable using widely accepted vehicle performance testing methodologies.

4.1 Drawbar pull coefficient at 20% slip as a vehicle mobility metric for characterizing performance in the range of optimal tractive efficiency

The drawbar pull coefficient is a widely used parameter for characterizing vehicle cross-country performance (SAE, 1967). At 20% slip, the tractive (drawbar) efficiency, which is the ratio of the product of vehicle drawbar pull and vehicle forward speed to the power delivered to the driven running gear (tire or track), is usually within its optimal range, as shown in Figure 4.1. The slip at which the tractive efficiency peaks, however, varies with vehicle designs and terrain properties.

It is proposed that the drawbar pull coefficient at 20% slip be a vehicle mobility metric for characterizing vehicle performance in the range of optimal tractive efficiency. This metric satisfies all the criteria listed above.

In many physics-based vehicle mobility models currently available, such as NTVPM for tracked vehicles and NWVPM for wheeled vehicles, the values of drawbar pull coefficient over a range of slips, including 20%, are part of the output of the models (Wong, 2008, 2010). Drawbar pull coefficient at 20% slip can be readily measured by conducting vehicle drawbar performance testing on all types of terrain.

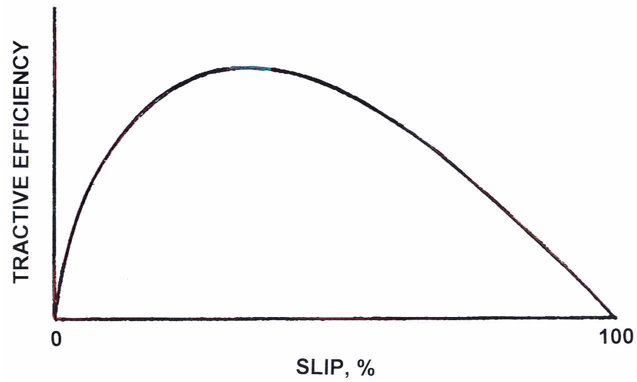

Figure 4.1 General characteristics of tractive efficiency-slip relationship.

4.2 Drawbar pull coefficient at 80% slip as a vehicle mobility metric for characterizing traction capability limits

To indicate vehicle cross-country mobility limits, it is proposed that the drawbar pull coefficient at 80% slip be used, as shown in Figure 4.2 (SAE, 1967). It should be noted that the drawbar pull coefficient at 100% slip is of little practical interest, as at 100% slip the vehicle forward speed is zero and the tractive efficiency is also zero, as shown in Figure 4.1, indicating no useful work can be performed. The drawbar pull coefficient at 80% slip, therefore, reasonably represents vehicle traction capability limits, as well as satisfies all criteria as a physics-based mobility metric given above.

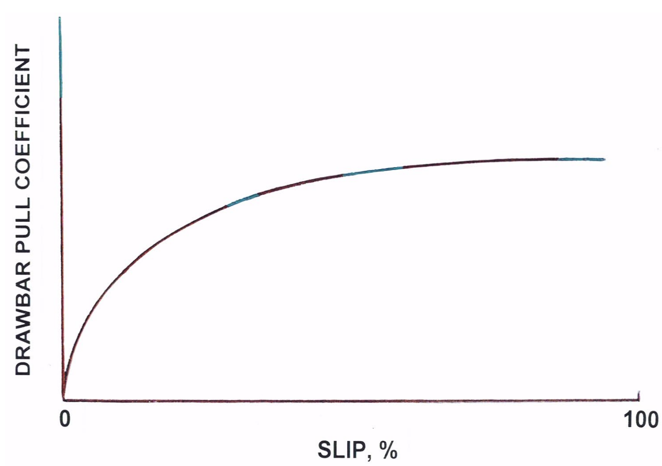

Figure 4.2 General characteristics of drawbar pull coefficient-slip relationship.

