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SELECTION OF THE WHEEL AND SUSPENSION SYSTEMS FOR VEHICLES AND MACHINES OPERATING IN DIFFICULT WETLAND CONDITIONS

Summary

Reliable estimation of mobility in harsh wetlands environment and development of guidelines for forming the structure of vehicles and machines running gear still remains an open issue. This paper presents the basic methods of determining the ability of overcoming ground of low bearing capacity by wheeled and tracked vehicles and their theoretical basics. For the evaluation of ability to overcome such ground the analytical methods were used – MMP method and VCI method, which take into account the value of maximum pressure and geometrical dimensions of running gear. Based on the available data their comparison, assessment of the credibility and usefulness during research on development of equipment operating in harsh terrain were performed. Moreover, taking into consideration the impact of running gear on the ground the division on technical, economic and ecological class of mobility was conducted.
Key words: *terrain with low bearing capacity, VCI method, MMP method, mobility*

PROBLEMY DOBORU UKŁADÓW JEZDNYCH DLA POJAZDÓW I MASZYN PRACUJĄCYCH W TRUDNYCH WARUNKACH WODNO-BŁOTNYCH

Streszczenie

Wiarygodne oszacowanie możliwości poruszania się w trudnych warunkach wodno-błotnych oraz opracowanie wytycznych do kształtowania układów jezdnych pojazdów i maszyn stanowi nadal otwarty problem. W referacie przedstawiono podstawowe metody określania zdolności pokonywania terenu o niskiej nośności przez pojazdy kołowe i gąsienicowe oraz ich podstawy teoretyczne. Do oceny zdolności pokonywania takiego terenu wykorzystano metody analityczne – metodę średnich nacisków maksymalnych MMP i metodę VCI, które uwzględniają wartość nacisków maksymalnych i wymiary geometryczne układu jezdnego. Na podstawie dostępnych danych przeprowadzono ich porównanie, ocenę wiarygodności i przydatności podczas prac nad rozwojem sprzętu pracującego w trudnym terenie. Ponadto, uwzględniając oddziaływanie układów bieżnych pojazdów i maszyn na podłoże dokonano podziału na techniczną, ekonomiczną i ekologiczną klasę mobilności.
Słowa kluczowe: *teren o niskiej nośności, metoda VCI, metoda MMP, mobilność*

1. Introduction

For effective performance of agro-technical tasks on wetlands, equipment is necessary whose mobility level is adequate to the ground's bearing capacity, and operation conditions and methods. It requires a special construction of the wheel and suspension system. Definition of guidelines for construction of wheel and suspension systems for vehicles and machines to be operated on ground with low bearing capacity is a complex problem, as vehicle parameters, ground properties and external loads need to be taken into account for reliable estimation of vehicle mobility in difficult wetland conditions.

From the perspective of the vehicle kinematics theory, a prerequisite for ensuring vehicle mobility is meeting several conditions. In order to pass over a trail with low bearing capacity, the driving force P_n on wheels or tracks may not be lower than vehicle rolling resistance P_f:

$$P_n \geq P_f = f \cdot W \tag{1}$$

where: f – rolling resistance coefficient which increases as the ground's bearing capacity becomes lower and the depth of the ruts formed increases; W - active gravitational mass of the vehicle.

The problem is, however, that the driving force is limited by the ground friction force P_φ – regardless of the motor power and transmission ratios applied in the drive system, according to the relation:

$$P_n \leq P_\varphi = \varphi \cdot W' \tag{2}$$

where: φ – friction coefficient – its value depends on the ground type and for typical wheel and suspension systems it becomes lower as the ground's bearing capacity decreases; W' – load on driven wheels or tracks.

Also, a surplus friction force P_φ should preferably be available over rolling resistance P_f – referred to as the traction force P_μ – necessary for vehicle acceleration, overcoming grade resistance, swivel resistance, towing resistance and process resistance due to operated tools and attachments.

The traction force is characterised by the coefficient of traction μ, which in case of an all-wheel or an all-track drive, is expressed by the formula:

$$\mu = \frac{P_\varphi - P_f}{W} = \frac{W(\varphi - f)}{W} = \varphi - f \tag{3}$$

It is assumed that availability of the traction force of ca. 0-10% of active gravitational mass (μ=0÷0.1) allows for a single pass over the ground. On ground with low bearing capacity, ruts are formed with the depth of ca. 0.3-0.4 m. It is a technical mobility level for vehicles. For a vehicle to be able to be effectively operated (with no continuous risk of bogging down), availability of the traction force of at least ca. 30% of active gravitational mass (μ=0.3) is required – it specifies the so-called economic mobility level. The ruts formed during a single pass are 0.15-0.20 m. deep. In such circumstances, many passes are possible over the same location [9].

