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TESTING GROUND VEHICLE MOBILITY IN SOFT SOIL: STANDARD OPERATING PROCEDURES AND ONGOING QUESTIONS

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ABSTRACT

Ground vehicle mobility in soft soil is crucial to many military missions. Thus, it has been tested and quantified in a metric called Vehicle Cone Index (VCI) since World War II. VCI provides an index of the minimum soil strength necessary for vehicle mobility. The standard operating procedure for VCI field testing and data analysis is detailed herein. Also, a new method for quantifying VCI uncertainty has been proposed, which uses confidence bounds on mean measurements of soil strength. A sample analysis of actual field data is provided.

INTRODUCTION

Soft soil mobility is an important factor in the assessment of a military vehicle's off-road performance. Since World War II, the U.S. Army Corps of Engineers has used Vehicle Cone Index (VCI) parameters to quantify the minimum soil strength soil necessary for a particular vehicle configuration to complete a specified number of passes. For mobility modeling and simulation purposes, the VCI_1, the minimum soil strength needed for one successful pass, is particularly important [1].

Although a standard methodology for field testing the VCI has been used for decades, new emphasis has been placed on improving its documentation and increasing awareness of the method within the ground vehicle mobility community. The method calls for natural off-road test lanes to be selected in areas with clayey soil and minimal slopes. The vehicle is driven back and forth on each lane until immobilization is reached. The number of passes successfully executed by the vehicle in each lane is recorded. After immobilization, data is collected regarding soil strength in the top 36 inches of soil near the immobilization point. Lanes are run at a variety of soil strengths to produce a range in the number of successful passes. A graph of successful passes versus soil strength is produced, and expert judgment is used to select the best representative VCI_1 based on the data trends.

New efforts have been made to verify repeatability and quantify the uncertainty of the measured VCI. Until this time, VCI_1 has been determined largely based on the evaluation of field test data of subject matter experts; thus, the uncertainty in VCI_1 has been difficult to determine. New methods for quantifying the uncertainty of measured VCI_1 are proposed herein.

VCI TEST PROCEDURE

Prior to vehicle testing, key vehicle parameters should be measured on a level surface and recorded. For wheeled vehicles, these parameters include: individual wheel loads, minimum ground clearance, tire pressure, tire deflection, and ride height. For tracked vehicles, the key parameters are the dimensions of the contact area between the track and the ground. These parameters should be monitored periodically throughout the evaluation to ensure consistent results.

Optional instrumentation may measure vehicle speed, individual wheel speed, drive shaft torque, and suspension displacement.

Test Lanes

The standard technique used to measure VCI_1 is through inference from zero- and multi-pass test data. For these tests, natural off-road lanes should be located on soft-soil terrain that provides a range of soil strengths near the expected VCI_1 magnitude. Test lanes should be a minimum of two vehicle lengths long, relatively straight and level, and of uniform consistency at the point of immobilization.

It is important that test lanes be located in soil that classifies as a CH (high plasticity clay) under the Unified Soil Classification System (USCS, [2]). This is the worst case scenario for vehicle mobility and is consistent with historical VCI measurements [1]. It is also important that the soil has no visible sand content. Even small percentages of sand can skew VCI to a lower than expected value.

Test supervisors must also pay attention to the moisture conditions of the soil when selecting and describing lanes. The soil must have appropriate moisture to achieve the necessary range of strengths near the expected VCI_1. However, the surface of the soil must not have excess water. This will cause a loss of traction (and thus overall mobility) due to the slipperiness, whereas VCI_1 testing seeks to quantify mobility losses due to soil strength failure.

For zero-pass immobilization tests, the vehicle will be operated in its lowest gear at a slow, steady speed (2-3 mph) in a straight line through the identified test area. Steady throttle is applied until the vehicle becomes immobilized, which is defined as complete loss of forward movement. The vehicle will then be placed in reverse and an attempt 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 (2-3 mph) with the vehicle's running gear travelling through the same tracks. The vehicle will traffic forward through the lane for the first pass and traffic backwards, in reverse, for the second pass. Any potentially negative effects due to trafficking in reverse are negligible since the dominant factor controlling VCI performance is the vertical contact pressure of the running gear bearing on the soil and producing sinkage [3]. Forward and backward passes are continued until the vehicle becomes immobilized. As with the zero-pass test, the immobilization point is the point where the vehicle can move neither forward nor backward. (Note that the number of passes used for analysis is the number of successful passes; thus if a vehicle makes eight good passes and becomes immobilized during the ninth pass, this would be considered an 8-pass lane.)