4.3 Speed-made-good as a vehicle mobility metric for traversability

Vehicle speed-made-good, which is the effective maximum possible vehicle speed from one location to another along a straight-line under steady-state conditions, is proposed as a vehicle mobility metric for traversability. Vehicle speed-made-good satisfies all the criteria listed above, and has already been widely used in evaluating cross-country traversability of military ground vehicles (Ahlvin and Haley, 1992).

Vehicle speed-made-good can be predicted using physics-based vehicle mobility models (such as NTVPM and NWVPM), together with vehicle powertrain characteristics. The physics-based procedure for predicting vehicle speed-made-good has been discussed previously (Wong, Jayakumar, Toma, and Preston-Thomas 2018; Wong, Jayakumar and Preston-Thomas, 2018). A summary of the procedure is given below:

(A) The external motion resistance of the tracked vehicle R_{tex} due to vehicle-terrain interaction on a given terrain is predicted using physics-based vehicle mobility models. Coupled with the measured internal motion resistance of the running gear (tire or track systems) R_{tin}, the total motion resistance of vehicle (the sum of R_{tex} and R_{tin}) can be determined.

(B) For steady-state straight-line motion on a level terrain, the vehicle must develop a tractive effort (thrust) F to overcome the sum of the internal and external motion resistances of the vehicle, that is, $F = R_{tex} + R_{tin}$.

(C) For a given tractive effort F, the corresponding vehicle theoretical speed V_t can be determined from the tractive effort-theoretical speed relationship of the vehicle. It is determined from the engine torque-speed curve (with throttle fully open), characteristics of the transmission (including the torque converter, gear box, and final drive), tire effective rolling radius for a wheeled vehicle or sprocket pitch radius for a tracked vehicle, and mechanical efficiency of the drivetrain. Figure 4.3 shows the tractive effort-theoretical speed relationship of a notional tracked vehicle.

(D) Based on the tractive effort-slip relationship of the vehicle predicted by physics-based vehicle performance models, the vehicle slip i for a given tractive effort F can be defined.

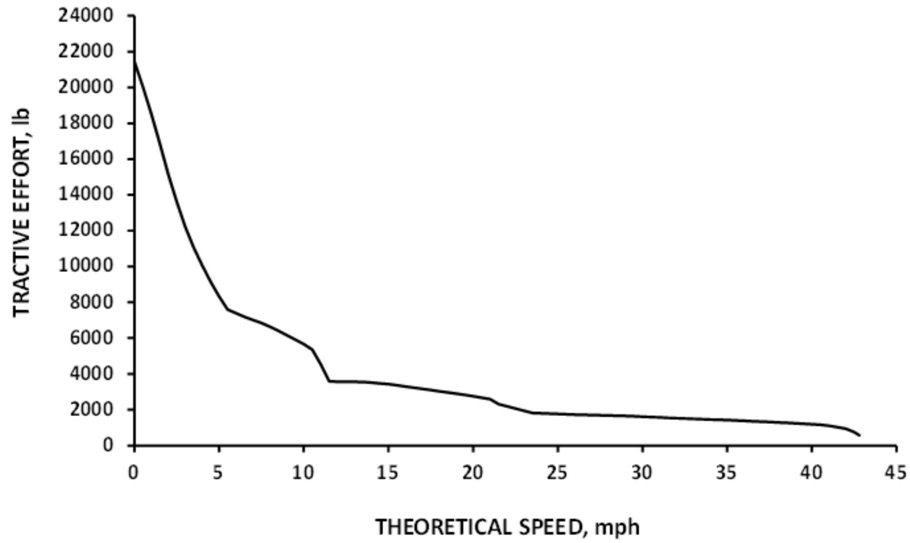

Figure 4.3 The tractive effort-theoretical speed relationship of a notional tracked vehicle.

