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# Clarification of vehicle cone index with reference to mean maximum pressure

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**Abstract**

The US Army developed Vehicle Cone Index (VCI) as a metric for directly quantifying the ability of vehicles to traverse soft-soil terrain. In order to ensure minimum soft-soil performance capabilities for their new military vehicles, the US Army has used VCI for many years as a performance specification. The United Kingdom's Ministry of Defence (UK MOD) has used the Mean Maximum Pressure (MMP) parameter for many years as a performance specification. It has been demonstrated that the MMP parameter relates to soft-soil performance capabilities, and hence, the UK MOD has ensured minimum performance capabilities for their new military vehicles by using MMP specifications. Both the VCI and MMP specification approaches have served their users well, but fundamental differences in the two specification approaches have produced some misunderstandings concerning what VCI really is and how it relates to MMP. This article clarifies that VCI is a performance metric, not a set of predictive equations, explains how VCI is measured, and compares different methods of predicting VCI for one-pass performance (i.e., $VCI_1$) of wheeled vehicles in fat clay soils. It is further clarified that MMP should not be compared with VCI but instead with Mobility Index (MI), which is the principal parameter used by the US Army for predicting VCI. Relationships are presented for using MMP to predict $VCI_1$ for wheeled vehicles in clay, and the resulting relationships allow comparison between MMP and MI in terms of their ability to predict VCI. Seventy-nine $VCI_1$ performance measurements were used for the comparison, and

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they demonstrate that MI describes the historical performance data somewhat better than MMP.


*Keywords:* Trafficability; Traction; Vehicle mobility; Soft soil; Off-road performance

**Nomenclature**

| | |
|---|---|
| $b$ | average tire section width (inflated; unloaded), in. |
| CF | clearance factor (part of MI) |
| CPF | contact pressure factor (part of MI) |
| $d$ | average tire outside diameter (inflated; unloaded), in. |
| DCF | deflection correction factor |
| EF | engine factor (part of MI) |
| GF | grouser factor (part of MI) |
| GVW | gross vehicle weight, lb |
| $h$ | average tire section height (inflated; unloaded), in. |
| $h_c$ | vehicle minimum clearance height, in. |
| $m$ | total number of axles |
| MI | mobility index |
| $MMP_M$ | newly proposed version of mean maximum pressure (by Maclaurin), psi |
| $MMP_R$ | original version of mean maximum pressure (by Rowland), psi |
| $n$ | average number of tires per axle |
| TEF | traction element factor (part of MI) |
| TF | transmission factor (part of MI) |
| $VCI_1$ | one-pass vehicle cone index, psi |
| $VCI_{50}$ | 50-pass vehicle cone index, psi |
| $w$ | average axle loading, lb |
| WF | weight factor (part of MI) |
| WLF | wheel load factor (part of MI) |
| $\delta$ | average hard-surface tire deflection, in. |

## 1. Introduction

The ability to traverse soft-soil terrain without becoming immobilized is an important performance consideration for vehicles that must operate in off-road environments. For defense planners, soft-soil immobilizations are among the most difficult to predict, yet militarily, could be the most disastrous. The lack of spatially distributed engineering soils data necessary to adequately quantify the constitutive characteristics for an area of interest, the scarcity of lightweight, portable, reliable testing equipment to collect such data, and the absence of schemes for accurately characterizing the problem using more theoretical approaches have led researchers to develop past-performance-based empirical methods for predicting soft-soil immobilizations. Translation of laboratory-derived methods to predict actual field performance has achieved only limited success, leading defense researchers to concentrate on methods derived from field experiments for greater predictability.