The immobilization-pass number is recorded, and notes are made of any significant observations of vehicle performance or test abnormalities. These notes are associated with soil strength data collected near the immobilization.

Soil Data Collection

Soil properties in the test lanes are characterized in six-inch layers, typically 0-6 in., 3-9 in., 6-12 in., 9-15 in., and 12-18 in. depths. The mass soil strength of the test lanes is characterized in terms of rating cone index (RCI). RCI is defined as the product of cone index (CI) and remold index (RI).

$$RCI = CI * RI \tag{1}$$

CI and RI data are collected for each test lane using a cone penetrometer and remolding equipment, respectively. Those performing RI and CI measurements should note any sand layers encountered or any soil that feels gritty against the soil equipment. They should also take note of any irregularities encountered in soil data collection. Additional soil consistency data, including soil density and moisture content are obtained to further characterize the test lanes.

CI is an index of soil shear strength obtained via a standardized trafficability cone penetrometer [4, 5]. The 300 psi dial cone penetrometer consists of a 30° cone of 0.50 sq-in. base area, an 18-in. long rod which can be joined with other rods to provide an 18- or 36-in. length of rod, a proving ring, a dial gauge, and a handle (Figure 1). When the cone is forced into the ground, the proving ring is deformed in proportion to the force applied. The stress (in psi) required to move the cone slowly (at a constant rate of approximately 0.1 ft/s [5]) through a given plane is indicated on the dial inside the ring. This stress is an index of the shearing resistance of the soil and is called the CI of the soil in that plane. The range of the dial is 0 to 300 psi, and 300 psi is calibrated to a vertical applied force of 150 lb. The cone penetrometer can be upgraded to a 750 psi dial using a 60° cone of 0.20 sq-in base area to measure firmer soils.

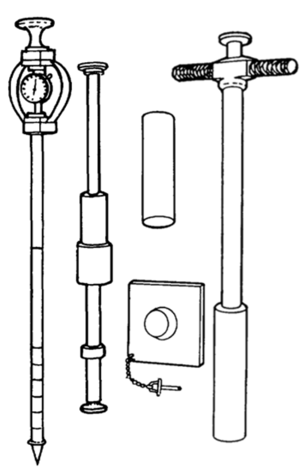

Figure 1: Soil equipment. From left to right: trafficability cone penetrometer, drop hammer, remold cylinder and base, and Hvorslev sampler.

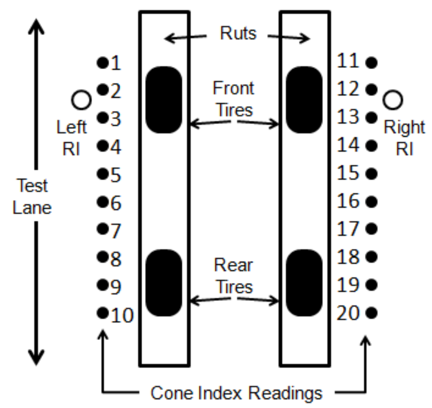

Figure 2: Soil data collection locations relative to the immobilized vehicle.

A minimum of ten cone penetrometer measurements are collected along each side of the test lane, resulting in twenty cone penetrometer measurements for each test lane (Figure 2). Additional cone index measurements may be taken next to the test lane ruts behind the spot of immobilization to support data results. The cone penetrometer measurements are collected near the area of immobilization but outside the area of disturbed soil created by the forward and reverse passes of the vehicles running gear.