An adequate traction force may be obtained by increasing friction force or decreasing rolling resistance which depends mainly on the depth of the ruts formed. The easiest way for improving friction and decreasing rolling resistance is to lower ground pressures by increasing the contact surface of the wheel and suspension system with the ground. A key to obtain an expected mobility level is ensuring a proper relation between the ground's bearing capacity and ground pressures.

For measurement of bearing capacity of drenched, fine-grained soils and determination of their ability to support moving vehicles, a special tester was designed in the USA as early back as in the 1930s (Fig. 1). The measurement consists in determination of a force necessary to push a cone with the tip angle of 30° and the base area of 0.5 square inch ($0.5in^2 = 3.23\ cm^2$) at a rate of 1.2 inch per second (1.2 in/s = 3 cm/s) down into the ground, 25 cm deep (in these conditions resistance does not increase) and referring it to the cone base area.

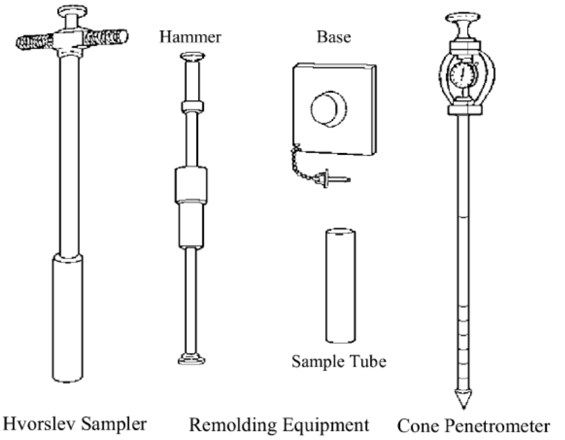

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Fig. 1. A set of tools used to determine the ground's ability to support loads exerted by vehicles

Rys. 1. Zestaw przyrządów do określania zdolności gruntu do przenoszenia obciążeń wywieranych przez pojazdy

Ground bearing capacity determined using this method is referred to as the Cone Index (CI) or, after taking into account the ground's liquefaction ability under repeated loads, the Rating Cone Index (RCI) [14]. These indices are commonly used for determination of the ground's ability to support loads generated by moving vehicles – Table 1.

Table 1. Typical bearing capacities of various grounds

Tab. 1. Typowe nośności podłoży

Ground type	CI, kPa
Snow	10 - 40
Mire, bog	5 - 15
Peat soil	30 - 60
Arable fields – friable and drenched	130 - 200
Wet clay soils	250 - 400
Humid clay soils	400 - 800
Dry clay soils	800 - 1500
Dry, compacted clay soils	1500 - 3000

Source: own work / Źródło: opracowanie własne

A problem lies in defining ground pressures exerted by vehicles. To this end, average or nominal pressures are generally used, which for tracked vehicles may be expressed by the formula [14]:

$$NGP = \frac{W}{n_T \cdot b_T \cdot L_T}, \tag{4}$$

where: n_T – number of tracks; b_T – track width (m); L_T – length of track on the ground (m);

while for wheeled vehicles, assuming that the length of the wheel's contact surface with the ground is equal to the wheel's radius – it takes the following form:

$$NGP = \frac{W}{2 \cdot n_A \cdot b_W \cdot r_W}, \tag{5}$$

where: n_A – number of axles; b_W – wheel width (m); r_W – wheel radius (m); D – wheel diameter (m).

A French formula is alternatively used, which takes tyre deflection into account [3]:

$$NGP = \frac{W}{2 \cdot n_A \cdot b_W \sqrt{r_W^2 - \left(r_W - \delta - z\right)^2}}, \tag{6}$$

where: δ – tyre deflection on hard ground (m); z – penetration depth of the wheel in the ground (m).

However, the pressures do not take into account concentration and accumulation of stresses in the ground under the wheel and suspension system, which are decisive for the depth of the ruts and resistance; neither do they take into account the size of the elements of the wheel and suspension system, which also have a major influence on the penetration depth of the system in soil, in line with Bekker's theory [1]:

$$z = \left(\frac{NGP}{\frac{k_c}{b} + k_\Phi} \right)^{1/n}, \tag{7}$$

where: b – lower value of the wheel's or track's contact surface with the ground; k_Φ – ground friction module; k_c – soil consistency module; n – exponent determined experimentally.

As a result, NGP pressures are not a reliable criterion for assessment of trafficability of ground with low bearing capacity. Due to the above, several analytical and experimental methods were developed whose aim is to determine minimum ground bearing capacity allowing its trafficability on the basis of vehicle parameters.

2. VCI method

During World War 2, a basic problem for ensuring field mobility of armed forces in the European combat theatre was trafficability evaluation of fine-grained arable land after rainfall, friable in structure and highly drenched – i.e. ground with relatively low bearing capacity, limiting manoeuvrability of resources. In order to resolve the problem, the Waterway Experiment Station of US Army Corps of Engineers (WES) developed a "go/no go" method. Ground trafficability is determined based on measuring actual ground bearing capacity using the Cone Penetration Test – Cone Index (CI) – and comparing it with the minimum ground bearing capacity necessary for a single pass of the selected vehicle over the ground, referred to as the Vehicle Cone Index (VCI), which is determined experimentally. Grounds with CI higher than VCI characteristic for a vehicle are trafficable ("go"), while if the measurement's result is worse than VCI, there is a high probability of the vehicle being bogged down ("no go").