The United States (US) Army's Engineer Research and Development Center (ERDC) at the Waterways Experiment Station (WES) developed a metric for quantifying the ability of vehicles to traverse soft-soil terrain, and they referred to this metric as the Vehicle Cone Index (VCI). VCI is defined as the minimum soil strength necessary for a self-propelled vehicle to consistently make a prescribed number of passes in track without becoming immobilized. Historical testing usually focused on measuring the minimum soil strength required for a vehicle to make one pass ($VCI_1$) and/or 50 passes ($VCI_{50}$). Using VCI measurements for a number of different vehicles, the US Army ERDC developed a set of empirical equations that predict $VCI_1$ and $VCI_{50}$ from relatively simple vehicle characteristics (i.e., weight and running-gear dimensions). This set of equations will be referred to herein as the ERDC VCI Prediction Methodology, and it uses a principal parameter referred to as the Mobility Index (MI) to relate VCI performance to vehicle characteristics. To ensure ample soft-soil performance capabilities for new military vehicles, the US Army has used performance specifications requiring vehicles to have a certain $VCI_1$ and/or $VCI_{50}$ performance or better. Evaluations to determine whether vehicles meet the US Army performance specifications have been accomplished using VCI measurements and/or predictions based on the ERDC VCI Prediction Methodology.

Another technique for evaluating the ability of vehicles to traverse soft-soil terrain was developed by the United Kingdom's Ministry of Defence (UK MOD). The UK MOD theorized that ground contact pressure is the most important vehicle attribute affecting soft-soil performance. They ran tests to measure vertical pressures in the ground under the passage of vehicle running gears. From these tests, they developed a metric referred to as "mean maximum pressure," which is defined as the mean of the peak pressure magnitudes that occur in the soil under each wheel station. Using "mean maximum pressure" measurements for a number of different vehicles, the UK MOD developed a method of predicting "mean maximum pressure" from relatively simple vehicle characteristics (i.e., weight and running-gear dimensions). This prediction method will be referred to herein as the Mean Maximum Pressure Criterion, and it uses a principal parameter that is referred to as the Mean Maximum Pressure (MMP) to relate "mean maximum pressure" performance to vehicle characteristics. The UK MOD demonstrated that the MMP parameter they derived from "mean maximum pressure" measurements was linearly related to soft-soil performance using some VCI measurements reported by the US Army. To ensure ample soft-soil performance capabilities for new military vehicles, the UK MOD has used performance specifications requiring vehicles to have a certain MMP or better. Evaluations to determine whether vehicles meet the UK MOD performance specifications have been accomplished using predictions from the Mean Maximum Pressure Criterion.

The US Army and UK MOD specification approaches both ensure minimum soft-soil performance capabilities for their vehicles, but there is a major difference in the approaches that has caused some misunderstandings. The US Army uses the VCI metric for their specifications, and this is a direct indicator of soft-soil performance capability. The UK MOD uses the Mean Maximum Pressure Criterion and, more specifically, the MMP parameter for their specifications. This is an indirect indicator of soft-soil performance capability. They also refer to the principal parameter as the "Mean Maximum Pressure" or MMP. This has resulted in the term "mean maximum pressure" being regarded as the empirical equations that make up the Mean Maximum Pressure Criterion, and it has also resulted in the term "vehicle cone index" being mistakenly regarded as the empirical equations that are used to predict it. The reality is that MMP is a parameter like MI that relates vehicle characteristics to expected soft-soil performance capability. Therefore, to evaluate which approach is better for predicting soft-soil performance, comparison should not be made between MMP and VCI. The more correct comparison is between the Mean Maximum Pressure Criterion, which is based on the MMP parameter, and the ERDC VCI Prediction Methodology, which is based on the MI parameter. In other words, MMP and MI should be compared on the basis of their ability to predict VCI, which by definition represents soft-soil performance capability.

The intent of this article is to clarify VCI in terms of what it is, how it is measured, and how it can be predicted. The scope of the test data and prediction methods presented in this article is limited to $VCI_1$ performance for wheeled vehicles in fat clay soils (i.e., CH by the Unified Soil Classification System). A large emphasis is placed on how to predict $VCI_1$, and specifically, two common methods of quantifying the ability of vehicles to traverse soft-soil terrain are compared for their quality in predicting $VCI_1$: (1) the ERDC VCI Prediction Methodology and (2) the UK's Mean Maximum Pressure Criterion.

