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IMPROVING A METHODOLOGY FOR ESTIMATING THE CROSS-COUNTRY ABILITY OF ALL-WHEEL-DRIVE VEHICLES

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The object of this study is the cross-country ability of four-wheel drive vehicles under off-road conditions.

Based on the results of analysis of known studies, it was determined that the procedures of experimental assessment of the load-bearing capacity of bearing surfaces (BS), based on the use of the cone index, are used in NATO member countries. They take into account the characteristics of the surface of the theater of operations and make it possible to determine the approximate speeds of all-wheel drive vehicles with the help of standardized computer software. In the procedures for assessing the load-bearing capacity of BSs, which use the soil deformation module E, there is no possibility for calculating the speed of the car with known axle loads. In addition, they provide for the determination of a number of parameters of the bearing surface, such as the coefficient of adhesion, the angle of internal friction in the soil, and the shear modulus during the formation of a track. This makes them much more difficult compared to the procedures used by NATO.

Therefore, the problem that is solved in this work is to improve the methodology for assessing the reference cross-country ability of four-wheel drive vehicles.

Based on the results of scientific research, motion modeling was carried out in the MATLAB Simulink environment to determine parameters of reference cross-country ability of four-wheel drive vehicles.

In order to determine the cross-country ability of samples of wheeled military vehicles (WMV) based on the indicator of the maximum pressure value (mean measure pressure – MMP), the conducted experimental studies were analyzed. They showed a difference in the speed modes of vehicles of the same gross weight but different layout schemes, within 11–12 %. Therefore, the methodology for assessing the cross-country ability based on MMP has been improved to take into account the features of the layout of WMV samples. Specifically, taking into account the different values of loads on the front axle of vehicles with hoodless and hood layouts at the same gross weight.

In general, the improved procedure makes it possible to give a quantitative assessment of the movement mobility of WMV samples with various layout schemes and an assessment of their potential cross-country ability on the basis of the proposed refinement of MMP calculation

Keywords: bearing capacity of the soil, motion simulation, reference car cross-country ability, determination of the cone index, cross-country ability assessment according to MMP

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1. Introduction

Designing all-wheel drive vehicles of the new generation is a priority task dictated by the transition of NATO member states, China, etc. to the latest models of vehicles that meet the requirements formed by the experience of their use in military conflicts. On the other hand, with the beginning of hostilities in Ukraine, the urgent need of combat units for four-wheel drive vehicles adapted for use in hybrid wars became obvious. The experience gained by the Ukrainian military allows us to conclude that the technical characteristics of four-wheel drive vehicles of Soviet production do not match the nature of the tasks to be solved and the low ability to perform tasks under difficult road and climatic conditions. Under such conditions, it is necessary to quickly design and put into production new models of military vehicles that meet the requirements of the experience of conducting modern local wars and armed conflicts.

One of the important operational characteristics of four-wheel drive vehicles is their cross-country ability under off-road conditions. It is known that changing the design parameters of a four-wheel drive car to increase cross-country ability can lead to a decrease in its operational characteristics on highways. An important and relevant component of the development of all-wheel drive vehicles of the new generation is the choice of optimal structural parameters that will allow it to be used with maximum efficiency on public roads and in the terrain.

Under the conditions of the armed conflict and the strategic goal of joining NATO, which was declared at the legislative level, regulatory requirements for military vehicles developed during the time of the former USSR remain valid in Ukraine. These requirements, taking into account the experience of military conflicts and achievements in the development of four-wheel drive vehicles, have already been changed in Russia, and have also lost their relevance in Ukraine today.

Under such conditions, the methodology for assessing the cross-country ability of a four-wheel drive vehicle both at the design stage and during its practical operation of the sample needs improvement. The issues of vehicle movement on hard bearing surfaces (BS) and roads with high bearing capacity have been studied at a sufficient level. However, the majority of real BSs are uneven and differ in physical and mechanical properties of soils both in length and in seasons. The processes of interaction of all-wheel drive vehicles with deformed BSs are much more complicated and insufficiently researched. Therefore, improving the methodology for assessing the reference cross-country ability of four-wheel drive vehicles is an urgent problem, the solution of which will make it possible to increase the efficiency of the use of four-wheel drive vehicles under the conditions of soil inhomogeneity, as well as uneven deformed BSs.