The RI is a measure of the sensitivity of soil to strength losses under vehicular traffic. RI is measured using remolding equipment (Figure 1), which consists of a Hvorslev sampler, a 2.5 lb drop hammer with a 12-inch drop, a cylindrical tube (2 inches in diameter and 8 inches long) mounted to a base plate, and a cone penetrometer. Soil samples are taken from three different soil layers: surface to 6 inches, 6 to 12 inches, and 12 to 18 inches below the ground surface. If the 3-9 inch layer is of particular interest, soil samples may be taken directly from this layer, or the average RI between the surface to 6 inch and 6 to 12 inch layer may be used.

Minimally disturbed soil samples are placed in the cylindrical tube. Cone penetrometer readings are measured in the sample at the surface (where the base of the cone enters the soil) and at each successive inch to a depth of 4 in. Then this sample is remolded by subjecting it to 100 hammer blows. Cone penetrometer readings are performed on the remolded sample. It should be noted if the hole from the first cone readings has not completely closed in the remolding process. In such cases, a new sample should be taken from a location adjacent to and at the same depth as the original. That sample can then be remolded and measured. The ratio of remolded strength to initial strength is the RI.

At minimum, RI should be measured on either side of the vehicle for each lane. If the RI measurements seem consistent with surrounding areas and with each other (within about 0.1), no further measurements are necessary. If the measurements do not agree, two additional measurements should be made, one on each side of the vehicle.

Details regarding the proper use of the trafficability cone penetrometer can be found in [6].

Other supporting soil data requires bulk sampling of six-inch layers across the testing site. Laboratory analysis should include sieve, hydrometer, and Atterberg limit testing to confirm a consistent, CH soil with very low sand content. Natural moisture content of each lane should also be sampled and recorded for each six-inch soil layer.

DATA ANALYSIS

Historically, VCI_1 has been determined based on subject matter experts' (SMEs) judgment of the available data. SMEs supervise the field testing and gather all the data for analysis, typically using 10-20 lanes for each vehicle configuration. The supervising SME must make judgments both in the field and in the data analysis about their perception of the quality of each lane.

Data Quality

To produce reliable and repeatable results, special attention must be taken to analyze the soil data for outliers that may affect the determination of the VCI_1. The CI profile with respect to depth should be analyzed for each measured location, as shown in Figure 3. Inconsistent layers, high water tables, foreign objects, or hard pans may skew the data, particularly when present in the first 18 inches. Therefore, uniform or uniformly increasing soil strength is required for the first 18 inches and is preferred for the 18 – 36 inch layers.

Furthermore, the distribution of CI measurements between locations should be investigated for trends which may affect the test results. For example, test lanes are often excluded from final analysis if the difference in strength between the right and left wheel paths is significant. This is usually noted in the field because a drastic left-right difference in soil strength may cause the vehicle to sink more on one side than the other. Thus, it may develop a notable lean toward the weaker side before it is immobilized. However, this is not always the case, so it is necessary to check for this trend during data analysis. While these lanes, coupled with rut depth measurements, may provide information pertinent to vehicle dynamics, care must be taken when applying these measurements to the determination of the VCI_1.

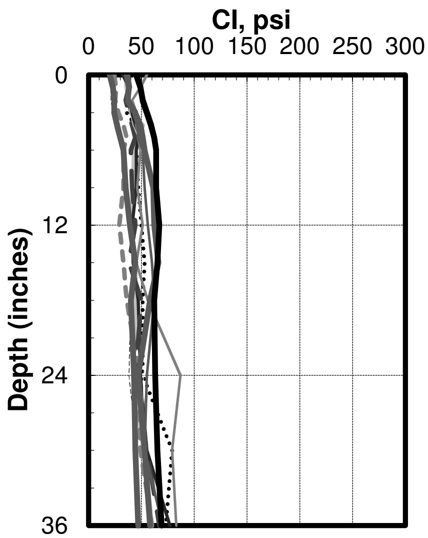

Figure 3: Example of fairly uniform CI data. Each line represents a CI measurement location.

Determining VCI

A lane's RCI is computed for each layer of interest by multiplying the average of all CI measurements within the layer by the average of all RI measurements within the layer. This computed RCI is usually rounded up to the next integer value (e.g., 28.3 will be rounded up to 29) to ensure conservatism in the analysis.