## 2. The VCI soft-soil performance metric

The International Society for Terrain-Vehicle Systems (ISTVS) defines VCI as the "minimum soil strength in the critical soil layer, in terms of rating cone index for fine grained soils or in cone index for coarse grained soils, required for a specific number of passes of a vehicle, usually one pass ($VCI_1$) or 50 passes ($VCI_{50}$)" [1]. From this definition, it should be apparent that VCI is a metric that defines soft-soil performance, and it does so in such a way that it can be measured and consequently predicted. It is analogous to the drawbar pull coefficient, motion resistance coefficient, maximum slope negotiable, and average rut depth performance metrics. Like these other four traction-related performance metrics, VCI is applicable to all types of ground-based vehicles. Perhaps even more important, it allows direct comparison between various vehicles regardless of the type of traction elements employed (e.g., the VCI of tracked vehicles can be directly compared to that of wheeled vehicles).

The critical layer is the layer of soil that exerts the greatest influence on trafficability, and it is typically a 6-in. layer with the upper edge located a few inches below the ground surface. For most vehicles, the critical layer is the 6-to-12 in. layer, but it varies dependent on the wheel loadings for wheeled vehicles or the gross vehicle weight for tracked vehicles. The VCI performance metric was one of the most significant products developed during the initial trafficability studies conducted by ERDC and reported in the "Trafficability of Soils" series of reports (i.e., WES Technical Memorandum No. 3-240 Report 1 and 20 supplements thereto) [2]. This trafficability research demonstrated that repeatable and predictable measurements of VCI performance in naturally occurring fine-grained soils could be made using a relatively simple measure of soil strength termed the rating cone index (RCI).

RCI is an index of soil shear strength that includes consideration of the sensitivity of soil to strength losses under vehicular traffic, and it is related to both the bearing capacity and tractive resistance of soils. RCI is defined as the product of cone index (CI) and remold index (RI) for a particular layer of soil, and these two constituent indexes are measured using trafficability equipment developed and standardized by ERDC (see Fig. 1). CI is an index of soil shear strength, and it is determined using a cone penetrometer, which consists of a cylindrical shaft, usually 18–36 in. in length, with a 30° right circular cone on one end and a calibrated load measuring device on the other end. The CI measurement is the average of pressure readings taken at specified depths of penetration of the base of the cone into the soil. RI is an index of the sensitivity of soil to strength losses under vehicular traffic, and it is determined using a Hvorslev trafficability sampler and remolding equipment. The Hvorslev sampler is a piston-type device used to obtain undisturbed samples of soil, and remolding equipment consists of a cylindrical tube mounted on a steel base and a 2-1/2-lb drop hammer. The RI measurement is defined as the measured CI in a sample taken after 100 blows of the drop hammer divided by the measured CI taken before 100 blows.

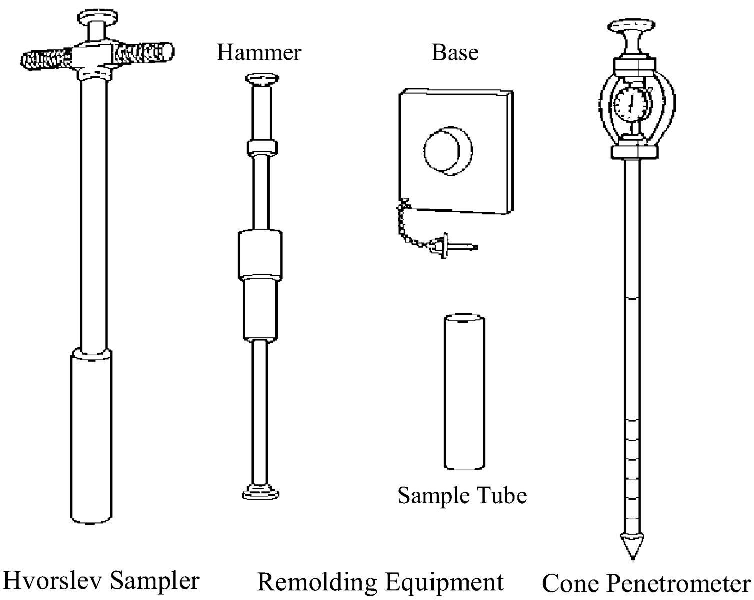


Fig. 1. ERDC trafficability equipment.

