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Assessment of the trafficability of military vehicles on Brazilian soils

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ABSTRACT: Soil trafficability is briefly defined as the ability of a vehicle to traverse the same terrain a certain number of times. Currently, in the Army, estimates of soil trafficability are based on drivers training, which does not always reach the desired event. This work presents a method of evaluation of trafficability, trying to evaluate the mobility corridors that can be used in military maneuvers. It has as premise the verification of the soil resistance, comparing it with the types of vehicles that will traverse the terrain. It presents results of the research carried out in experimental fields of Military Academy and Army Assessment Center. It proposes a protocol for the verification of the cone index of the vehicle, and suggests tools for the elaboration of trafficability maps. Finally, it highlights the need for the continuity of the research, acclaiming the validation of the proposals presented.

KEYWORDS: Soil trafficability. Evaluation method.

RESUMO: A trafegabilidade de solos é definida, resumidamente, como a capacidade de um veículo passar por um mesmo terreno um determinado número de vezes. Atualmente, no Exército as estimativas de trafegabilidade de solos são embasadas no tirocínio dos motoristas, o qual nem sempre alcança o evento almejado. Este artigo apresenta um método de avaliação da trafegabilidade, procurando avaliar os corredores de mobilidade que possam ser utilizados em manobras militares. Possui como premissas a verificação da resistência do solo, comparando-a com os tipos de veículos que transitarão pelo terreno. Apresenta resultados das pesquisas desenvolvidas em campos experimentais da Academia Militar das Agulhas Negras e do Centro de Avaliação do Exército. Propõe um protocolo para a verificação do índice de cone da viatura, assim como sugere ferramentas para a elaboração de mapas de trafegabilidade. Por fim, evidencia a necessidade da continuidade da pesquisa, aclamando a validação das propostas apresentadas.

PALAVRAS-CHAVE: Trafegabilidade de solos. Método de avaliação

1. Introduction

For troops to be deployed in the theater of operations, the combat forces need "mobility corridors" (access routes) that ensures adequate travel until they achieve their objectives. Mobility corridors vary according to the type of troop employed in the operation and form access routes for the various maneuver elements of a given level (platoon, battalion or military brigade).

The success of a military operation depends, among several aspects, on the analysis and interaction between the terrain and the weather conditions for the sake of the mobility of the troops. The result of these analyses is an important variable in battles, distinguishing, for example, between a "trafficable" region and another "non-trafficable" region for vehicles. This is important information for the decision making analyses carried out by the troop commander and their staff. In certain historical reports, some war maneuvers had difficulties in achieving success in the face of the lack of trafficability of vehicles.

The trafficability of vehicles is defined as the ability of the soil to allow a vehicle to traverse through the same site for a certain number of times [1].

The assessment of trafficability is premised on the study of the vehicle and its interaction with the terrain. The cone penetrometer, an equipment for field testing, plays a major role in the analyses used in this technique. The results of these tests are considered in conjunction with vehicle tests on experimental tracks [2].

The Brazilian Army (EB) field manual C5-38 [3] presents a method of trafficability analysis. It was developed by the United States Army (USA) through field trials in the country over more than five decades. As such, the analysis models are based on research in soils of temperate climate regions and peculiar characteristics of their test fields.

A study conducted by Vieira [1] found that the calculation parameters adopted for the soils of temperate regions (USA and Europe) are not suitable for Brazilian soils. On the other hand, the methodology, the use of the equipment adopted by the US Army, such as the cone penetrometer, the definitions of the analysis variables and other information are pertinent to be used for research with the Brazilian soil. Thus, the concepts presented in the literature constitute a significant subsidy for the development of the Brazilian Army's own technology in the field of trafficability of military vehicles. However, it warns of the need to adapt them to our peculiar characteristics of soil, vegetation, climate, geology, equipment, methods and vehicles.

On the other hand, the method presented in this article has two uses. It can be used in situations of national defense, but it is also suitable for the civil daily life of certain activities, such as the practices of evaluating the compaction of agricultural soil. Another possible dual application of the method is the development of a rural road management system in sites with difficult access to automotive traffic. This system may, for example, allow city halls to prepare municipal highway maintenance plans. Thus, it enables the elaboration of seasonal traffic maps (rainy and dry season), facilitating support during public disasters and in humanitarian logistics. Another science that uses the equipment and certain methods presented here is agricultural engineering.

The study on soil trafficability can be described by two distinct lines of research, depending on the objectives to be achieved: 1) trafficability assessment; 2) trafficability prediction. A pragmatic comparison between these is the purpose of each study. While trafficability assessment aims to determine mobility corridors for the prompt use of the troop (tactic), trafficability prediction aims to infer the use of the troops in future situations (strategic), defining, for instance, the type of vehicle to be used in a certain area, types of tires to be used in vehicles, period of the year for the best use of troops due to missions and climatic conditions at the time of operations. [2].

