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# PROPOSAL OF A NEW EVALUATION SYSTEM OF TERRAIN TRAFFICABILITY FOR WHEELED VEHICLES MEASURED BY THE TELESCOPIC PENETROMETER

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## *Abstract:*

*In most areas of human activity where vehicles are used, ensuring their mobility is important. One of the components addressed in the framework of mobility is also the movement of vehicles in the field. The article deals with the assessment of wheeled vehicles' trafficability through low-bearing terrain. Therefore, it is important to be able to reliably evaluate whether the terrain is passable or not, i.e. determining the trafficability of the terrain. Currently, two assessment systems are used in the ACR environment to evaluate the bearing capacity of the terrain – one using a PT-45 telescopic penetro-meter and the other using a cone penetrometer. Each of the systems has its advantages and disadvantages, but unfortunately, none of them meet the current requirements of users. Both methods designed for evaluating the passability of wheeled vehicles on terrain always compare the "value of the land" and the "value of the vehicle". Based on the advantages and disadvantages of both evaluation methods, the authors decided to find out whether it would be possible to combine the advantages of both methods and propose a new evaluation system for the telescopic penetrometer, based on the evaluation system for the cone penetrometer. The following was carried out: i) comparison of individual devices and assessment procedures, ii) correlation of permeability measurement results obtained using both penetro-meters, iii) analysis of individual vehicle parameters included in existing assessment methods. The authors present the results of the analysis of the parameters, propose their reduction, and introduce a new important parameter, which significantly affects the result, that is, whether the vehicle will pass the terrain. In conclusion, a completely new system for measuring the passability of wheeled vehicles through the terrain was designed. The correctness and reliability of the entire newly designed system was verified by measurements in the field. Due to the fact that the authors proceeded to solve the problem of trafficability on the basis of requirements from the field, its results will have a great practical impact – the implementation of the new evaluation system into the Field Manual used by the ACR.*

**Keywords:** *mobility, terrain trafficability, passability of wheeled vehicles, penetrometer, systems of the determining trafficability*

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## 1. Introduction

Mobility is addressed in many areas – agriculture, industry, transport and, unfortunately, also during military operations. Thanks to vehicles, it is possible to transport material, animals, and people over long distances within a short time interval. However, vehicles are not only used in ideal conditions and only on roads, but in different terrains, both in the dry and rainy season, floods, snow, and other climatic conditions. In all these climatic conditions, the vehicle must be able to cover the designated route. Therefore, it is important to be able to reliably evaluate whether the terrain is passable or not, i.e. determining the trafficability of the terrain.

During their many years of experience measuring trafficability through terrain, the authors came across another factor that significantly affects trafficability. This factor is the drivers themselves, whose skills vary significantly with experience. This factor is also mentioned in work (Kozlowski et al., 2023), but it has not yet been investigated in detail. If the hypothesis regarding the influence of the driver on the result were to be confirmed, there would be a big change in the perception of the evaluation of trafficability in its entirety. This would create the necessity for further expansion of existing research in this area. Solving the effect of driver ability could later be beneficial for training autonomous vehicles controlled by artificial intelligence.

Penetrometers are used to evaluate the bearing capacity of the terrain. A penetrometer is any device forced into the soil to measure resistance to vertical penetration (Davidson, 1965). Currently, two systems are used in the ACR (Army of the Czech Republic) for evaluating the trafficability of low-bearing terrain using two different penetrometers. Unfortunately, none of these systems meet the set needs – speed, accuracy, establishment.

Therefore, the following steps were taken:

- finding out the current state of the world's trafficability solutions,
- comparison of existing evaluation systems in the ACR,
- performing an analysis of the factors affecting the trafficability result in existing systems,
- the introduction of a new factor of the driver,
- the design of a new evaluation system for trafficability,
- field verification of the validity and reliability of the new system.

## 2. Literature review

Mobility is crucial for all ground vehicles, both manned and unmanned. The Army, particularly its engineers, aims to develop technology that accurately predicts the trafficability of each vehicle. This involves estimating soil strength to predict behavior, traction, motion resistance, and the sinkage of tires/tracks off-road. Critical data for these estimates are obtained from devices such as penetrometers and bevameters. Soil trafficability measures the soil strength needed to support the movement of military wheeled or tracked vehicles.

NATO uses the NATO Reference Mobility Model (NRMM) to predict vehicle mobility on off-road terrains. Developed in 1979 and upgraded in 1992, the NRMM is a widely used and precise model. Recent studies have reviewed the NRMM, and efforts are underway to update it to predict the trafficability of vehicles with advanced technologies (McCullough et al., 2017).

Article (Williams et al., 2019) reviews the development of the Vehicle Cone Index (VCI) and Mean Maximum Pressure (MMP) and their applications in evaluating vehicle mobility. Advances in terramechanics and modeling and simulation techniques have spurred interest in developing physics-based mobility metrics for next-generation vehicle mobility models (Jekl & Jánský, 2024).

The increase in the number and variety of tracked and wheeled vehicles has made off-road trafficability planning more complex. Accurate and reliable trafficability measurements are essential for successful operations. Peat and highly organic soils present significant challenges for vehicles. Article (Parker at al., 2021) details year-round mobility experiments with modern military vehicles on organic soils.

Remote sensing of geo-parameters is emerging as a future method for determining trafficability. Terrain similarity analysis has been used to find homogeneous soil patches, as discussed in articles (Pundir & Garg, 2021) and (Pundir & Garg, 2022). Advances in remote sensing technologies and digital ground surveys have improved result accuracy and enhanced the understanding of geo-spatial data utilization.

A study in (Liu et al., 2020) develops a simulation-based mission mobility reliability (MMR) analysis framework to address the uncertainty in predicting the mobility of off-road ground vehicles during mission planning. The concept of MMR is introduced to quantify the reliability of a mission path traversing various soil types. To manage the computational challenges of MMR assessment due to costly mobility simulations, a single-loop Kriging surrogate modeling method is employed.

Penetrometers are the most crucial devices for determining trafficability. A model for the interaction of a penetrometer's cone with terrain, considering both normal pressure and shear stress distributions on the cone-terrain interface, is discussed in (Huang et al., 2020). Another device for measuring trafficability is the bevameter, which is more complex and provides more accurate data. Experimental methods in (Mason et al., 2022) are used to convert cone index measurements to bevameter parameters, supporting vehicle soil/tire/track interactions for sand and lean clay. This conversion allows for the use of extensive existing cone index data to determine traction and motion resistance. Additionally, the dynamic cone penetrometer (DCP) (Lee et al., 2019) , which measures dynamic responses at the cone tip and applies energy conservation principles, suggests dynamic cone resistance as a new strength index as it increases with the depth of the instrumented DCP. Moreover, it provides a reliable subgrade strength profile.

Vegetation significantly impacts various soil strength parameters. The influence of vehicle operations on vegetation and vice versa, including their effect on vehicle performance and trafficability, is reviewed in (Wieder & Shoop, 2018). Vegetation types relate to mobility measures like maximum safe vehicle speed, tire slip, and fuel consumption.

In (Wasfy et al., 2018), the authors present a finite element vegetation model to predict the dynamic interaction of ground vehicles with vegetation. The model includes both vegetation and vehicles, accounting for the effects of normal contact and friction with the vehicle, interactions between stems, stem breaking, and aerodynamic forces on stems.

Article (Ewing et al., 2020) studies the use of Apparent Thermal Inertia (ATI) in conjunction with GeoGauge for directly testing soil stiffness. Another approach to improving off-road trafficability assessment is through autonomous vehicles. Paper (Goodin et al., 2020) discusses the factors affecting trafficability for autonomous off-road vehicles and presents an algorithm for real-time trafficability assessment. The predicted results are compared with ground-truth metrics, demonstrating how a trafficability metric can be automatically calculated using physics-based simulations with the MSU Autonomous Vehicle Simulator (MAVS).

For easy access to a database of parameters for assessing tracked and wheeled vehicles on various soils, the Database Records for Off-Road Vehicle Environments (DROVE) (Vahedifard et al., 2017), (Wiejak et al., 2023) was created. It contains over 8,000 field and laboratory tests, facilitating new studies. DROVE supports the unified equation of the characteristic curve for predicting the gross traction of a wheel over a range of powered, towed, and braked modes on clay soils (Mason et al., 2022).

Article (Calderon & Piedrahita, 2019) presents standard methods for identifying dynamic parameters of mechanical systems and introduces a new methodology for identifying inertial parameters in low mobility mechanical systems. The methodology involves formulating a symbolic model based on the transfer of inertial properties and a reduction using dynamic contribution indices based on CAD approximations. This new method, applied to the front suspension of an electric vehicle, results in a model with few parameters that accurately reproduce the system's dynamic behavior.