After all of the data have been aggregated, the first step toward determining VCI_1 is to determine which soil layer is most critical for the mobility of a given vehicle configuration. Typically, the layers that are considered for this are six-inch overlapping layers at the following depths (in inches below the undisturbed ground surface): 0-6, 3-9, 6-12, 9-15, and 12-18. Table 1, reproduced from [6], shows the normal critical layer for various vehicle configurations, assuming they are running on fine-grained soil.

Table 1: Normal critical layer based on vehicle type.

Type of Vehicle	Configuration	Critical Layer (inches)
Wheeled	Wheel loads under 2,000 lb	3-9
	Wheel load between 2,000 and 15,000 lb	6-12
	Wheel load over 15,000 lb	9-15
Tracked	Ground contact pressure less than 4 psi	3-9
	Weight less than 100,000 lb	6-12
	Weight over 100,000 lb	9-15

However, during VCI_1 testing, it is necessary to analyze each soil layer separately to confirm that the correct critical layer has been selected. For each soil layer, a plot of soil strength (RCI) versus number of passes is created (Figure 4).

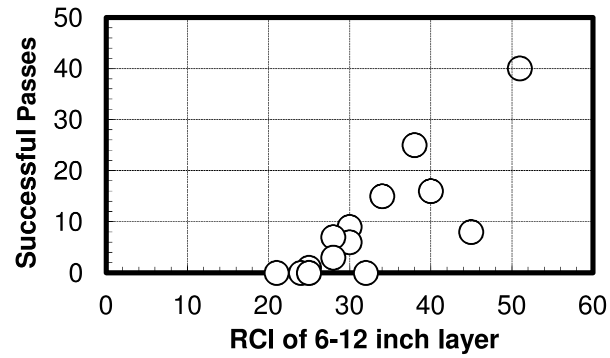

Figure 4: Sample VCI plot.

A go/no-go separation chart is also created (Figure 5). This chart simply shows the number of lanes that had a given RCI and classifies each as either a zero-pass or multi-pass lane.

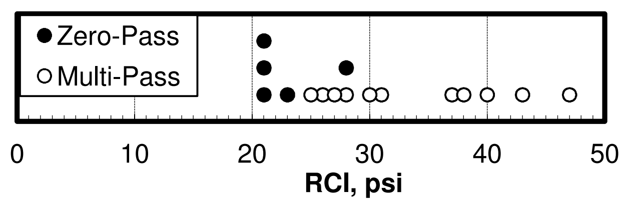

Figure 5: Sample go/no-go separation chart.

The layer with the highest correlation and best separation of zero and multi-pass data is considered the critical layer for the VCI_1 determination. For test points where the 6-in. layer below the critical layer is weaker, the weaker soil strength is used [7]. For example, if the RCI value of the 12-18 in. layer for any given test lane is lower than the RCI value of the 6-12 in. layer, the RCI value from the 12-18 in. layer is used. This rule is commonly referred to as the "Drop Layer Rule."

Once a critical layer has been selected and the Drop Layer Rule has been applied, a final plot of passes made good versus RCI of the critical layer is used to determine the VCI_1. This is the RCI that appears to correspond to one pass based on the trend of the available data points. Often, the VCI_1 is determined by adding one to the RCI of the highest zero-pass lane. It is not uncommon for a one- or two-pass lane to have a lower strength than the highest zero-pass lane. The key is that VCI_1 is the strength that will *consistently* allow one pass of the vehicle.

It should also be noted that occasionally a zero-pass lane is measured at an RCI value unexpectedly higher than a multi-pass lane (for instance, several RCI points higher than a 10-pass lane). In such cases, it is necessary for the test supervisor to consider whether soil surface slipperiness or other factors may have skewed the results of this lane.

To validate the analysis, the VCI_1 for each vehicle is compared to the historical database of VCI_1 for various active and retired military vehicles. All vehicles are ranked according to their Mobility Index (MI) values. The MI is a parameter computed from many vehicle characteristics, such as weight and tire dimensions, that are known to influence traction. Vehicles with similar MI are expected to have similar VCI_1. For details regarding MI computation, see [8].