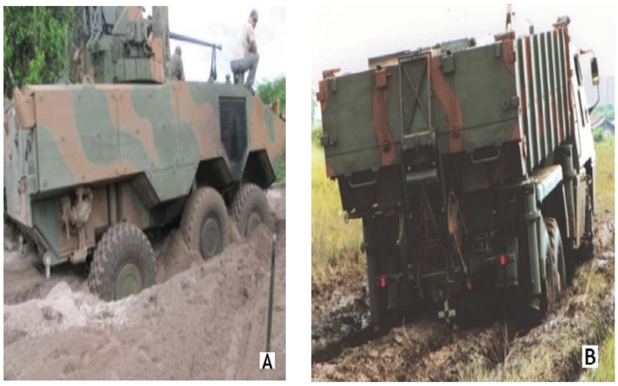
The aim of this article is to present the main aspects required to assess trafficability in "off-road" situations, as well as the results of evaluating the trafficability of logistic vehicles obtained in field trials. The tests were carried out in military areas of the Academia Militar das Agulhas Negras (AMAN), Resende/RJ, and the Centro de Avaliaçao do Exército (CAEx), Rio de Janeiro/RJ.

2. Development

The possibility of a vehicle to move on terrains with low support capacity is influenced by several parameters. The type of vehicle, the skills of the driver, the characteristics of the relief and soil, the natural and artificial obstacles, the climate and the circumstances of the military mission [1]. Furthermore, the boundary conditions that deepen trafficability models are the bearing resistance of the vehicle and the support capacity of the terrain to withstand traffic stresses [4]. These efforts are consequences of the application of vertical and horizontal loads on the ground and its responses to the requests.

Commonly in EB, soil trafficability assessments are based on the individual training of military drivers. No scientific method is used in these estimates. Figs 1a and 1b contextualize the "getting bogged down" phenomenon and exemplify that individual training does not always achieve the objective of overcoming a region of low traffic capacity without prior analysis of the terrain.

VOL.39 Nº2 2022
https://doi.org/10.22491/IMECTA.10851.en



Guarani vehicle (1a) Astros vehicle (1b)

Fig. 1 - Vehicles unable to travel. **Source: [2]**

The characterization of a given terrain in terms of trafficability requires consideration of many interrelated parameters, some of them difficult to determine. Thus, many of these factors need to be estimated rather than measured [1]. Scientifically, the process of trafficability analysis requires the gathering of technologies from various fields of knowledge, such as terramechanics, agronomy, agricultural engineering, meteorology, geotechnics, geomorphology, cartography and others (multidisciplinary theme).

The physical properties of the ground can be changed after vehicle traffic, mainly by heavy military vehicles. According to Schlosser [5], the technique of trafficability assessment can guide the running order of a column of vehicles. Thus, different types of vehicles, with the respective vehicle cone index (VCI), can be rationally organized to overcome a given region, considering the interaction between ground *versus* vehicle, the respective mobilization of the ground and its possible loss of resistance by the effect of traffic. Barbosa *et al*. [6] confirm this observation by analyzing the difference in the effect of traffic intensity in a straight and pivoted line, showing that the shear caused by vehicle traffic on the ground is also due to the shape of the dislocation, whether straight or curved.

Generally, the tensile capacity of soils depends on their shear resistance [7]. Limited to traffic, soil shear resistance is due to the combination of normal and tangential stresses caused by vehicle traffic, which produce plastic deformations in the structure of the vehicle support surface [2].

When assessing trafficability, soil shear resistance is evaluated *in situ*. It is known that this evaluation is performed by empirical interpretation of the tests, and the results are compiled in an index called cone index (CI). Soils with higher CI values have higher shear resistance, and vice versa. The soil CI is obtained by the use of cone penetrometer equipment, which represents the resistance of a soil to the penetration of a cone of 30º, with 0.5 in^2 of base area [3]. This index reflects the resistance to soil shear during penetration of the cone tied to a stress meter [8].

The cone penetrometer has use in the military area (for being a portable and robust equipment). Its use also extends to the areas of agronomy and agricultural engineering. The cone penetrometers used meet ASAE S313.3 [9] and ASAE EP542 standards. [10]. Figs 2a and 2b exemplify types of cone penetrometers.

Analog Penetrometer (2a) Electronic Penetrometer (2b)

Fig. 2 - Examples of cone penetrometers. **Source: [2]**

3. Presentation of a Brazilian method of soil trafficability assessment

In a specialized engineering reconnaissance, after evaluating the CI, this is compared with the vehicle cone index (VCI), and thus the traffic of that terrain for that type of vehicle is defined. If the CI is greater than the shear stresses applied by the vehicle on the surface of the terrain (interpreted as CI > VCI), the vehicle will have trafficability conditions at that site. That is, if the soil offers greater resistance than the vehicle requires to travel, then the terrain is said "trafficable"; otherwise, "non-trafficable" for the vehicle in question [2].