Another approach to predicting trafficability is through mobility maps, which consider various parameters (Mason et al., 2020), and vehicle type and characteristics. In Poland, detailed cartographic studies, including a soil-agricultural map at a scale of 1:25,000 (Borkovska & Pokonieczny, 2021) have been used to develop maps concerning soil trafficability. These maps are based on field measurements with specialized equipment such as an electronic cone penetrometer and consider the type of combat vehicle and the number of its passes in the analyzed area. Soil trafficability is classified into three classes: GO, SLOW-GO, and NO-GO TERRAIN. The analysis of these maps shows that trafficability conditions can significantly change with an increase in the number of vehicle passes. The study demonstrates the possibility of using existing soil databases and penetrometric measurements to develop trafficability maps that consider soil conditions, providing geospatial support for military operations and crisis management.

Vehicle mobility models also play a crucial role in predicting trafficability remotely. In (Wasfy et al., 2018), a high-performance computing (HPC) design-of-experiments (DOE) procedure integrates multibody dynamics for modeling vehicles and the discrete element method (DEM) for modeling soil into one solver.

Machine learning is another method for creating mobility maps. In (Mechergui & Jaykumar, 2020), supervised machine learning algorithms such as support vector machines (SVM), nearest neighbor classifiers (k-NN), decision trees, and boosting methods are used to create trained models.

Soil compaction is a significant concern not only in military operations but also in agriculture. The growth of plants (Moraes et al., 2014) and the ability of tractors to pass through fields (Prikner et al., 2017) depend on soil compaction. Effective soil compaction management can enhance agricultural productivity and ensure the mobility of agricultural machinery.

In their study (Alesso et al., 2018), researchers investigated the impact of three tillage depths—up to 10 cm, 10–20 cm, and 20–30 cm—on soil penetration resistance and its spatial distribution. Mapping this effect can provide valuable insights into both local and global soil responses to tillage practices, aiding in the targeted application of tillage techniques within fields.

Each pass of a tractor increases soil penetration resistance. Another study (Alesso et al., 2020) developed a model to analyze the spatial distribution of soil mechanical strength. Conducted on a Typical Argiudoll soil under four traffic intensities with the use of a 120 HP tractor, the study utilized a cone penetrometer and geostatistical methods to differentiate between wheeled and non-wheeled zones. The results indicated a quadratic relationship between cone index and depth across all treatments. However, due to significant variability in grid cell measurements, this parameter may not reliably guide future experimental designs.

In a separate investigation (Di Maria et al., 2021), researchers assessed rut formation and rolling resistance using cone penetration tests across firm, soft, and wet saturated soil. They found that varying wheel width and diameter impacted rut formation and rolling resistance differently depending on soil deformability. Larger diameters reduced rolling resistance, particularly in more deformable soils, while wider wheels reduced sinkage but influenced rolling resistance through soil volume deformation. The study also compared contact stress against literature-recommended thresholds to inform optimal running gear dimensions.

Furthermore, differences in mobility outputs exist even among vehicles of the same type, influenced by factors such as tire type, torque, and load. Variations in mobility are also evident between commercial and military tracked vehicles, as highlighted in a study (Malik et al., 2020). Most existing models neglect crucial factors like cooling fans, soft ground rolling resistance, and torque converters, thereby limiting their applicability for military vehicles. To address these issues, researchers developed a MATLAB/SIMULINK model specifically for a 65-ton Main Battle Tank (MBT), incorporating these factors. Their simulation demonstrated accuracy within 91–97% when compared against published data, underscoring the model's utility in predicting vehicle performance accurately.

While tracked chassis are generally considered superior to wheeled chassis, wheeled vehicles also exhibit varying performance characteristics. The type and condition of tires notably affect their trafficability. For instance, tire pressure directly influences wheel sinkage and overall trafficability. In (Oh et al., 2019), researchers investigated the impact of tire inflation pressure on real-time estimation of the rating cone index (RCI) of soil using wheel sinkage. They developed an equation to estimate RCI and conducted experiments to measure wheel sinkage, slip, and tire deflection at different inflation pressures. Results indicated that increasing tire inflation pressure led to higher wheel sinkage and slip, while decreasing tire deflection.

Statistical analysis of the data revealed significant changes in calculated RCI with varying tire inflation pressures. These findings provide insights into determining optimal tire inflation pressures for indirectly estimating RCI.

As tires age during service, their tread patterns wear down and stiffness decreases. In (Wong et al., 2020), researchers conducted a sensitivity analysis to evaluate the effects of tire aging and wear on stiffness characteristics, as well as longitudinal friction.

The capability of a vehicle to navigate through forested areas hinges on whether it can maneuver between tree trunks or surpass individual trees altogether. Overriding tree obstacles may prove more efficient if a vehicle can quickly traverse a number of tree trunks instead of maneuvering around each one. Vehicle movement within a forest stand is influenced by vegetation factors such as tree stem diameter, spacing, and root characteristics, which determine tree stability under mechanical stress, and a vehicle's ability to navigate around or over them. Additionally, technical specifications like width, length, turning radius, weight, and traction force of the chosen military vehicle are crucial in determining its off-road maneuverability. Author (Rybansky, 2020) discusses theoretical predictions of vehicle movement in forest stands and summarizes findings from extensive testing on vehicle ability to negotiate individual trees.

Research into the mechanical properties of snow are described in e.g. (Hasilová et al., 2023), (Shenvi et al., 2022). A significant challenge in assessing snow trafficability is measuring penetration resistance. In (Mahonen et al., 2021), a new portable bevameter designed for field measurement of snow properties is introduced. Initial test results are presented, demonstrating the bevameter's capability to measure snow properties essential for simulating interactions between snowmobiles and soft snow. While parameters extracted from the data were usable, improvements are needed to enhance measurement quality. One issue noted was noise caused by mechanical part interactions and the bevameter's low mass. Enhancements in usability could involve reducing cables, which are vulnerable in cold weather, and replacing the laser distance sensor with a string wire potentiometer (Sládek & Kolář, 2023).

Regions experiencing severe winters, with extensive snow cover, must assess snow trafficability effectively. Article (Zhukov et al., 2020) discusses the necessity of developing mobility maps as an evolution of Professor Belyakov's mobility theory. The analysis underscores the relevance of creating "snow mobility maps" for Russia, detailing the methodology's stages. These include terrain analysis to determine movement zones, assessing object mobility parameters, and integrating vehicle mobility calculations into geographic information systems.

## 3. Research methods

Trafficability is affected by many factors, some of which can be seen in Fig. 1. According to Fig. 1, the distribution of factors affecting trafficability is divided into four groups. The first factor is climatic conditions, when, for example, there are frequent periods of rain in the spring and autumn months, and in winter the terrain is covered with a layer of snow, which significantly affects the trafficability. The second factor is soil properties. The dependence of trafficability on the grain size of the fraction is known both from laboratory and field measurements (United States Army, 1994). Another factor is the terrain itself, which with regard to vegetation, obstacles, and slopes becomes more difficult to overcome. The last factor is the vehicle itself. Both passenger cars and trucks are designed with regard to the intended function of use. Trucks that work in difficult terrains, unlike those that use only paved roads to move, have a larger number of axles, two-wheel mounting with deep-tread tires.

Based on the information obtained from the literature review, the authors decided to propose a new assessment method for the evaluation of the trafficability in the low endurable terrain. At first, they focused on the case of one pass and on wheeled vehicles. If the correctness of the newly proposed method is confirmed, this method will be further extended to tracked vehicles and more passes.

The following steps had to be taken in order to propose a new method:

1. Carry out a comparison of the used methods of evaluating terrain trafficability and find out whether the values of the measured resistance of the soil against the penetration of thorns from the selected penetrometers are interdependent–comparable → then an evaluation system of one can be applied on the other. (Section 4, 5).
2. Analyze the factors affecting trafficability and decide which parameters are necessary for our evaluation method. (Section 6).
3. Determine whether there are any other factors that affect trafficability that are not described or included anywhere. (Section 7).
4. Propose a new method of evaluating trafficability for the PT-45 telescopic penetrometer. (Section 8).