UNCERTAINTY ANALYSIS

Typically, the uncertainty in field VCI_1 values is either ignored or assigned a value based on SME evaluation. Due to the nature of the data, it has been difficult to establish a standard mathematical approach to determining the VCI_1, or the uncertainty associated with it.

One difficulty in this analysis is that the VCI_1 is a function of the number of passes and RCI. However, not all lanes have equal influence on the final determination of the VCI_1. Lanes with successful passes close to 1 or soil strengths close to the final VCI_1 have the most weight in the SME's evaluation. Other lanes provide supporting data, but may not be fully considered.

Also, RCI, which is a function of RI and CI, has its own uncertainties associated with the field measurements. Uncertainty in a lane's CI measurements may be statistically analyzed, since there are usually 60 total CI measurements used per lane (20 cone measurement locations with 3 readings each, one at the top, center, and bottom of the critical layer). However, RI data is usually more scarce (typically only 2-4 measurements per lane) due to the time it takes to collect. Thus, the uncertainty of RI measurements cannot be effectively analyzed on a per lane basis.

Descriptive Statistics, Lane by Lane

One approach is to return to the raw data (CI and RI measurements) associated with each lane and attempt to describe the uncertainty of each individual lane.

This method primarily addresses the variability in RCI measurements. The question being asked here is, "What values are likely to be obtained for RCI for this lane if it is measured again?"

To answer this question, each raw CI (usually 60 values) and RI (usually 2-4 values) within the critical layer are multiplied together to provide a population of all possible RCIs, which usually consists of at least 120 values. With this sample population, it is feasible to calculate descriptive statistics as well as confidence intervals. Based on the large sample population, it is appropriate to use a two-sided *t*-interval [9] to describe our confidence about the mean RCI, as shown in equation (2).

$$\mu \in \left(x - \frac{t_{\alpha/2,n-1} s}{\sqrt{n}}, x + \frac{t_{\alpha/2,n-1} s}{\sqrt{n}} \right) \qquad (2)$$

Equation (2) indicates that the true mean RCI value, μ, is within the interval centered on the average RCI, x, with an error margin based on α (the desired uncertainty level, e.g. 0.05 for a 95% confidence level), s (the standard deviation of RCI values used), and n (the number of RCI values used).

This concept itself is not new, but it has not previously been applied to VCI measurements in this manner. Analysis of recent data using this method resulted in 95% confidence intervals with error margins ranging from 0.7 to 2.3 on the lanes that were kept for final analysis. For the 15 lanes analyzed, the median and the average error margin were approximately 1.3.

VCI_1 Analysis Using Upper and Lower Bounds

To apply the lane by lane descriptive statistics to the VCI_1 analysis, it is necessary to evaluate how the differences in individual lanes will affect the final uncertainty in VCI_1. Although this could be executed in several ways, the most intuitive way is to perform separate VCI_1 determinations, one based on the lower bound and one based on the upper bound of each lane. VCI plots and go/no-go separation charts, such as those in Figures 4 and 5, can be created for the twice per vehicle configuration, once for the lower bound of the average and once for the upper bound. Then identical VCI analysis techniques can be applied to both. The final VCI_1 can reasonably be said to be between these two numbers. The average VCI_1 can still be determined for comparison to historical data.

Example Analysis

For example, the data represented in Figure 6 could be interpreted to have a lower bound VCI_1 of 27 and an upper bound VCI_1 of 30. This VCI_1 was previously determined (based on each lane's average RCI values) to be 29. Thus the VCI_1 can be reported either as 27-30 or 29 +1/-2 (based on 95% confidence bounds for each lane).

Note that the confidence bounds in equation (2) are equally spaced from the average, but the range in VCI_1 does not appear to be symmetric. In this case, the asymmetry is attributable to rounding error because RCI and VCI are always expressed as whole numbers.