It should be noted that the parameter is dependent on the soil resistance conditions at the time of evaluation. This observation thus has a "short expiry date", since the interference of weather conditions, such as rainfall, can affect soil resistance.

The trafficability study is focused on the "surface cover of the terrain", around 60 cm deep. This layer is naturally heterogeneous. Its properties can vary greatly from one point to another, even within a single topographic area.

For example, its *in-situ* behavior related to water flow (natural permeability) is often controlled by macropores, fractures, groundwater level, layers of different resistances, existence of living organisms and other aspects. And these local characteristics can change from one point to another on the ground [2]. Vennik *et al*. [11] performed measurements and simulations of groove depth (critical layer) due to single and multiple passages of a military vehicle in different types of soil.

The objective of soil traffic assessments is to gather the information of the terrain, comparing it with the characteristics of the vehicles, and to consolidate this information into thematic maps of trafficability.

As a result of implementing the method, it is suggested that these evaluations be carried out in peace-time, and can be validated through empirical research. Sometimes performance patterns from one region can be transferred to another, considering similar specific characteristics and limitations of each model.

The use of electronic penetrometer can bring some advantages over analog ones. For example, by combining the CI results with the geographic coordinates of the points of a terrain reconnaissance campaign, it is possible to assemble trafficability maps with the characteristics of the area studied.

The electronic penetrometer exemplified in Fig. 2b (penetroLOG) is manufactured by the company Falker. It has a test speed control system by means of an ultrasound emission/reception sensor, which is reflected by a metal base. When the test speed exceeds the standard value, the system alerts the operator. Also, this equipment evaluates the CI along the soil profile during the test, with an accuracy of up to 1 cm depth, storing up to 2,000 readings (points). This data can be transmitted to a portable computer through specific data analysis *software* called "Compactação do Solo" (soil compaction). Fig. 3 exemplifies the graphic result of a penetration test on a beach sand, exposed in the mentioned *software*. The geographic coordinates of this point were obtained by means of a GPS (Global Positioning System) device coupled to the equipment at the time of data collection.

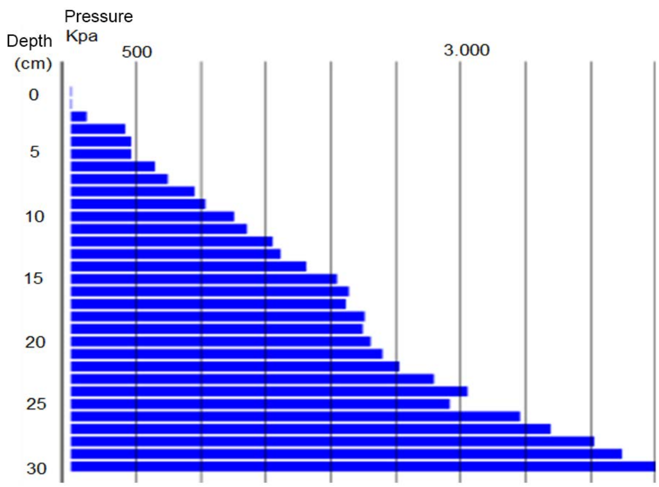


Fig. 3 - Graphic result of a CI (kPa) test at Praia do Forte São João - Urca (Rio de Janeiro/RJ). **Source: [2]**

VOL.39 Nº2 2022
https://doi.org/10.22491/IMECTA.10851.en

During the development of the research, it was verified that Falker is a Brazilian company that produces the electronic penetrometer and its respective *software* implemented at a commercial scale. The company also provides a system for drawing up soil maps, which combines the geographical coordinates and their results from the CI tests obtained over the test profiles. This system is called FalkerMap.

The diagram in Fig. 4 presents an example of a soil map of a separate area in plots, numbered from 39 to 50, with the respective CI at depths 15 cm, 30 cm and 45 cm. This soil map was elaborated by compiling the results of tests performed with the electronic cone penetrometer, which were "imported" and organized in FalkerMap through a geographic information system.

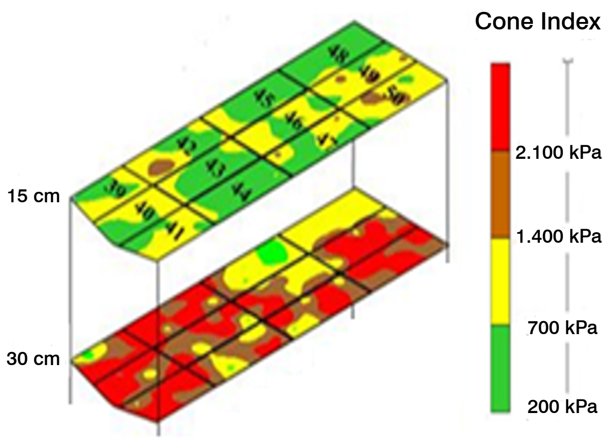


Fig. 4 - Diagram of soil maps separated into layers with the respective mean values of CI. **Source: [2]**