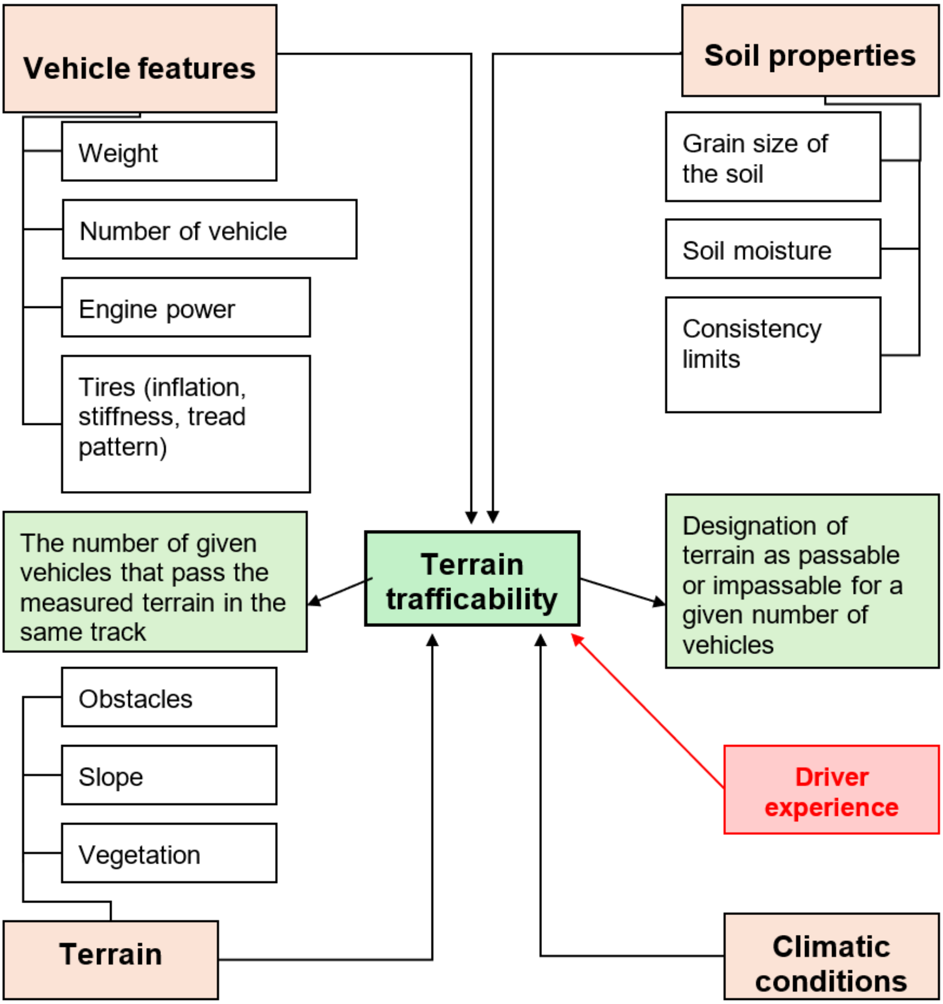


Fig. 1. Factors affecting terrain trafficability

## 4. Systems of determining trafficability

In the case of a low-bearing terrain, it is necessary to find out whether the vehicles in question will be able to pass through the terrain or get stuck. In order to determine how many and which vehicles will pass through a given terrain, two values need to be compared – the value of the land and the value of the vehicle.

As mentioned above, the Czech Army currently uses two methods for the evaluation of trafficability from two different sources. The first and main source is the Czech Field Manual for Engineers ŽEN 2-16 (Ministry of Defence, 1987) (Žen from the Czech word "ženista", which means Engineer). The second source is the Field Manual of US Army FM 5-430-00-1 (United States Army, 1994), used by several NATO countries. Both methods of evaluation of low endurable terrain described in these manuals are described below.

### 4.1. Field manual ŽEN 2-16 military roads and ways

Based on this manual, the trafficability of the terrain can be determined in four ways. Firstly, it can be estimated visually, by some objectively occurring signs – green grass etc. Second system uses a human footprint to measure. The third system use the engineer's crowbar. It is only for a rough assessment of ground penetration according to the depth of the crowbar's penetration when falling from a height of 0.5 m. These three systems are very inaccurate and unreliable.

The last system measures with a device – telescopic penetrometer PT-45 (Fig. 2). PT-45 is an instrument designed for measuring the bearing capacity of terrain obtained by penetrating the thorn that is pressed against the head of the penetrometer (the top cap of the device) to the soil. The scale takes readings indicated by the position of the drift ring. When it is returned to the initial zero position, the pressure in MPa is read and then with an evaluation form, the bearing capacity of the terrain is determined, which is the "value of the land" that we need to compare with the "value of the vehicle". Within this system, we assess only one property of the vehicle, and that is its weight. There are three categories (up to 4.5 tons, 4.5 – 9 tons, and over 9 tons). By comparing the "value of the land" and the "value of the vehicle" according to the prescribed procedures/evaluation forms, we will found out many cars of three different weight categories can pass the given terrain.

PT-45 is a tenacious device and measuring with it is fast and simple. Additionally, it is sufficiently reliable. What is a significant problem, however, is the evaluation system, respectively the evaluation of the "value of the vehicle". As described above, only one property is considered and it has very broad parameters. It has been proven that the trafficability depends mainly on the weight (Jaykumar & Wasfy, 2021), (Jaykumar & Wasfy, 2021), and if it changes by even 100 kg it can cause the vehicle to get stuck in a place where it passed without problems before (Cibulova, Priesner, 2022). Therefore, the division of vehicles into three categories, with a difference of several tonnes between them, is unsatisfactory.

### 4.2. Field manual 5-430-00-1 planning and design of roads, airfields, and heliports in the theater of operations – road design

According to the Field manual, the terrain trafficability is evaluated by comparing two indexes. The RCI (rating cone index – index of soil) and the VCI (vehicle cone index). Based on the comparison, the terrain is then evaluated as passable or impassable for the given vehicle and number of passes.
RCI < VCI → impassable terrain
RCI > VCI → passable terrain
The RCI is determined by a cone penetrometer (Fig. 3), and it is operated in the same way as the PT-45. A penetrating thorn is pressed against the head of the penetrometer until it reaches the required depth and then the value is read from an analogue display. The detailed measurement procedure is then described in (United States Army, 1994).

The VCI is tabulated for some conventional vehicles, but it could be calculated for every vehicle with different weight. To obtain the VCI, we must calculate the mobility index (MI). This index considers different vehicle features, as it is shown in the following formula from the FM (United States Army, 1994):

$$\mathrm{MI} = \left[\frac{\mathrm{CPF}\times\mathrm{WGTF}}{\mathrm{TF}\times\mathrm{GF}} + \mathrm{WF} - \mathrm{CF}\right] \times \mathrm{EF} \times \mathrm{TMF} \tag{1}$$

where
CPF – contact pressure factor (lb/inch$^2$)
WGTF – weight factor (kp)
TF – tire factor (inch)
GF – grouser factor (without unit)
WF – wheel load factor (kp)
CF– clearance factor (inch)
EF – engine factor (kW/ton)
TMF – transmission factor (without unit)
If the vehicle is all-wheel drive, the VCI is read from the graph (by MI) or by the formulas (2) and (3) given in the manual (United States Army, 1994):

$$\mathrm{VCI} = 11.48 + 0.2 \times \mathrm{MI} - \left(\frac{39.2}{\mathrm{MI}+3.74}\right) \tag{2}$$

Fig. 2. Telescopic penetrometer PT-45

Fig. 3. Cone penetrometer

If the vehicle is not all-wheel drive, the calculation of the mobility index remains the same and the formula for VCI is:

$$\mathrm{VCI} = 1.4 \times \mathrm{MI} \quad (3)$$

The results obtained with the cone penetrometer are considered to be very accurate, however they are very time-consuming to determine. The large kit is prone to loss of smaller parts. Furthermore, the instruments often suffer from careless handling and irreversible damage.

### 4.3. The comparison of both systems

As previously written, there are two systems used for the evaluation of low endurable terrain. One is described in the Field Manual ŽEN 2-16 and the second in the Field Manual FM 5-430-00-1. The advantages and disadvantages are summarised in Table 1.

Both methods designed for evaluating the passability of wheeled vehicles on terrain always compare the “value of the land” and the “value of the vehicle”. Based on the advantages and disadvantages of both evaluation methods, the authors decided to find out whether it would be possible to combine the advantages of both methods and propose a new evaluation system for the telescopic penetrometer, based on the evaluation system for the cone penetrometer. For this to be possible, it is necessary to find out whether the values measured by the devices are comparable.

Table 1. Comparison of advantages and disadvantages of evaluation methods

| Method | PROS | CONS |
|---|---|---|
| ŽEN 2-16 | Suitable device (quick and easy measurement, compact, light). It is established in the ACR-availability. | Unreliable evaluation system (considers only 3 vehicle weight categories and no other vehicle properties). |
| FM 5-430-00-1 | Unsuitable device (slow and complex measurement, prone to breakage – fragile, the entire measurement set is large and heavy). | Reliable evaluation system (considers several vehicle parameters, corresponds to the actual number of vehicles that passed during the measurement. |

## 5. Comparison of values measured by the penetrometers

The dependence between the values read from the telescopic and cone penetrometer was searched for when measuring the resistance of the soil against the penetration of their spikes into predetermined depths of the soil. The measurements were carried out over several years, under different climatic conditions and in different areas, in order to capture all possible cases (different types of soil, different humidity, etc.).