## 3. Typical procedure for measuring VCI

Measuring VCI is a complex and arduous task, and it requires the conduct of multi-pass experiments. In a typical multi-pass experiment, a level, straight-line, homogeneous (as much as possible) test lane is located, and cone index measurements are taken throughout the lane. Then the vehicle traverses through the test lane at a slow, steady speed (approximately 2 mph) in its lowest gear. The experiment is usually conducted with the vehicle first traversing forward through the test lane for pass number one and then traversing backward (i.e., in reverse gear) through the test lane for pass number two. The vehicle will continue to make passes until immobilization occurs. When immobilization is reached, the immobilization pass number is recorded and other supporting soil consistency data are measured (e.g., remold index, moisture content, density, etc.). The supporting data are measured in a spot adjacent to the immobilization, but out of the zone of disturbance. The cone index and supporting soil consistency measurements are intended to represent the soil characteristics with the greatest influence on the immobilization for the particular vehicle and terrain conditions.

To establish the VCI measurement for a particular vehicle configuration, several multi-pass experiments are conducted in a range of soil strengths to acquire several observations for passes-made-good versus soil strength in the critical layer. The critical layer for the VCI of wheeled vehicles in fine-grained soils is typically the 6-to-12 in. layer, and, as previously stated, the soil strength used in fine-grained soils is the RCI. The RCI at which the vehicle is capable of consistently completing a minimum number of passes (normally one or 50) is determined from a graph of the various multi-pass observations, and this value of RCI represents the VCI performance measurement. Fig. 2 provides a sample graph of multi-pass observations that were used to determine the $VCI_1$ measurement for a vehicle configuration considered in this research.

## 4. Predicting $VCI_1$ using the ERDC VCI prediction methodology

For performance of wheeled vehicles in fat clay soils, $VCI_1$ predictions from the ERDC VCI Prediction Methodology are based primarily on the MI parameter. MI was initially developed based on the results of trafficability studies conducted by ERDC from 1945 through 1951 [3], and MI for wheeled vehicles was then upgraded to its current form based on additional trafficability studies conducted during the 1960s [4] and a reevaluation of all ERDC VCI measurements through the early 1990s [5]. MI was originally developed to predict $VCI_{50}$, but it was also later adopted for predicting $VCI_1$. The MI parameter is actually an aggregation of eight factors, each of which is based on some vehicle characteristic considered to influence mobility in soft soils. MI for wheeled vehicles is calculated as shown below:

$$\mathrm{MI} = \left(\frac{(\mathrm{CPF})(\mathrm{WF})}{(\mathrm{TEF})(\mathrm{GF})} + \mathrm{WLF} - \mathrm{CF}\right)(\mathrm{EF})(\mathrm{TF}).$$