The minimum VCI characteristic for a given type of vehicle and necessary to ensure trafficability was determined experimentally. The tests consisted in passing back and forth over trails whose RCI was known, until the vehicle bogged down. On the basis of tests completed on various grounds, a diagram was made of the obtained number of passes as a function of RCI; next, using extrapolation $VCI_{1(RCI)}$ was determined which was sufficient for a single pass over liquefied ground. These diagrams allowed also for direct determination of $VCI_{n(RCI)}$ necessary for passage of an entire convoy with a known number of vehicles "n". With a view to verification of the results, actual stresses in the ground during vehicles' passage were also registered during tests, forming a basis for analytical works.

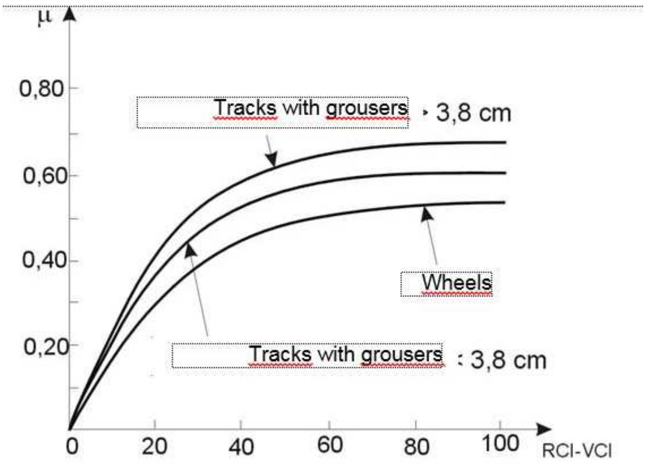


Fig. 2. Characteristics of the traction force coefficient for 50 passes of wheeled and tracked vehicles as a function of the surplus ground bearing capacity – VCI method [2]
Rys. 2. Charakterystyka współczynnika siły uciągu dla 50 przejazdów pojazdów kołowych oraz gąsienicowych w funkcji nadwyżki nośności gruntu – metoda VCI [2]

Further development of the VCI method involved determination of transport vehicles/ abilities when passing over difficult terrain. As their reference value, the traction force was utilised – a surplus friction force over momentary resistance – which is necessary to overcome swivel resistance, trailer towing resistance, grade resistance, acceleration etc.

In order to make the results more general, the traction forces measured were referred to active gravitational mass of vehicles, and characteristics of the μ for wheeled and tracked vehicles were determined. As the surplus friction force occurs only on those grounds whose bearing capacity is higher than VCI – the characteristics were designed as a function of the surplus ground bearing capacity: RCI minus VCI_{RCI} (Fig. 2).

Introduction of new tyre types (broad-profile, radial), and a poor correlation between actual traction abilities (particularly on grounds with higher bearing capacity) and those determined using the VCI method, made the American army and its research centre – Waterways Experiment Station of US Army Corps of Engineers (WES) develop an analytical method allowing for a more precise estimate of available traction forces of wheeled vehicles on the ground with known CI. The method was based on field tests of traction forces of vehicles and stand tests of (various sizes of) wheels with a tyre, operated with a 20% spin on various grounds [6].

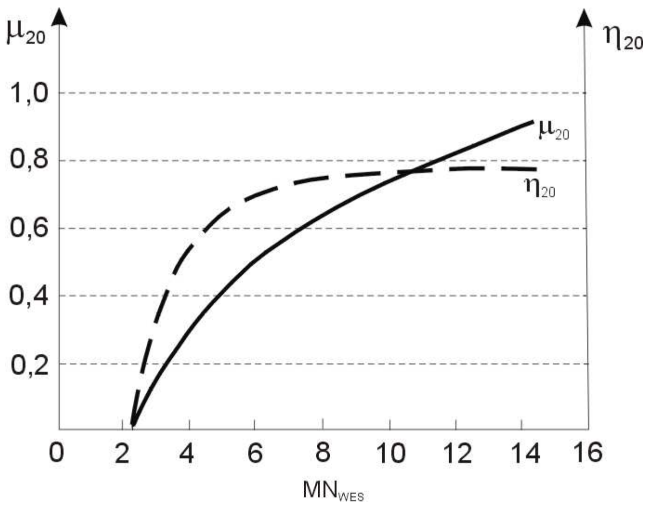


Fig. 3. Characteristics of the coefficient of traction and efficiency of drive transmission to the ground for a wheeled vehicle, as a function of the MN (Mobility Number) – the WES method [14]
Rys. 3. Charakterystyka współczynnika siły uciągu i sprawności przeniesienia napędu na grunt dla pojazdu kołowego, w funkcji wskaźnika mobilności MN – metoda WES [14]