It is assumed that this dependence is linear. To find the considered relationship, a linear regression model is used, which in our case will be a regression line in the form $L(x) = \beta_1 + \beta_2 x$. Since a telescopic penetrometer is mainly used to measure soil bearing capacity in the ACR, the regression model considers a functional dependence between the independent (explanatory) variable $x$ (values obtained on the telescopic penetrometer) and the dependent (explained) variable $y$ (values obtained on the cone penetrometer) in the form of $y = \varphi(x)$, where the linear function $\varphi(x)$is unknown.

However, due to various random influences, we do not get the value of $y_i$ according to the relation $y = \varphi(x)$ at the set value $x_i$, but a different value in general. Our task was to estimate the parameters of this function based on the measurements made, so that the replacement was, in a certain sense, the best. The method of least squares was used to determine the estimates of the parameters $\beta_1$ and $\beta_2$ of the regression line. The Maple program with the Statistics package was used to process the measured data.

When searching for the coefficients, it was assumed that there are no systematic errors in the measurement of the quantity y and that the variances of the measurement errors are independent of the individual values of $x_i$.

Values in the range of 0 to 4.5 on the scale were repeatedly measured on the telescopic penetrometer, and values of 15 to 240 on the scale corresponded to these values on the cone penetrometer. A total of 563 values were measured.

The result of the regression model could be influenced by outlying (influential) measurement points. Fig. 4 shows the entire correlation field, from which it can be seen that there are no outliers in it. From the data distribution in the figure, it is clear that our original assumption was confirmed, namely that there is a linear relationship between the penetrometers. This functional dependence is expressed in the following form:

$$L(x) = 21.49 + 44.96\, x. \tag{4}$$

Subsequently, it was necessary to verify whether the chosen regression model is suitable. First, we focused on the calculated coefficients $\beta_1$ and $\beta_2$ in the regression line. A null hypothesis, which was the same for both coefficients, was established as to whether a given coefficient is significant in the model or can be dropped from the model.

The null hypothesis $H_0\colon B_i = 0, i = 1,2$ was tested (in this case, the coefficient in the model is insignificant) against the alternative hypothesis $H_1\colon B_i \neq 0, i = 1,2$. In Table 2 the results of partial $t$-tests on the significance of regression coefficients $\beta_1 = 21.49$ and $\beta_2 = 44.96$ are shown. Given that the $p$-value was equal to 0 at the significance level of $\alpha = 0.05$ for both coefficients, the null hypothesis was rejected in favor of the alternative one, and therefore the coefficients cannot be removed from the model.

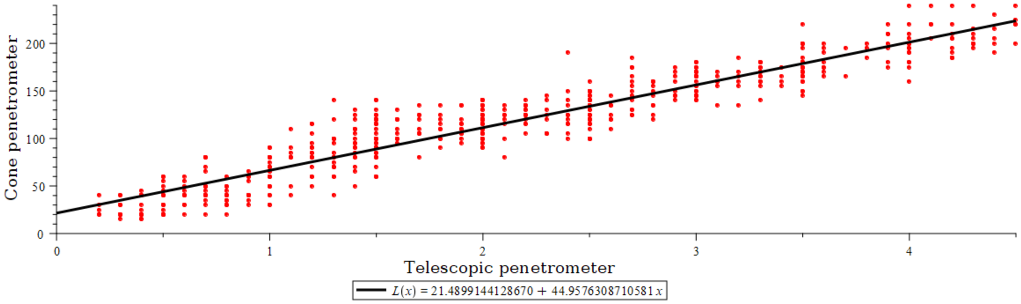


Fig. 4. Dependence between penetrometers

For both coefficients, their 95% confidence intervals were also determined. For coefficient $\beta_1$ the interval was $(18.41;\ 24.57)$, for coefficient $\beta_2$ the interval was $(43.67;\ 46.25)$.

The suitability of the used model is indicated by the coefficient of determination $R^2 = 1 - \frac{SS_e}{SS_Y}$, where $SS_e$ is the sum of squared errors (residuals) and $SS_Y$ is the sum of squared deviations of the dependent variable $y$ from its mean value $\bar{y}$. The coefficient of determination can take on a maximum value of 1, which means a perfect prediction of the values of the dependent variable. On the contrary, a value of 0 means that the model does not provide any information for the knowledge of the dependent variable, it is completely useless. In our case, the value of the determination index was 0.89, which indicates a relatively suitable choice of model. Homoscedasticity was proved.

It is clear from the measurement principle that if we measure a new value of $x_*$ on a telescopic penetrometer, we will not get the exact value of $y_*$ on a cone penetrometer using the calculated regression line (4). For the value of the explained variable $y$, i.e. the value we would like to obtain on the cone penetrometer based on the measurements on the telescopic penetrometer, we will also determine the confidence interval.

The limits of this interval are (-13.34; 56.32) for $x_* = 0$ and (188.94; 258.66) for $x_* = 4.5$. The confidence band (see Fig. 5) is narrowest at the point $x = \frac{1}{n}\sum_{i=1}^{n} x_i$, it widens towards the edges, its graph is a hyperbola. It is evident that the interval is relatively wide. For better results, it would be advisable to carry out additional measurements, based on which the shape of the regression line could be corrected.

## 6. Analysis of vehicle parameters influencing trafficability

If we want to use the evaluation system, we need to check which individual vehicle parameters are used to obtain the VCI vehicle index, or mobility index MI (see section 4.2). This will be followed by an analysis of the individual input parameters in order to find out what effect they have on trafficability and if they are necessary for its assessment.

Now we will work with the formula for MI for wheeled vehicles (1), where the individual factors are calculated as follows according to (United States Army, 1994):

**Contact pressure factor (CPF)**:

lb/inch$^2$) $$\mathrm{CPF} = \frac{2\times \mathrm{WGT}}{\mathrm{TW}\times\left(\frac{\mathrm{TOD}}{2}\right)\times \mathrm{WN}}, \qquad (5)$$

where

WGT – total weight (lb)
TW – tyre width (inch)
TOD – tire outside diameter (inch)
WN – wheel number (without unit)

Table 2. Results of partial $t$-tests on the significance of regression coefficients $\beta_1$ and $\beta_2$

| **Coefficients** | **Estimate** | **Standard Error** | **$t$-value** | **P(> \|$t$\|)** |
|---|---|---|---|---|
| $\beta_1$ | 21.49 | 1.57029 | 13.6853 | 0 |
| $\beta_2$ | 44.96 | 0.655427 | 68.5929 | 0 |

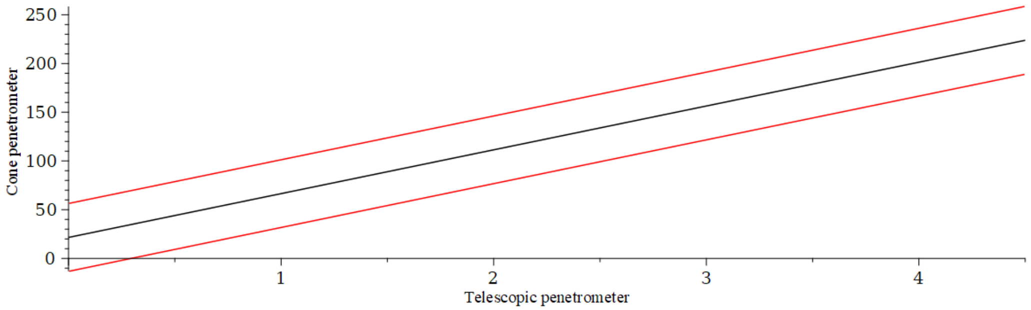


Fig. 5. Confidence interval for the value of the explanatory variable

**Weight factor (WGTF)** (kp)
To calculate the factor WGTF, we need to know the distribution of vehicles by weight range – see Table 3.