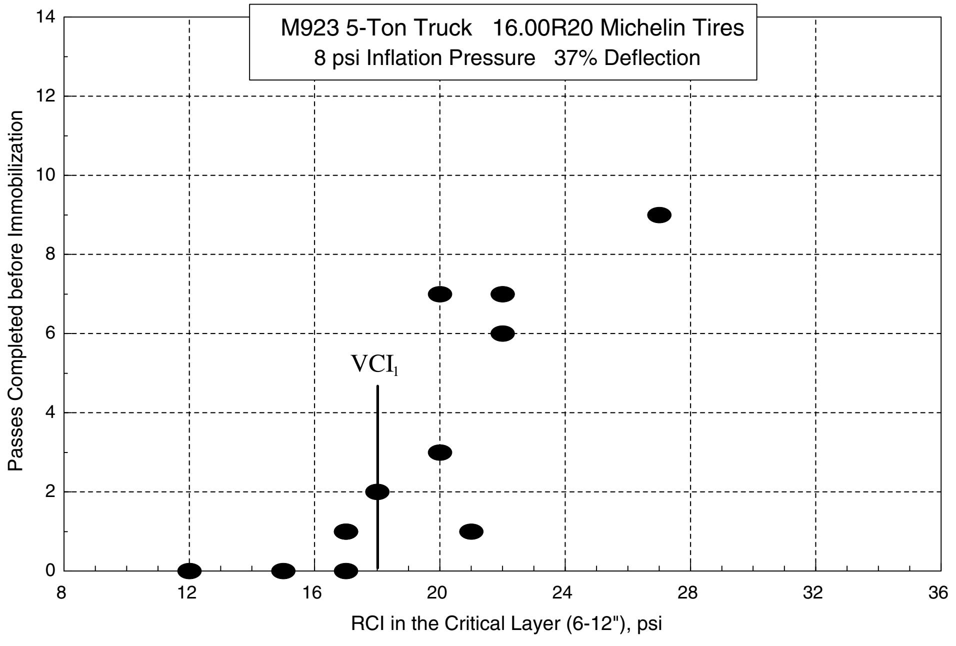


Fig. 2. Sample multi-pass observations used for determining $VCI_1$.

The eight factors are calculated as follows (see nomenclature for descriptions):

$$\mathrm{CPF} = \frac{w}{0.5ndb}, \quad \mathrm{TEF} = \frac{10+b}{100},$$

$$\mathrm{WLF} = \frac{w}{2000}, \quad \mathrm{CF} = \frac{h_c}{10},$$

$$\begin{aligned} \mathrm{GF} &= 1 + 0.05c_{\mathrm{GF}}, \quad \text{where } c_{\mathrm{GF}} = 1 \text{ if tire chains are used or 0 if not,} \\ \mathrm{EF} &= 1 + 0.05c_{\mathrm{EF}}, \quad \text{where } c_{\mathrm{EF}} = 1 \text{ if PWR} < 10 \text{ hp/ton or 0 if not,} \\ \mathrm{TF} &= 1 + 0.05c_{\mathrm{TF}}, \quad \text{where } c_{\mathrm{TF}} = 1 \text{ if manual transmission or 0 if automatic,} \end{aligned}$$

$$\mathrm{WF} = c_{\mathrm{WF1}}(w/1000) + c_{\mathrm{WF2}},$$

$$\text{where} \begin{cases} w < 2000 \text{ lb} & \Rightarrow c_{\mathrm{WF1}} = 0.553 \text{ and } c_{\mathrm{WF2}} = 0, \\ 2000 \leqslant w < 13,500 \text{ lb} & \Rightarrow c_{\mathrm{WF1}} = 0.033 \text{ and } c_{\mathrm{WF2}} = 1.050, \\ 13,500 \leqslant w < 20,000 \text{ lb} & \Rightarrow c_{\mathrm{WF1}} = 0.142 \text{ and } c_{\mathrm{WF2}} = -0.420, \\ 20,000 \leqslant w < 31,500 \text{ lb} & \Rightarrow c_{\mathrm{WF1}} = 0.278 \text{ and } c_{\mathrm{WF2}} = -3.115, \\ 31,500 \leqslant w & \Rightarrow c_{\mathrm{WF1}} = 0.836 \text{ and } c_{\mathrm{WF2}} = -20.686. \end{cases}$$

Tire deflection is not considered in MI because most of the VCI performance measurements considered during its development involved vehicles with tire deflections around 15% of the section height. After the commercialization of radial tires, VCI performance measurements were obtained for vehicles with much higher tire deflections, and as a consequence, the quality of MI as a predictor for VCI was somewhat diminished. This prompted ERDC to develop the Deflection Correction Factor (DCF) to account for the effect of tire deflection on VCI performance. DCF is calculated as shown below [6]:

$$\mathrm{DCF} = \left(\frac{0.15}{\delta/h}\right)^{0.25}.$$

DCF acts to normalize VCI to a performance magnitude at 15% tire deflection, and it is applied as a multiplier to equations that were originally developed to predict VCI as a function of MI alone. The equations for predicting $\mathrm{VCI}_1$ as a function of MI and DCF are founded on more than 50 years of field test data with a broad variety of vehicles. These equations are shown below [6]:

$$\mathrm{VCI}_1 = f(\mathrm{MI}, \mathrm{DCF}),$$

$$\text{where} \quad \begin{cases} \mathrm{MI} \leqslant 115 \;\Rightarrow\; \mathrm{VCI}_1 = \left(11.48 + 0.2\mathrm{MI} - \frac{39.2}{\mathrm{MI}+3.74}\right)\mathrm{DCF}, \\ \mathrm{MI} > 115 \;\Rightarrow\; \mathrm{VCI}_1 = \left(4.1\mathrm{MI}^{0.446}\right)\mathrm{DCF}. \end{cases}$$