Interpreting the diagram, it can be verified that in plot 44 (Fig. 4) the CI results of the 15 cm deep layer are located between 200 and 700 kPa (in green); in plot 50, at this same depth, the results are located between 700 and 1,400 kPa (in yellow). In the context of soil trafficability, a vehicle with VCI of 800 kPa and depth of the critical layer of 15 cm would not travel in plot 44 (CI < 700). However, when choosing to travel in another gleba, I would traffic in most of plot 50 (Fig. 5), because in it the CI is superior to the VCI (CI > VCI).

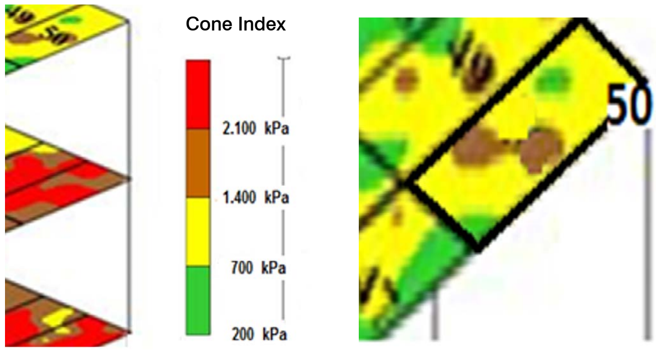


Fig. 5 – Details of the soil map diagram separated into layers with the respective CI values. **Source: [2]**

Given the peculiarities of the subject of trafficability, the electronic penetrometer has some advantages over the analog penetrometer.

- The academic environment has used this equipment for analysis in the agronomic area; thus, the research developed can complement the studies of the terrain of a theater of operations.
- The equipment can be operated by a single individual, while the C5-38 manual [3] specifies two people for the analog penetrometer to be used. Other characteristics of the electronic penetrometer are cited:
  - it allows to collect CI in an automated manner throughout the profile being analyzed, has a speed control mechanism during the test, has discretization of the results every 1 cm and reaches sufficient depths for the trafficability analysis;
  - during operation, the storage of the tests is automatic, and is even facilitated by the *software* "Compactação do Solo";
  - electronic penetrometer data can be processed in a map;
  - it is manufactured and marketed by a Brazilian company, meeting the government guidelines for the promotion of the "national defense industry"; and
  - it is a simple-to-use and suitable equipment to be transported individually.

3.1 Description of the terrain and its CI

The systemic observation of soil resistance behavior allows us to understand that certain types of terrain are more susceptible to loss of support capacity in the face of seasonal meteorological changes. Typically, these are located in flat or slightly wavy areas. The Brazilian Institute of Geography and Statistics (IBGE) [8] defines the following types of terrain topography, qualified by the criterion of slope (Table 1):

Table 1 - Slope classes of the terrain.

Slope classes	Slope (%)
Flat	0 to 3%
Slightly wavy	3 to 8%
Wavy	8 to 20%
Very wavy	20 to 45%
Mountainous	45 to 75%

Source: IBGE [12]

Thus, the simple discrimination of terrain in a slope map already provides a qualification of places to be considered regarding trafficability. After all, explained even by the morphology of the terrain, soils of flat slope (0 to 3%) can be formed by natural sedimentation of erosive processes (transported soils). Thus, most young soils are considered, which raise the need for further studies on their resistance. It is important to highlight that this is a first analysis, in view of the need to combine other variables to better clarify the possibility of a vehicle traveling on a terrain.

Fig. 6 presents a sketch that relates the topography of the terrain with its respective resistance (CI), resulting in the difficulty of trafficability. For example, in a general context, at the extreme of the graph one can exemplify a soil of high resistance and flat topography, which will probably present a great ease of traffic for various types of vehicles. On the other hand, a wavy terrain with low resistance will present high difficulty of traffic, as is the case of coastal dune regions or even dunes in desert areas.

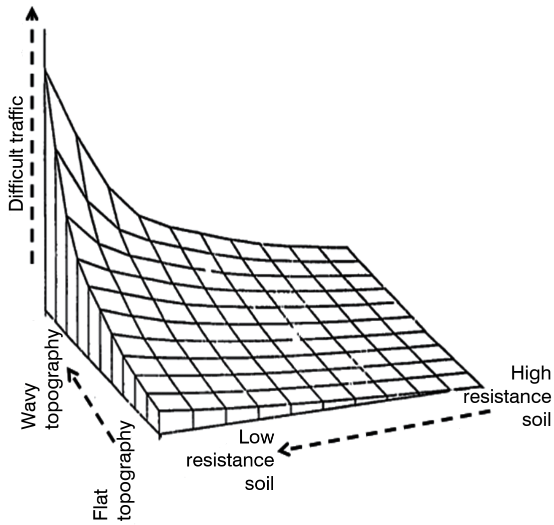


Fig. 6 - Draft correlating soil resistance characteristics and topography with difficulty of trafficability. **Source: [2]**

The systemic use of aerial images greatly assists the demarcation of regions for an initial investigation. For this, the use of the most diverse sources of information is provided, but the systemic use of unmanned aerial vehicles (UAV) in obtaining updated images of the areas under study stands out in this research.