**Tire factor (TF)** (inch):

$$\mathrm{TF} = \frac{10+\mathrm{TW}}{100}, \tag{6}$$

**Grouser factor (GF)** (without unit):

- with chains: GF = 1.05
- without chains: GF = 1.00

**Wheel load factor (WF)**:

$$\text{(kp)}\ \ \mathrm{WF} = \frac{\mathrm{WGT}}{\mathrm{WN}}, \tag{7}$$

**Clearance factor (CF)** (inch):

$$\mathrm{CF} = \frac{\mathrm{CL}}{10}, \tag{8}$$

$\mathrm{CF} = \frac{\mathrm{CL}}{10}$; where CL – clearance (inch):
**Engine factor (EF)**: (kW/ton)

- horsepower / weight of vehicle in tons ≥ 10: EF = 1.00
- horsepower / weight of vehicle in tons < 10: EF = 1.05

**Transmission factor (TMF)**: (without unit)

- hydraulic transmission: TMF = 1.00
- mechanical transmission: TMF = 1.05

Now follows the analysis of the individual input parameters to find out what effect they have on the trafficability and whether they are necessary for its assessment or are insignificant. Math software Maple was used to investigate the dependencies of each parameter. The parameter dependencies were also graphically depicted for better visualization.

## 6.1. Vehicle weight

Weight is generally considered as the main criterion that fundamentally influences the trafficability of a given vehicle. This parameter is present in all evaluation systems and is considered the most. As already mentioned, vehicles are divided into three weight categories when determining trafficability with PT-45, but this is the first step towards inaccuracy due to the large variety of different vehicles. The FM method reflects the instantaneous weight of the vehicle and even a small change in the weight parameter will have a very significant effect on the result.

**Result:** The authors found out (Cibulová & Priesner, 2022) that, on average, a 1% change in the input weight value results in a 1.5% change in the final result. Due to this fact (Fig. 5b), it is essential that the weight factor of the vehicle remains in the formula.

## 6.2. Tire characteristic

Wheels are the main surfaces on which a vehicle comes in contact with the terrain. There is a considerable emphasis on the tires themselves and there are countless types of them. They differ in material, stiffness, tread depth, tread pattern, width, and diameter. Each tire has its own use, speed tires have no tread and off-road ones go over a few centimetres deep.

It is therefore clear that if the same vehicle is fitted with different tires, the ability to cross unpaved roads will vary considerably. However, even with the same tires, different results can be achieved. More experienced drivers often improve handling of the vehicle by decompressing the wheels. If the tire pressure is reduced, the contact patch is subsequently increased and therefore trafficability is increased. What is not considered, however, is the fact that this step reduces the diameter of the wheel, which in practice means a reduction in clearance. The question is whether reducing pressure is therefore advantageous. According to the calculations and simulations in the software Maple, the improvement in trafficability has been confirmed (Fig. 6a and Fig. 6b).

Table 3. Table for calculating the weight factor WGTF

| **Weight range *** | **WGTF** |
|---|---|
| $<\ 2\,000$ | $\mathrm{WGTF} = 0.553\,x$ |
| 2 000 – 13 500 | $\mathrm{WGTF} = 0.033\,x + 1.050$ |
| 13 501 – 20 000 | $\mathrm{WGTF} = 0.142\,x - 0.420$ |
| $>\ 20\,000$ | $\mathrm{WGTF} = 0.278\,x - 3.115$ |
| *Weight range $= \frac{\mathrm{WTG}}{\mathrm{AN}}$ (lb) | $x = \frac{\mathrm{WTG}}{\mathrm{AN}}$ (kp) |

where: AN – number of axles.

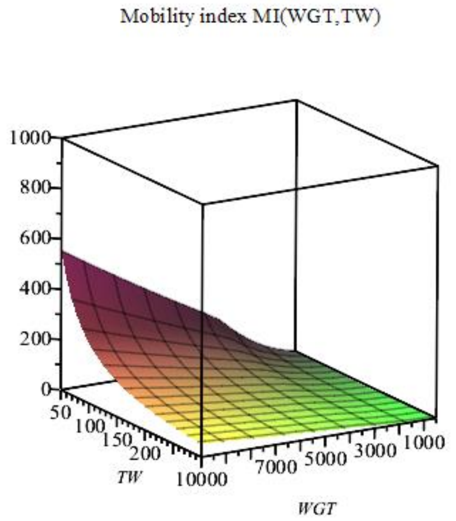


Fig. 5a. Change of the MI depending on WGT

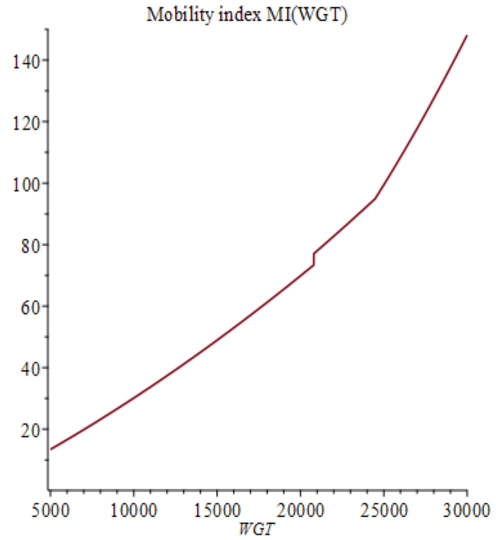


Fig. 5b. Change of the MI depending on WGT and TW

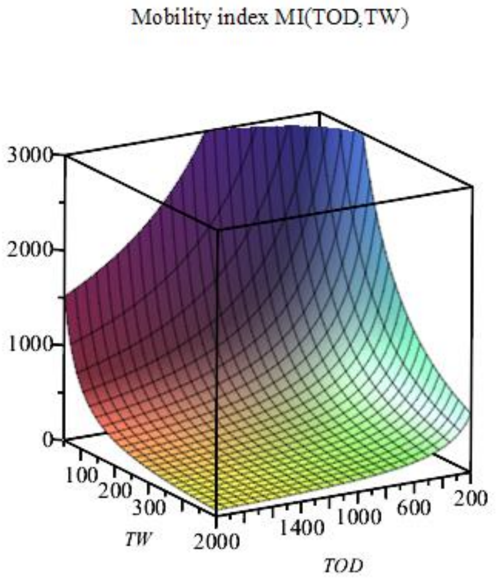


Fig. 6a. Change of the MI depending on TOD and TW

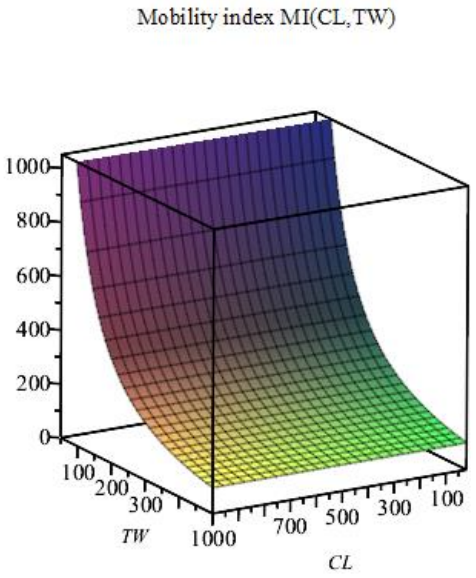


Fig. 6b.Change of the MI depending on CL and TW

**Result:** The tire characteristic is therefore an important factor and needs to be considered when determining trafficability. This is the factor that is missing when evaluating with the PT-45.

### 6.3. Wheels and axles

The number of wheels as well as the number of axles are other important factors. Together with the weight of the whole vehicle, they contribute significantly to the vehicle's ability to overcome terrain. With an increase in the number of wheels and axles, the weight is distributed over a larger area; of course, this is not a proportional distribution – that would depend on the vehicle design. The type of wheel chassis is therefore another important parameter that needs to be retained in the mobility index calculation. (Fig. 7a. and 7b.)

Hand in hand with the chassis goes the vehicle drive. It is important to know whether it is a single-axle drive or all-wheel drive. If the vehicle is all-wheel drive, it is capable of overcoming much more difficult bumps. Therefore, FM again serves as a suitable template for the creation of a new evaluation form that will include the all-wheel drive factor.

**Result:** It was proved that the number of wheels and axles is an important factor for determination of the mobility index. As the number of axles and wheels increases, the ability of the vehicle to overcome the terrain increases in direct proportion, and it is therefore necessary to include them in the calculation, just as much as whether the vehicle is all-drive or is not.

### 6.4. Snow chains

Another factor is the use of snow chains. Wheels equipped with snow chains have much better terrain characteristics and therefore increase the mobility index of the vehicle. Because they prevent the wheels from slipping, engine power is transferred to wheels much more effectively. Although chains are mandatory equipment on most cars, they are not regularly used, mainly because of the complexity of installation.

**Result**: The factor of snow chains should remain in the calculation, because it is not negligible and can ultimately have a considerable impact.

### 6.5. Vehicle clearance

Clearance is a factor that appears to affect trafficability. However, when carefully examining the effect of ground clearance in the formula, we come to a surprising conclusion.

**Result**: As can be seen in Fig. 8a and Fig. 8b, based on the calculation, even a notable change in clearance does not significantly affect the mobility index. For this reason, clearance factor was recommended to be excluded from the calculation of mobility index.