To evaluate the quality of the ERDC VCI Prediction Methodology for predicting $\mathrm{VCI}_1$ performance of wheeled vehicles, a set of measured $\mathrm{VCI}_1$ observations were acquired from a readily accessible source recently assembled by ERDC [7]. The ERDC VCI Prediction Methodology is only applicable to vehicles with all axles powered (although procedures have been developed which provide predictions for vehicles with non-powered axles); therefore, observations from the referenced source involving vehicles with non-powered axles were not used in this research. A few of the observations in the referenced source originated from experiments designed specifically for determining $\mathrm{VCI}_{50}$, and some of these observations were not used in this research since they involved low-confidence estimates for $\mathrm{VCI}_1$. After omitting the inappropriate observations, 79 $\mathrm{VCI}_1$ measurements remained.

MI and DCF were calculated for each of the 79 observations, and the data were plotted with the ERDC equations as shown in Fig. 3. Note that it was necessary to divide $\mathrm{VCI}_1$ by DCF in order to generate the simple two-dimensional graph. The figure shows that the data are described reasonably well by the ERDC VCI Prediction Methodology. The standard error was 2.68 psi, and the adjusted coefficient of determination (i.e., $R^2$) was 0.903.

## 5. Predicting $\mathrm{VCI}_1$ using the mean maximum pressure criterion

For performance of wheeled vehicles in fat clay soils, $\mathrm{VCI}_1$ predictions from the Mean Maximum Pressure Criterion are based on the MMP parameter. MMP was

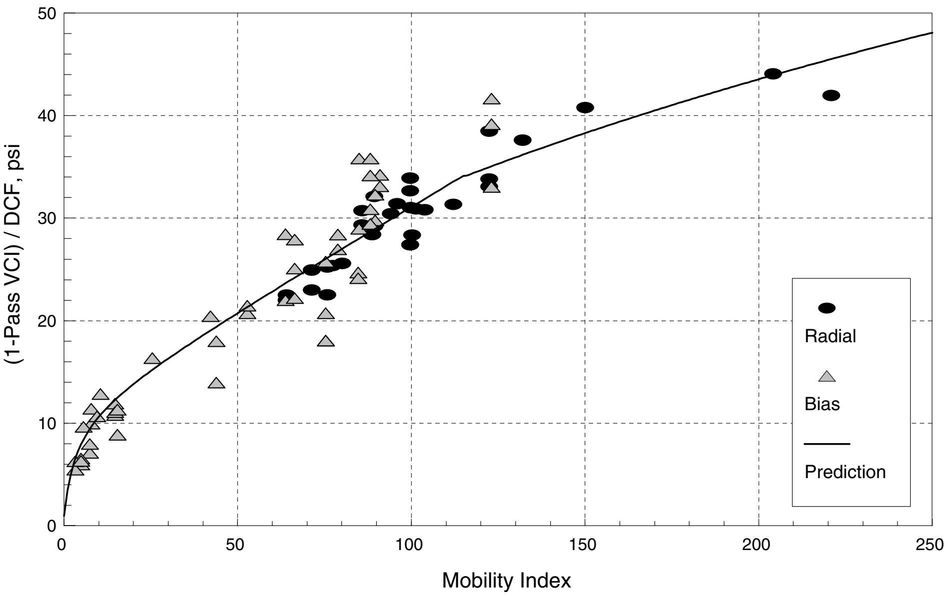


Fig. 3. Relationship between ERDC's MI and $VCI_1$.

developed by what is now the UK MOD's Defence Science and Technology Laboratory (DSTL). The original MMP for wheeled vehicles was developed in the mid 1970s by Rowland as a parameter for estimating the mean peak pressure under the tires that would be directly comparable, in terms of VCI performance, to the MMP he developed a few years earlier for tracked vehicles [8]. Rowland developed the MMP parameter for wheels based in large part on the results of laboratory research performed by ERDC. The original MMP was actually a recast and slightly altered form of a numeric for the performance of tires in clay soils reported by Freitag [9]. A new version of MMP was recently proposed based on the results of drawbar experiments conducted by DERA with a field-deployable, computer-controlled, single-wheel tire tester [10]. Both of these versions of MMP are evaluated herein.