3.2. Studies of the vehicle cone index (VCI)

The VCI is the index assigned to a given vehicle that indicates the minimum resistance of the ground, in terms of CI, required for the vehicle to traverse a test track. It is a peculiar parameter of each vehicle that empirically summarizes the efforts that it exerts in the surface layers of the terrain for the purpose of traffic. This index results from the technical characteristics of the vehicle, such as ground pressure, traction type, wheel load, engine power, type of wheel (tire or track), among other parameters, all interacting with the characteristics of the terrain [2].

Low VCI values are attributed to the best performance of the vehicle in terms of "off-road" trafficability. A VCI vehicle equal to 480 kpa will indicate that it has attributes compatible with CI terrains greater than 600 kpa, for example (VCI < CI).

Vehicles under caterpillars are usually more able to travel on low support capacity (low CI) terrain compared to some logistic trucks or even some administrative vehicles. Figs 7a and 7b present two types of military vehicles that have different performances in relation to trafficability, whether with continuous track (7A) or wheels (7B). These vehicles employ different requests on the ground, and therefore have different VCI. For example, most vehicles with continuous tracks have smaller VCIs than most heavy-wheeled vehicles. In this context, the VCI is a parameter assigned to a given vehicle, which indicates the shear efforts that the vehicle applies on the ground so that it can move. The lower the VCI, the better the performance of the vehicle in terms of trafficability.

Leopard vehicle (7a) Marruá vehicle(7b)

Fig. 7 –Vehicles with different performance. **Source: [2]**

The parameter of the cone index of the vehicle can be modeled by means of mathematical expressions, but these models require constant calibrations, given the amount of variables that interfere in the operability of vehicles. Thus, this index is best evaluated through empirical experiments in standardized experimental tracks or controlled natural tracks. In them, it is possible to measure the moisture content and soil resistance, recording the interaction of the vehicle with the terrain. The goal is to compare the situation of the "bogged down" vehicle with the respective CI of the track, asking the question: which is the lowest CI of the track (or terrain) where the vehicle can ride? This value refers to the definition of the VCI.

In the context of traffic, Fig. 8 exemplifies some experiments running in the Aberdeen Test Center test fields, which has different types of tracks and respective protocols of military vehicle testing [13].

Fig. 8 – Example of traffic test being performed on artificially prepared tracks. **Source: [13].**

3.2.1 Proposal for an empirical testing protocol

Experimental tracks are used in the VCI definition test, whether natural or artificial.

3.2.1.1 Artificial experimental track

The following is a proposal for an artificial experimental track, outlining a test protocol for the definition of the VCI of vehicles that are evaluated at the Centro de Avaliação do Exército (CAEx).

Following the techniques of empirical evaluation of tractor analyses by agricultural engineering, it is understood that artificial runways should be constructed with the types of "extreme" soils with difficult trafficability.

Therefore, two types of standardized tracks are listed as a proposal: one with sand-like soil and another with fine-grained soil of low resistance.

VOL.39 Nº2 2022
https://doi.org/10.22491/IMECTA.10851.en

Standardized tracks for traffic tests must have the following characteristics:

- flat, with inclinations close to 0%;
- prepared, to absorb water and thus increase moisture when it is convenient;
- having a system to simulate rain precipitation;
- having operating conditions of equipment that can revolve the surface soil layer, such as tractors equipped with disc grid implements, rotary hoe, and others;
- be at least 50 m long, 8 m wide and 2 m deep;
- it should not have materials that may serve as obstacles during testing, such as stones or others; and
- it should have a regular surface, avoiding considerations of the irregularity of the terrain that interfere with trafficability.

The diagrams in Figs. 9 and 10 present the geometry of the proposal of a "standardized track", adapted by Francisco [14], as well as the rain simulation devices for damping of the terrain and electronic equipment for measuring travel speed and filming of the tests.