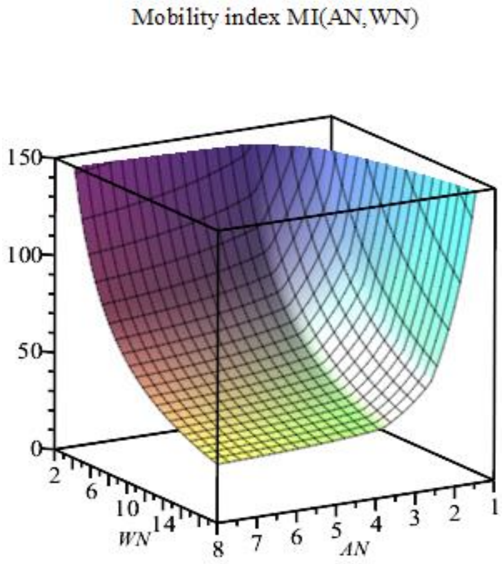


Fig. 7a. Change of the MI depending on AN and WN

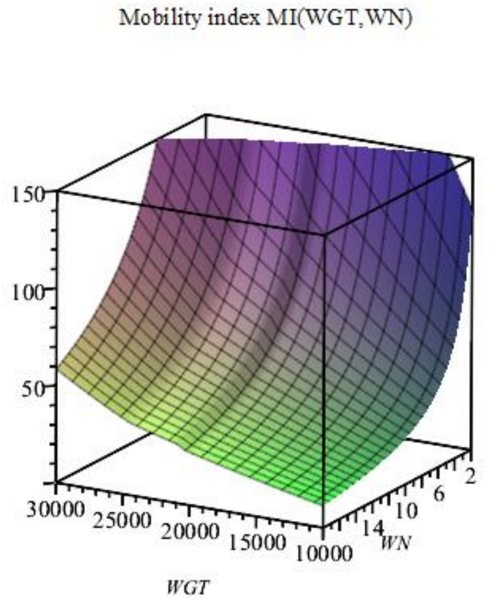


Fig. 7b. Change of the MI depending on WTG and WN

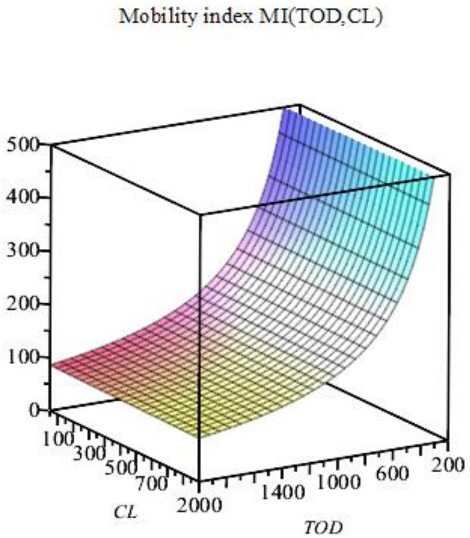


Fig. 8a. Change of the MI depending on TOD and CL

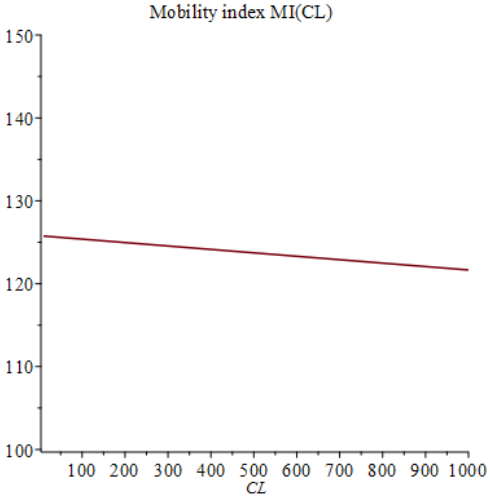


Fig. 8b. Change of the MI depending on CL

### 6.6. Engine performance

The engine's capabilities, and therefore its performance, continue to grow. However, off-road driving necessarily doesn't need a powerful engine and can be detrimental to driving. If the driver is unable to handle the power of the engine, the wheels may spin and thus lose traction, stopping the vehicle from moving and possibly getting stuck. The field manual compares engine power to weight and then distinguishes between two values of 1.00 or 1.05 at lower power.

**Result:** Due to given reasons, the engine factor is not an essential factor, and it is therefore not necessary to include it in the mobility calculation (Fig. 9).

### 6.7. Transmission

According to FM, the type of gearbox is also evaluated in terms of vehicle trafficability. A hydraulic transmission can improve the mobility index due to smoother transmission between gears (Fig. 10).

**Result:** The resulting difference between the mechanical and hydraulic transmission is not significant and since the given gearbox type may not always be known to soldiers, it is recommended to disregard the transmission factor.

## 7. Proposal of a new parameter: driver factor

The last task is to evaluate whether there are any other factors that affect driving and are not included in the given formula (1).

Based on the experience of measurements carried out over 8 years, starting in 2014 (Cibulová & Priesner, 2022), (Cibulová et a., 2020), the authors observed the influence of the driver on the passage of the terrain. This has not yet been described or qualified anywhere, although it is evident that the driver's experience and skills do have an influence on overcoming the terrain. Therefore, it was further studied (by field measurements) whether the driver's experience really has an effect on trafficability and to what extent (Kozlowski et al., 2023), (Kurfiřt, 2014), (Wright et al., 2019).

Subsequently, the question was asked whether the existing systems were missing any important parameter. Scientific research in terms of trafficability focuses mainly on vehicle or subgrade characteristics. Countless studies on the effect of waterlogged or organic terrain have been conducted (Parker et a., 2021), (Pundir & Garg, 2021), (Pundir & Garg, 2022), as well as research that has looked at the effect of tires or the difference between civilian and military vehicles (Oh et al., 2019), (Wong et al., 2020). However, no study has examined the skills of the driver of the vehicle. However, due to their experience and previous research on the Department of Engineer Technology at University of Defence, the authors identified this parameter as important. This led to the driver parameter, which was then investigated in detail and numerically supported.

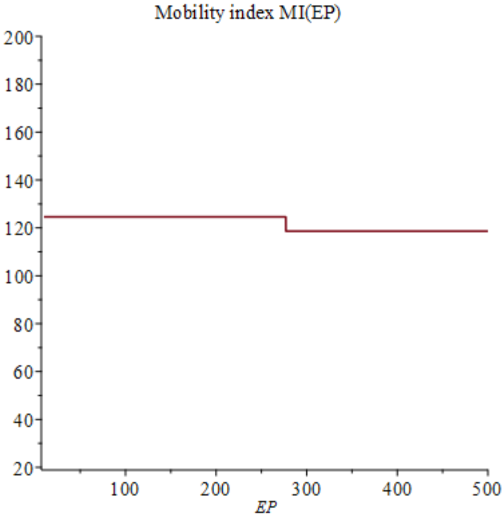


Fig. 9. Change of the MI depending on EP

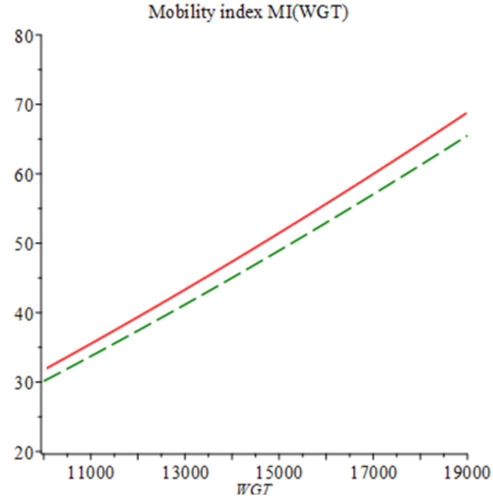


Fig. 10. The effect of manual (red) and hydraulic (green) transmission on the MI

### 7.1. Proposal of driver categories

In the first step, it was necessary to determine the different categories of drivers. It seemed appropriate to divide them into three groups according to their experience. This proposal would also correspond to the same classification as in the structure of the Army of the Czech Republic (which would facilitate introduction into the army where the system would be used). The proposed categories are:

| | |
|---|---|
| Group 1 (L) | Low experienced drivers. |
| Group 2 (M) | Middle experienced drivers. |
| Group 3 (H) | High experienced drivers. |

The measurements of the driver factor took place over a period of two years, in different places, under different climatic conditions, and with different drivers, divided according to the categories mentioned above. In each measurement, the drivers performed the same task independently, at their own responsibility. The aim was to evaluate and confirm that driver experience and intuition can influence vehicle's trafficability. Widespread vehicles of the Czech Armed Forces were used for testing: the UAZ 469 as a passenger off-road vehicle, which has excellent trafficability (good VCI), and the heavy vehicle Tatra T-815 which undoubtedly the most frequently used truck and it is known for its driving characteristics and its ability to overcome almost any terrain (also good VCI). The measurement results are summarized in Table 4.