There is a MMP test, which is based on measurements from in-soil pressure sensors buried at a depth of about 9 in., and the MMP formula for tracks was derived from such measurements [11]. However, the original and latest proposed MMP formulas for wheels were not derived from in-soil pressure measurements [10]. Coarse correlations have been made between MMP and VCI performance measurements, but no sound relationship has ever been established to use MMP as a predictor for $VCI_1$. Therefore, least-squares regression was used to develop relationships between the two versions of MMP and $VCI_1$ using the same 79 $VCI_1$ observations that were used to evaluate the ERDC VCI Prediction Methodology.

The formula used for determining the original MMP is shown below [8]:

$$\mathrm{MMP_R} = \frac{0.97\mathrm{KGVW}}{nmb^{0.85}d^{1.15}\sqrt{\delta/h}},$$

$$\text{where for all-drive vehicles} \quad \begin{cases} m = 2 \Rightarrow K = 3.66, \\ m = 3 \Rightarrow K = 3.90, \\ m = 4 \Rightarrow K = 4.10, \\ m = 5 \Rightarrow K = 4.32. \end{cases}$$

This formula is actually slightly different from the MMP formula found in the reference. The true formula had the constant 2 in place of the average number of tires per axle ($n$), but two of the $\mathrm{VCI}_1$ observations that had three axles with dual tires on the rear two axles ($n = 3.333$) demonstrated that $n$ was more appropriate. The $\mathrm{VCI}_1$ measurements were plotted versus $\mathrm{MMP_R}$, and a linear trend resulted. Therefore, a linear equation was developed for predicting $\mathrm{VCI}_1$ as a function of $\mathrm{MMP_R}$ as shown below:

$$\mathrm{VCI}_1 = 3.65 + 0.477\mathrm{MMP_R}.$$

Fig. 4 shows a graph of the best-fit equation with the 79 $\mathrm{VCI}_1$ measurements. The figure demonstrates that the trend is linear and that $\mathrm{MMP_R}$ describes the $\mathrm{VCI}_1$ performance data reasonably well. The standard error was 2.91 psi, and the adjusted coefficient of determination (i.e., $R^2$) was 0.885.

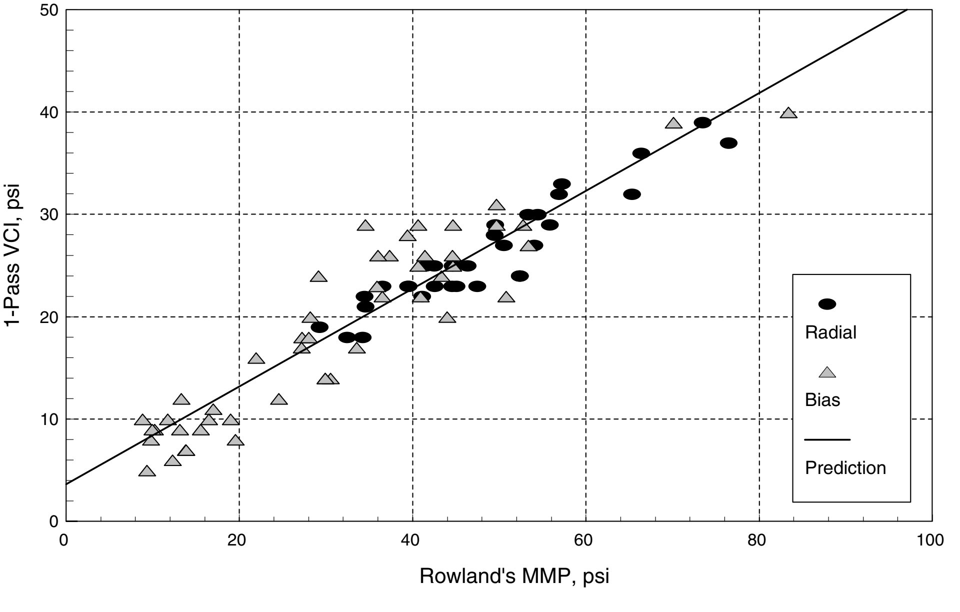


Fig. 4. Relationship between Rowland's original MMP and $\mathrm{VCI}_1$.