(E) From theoretical speed V_t determined in (C) and slip i predicted in (D), for a given tractive effort required to maintain steady-state operation, the actual vehicle speed can finally be predicted. The speed-made-good V_{max} (i.e., the steady-state maximum possible vehicle speed) in straight-line motion on a level terrain can be determined by

$$V_{max} = V_t \ (1- i) \tag{4.1}$$

where V_t is theoretical speed of the vehicle at the required tractive effort F from (B), and is determined from the vehicle tractive effort-theoretical speed relationship; i is the slip of the vehicle corresponding to the required vehicle tractive effort and can be determined using the tractive effort-slip relationship predicted by physics-based vehicle mobility models.

5. Closing remarks

(A) Vehicle cone index (*VCI*) represents the minimum soil strength required for a vehicle to consistently make a specified number of passes, usually one pass or fifty passes.

(a) In the current version of NATO Reference Mobility Model (NRMM II), the use of *VCI* as a vehicle mobility metric is restricted to fine-grained soils and muskeg. It is not used in evaluating vehicle mobility on coarse-grained soils or on shallow snow on frozen ground.

(b) On fine-grained soils, while there are sufficient experimental data available for evaluating the validity of the empirical relation between *VCI* and *MI* for wheeled vehicles, there are relatively few experimental data available for evaluating the validity of the empirical relation between *VCI* and *MI* for tracked vehicles. On muskeg, there are insufficient experimental data available for evaluating the validity of the empirical relation between *VCI* and vehicle design parameters for both wheeled and tracked vehicles.

(c) *VCI* is not a metric that can be used to quantitatively assess vehicle cross-country performance, like drawbar pull coefficient or motion resistance coefficient. On fine-grained soils, to predict vehicle cross-country performance parameters, such as drawbar pull coefficient and motion resistance coefficient, empirical equations based on the difference between *VCI* and the rating cone index (*RCI*) of the terrain on which the vehicle operates are employed. On muskeg, to predict vehicle cross-country performance parameters, another set of empirical equations based on the difference between *VCI* and cone index *CI* is used.

(B) Following an empirical approach, another mobility metric, known as the mean maximum pressure (*MMP*), which is defined as the mean value of the maxima occurring under all the wheel stations of a vehicle, has been adopted for evaluating or classifying vehicle mobility by the British Ministry of Defence and by some other NATO countries.

(a) *MMP* is related to a handful of vehicle design parameters, but is independent of terrain properties. Experimental evidence has shown that terrain characteristics have a significant influence on the value of *MMP.* Thus, the methodology of *MMP* is inconsistent with the physical nature of vehicle-terrain interaction and its validity is uncertain.

(b) Furthermore, the *MMP* methodology could only be used to evaluate vehicle mobility on a GO/ NO GO basis and cannot be used to quantitatively assess vehicle mobility, like drawbar pull coefficient or motion resistance coefficient.

(C) In the initial development of *VCI* and *MMP*, the understanding of the physical nature and techniques for analysis of vehicle-terrain interaction were such that it was considered more practical to follow the empirical approach. With the progress made in the development of terramechanics and in modeling and simulation techniques in recent years, there is a growing desire to develop physics-based next generation vehicle mobility models. Thus, physics-based mobility metrics are needed to replace empirically based *VCI* and *MMP*. It is proposed that a mobility metric for next generation mobility models for military ground vehicles be:

(a) physics-based, instead of empirically based;

(b) capable of assessing vehicle cross-country performance on a quantitative basis, instead of on a Go/ No Go basis;

(c) applicable to all types of terrain;

(d) readily measurable using widely accepted vehicle performance testing methodologies.

(D) Based on the criteria proposed above, the following mobility metrics for next generation mobility models for military ground vehicles are recommended:

(a) the drawbar pull coefficient at 20% slip be designated as a mobility metric for characterizing performance in the range of optimal tractive efficiency;

(b) the drawbar pull coefficient at 80% slip be designated as a mobility metric for characterizing traction capability limits;

(c) the speed-made-good be designated as a mobility metric for characterizing traversability in cross-country operations.

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