Consequently, new characteristics were determined of the coefficient of traction μ_{20} (for the spin s = 20%) and efficiency of drive transmission to the ground η_{20} (Fig. 3). What differs them from the VCI method is that they are not a function of surplus bearing capacity (RCI minus VCI), but of the MN (Mobility Number), the latter expressed for clay soils by the following formula:

$$MN_{WES} = \frac{CI \cdot b \cdot d}{W_k} \left(\frac{\delta}{h} \right)^{0,5} \left(\frac{1}{1 + \frac{b}{2d}} \right), \qquad (8)$$

where: W_k – wheel load (kN); CI – ground bearing capacity determined with the VCI method (kPa); δ – tyre deflection (m) on hard ground under load W_k; h – height of the tyre profile (inflated, no load) – over the rim, without tread (m); d – external diameter of the tyre with tread – inflated, no load (m).

Development of the Mobility Number which standardizes wheel sizes and loads allowed for better correlation between estimated and measured traction force values for the examined group of vehicles.

The Mobility Number for which the coefficient of traction $\mu_{20} = 0$ (all the friction force is used up for overcoming resistance) determines the minimum CI_{gr}, allowing trafficability (Fig. 3). Hence, after transformation of the relation (14) – the VCI_{WES} breakpoint for clay soil may be expressed as:

$$VCI_{WES} = \frac{k \cdot W}{2 \cdot n \cdot b \cdot d \cdot \left(\frac{\delta}{h}\right)^{0,5} \left(\frac{1}{1+b/2d}\right)}, \qquad (9)$$

where: k – MN breakpoint (μ=0); n – number of axles (wheels on one side of the vehicle); W – active gravitational mass of a vehicle (kN).

MN breakpoints (μ_{20} =0) for clay soils, determined on the basis of tests and the adopted MN formula, are presented in Table 2. It shall be noted that highest values result from trafficability tests, completed by actual wheeled vehicles – testers are distinctly underrating the ground bearing capacity necessary for trafficability.

Similar tests were made for wheeled vehicles, but their results are restricted and are included in the NATO Reference Mobility Model.

Table 2. MN breakpoints [6]

Tab. 2. Wartości graniczne wskaźnika mobilności MN [6]

Test conditions	k
Field tests – mobile tester – variable spin	1.85
Field tests – mobile tester – constant spin	1.79
Field tests – multipass trials – radial tyres	2.08
Field tests – multipass trials – cross-ply tyres	2.25
Field tests – vehicle traction force measurements (DBP – drawbar pull tests)	1.43
Laboratory tests – single wheel (DBP – drawbar pull tests)	1.64

3. MMP method

In the beginning of the 1970s, Rowland (RARDE – Royal Armament Research and Development Establishment, UK) proposed an evaluation method for trafficability of ground with low bearing capacity by tracked vehicles, based on an analysis of maximum pressures under the wheels of a track. As a result of an analysis of unit ground pressure (stress) traces and resistance of tracked vehicles it was found that a precondition for trafficability of the ground with low bearing capacity is that its bearing capacity is not exceeded by an average of maximum stresses (unit pressures) under the wheels (Mean Maximum Pressure – MMP). Their value is determined with the following empirical relation [7, 8]:

$$MMP = \frac{1,26 \cdot W}{2 \cdot n \cdot b \cdot (t \cdot d)^{0,5}}, \qquad (10)$$

where: W – active gravitational mass (kN); b – track width (m); d – wheel diameter (m); t – track pitch (m).

It was defined on the basis of an analysis of pressure traces (stresses in the ground) under the tracks, measured during field tests on the depth of 0.25 m – the purpose was to obtain maximum possible consistency with trafficability test results. For vehicles equipped with track belts mating with pneumatic wheels, the MMP mobility number takes the form [9, 14]:

$$MMP = \frac{0,5 \cdot W}{2 \cdot n \cdot b \cdot (d \cdot \delta)^{0,5}}, \qquad (11)$$

where: δ – tyre deflection (m) on hard ground.

For wheeled vehicles, MMP is expressed by the following formula [5]:

$$MMP = \frac{k \cdot W}{2 \cdot n \cdot b^{0,85} \cdot d^{1,15} \cdot (\delta / h)^{0,5}}, \qquad (12)$$

where: k – coefficient of the number of driving axles (Table 3); W – active gravitational mass (kN); b – tyre width (inflated, no load) (m); d – outer diameter of a wheel (inflated, no load) (m); δ – tyre deflection (m) on hard ground; h – height of the tyre profile (inflated, no load) – over the rim, without tread (m).