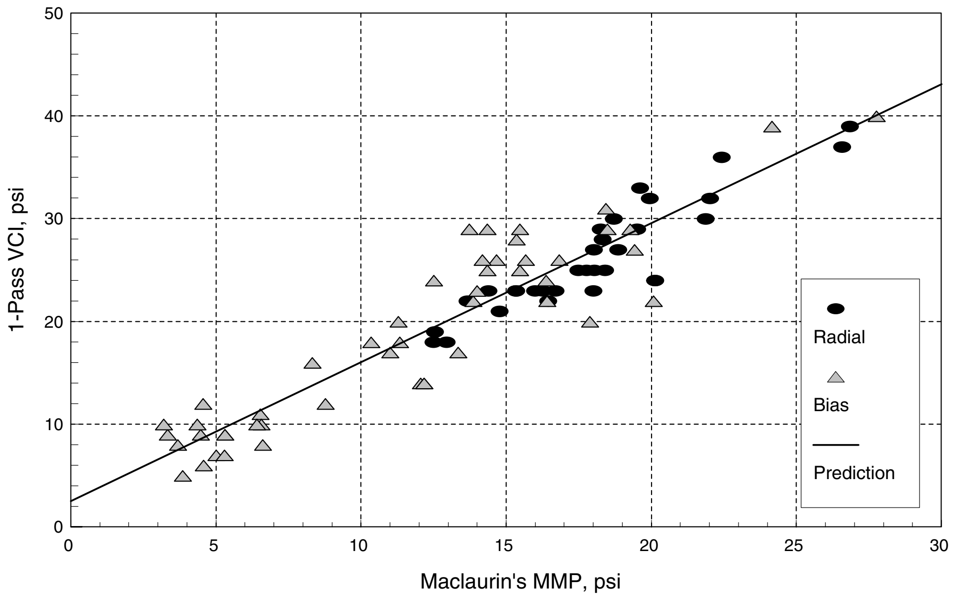


Fig. 5. Relationship between the newly proposed MMP and $VCI_1$.

The formula used for determining the newly proposed version of MMP is shown below [10], where *n* was used instead of the constant 2 shown in the reference for reasons previously described regarding the original MMP,

$$MMP_M = \frac{GVW}{nmb^{0.8}d^{0.8}\delta^{0.4}}.$$

The $VCI_1$ measurements were plotted versus $MMP_M$, and, once again, a linear trend resulted. Therefore, a linear equation was developed for predicting $VCI_1$ as a function of $MMP_M$ as shown below:

$$VCI_1 = 2.53 + 1.35MMP_M.$$

Fig. 5 shows a graph of the equation with the 79 $VCI_1$ measurements. The figure demonstrates that the trend is linear and that $MMP_M$ describes the $VCI_1$ performance data reasonably well. The standard error was 3.01 psi, and the adjusted coefficient of determination (i.e., $R^2$) was 0.877.

## 6. Conclusions

It has been clarified that VCI is a soft-soil performance metric that can be measured using multi-pass experiments or predicted using parameters molded from pertinent vehicle characteristics. Two common methods of quantifying the ability of vehicles to traverse soft-soil terrain were evaluated for their quality in predicting

$VCI_1$ for wheeled vehicles in fat clay soils. The evaluations were performed using 79 $VCI_1$ measurements. The ERDC VCI Prediction Methodology, which is primarily based on MI, was shown to describe all of the $VCI_1$ measurements somewhat better (i.e., lower standard error and higher $R^2$) than both the original and the latest proposed versions of MMP. However, the new equations provided herein can be used to make reasonable predictions for $VCI_1$ using the two versions of MMP.

## Acknowledgments

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