There were three areas:

Area 1 – wet area with 3 water surfaces. When the driver did not pass any 0%, when he passed all three 100%. Area 2 – obstacle area with 3 waves, the same rating as in the first area.

Area 3 – slope. The distance how far the vehicle pass was calculated, or rather it was measured how many meters from the top the vehicle stopped. In the case of Tatra in the slope, it was not evaluated, there was not a sufficient obstacle, there is no problem for the Tatra to overcome it.

**Result:** The data obtained from the field experimental measurements confirm that under the same conditions (soil and vehicle) different driving results were achieved, and these depended on the experience and skills of the drivers. Based on the above-mentioned results (Table 3), the authors propose to keep the suggested distribution of driver categories – it is considered to be appropriate.

Table 4. Evaluation of the proposed distribution of drivers in percentages

| | UAZ wet area | UAZ obstacles | UAZ slopes | Tatra wet area | Tatra obstacles | Tatra slopes | % |
|---|---|---|---|---|---|---|---|
| **Group 1** | 0.00 | 0.00 | 36.00 | 33.00 | 66.00 | N | 27.00 |
| **Group 2** | 33.00 | 33.00 | 44.00 | 66.00 | 100.00 | N | 55.20 |
| **Group 3** | 66.00 | 100.00 | 61.00 | 100.00 | 100.00 | N | 85.40 |

## 7.2. Proposal of the Driver Experience Factor

It is necessary to propose a corresponding value of the factor for each group – category of drivers. For this reason, further field measurements were carried out. These measurements were conducted in a similar way as the previous ones. Data were taken during all seasons, but the main emphasis was on the spring and autumn months when the soil is most saturated with water and therefore least passable. Additionally, a larger variety of vehicles was used.

The measurement was carried out as follows: the values of the vehicle and the values of the soil were determined according to the FM method. Soil values were always measured on site and at a given moment. The vehicle values were calculated according to (1), (2) and (3) and are listed in Table 5.

To determine the soil index, it was necessary to find enough wide terrain which has several lines with the same conditions for different drivers. The selected areas were divided into three or more lanes, which were marked out with wooden poles at certain distances. Subsequently, the track was measured with a cone penetrometer. If there were no significant differences on the lines, the vehicles started to try to overcome the given route. When the vehicle got stuck and was not able to move, the distance of the route was measured.

Table 6 shows the results from one measurement as an example. It is possible to read the values of VCI and RCI and from them the assumption calculated whether the vehicle would pass or not. In the next column is the actual status of whether the vehicle passed. The last column contains the evaluation. This means that although the input conditions (vehicle VCI, soil RCI) were the same, different drivers were able or unable to overcome the given route. What influenced the length of the route, therefore, were the driver's skills.

**Result:** Based on the data collected over two years, it was possible to determine the coefficients of all three categories of drivers. Drivers from the middle-experienced category achieved results consistent with the predicted vehicle trafficability according to the vehicle index calculation, with minor variations. The drivers from the high-experienced category managed to regularly overcome the terrain, which was about 10 % less bearable than the vehicle should be able to overcome according to the field manual. The low-experienced drivers had the worst results and in most cases the limit set by the field manual was beyond their ability. The difference from the calculation was also about 10%.

Due to the measurement results, the values of the driver experience factor were proposed as follows Table 7.

However, it is necessary to add that the proposed system will be primarily used in the army and the classification of drivers corresponds to the classification of drivers according to their rank. Nevertheless, determining the value of the driver factor will always depend on the evaluator, who knows how experienced the driver is and who will evaluate the trafficability himself.

Table 5. MI and VCI of tested vehicles

| Vehicle | Mobility index (MI) | Vehicle cone index (VCI) |
|---|---|---|
| UAZ 469 | 76.68 | 26.33 |
| Land Rover 110 | 114.52 | 34.05 |
| Toyota Hilux | 73.94 | 25.76 |
| T-810 6x6 | 15 856 | 42.95 |
| T-815 8x8 VT | 86.45 | 28.33 |
| T-815 8x8 VVN | 105.27 | 32.17 |
| T-815 6x6 S3 | 141.87 | 39.58 |
| T-815 6x6 VVN | 123.16 | 35.80 |

Table 6. An example of the results of one measurement – comparison of the VCI and RCI indexes and the actual state of driving through the terrain for different drivers

| **Vehicle** | **VCI** | **Measured RCI** | **Driver Experience** | **Calculated Trafficability** | **Real Trafficability** | **Result *** |
|---|---|---|---|---|---|---|
| T-815 8x8 VVN | 32.17 | 35 | Low | pass | fail | ↓ |
| | | 31 | Middle | fail | fail | ok |
| | | 31 | High | fail | pass | ↑ |
| T-815 8x8 VT | 28.33 | 29 | Low | pass | pass | ok |
| | | 27 | Middle | fail | fail | ok |
| | | 27 | High | fail | pass | ↑ |
| UAZ 469 | 26.33 | 27 | Low | pass | fail | ↓ |
| | | 25 | Middle | fail | fail | ok |
| | | 22 | High | fail | pass | ↑ |
| T-815 6x6 VVN | 35.80 | 36 | Low | pass | pass | ok |
| | | 28 | Middle | fail | fail | ok |
| | | 28 | High | fail | fail | ok |
| T-810 6x6 VVN | 42.95 | 44 | Low | pass | pass | ok |
| | | 40 | Middle | fail | fail | ok |
| | | 38 | High | fail | pass | ↑ |
| Toyota Hilux | 25.76 | 28 | Low | pass | fail | ↓ |
| | | 28 | Middle | pass | pass | ok |
| | | 26 | High | pass | pass | ok |

* Symbol “ok” means that the driver actually drove as calculated.
Symbol ↑ means that the driver drove better than was calculated.
Symbol ↓ means that the did not complete the route according to the original calculation.

Table 7. Proposed driver experience factor (FZR) values

| **Driver** | **FZR** |
|---|---|
| Low experienced | 1.1 |
| Middle experienced | 1.0 |
| High experienced | 0.9 |

## 8. Proposal of a new evaluation method for telescopic penetrometer

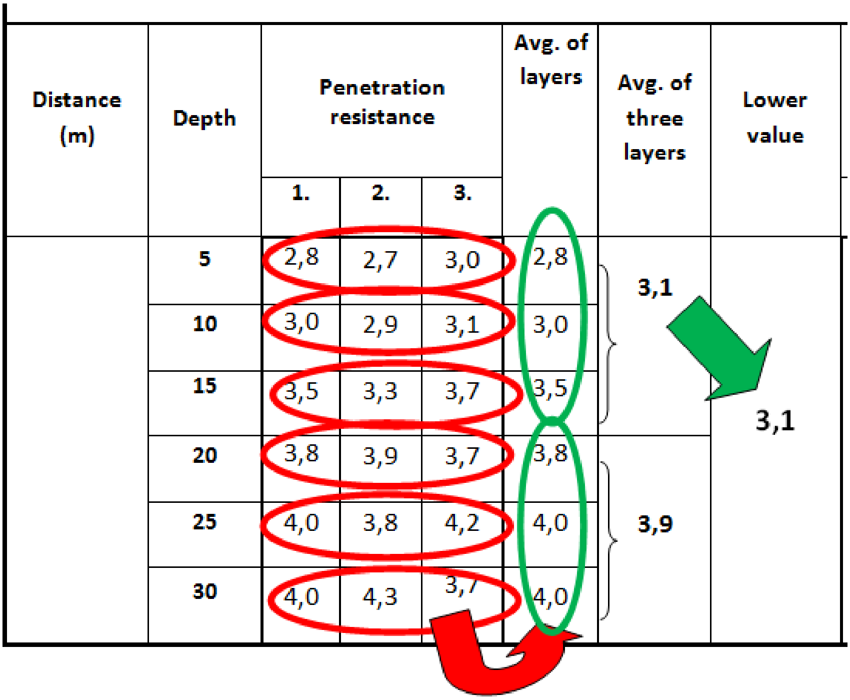
Based on the conclusion in chapter 4.3, it was decided to combine the advantages and disadvantages of both methods and to propose a new evaluation system for the existing telescopic penetrometer used in the Czech Army. The proposal for a new method of evaluating low-bearing terrain using a PT-45 telescopic penetrometer is described below. The entire evaluation process remains on the same principle – comparing the value of the land with the value of the vehicle. The soil index $I_P$ is obtained by penetrometric measurement, and the vehicle index $I_V$ is calculated according to the newly proposed procedure. The symbols for the factors are based on their names in the Czech language, where they will be primarily used, and because they are calculated in different units. There is also the advantage that there will be confused with the existing system for the cone penetrometer.