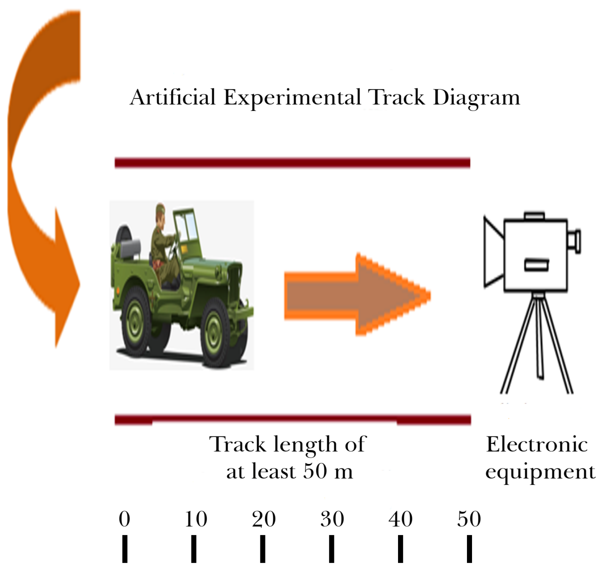


Fig. 9 – Plant diagram of the standardized track for the trafficability test. **Source: [2]**

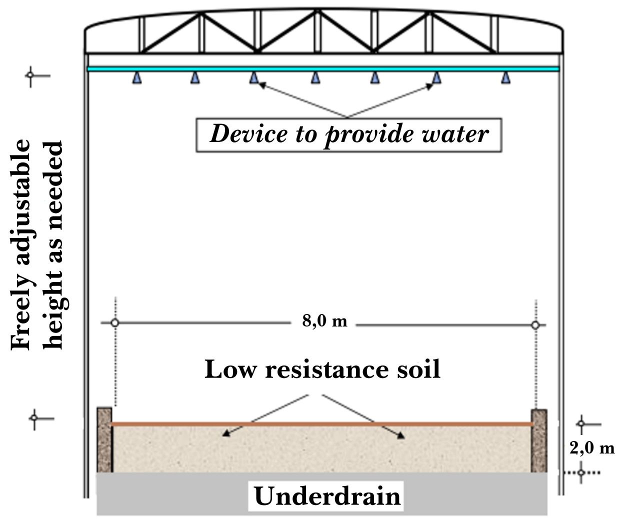


Fig. 10 – Cross-sectional diagram of the standardized track for the trafficability test. **Source: [2]**

The electronic measuring equipment (Fig. 8) has the following purposes: 1) filming each traverse during the tests, allowing for further analysis; and 2) measurement of the travel speed, and defining the VCI parameter.

3.2.1.2 Natural experimental tracks

The natural test tracks should be analyzed before the tests themselves. Parameters must be obtained such as the soil type and its respective classification by the Unified Soil Classification System (USCS), from the surface layer of the track to the depth of 60 cm. Parameters of the *in situ* situation of the terrain, such as soil moisture before the start of the tests, natural apparent specific weight, soil porosity and degree of saturation, should also be considered.

The use of portable equipment such as "Vane Test" [2] may also help in the characterization of these natural experimental tracks.

In order to reach a "non-trafficable" situation on these tracks, the terrain may be wet until the soil saturation situation during the tests.

3.3 Presentation of the test method

The tests for the definition of the VCI are performed on the experimental tracks. There are some observations to be included in the proposed VCI test protocol.

- Tests should be carried out on non-raining days in order to avoid external interference.
- Performance is predicted for each vehicle operating in isolation.
- The VCI is defined by means of a graphical interpolation obtained during the tests on the standard track, in order to meet the aforementioned speed limitation. This form of definition reduces the subjectivity exposed in the literature related to the subject, favoring the elaboration of a test protocol to be adopted by CAEx.
- The characteristics of the vehicle during the test should be:

✓ maximum permissible load, with fuel tank full;
✓ all trafficability improvement mechanisms functioning, i.e., all-wheel drive, traction control, or others; and
✓ tire calibration corresponding to the type of soil, according to the manufacturer's guidelines.

- The performance characteristics of the test should be:

✓ the initial moisture content of the fine-grained soil track must correspond to a content that leads to start the tests in a situation that is unfavorable to trafficability;
✓ first gear travelling of vehicles;
✓ travel speed at the beginning of the test, that is, at the entrance of the track, around 20 km/h;
✓ travelling in a straight line, avoiding turning the direction to try to get out of a bogged down situation; and
✓ repetition of the test procedures to validate the interpretations; it is estimated that three repetitions are necessary to ratify the results obtained.

The track test begins by characterizing the initial CI and the respective soil moisture. Subsequently, the vehicle is positioned for the test at the beginning of the track, at an entry speed into the test area around 20 km/h. Then the first passage of the vehicle begins. Meanwhile, the speed is measured by means of electronic equipment. After completing the first passage, the depth of the critical layer is measured. The track is then revolved (and dampened, if applicable), worsening trafficability conditions. Each "worsening" of the trafficability conditions thus leads to decrease travel speed.

The definition of the "bogged down" condition in this research was adjusted to the time variable. In general, the situation is characterized as "not traversible" during the track tests if the vehicle is stuck (immobilized) for ten seconds trying to leave the site.