The δ/h ratio depends mainly on tyre (carcass) rigidity and pressure in tyres. For preliminary estimates, it is assumed to amount to:

- δ/h = 0.18 – for nominal pressure (allowing for on-road travelling with a nominal speed at nominal load);
- δ/h = 0.25 – for pressure reduced to ca. 70% of nominal pressure (for off-road travel with reduced speed);
- δ/h = 0.35 – for pressure maximally reduced to ca. 30% of nominal pressure (for negotiating difficult trails) – at such a low pressure, the tyre's transversal rigidity decreases and the vehicle steerability becomes considerably reduced – at lower pressure the tyres may be damaged or even become detached from the rim.

The bearing capacity breakpoint defined by the formula (12) allows to express Rowland's Mobility Number for wheeled vehicles as:

$$MN_R = \frac{k \cdot n \cdot CI \cdot b^{0,85} \cdot d^{1,15}}{W} \sqrt{\frac{\delta}{h}}. \qquad (13)$$

Table 3. Coefficient *k* of the number of driving axles [5]

Tab. 3. Wartość współczynnika k liczby mostów napędowych [5]

Number of axles	Coefficient of the number of driving axles to the number of axles						
	1	3/4	2/3	3/5	1/2	1/3	1/4
2	3.65	-	-	-	4.4	-	-
3	3.9	-	4.35	-	-	5.25	-
4	4.1	4.44	-	-	4.95	-	6.05
5	4.32	-	-	4.97	-	-	-
6	4.6	-	5.15	-	5.55	6.2	-

Necessary multipass ground bearing capacity in the MMP method shall be determined according to the following formula [10]:

$$CI_n = k_n \cdot MMP \,, \tag{14}$$

where: k_n – coefficient of the number of passes (Table 4).

Table 4. Coefficient of the number of passes k_n in the MMP method
Tab. 4. Współczynnik liczby przejazdów k_n w metodzie MMP

Number of passes n	1	2	5	10	25	50
Coefficient of the number of passes k_n	1	1.20	1.53	1.85	2.35	2.80

Source: own work / Źródło: opracowanie własne

Once the broad-profile tyres became more popular, the δ/h ratio no longer provided a unique reflection of an increased tyre's contact surface with the ground as a result of pressure decrease. In low- and broad-profiled tyres, actual tyre deflection δ and contact surface were considerably lower than that typical of normal-profile tyres with the same δ/h ratio. The calculations could be more precise as a result of the new form of the MMP formula with the modified value of the "k" coefficient (Table 5) [4, 9]:

$$MMP = \frac{k_2 \cdot W}{2 \cdot n \cdot b^{0,85} \cdot d^{1,15} \cdot (\delta / d)^{0,5}} \,. \tag{15}$$

During further works, MMP models were also developed for vehicles equipped with twin wheels, with wheels of different sizes, and models for passing over sandy grounds [9].

On the basis of tests, three trafficability levels [5] were defined, depending on the MMP value typical of a given vehicle (Table 6): very good, good and acceptable. The first one corresponds to multipass or full operational abilities, while acceptable is typical of vehicles which demonstrate a single pass ability (technical mobility).

4. VLCI method

As subsequent publications were released on weak [10, 11, 13] or no correlation whatsoever [12] of traction forces determined according to the WES model with those obtained in tests, the British Defence Evaluation and Research Agency (DERA) decided in the 1990s to develop a more precise analytical method of VCI determination – it is now referred to as the Vehicle Limiting Cone Index (VLCI).

The method was based on the traction force tests completed using a single track mobile tester (wheel diameter, track pitch and load were modified) or a single wheel tester (tyre size and load were modified – only radial tyres were tested). In case of wheeled systems, the tyre was rolled 4 times back and forth, simulating a passage of a multi-axle vehicle. Most measurements, both for wheels and tracks, were taken at variable spin (20-100%), but for the sake of comparison, measurements as a constant spin of 20% were also taken. Movement of wheels and tracks were examined in the same ground conditions, and the ground bearing capacity was determined in an intact state (prior to passage) using the cone penetration method – CI. The tests proved that for the tested ground, RCI is lower by 30% (RI = 0.7) [6].

At the first stage, the results were standardised (in a way similar to the WES and MMP method) and an individual Mobility Number MN was developed [6]:

$$MN_{DERA} = \frac{CI \cdot b^{0,8} \cdot d^{0,8} \delta^{0,4}}{W_t} \tag{16}$$

hence, after transformation (for MN_{gr} = 1.85), the following formula was obtained [6]:

$$VLCI = \frac{1{,}85 \cdot W}{2 \cdot n \cdot b^{0,8} d^{0,8} \delta^{0,4}} \,. \tag{17}$$

Table 5. Coefficient k_2 of the number of driving axles [9]
Tab. 5. Wartość współczynnika k_2 liczby mostów napędowych [9]