If the value of the soil index $I_P$ is less than the vehicle index $I_V$ , then the terrain is passable and vice versa:

$I_P < I_V$ → impassable terrain
$I_P > I_V$ → passable terrain

### 8.1. Determination of the soil index

The handling of PT-45 and the determination of the soil resistance remains according to the principle mentioned in the Field Manul ŽEN 2-16. Three measurements will be taken per quarter metre, each to six depths ranging from 5 cm to 30 cm. The values of each layer are averaged, then the first three layers and the remaining layers are averaged. Further, a lower value is calculated – see Fig. 11.



| Distance (m) | Depth | Penetration resistance | | | Avg. of layers | Avg. of three layers | Lower value |
|---|---|---|---|---|---|---|---|
| | | 1. | 2. | 3. | | | |
| | 5 | 2,8 | 2,7 | 3,0 | 2,8 | 3,1 | 3,1 |
| | 10 | 3,0 | 2,9 | 3,1 | 3,0 | | |
| | 15 | 3,5 | 3,3 | 3,7 | 3,5 | | |
| | 20 | 3,8 | 3,9 | 3,7 | 3,8 | 3,9 | |
| | 25 | 4,0 | 3,8 | 4,2 | 4,0 | | |
| | 30 | 4,0 | 4,3 | 3,7 | 4,0 | | |

Fig. 11. Trafficability protocol

The formula (4) is used in order to obtain the necessary $I_P$ soil index,

$$I_P = 44.96 \times O_N + 21.49 \ , \tag{9}$$

where: $O_N$ – lower value of penetration resistance from three layers.

It must be remembered that the obtained trafficability results are, due to climatic conditions, valid only at the time the measurements were made and for a very short time afterwards

## 8.2. Determination of the vehicle index

For all-wheel drive vehicles, the vehicle index (Iv) is calculated according to the formula (2).

$$I_V = 11.48 + 0.2 \times I_M - \left(\frac{39.2}{I_M + 3.74}\right), \tag{10}$$

If the vehicles are not all-wheel drive, the calculation is due to the formula (3).

$$I_V = 1.4 \times I_M, \tag{11}$$

where

$$I_M = \left[\frac{FT \times FV}{FP \times FR} + FZK\right] \times FZR, \tag{12}$$

where FT is a pressure factor and FV weight factor. (It has to be mentioned that the abbreviation were chosen with respect to the Czech language, as the main user of the results will be Czech army.)

**Pressure factor (FT)** (kg/mm$^2$):

$$FT = \frac{2\,845 \times CVV}{SP \times PP \times PK}, \tag{13}$$

where

CVV – total weight (kg)
SP – tire width (mm)
PP – tire outside diameter (mm)
PK – number of wheels (without unit).

**Weight factor (FV)** (kg):

To calculate the factor FV, we need to know the distribution of vehicles by weight range - see Table 8.

Table 8. Table for calculating the weight factor FV

| **Weight range *** | **WGT** |
|---|---|
| $< 907$ | $\mathrm{FV} = 0.00122\,x$ |
| $907 - 6124$ | $\mathrm{FV} = 0.0000727\,x + 1.050$ |
| $6124 - 9072$ | $\mathrm{FV} = 0.000313\,x - 0.420$ |
| $> 9072$ | $\mathrm{FV} = 0.0006127\,x - 3.115$ |
| * Weight range $= \frac{\mathrm{CVV}}{\mathrm{PN}}$ (kg) | $x = \frac{\mathrm{CVV}}{\mathrm{PN}}$ (kg)<br>where: PN means number of axles |

**Tire factor (FP)** (mm):

$$\mathrm{FP} = (254 + \mathrm{SP}) \times 0.000\,394, \tag{14}$$

**Grouser factor (FR)** without unit:

- with chains: FR = 1.05
- without chains: FR = 1.00

**Wheel load factor (FZK)** (kg):

$$\mathrm{FZK} = \frac{\mathrm{CVV}}{\mathrm{PK}} \times 0.0022, \tag{15}$$

**Driver experience factor (FZR)** (without unit)

Table 9. Driver experience factor table

| **Driver** | **FZR** |
|---|---|
| Inexperienced | 1.1 |
| Normal | 1.0 |
| Experienced | 0.9 |

## 9. Verification of the new evaluation method

In order to confirm the newly proposed method, experimental measurements were carried out focusing not only on the driver factor, but on the entire evaluation method in general.

Soil indices measured using a telescopic penetrometer, whose values were adjusted according to (4), were compared. Furthermore, vehicle values were calculated using the new method. The following steps were taken for the objectivity of the measurements, measures taken in different types of terrain, with different soils, and under different climatic conditions. Furthermore, a wide representation of drivers from each category was selected. Number of drivers was 28. Finally, the measurements were carried out with different types of vehicles – as in the case of the measurements in Table 5.

The results obtained from the measurement clearly confirmed the proposed evaluation method as well as the fact that the drivers overcame different low-bearing terrains according to their experience.

## 10. Discussion and conclusion

The aim of the published work was the creation of a new system for evaluating terrain trafficability. The following steps were taken to realize the objective with the following results:

- Detailed research of current literature dealing with terrain trafficability, which showed that two evaluation systems are currently used in the ACR environment – one using a telescopic penetrometer and the other using a cone penetrometer. (Section 2)
- Furthermore, a comparison of individual devices and evaluation procedures was carried out. Each of the systems has its advantages and disadvantages, unfortunately, none of them meet the current user requirements. Therefore, it was necessary to find out whether the values of the measured soil resistance against the penetration of thorns from the selected penetrometers are dependent on each other. After performing the correlation of the trafficability measurement results obtained using both penetrometers, a functional dependence was found, and thus it was possible to use the evaluation system of one penetrometer to evaluate the measurement results of the second penetrometer. Soil simulations are so complex due to their specific properties that they have not been performed. (Sections 4, 5)
- Analysis of individual vehicle parameters included in existing evaluation methods. The authors present the results of the parameter analysis, on the basis of which some parameters were excluded (clearance factor, engine factor). (Section 6) and conversely a new parameter has been added. This is a “driver experience factor” that significantly affects the result, i.e. whether the vehicle will pass the terrain. The influence of the driver on trafficability is known, but it has not yet been described and quantified anywhere. (Section 7)

- In conclusion, a completely new system for measuring the trafficability of wheeled vehicles through the terrain was designed. The accuracy and reliability of the entire newly designed system was verified by field measurements. (Section 8)
- The authors proceeded to solve the problem of trafficability on the basis of requirements from the field, and its results will have a great practical impact – the implementation of the new evaluation system into the Field Manual. The new evaluation system for the telescopic penetrometer considers many more parameters than its predecessor, where only the weight of the vehicle was taken into account, while retaining all its existing positives (easy handling, speed, establishment). In this way, it is possible to solve the growing requirements for securing mobility.

Based on the authors' experience from several years of trafficability measurement, it was proposed to introduce a new parameter – a “driver experience factor”, which significantly affects the result, i.e. whether the vehicle will pass through the terrain or get stuck. Specific weights have also been determined for this factor based on measurements.

As part of further scientific research, it would be advisable to extend the knowledge of the trafficability of wheeled vehicles presented in this thesis to tracked vehicles as well. The mobility issue itself is the same for both types of chassis, but the input parameters are different. Therefore, it is necessary to perform similar analyzes and parameter measurements for tracked vehicles as well and for more passes, because the dependencies for more passes may vary (Vennik et al., 2018). The rise in the percentage of tracked vehicles is increasing, the authors will therefore focus on this area in further research.

The work can also serve as a model for further monitoring of the driver's influence on vehicle movement. In the following period, it is possible to monitor and try to quantify driver fatigue, as drivers often spend a large amount of time behind the wheel and often must drive all night, which naturally reduces concentration and the ability to drive efficiently.

Another sector in which the results of this work could be used in the future is the field of unmanned vehicles. Despite the absolute predominance of human-driven vehicles, the occurrence of unmanned vehicles has been growing significantly recently. The knowledge gained can also be beneficial for programming these vehicles.

Finally, it is possible to say that the issue of mobility has been addressed for a long time in both the civilian and military spheres. The development of vehicles is ongoing, and it is clear that considerable attention will be paid to their mobility in the future as well. The requirements for the ability, speed, and especially the reliability of evaluating the trafficability of low-bearing terrain are growing. This work may set a new direction in research in the area of patency.

## Acknowledgment

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