The test is repeated *n* times, measuring the new travel speed and the CI corresponding to each passage of the vehicle. When the vehicle gets stuck (prevented to move for ten seconds), the tests are stopped and the ground CI and the depth of the critical layer are measured. The CI should be measured around the vehicle wheels, identifying the lowest of the values of this index at that time. Soil samples are collected to identify moisture. The results of each passage are processed and then condensed into a graph of: CI *versus* Travel Speed. From then on, the VCI is inferred.

It is understood that the worse the soil trafficability condition, the vehicle finds greater resistance to travel, and, for this reason, decreases its speed. In order to clarify gaps in the literature on the subject, the criterion for defining the VCI was correlated with military practices. Thus, taking into account that the troop's walking speed is 4 km/h (military manual data), it was defined that the minimum travel speed limit on the VCI identification tests should be:

- Logistics vehicles ≥ 5.0 km/h;
- Operational vehicles ≥ 10.0 km/h

VOL.39 Nº2 2022
https://doi.org/10.22491/IMECTA.10851.en

That is, the VCI is defined in favor of safety by means of a technical criterion of travel speed, instead of using subjective criteria. This VCI criterion is then understood as the minimum acceptable speed in tactical travelling.

Ratifying, the VCI is a technical characteristic of a given vehicle, which relates to the minimum soil resistance necessary for the passage of such a vehicle on a test track, meeting the criterion of minimum travel speed. This index seeks to summarize all the trafficability qualities that this vehicle has, assuming that it is moving at a low, constant speed, in the plane and without towing another vehicle.

4. TRAFFICABILITY ASSESSMENT RESULTS OBTAINED IN FIELD TESTS

The sites where the *in situ* tests were carried out are the AMAN instruction field and the CAEx evaluation test areas. The reasons that led to the choice of these areas are the most common types of terrain in those plots, with soils with fine texture in the AMAN area and sandy soils typical of the coastal region in the CAEx area.

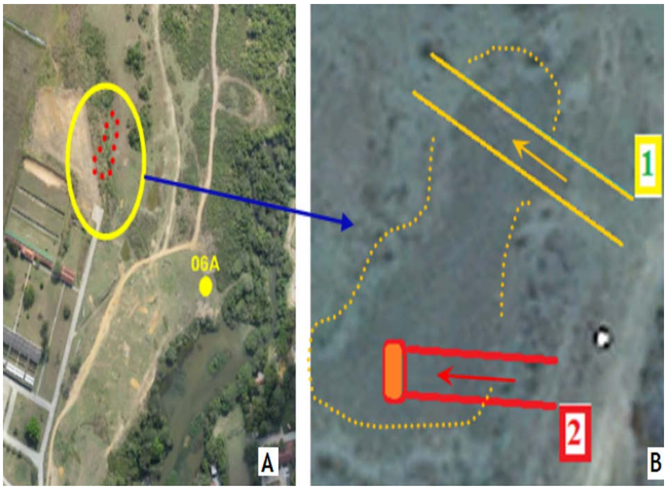
Karafiath [15] mentioned that until 1977 there was no soil classification system adopted by technicians who study terramechanics. This argument was ratified throughout the trafficability studies carried out by Cordeiro [2], which shows that there are no specific soil classifications for the analysis of the interaction "terrain *versus* vehicle". It should be noted that the tests were carried out with the logistical and technical support of agronomist engineers of the Brazilian Agricultural Research Corporation (Embrapa) and military personnel of the Academy's Engineering Course, in the tests carried out at AMAN, as well as CAEx military personnel in the tests carried out at the evaluation center [2].

Faced with a logistical difficulty in building a standardized test track, the research continued with the guidance of the tracks on natural terrain of the mentioned test fields. To this end, the research carried out with tractors at the School of Agricultural Engineering of the Federal University of Santa Maria/RS and the School of Agricultural Engineering of the Federal University of Viçosa/MG served as motivation, which use natural terrains for testing activities.

4.1. *In situ* tests performed at AMAN

Fig. 11 presents some tests carried out in the AMAN training field (Resende/RJ), on a natural terrain track.

The test area at AMAN is a flat region, with hydromorphic soil (very poorly drained). Fig. 12b shows test sites 1 and 2 in detail. Site 2 presented trafficability difficulties for all vehicles tested, but on site 1 all vehicles were successful in travelling.



Area of low resistance soil and fine grained soil

Fig. 11 – Location of the tests carried out at AMAN. **Source: [2]**

The lack of trafficability presented in site 2 of Fig. 11b was verified by means of an electronic penetrometer. Fig. 12a and Fig. 12b present the performance of the soil trafficability assessment tests. At the time, it was found that the support capacity of site 2 was incompatible with the shear forces applied by the vehicles on the surface of the terrain. Thus, the soil showed no trafficability, that is, CI < VCI.