Number of axles	Coefficient of the number of driving axles to the number of axles						
	1	3/4	2/3	3/5	1/2	1/3	1/4
2	1.83	-	-	-	2.20	-	-
3	1.95	-	2.17	-	-	2.62	-
4	2.05	2.22	-	-	2.48	-	3.02
5	2.16	-	-	2.48	-	-	-
6	2.30	-	2.57	-	2.77	3.10	-

Table 6. MMP breakpoints for skid-steer vehicles – ground bearing capacity measured using the CI method [5, 9, 14]
Tab. 6. Graniczne wartości MMP dla pojazdów o skręcie burtowym - pomiar nośności gruntu metodą CI [5, 9, 14]

Ground	Trafficability – allowable MMP value, kPa		
	very good (excellent)	good (satisfactory)	acceptable
wet, fine-grained – moderate climate	125 (150)	165 (200)	250 (300)
wet, fine-grained – tropical climate	75 (90)	115 (140)	200 (240)
peat soil	30	50	60
mire or bog	5	10	15
snow	10	25	40

This relation is correct for 4x4 up to 8x8 [6] drive systems – differences due to different number of axles do not exceed 5%. Its notation is similar to the MMP formula, from which an ambiguous tyre height *"h"* (measured with or without tread, measured to the rim's centre or edge) was removed, as was the δ/h ratio which prevented proper evaluation of tyre deflection impact on the ground contact surface.

Following the same procedure, the following formula [6] was obtained for tracked vehicles:

$$VLCI = \frac{1{,}56 \cdot W}{2 \cdot n \cdot b\ t^{0,5} d^{0,5}}. \tag{18}$$

5. Comparison of mobility evaluation methods

The Mobility Number formula assumed in the VLCI method for wheeled vehicles allows to obtain good correlation of the estimated traction forces with values obtained during tests using a mobile tester (Fig. 4) and shall be viewed as a significant improvement when compared with the WES model – Fig. 5. However, its reliability and suitability for estimation of vehicle traction forces have not yet been verified experimentally. Taking into account actual interactions between assemblies of the wheel and suspension system and of the drive system may have a significant impact on the obtained traction force characteristics.

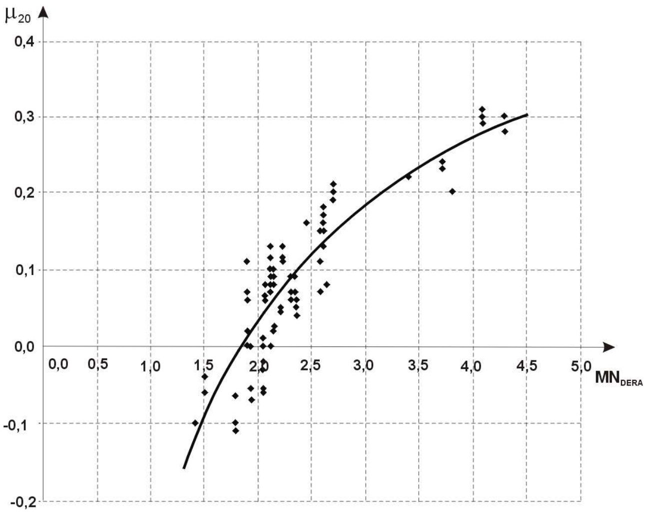


Fig. 4. Characteristics of the coefficient of traction of a tyred wheel μ_{20} as a function of the mobility number MN_{DERA} [6]

Rys. 4. Charakterystyka współczynnika siły uciągu koła ogumionego μ_{20} w funkcji wskaźnika mobilności MN_{DERA} [6]

What arises further doubts is the adopted MN breakpoint. In the light of experiments [9], for obtaining a technical (single pass) mobility level, a certain minimum surplus traction force must be available (coefficient of traction of ca. $\mu = 0 \div 0{,}1$) due to ground heterogeneity. The adopted value MN = 1.85 does not meet this criterion – measurement data (Fig. 4) indicate that the breakpoint should not be lower than $MN_{(\mu=0\div0,1)}$ = 2.15. This conclusion is also consistent with the WES test results (Table 2) which indicate that in case of wheeled vehicles, interactions taking place in the wheel and suspension system and in the drive system result in lowering trafficability. Testers are distinctly underrating the necessary ground bearing capacity in relation to bearing capacity necessary in case of actual wheeled vehicles.