Although this is helpful in quantifying uncertainty, this method still does not account for the uncertainty of SME judgment about the value of VCI_1. For instance, the authors of this paper had some doubts about the highest strength zero-pass in the Figure 6. Because this lane had a higher measured soil strength than a 1-, 3-, and 9-pass lane, it seems odd. Since this data was collected over a year ago and most of the authors were not present at the time of collection, we must rely on the field data records to determine whether this is a valid point. The CI and RI measurements for the lane appear valid. Thus, the VCI_1 is the RCI of this lane plus one. However, it is possible that another SME would have chosen to ignore the last zero-pass.

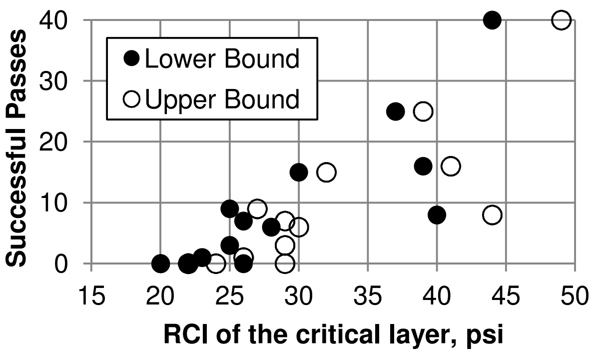

Figure 6: Example of upper and lower confidence bounds applied to a VCI plot.

CONCLUSION

Uncertainty in VCI_1 arises from both field data collection and from the final analysis of the data. However, with improved awareness of the existing standard VCI testing procedures, the uncertainty may be better understood and may decrease with some future refinements to the data analysis process.

It has been suggested that all future VCI_1 analysis should include some statement of uncertainty. This may most readily be obtained by computing an upper and lower confidence bound on each lane and then performing two separate VCI_1 determinations, one based on the lower bound and one based on the upper bound of each lane.

These measures will only work if the VCI_1 can be consistently determined from any given set of data. Currently, the "rules" for VCI_1 determination are as follows:

1) Remove suspect lanes from analysis, both during the field and in the office.
2) Approximate average RCI values by rounding up the product of the RI and CI (e.g., 28.1 becomes 29).
3) Use the critical layer from [6] unless a different soil layer provides a clearly superior correlation.
4) Drop Layer Rule: Use the RCI of the critical layer unless the layer directly below this has a lower strength.
5) Scrutinize and potentially ignore zero-pass lanes that have measured RCI values higher than 10-pass lanes.
6) Use a minimum of the highest legitimate zero-pass plus one.

Even with these rules, independent analysis of the data by multiple SMEs may initially result in slightly different values for VCI_1. Further work to standardize the analysis process is needed.

REFERENCES

[1] C.J. Nuttall, Jr., C.W. Wilson, and R.A. Werner, "One-pass Performance of Vehicles on Fine-grained Soils", Contract Report No. 3-152, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, 1966.

[2] American Society for Testing and Materials, "Standard practice for classification of soils for engineering purpose (Unified Soil Classification System)", Designation D 2487-11, Philadelphia, PA, 2011.

[3] J.D. Priddy, "Improving the traction prediction capabilities in the NATO Reference Mobility Model (NRMM)", Technical Report GL-99-8, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, 1999.

[4] D.R. Freitag, "Penetration Tests for Soil Measurements", Miscellaneous Paper No. 4-960, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, 1968.

[5] G.W. Turnage and D.R. Freitag, "Effects of Cone Velocity and Size on Soil Penetration Resistance", Miscellaneous Paper No. M-69-7, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, 1969.

[6] U.S. Department of the Army, "Planning and Design of Roads, Airfields, and Heliports in the Theater of Operations – Road Design", FM 5-430-00-1, 1994.

[7] B.G. Schreiner, "Mobility Exercise A (MEXA) Field Test Program", Technical Report M-70-11, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, 1971.

[8] R.B. Ahlvin and P.W. Haley, "NATO Reference Mobility Model Edition II, NRMM II, User's Guide", Technical Report GL-92-19, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, 1992.

[9] A. Hayter, "Probability and Statistics for Engineers and Scientists", 3rd edition, Thomson, Belmont, CA, 2007.