The tests, as performed in AMAN's field of instruction, served to validate the perception of the difference between vehicles and soil heterogeneity.

VOL.39 Nº2 2022
https://doi.org/10.22491/IMECTA.10851.en

One fact that should be emphasized is that these sites distance themselves by less than 30 m, but offer characteristics different enough to present distinct trafficability capabilities.

Also, as shown in Fig. 12, in view of the need to use the repeater plate of the penetroLOG, a “buoy” was adapted to support said plate during the tests with the presence of hydroplaning. This adaptation refers to the investigation of watercourse beds, identifying the CI of fords possible to be used in crossings in military maneuvers.

CI test with electronic cone penetrometer

Fig. 12 – Tests at AMAN. **Source: [2]**

In this sense, in order to evaluate the proposed method for the definition of the VCI, *in situ* tests were conducted in CAEx and AMAN with administrative vehicles of the Brazilian Army. Fig. 13 represents some tests carried out in the AMAN test field (Resende/RJ), site 2.

Marruá vehicle - test in a site with fine grained soil.

Fig. 13 – Tests performed at AMAN. **Source: [2]**

4.2. *In situ* tests performed at CAEX

Fig. 14 presents some tests carried out in the CAEX test field (Rio de Janeiro/RJ), on a natural terrain track, with sandy soils in the beach region or on mangrove terrain.

Fig. 15 – Marruá vehicle during trafficability test in sandy soil typical of coastal region (A) and Hilux vehicle in typical mangrove soil (B). **Source: [2]**

In the tests performed, the empirical methods summarized in section 3.2 of this study were adopted in order to measure a VCI that could characterize the capacity of the vehicles with respect to trafficability.

4.3. Results achieved at both test locations

In the tests performed, the empirical methods summarized in topic 3.2 of this article were adopted in order to assess the VCI that allowed the trafficability of the vehicles on the terrain. Table 2 shows the basic characteristics of the vehicles that participated in these tests.

Table 2 – Description of the vehicles.

Marruá operational vehicle 4x2, Agrale brand
maximum weight on the wheel: 745 kgf (not loaded)
Hilux transport vehicle, Toyota brand
maximum weight on the wheel: 967 kgf (not loaded)
Logistics transport vehicle, Volk brand
maximum weight in the dual wheel set: 2185 kgf (not loaded)
Vehicle with truck bed 10m^3, Mercedes-Benz brand
maximum weight in the dual wheel set: 1620 kgf (not loaded)

Source: [2]

Table 3 summarizes the values obtained in the VCI identification tests via interpretation of values obtained in the tracks, as well as in field tests in other opportunities or technical data from the literature. This table presents the results in kPa and Psi, in order to allow future evaluations with literature from the US Army, since in their manuals the units adopted for the calculations of the VCI result in values in Psi.

Table 3 – VCI values of the vehicles tested.

Vehicle Type	VCI (kPa)	VCI (Psi)
Marruá	470	69
Hilux	540	79
Volk	800	116
Truck bed	930	135

Source: [2]

The Volk brand logistics vehicle presented greater trafficability facilities compared to the truck bed (test site 2 – AMAN). This fact can be explained by the weight on the wheel of the former being greater than the weight on the wheel of the latter, when the two vehicles are not loaded.

The logistics (administrative) vehicles tested presented similar performances.

5. Conclusion

This article presented the main aspects used to assess trafficability.

It is worth noting that it is necessary to develop a peculiar and regional way for field specialists to interpret the information available in a given region. This convenience leads us to the concepts of hierarchization concerning the technique of trafficability assessment or prediction. That is, initial analyses may provide a provisional opinion of the terrain.

But this opinion can be built, reformed, maintained and expanded throughout modeling validation activities. In this sense, the use of the method based on the cone penetrometer is presented as the main process of soil study to infer soil resistance. Such equipment has the advantage of the robustness necessary for tactical combat activities and offers results that express the variability of the terrain.

More specifically, the electronic cone penetrometer brings significant advantages to the assessment of trafficability compared to the analog penetrometer. The proposal to identify the cone index of the vehicle based on the minimum travel speed defines a less subjective method compared to that described in the literature.

The results collected from VCI in the AMAN and CAEx experimental fields give credence to the proposed method and, most of all, establish important parameters for the tactical planning of military operations that involve the trafficability of the vehicles analyzed in this study.

It is believed that the innovations of this research have the ability to invite experts from the Engineering Weapons field to further deepen the subject of military troop mobility.

After all, the number of variables for the analysis of the terrain goes beyond technical considerations, extending to the human individuality when driving the vehicle. On the other hand, trafficability assessment techniques are powerful tools for planning military operations.

Finally, the assessment of trafficability in mobility corridors in the Brazilian borders is an example of the application of this method. Conducting strategic studies to define trafficability corridors to be applied in this region of Brazil contributes to ensuring national sovereignty.

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