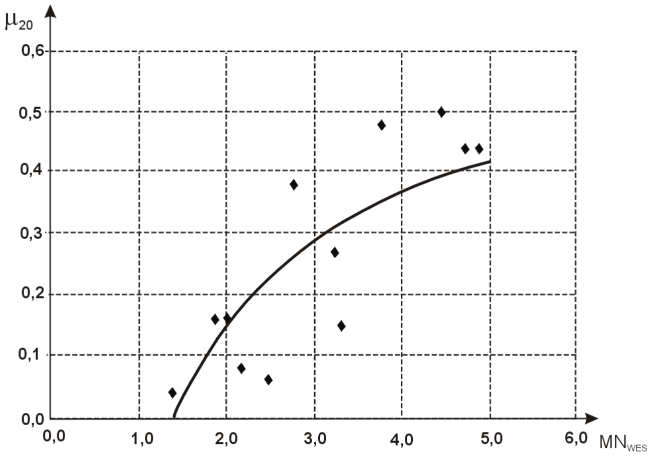


Fig. 5. Characteristics of the coefficient of traction of a tyred wheel μ_{20} as a function of the mobility number MN_{WES} [6]

Rys. 5. Charakterystyka współczynnika siły uciągu koła ogumionego μ_{20} w funkcji wskaźnika mobilności MN_{WES} [6]

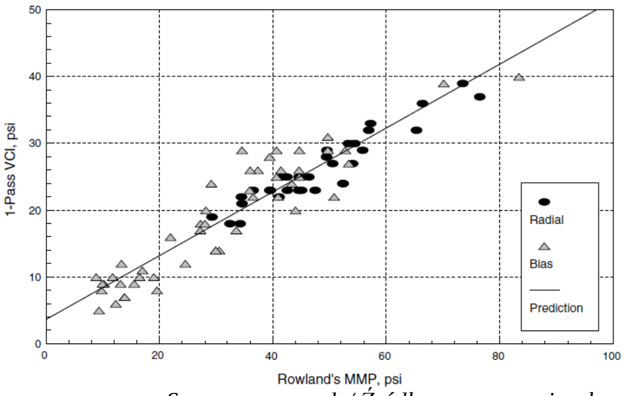
The VLCI formula in its current form results in much better results of wheeled vehicles, which can be noted by comparison of allowable weights of armoured wheeled vehicles with trafficability of ground with low bearing capacity comparable to that of the „Challenger 2" battle tank and of the „Warrior" tracked IFV – determined using the VLCI and MMP method – Table 7 [2]. Results obtained by the VLCI method are so much different from the MMP method results that they are highly questionable. In order to resolve this issue, actual ground pressures were measured for selected wheeled vehicles [3] and it was found that pressures determined using the MMP method are practically consistent with measurement results, while the VLCI method is distinctly underrating stresses in the ground. Poor reflection of ground pressures does not mean, however, that ground trafficability, dependent on the available traction forces, is estimated incorrectly. In order to decide which of the methods offers a better reflection of modern tyres' abilities, classical multipass trials shall be performed on clay soils with various bearing capacities.

It shall be noted that in spite of their different numerical values, results obtained using the VCI, MMP and VLCI are characterised by a very good correlation – Fig. 6 and Fig. 7. Evaluation criteria of the results are the key to reliable calculations and design recommendations. In the VCI method, an acceptable mobility level for heavy-duty vehicles, VCI = 30 PSI (pound per square inch) = 206 kPa is assumed (the M1 Abrams battle tank is characterised with VCI=29). In the MMP method, the same mobility level corresponds to MMP=300 kPa for vehicles with low swivel resistance (250 kPa for skid-steer vehicles). Therefore, these calculations may be treated interchangeably, taking into account that allowable MMP values are by ca. 50% higher than VCI. An advantage of the MMP method consists in easy access to the relations describing alternative, non-standard wheel and suspension systems, and clear evaluation criteria..

Table 7. Allowable weights of wheeled vehicles with the 8x8 drive system, with 16.00 R20 size tyres and a central inflation system [2]

Tab. 7. Dopuszczalne masy pojazdów kołowych o układzie jezdnym 8x8, wyposażonych w ogumienie o rozmiarze 16.00 R20 i centralny układ pompowania [2]

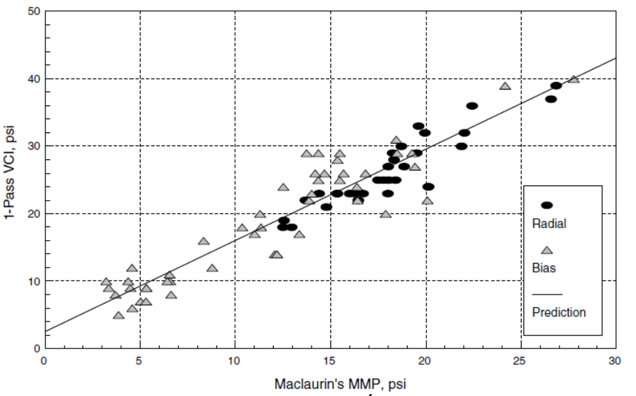
Required mobility level on the ground with low bearing capacity	Maximum weight of a wheeled vehicle determined using the MMP method, t	Maximum weight of a wheeled vehicle determined using the VLCI method, t
Comparable to the „Challenger 2" battle tank (weight: 62.5 t)	19	43
Comparable to the „Warrior" IFV (weight: 25.7 t)	14	32



Source: own work / Źródło: opracowanie własne

Fig. 6. Comparison of the MMP mobility number with the VCI one

Rys. 6. Porównanie zgodności wskaźnika MMP ze wskaźnikiem VCI



Source: own work / Źródło: opracowanie własne

Fig. 7. Comparison of the VLCI mobility number (MMP acc. to Maclaurin) with the VCI one

Rys. 7. Porównanie zgodności wskaźnika VLCI (MMP Maclaurin'a) ze wskaźnikiem VCI

6. Summary

Precise estimation of ground trafficability and of available traction forces depends mainly on the quality of the adopted Mobility Number model. Ground heterogeneity and a broad scope of its varying parameters result in a lack of a universal model. However, of vital importance are also the following factors: location of the centre of gravity in relation to the wheel and suspension system, design of drive systems and wheel and suspension systems, and rapidly developing production technologies of tyres and flexible track belts. Due to this progress, it is necessary to verify the adopted formulae and assumptions on an ongoing basis.

In fact, evaluation of the vehicles' trafficability of ground with low bearing capacity includes two issues:
evaluation of a single pass ability over ground with low bearing capacity;
evaluation of operation (multipass) abilities on the ground with low bearing capacity (estimation of the available traction force).

On the basis of the available data it can be said that the most comfortable method for estimation of available traction forces (operational ability evaluation) on drenched clay soils is the VLCI method. The assumed Mobility Number MN_{gr} = 1.85 as the trafficability breakpoint seems to be too optimistic. It is recommended to verify it empirically, in order to take into account interactions between wheel and suspension system assemblies and their influence on ground trafficability.

It seems that the most comprehensive and an adequately reliable method to-date for evaluation of ground trafficability and construction of wheel and suspension systems is the MMP model. It is based on verified empirical data; furthermore, its application scope was clearly defined and limited to technical mobility evaluation already at the designing stage. In addition, this method offers many models for various wheel and suspension systems and clear evaluation criteria.

All the presented trafficability estimation methods are based on an empirical relation. As a result, for the calculation and analysis results to be reliable, the following three requirements must be met:

- all the quantities used are expressed in specified units;
- design of the analysed vehicles and their wheel and suspension systems do not differ greatly from the solutions used in tests;
- parameters of the ground to be passed over do not differ greatly from the parameters of the ground on which test were conducted.

Ground bearing capacity tests undertaken in Europe indicate that the least trafficable (highly drenched) arable land after rainfall has features CI of ca. 130-200 kPa, while bog – of ca. 15-60 kPa. The differences are quite considerable and the developed models are based mainly on solutions typical of military vehicles passing over drenched arable fields. Therefore, the results obtained cannot be taken for granted, as they may be burdened with a relatively high error. In the designing process of wheel and suspension systems for machines operated in difficult wetland conditions, additional comparative research is therefore recommended.

7. References

[1] Bekker M.G.: Theory of land locomotion: the mechanics of vehicle mobility. University of Michigan Press, 1956.

[2] Hetherington J.G.: The applicability of the MMP concept in specifying off-road mobility for wheeled and tracked vehicles. Journal of Terramechanics, 2001, 38 (2).

[3] Hetherington J.G., White J.N.: An investigation of pressure under wheeled vehicles. Journal of Terramechanics, 2002, 39 (2).
[4] Larminie J.C.: Modifications to the mean maximum pressure system. Journal of Terramechanics, 1992, 29 (2).
[5] Larminie J.C.: Soft-ground performance of military vehicles. International Defence Review, 1988, 4.
[6] Maclaurin E.B.: The use of mobility numbers to describe the in-field tractive performance of pneumatic tyres. Proceedings of the 10th International ISTVS Conference, Harper Adams University, 2003.
[7] Rowland D.: Tracked vehicle ground pressure and its effect on soft ground performance. Proceedings of the International ISTVS Conference, Stockholm, 1971.
[8] Rowland D., Peel J.W.: Soft ground performance prediction and assessment for wheeled and tracked vehicles. Institute of Mechanical Engineering, 1975, 205, 81.
[9] Saarilahti M.: Soil interaction model. Development of protocol for ecoefficient wood harvesting on sensitive sites. Quality of Life and Management of Living Resources Contract No. QLK5-1999-00991. Report No. 3, Helsinki, 2002.
[10] Schmid I.C.: Interaction of vehicle and terrain results from 10 years research at IKK. Journal of Terramechanics, 1995, 32 (1).
[11] Shoop S.: Thawing soil strength measurements. Journal of Terramechanics, 1993, 30(6).
[12] Upadhyaya S. K., Wulfsohn, D.: Traction prediction for radial ply tyres. Proceedings of the 10th International ISTVS Conference, Kobe, Japan, 1990.
[13] Wong J.Y.: Wheel-soil interaction. Journal of Terramechanics, 1984, 21 (2).
[14] Wong Y.J.: Theory of ground vehicle. McGrow-Hill, 1993.