2. Literature review and problem statement

In work [1] it was determined that the properties of tires and their models play a more important role in all types of vehicle dynamics research. Also, the theoretical foundations of the mechanics of the interaction of an off-road vehicle with off-road (terramechanics) are given. In addition, the need for systematic studies of the principles of rational development and design of off-road vehicles using modern modeling technologies is substantiated. However, the work does not provide models for determining the cross-country ability of a specific car.

Work [2] reports the results of research on the development of detailed maps of cross-country ability, which are used for military purposes. It is shown that the development of the author's methodology uses the data of high-resolution relief models. They are obtained with the help of on-board laser scanning and photogrammetry from an unmanned aerial vehicle and are used to develop maps of the cross-country ability of military vehicles. At the same time, these studies do not take into account changes in the humidity of BS in real time.

Paper [3] proposed a method for evaluating tire and road parameters by combining offline and online identification. In particular, a 3-DOF nonlinear dynamic model is built, and the interaction between the tire and the road is described by the Brasch nonlinear tire model. Later, the horizontal and longitudinal stiffness of the tire is determined offline using a particle swarm optimization algorithm with adaptive inertia weight. Referring to the formula of the Burckhardt adhesion coefficient, the recursive least squares method is applied to determine the road adhesion coefficient in online mode. The specified procedure was developed to assess the cross-country ability of robotic wheeled vehicles, and for its practical implementation it is necessary to use a significant array of input parameters and characteristics of BS and tires.

Work [4] devised a method for determining access routes to hard-to-reach places located outside the regular transport network. The research used the existing road network, terrain maps, as well as high-resolution digital terrain models along with vehicle traction parameters. This made it possible to carry out a detailed analysis of the microrelief and exclude hard-to-reach areas of the terrain, the use of which is unlikely under the conditions of the use of military vehicles (WME) during hostilities.

In [5], a method of identifying the movement of a convoy of SUVs was developed, in which a data set with the involvement of a platoon was used for evaluation, and the proximity of the car, speed, and direction of movement were chosen as the criteria of the geographic information system. The method devised allows one to correctly determine the movement of a convoy off-road, and to estimate the relationship between the speed of the vehicle on and off the road. The cited work is focused on the same type of vehicles and does not make it possible to determine the speed of the convoy with different types of automatic transmission with sufficient accuracy.

In [6], terrain relief was evaluated based on the rules for classifying off-road cross-country ability into four traffic categories: good, limited, limited by engineering measures, and difficult. This makes it possible to improve the assessment of off-road terrain in difficult-to-access areas in many countries of the world. A comprehensive assessment of favorable factors is quite difficult, as it is necessary to additionally take into account other little-studied factors. Due to the available research, it is possible to obtain separate maps for tracked and wheeled vehicles in four categories. The work considers the assessment of the cross-country ability of the terrain and allows for the assessment of the mobility of the movement of various machines.

In [7], a method of collecting and measuring parameters of the vehicle's geometric cross-country ability is considered. The method makes it possible to replace the current empirical manual measurement methods and efficiently perform data collection tasks since the geometrical parameters of cross-country ability are key to ensuring the cross-country ability of vehicles. At the same time, the work does not consider the parameters of the basic cross-country ability, which form the mobility of the WMV movement.

However, the question of forming the cross-country ability and mobility of military vehicles with different off-road layouts remains unresolved. All this gives grounds for conducting a study aimed at the development of methods for determining the cross-country ability of military vehicles on off-road roads, which is vitally necessary if they are to be used during hostilities.

3. The aim and objectives of the study

The purpose of our study is to improve the methodology for assessing the basic cross-country ability of four-wheel drive vehicles under off-road conditions and the index of cross-country ability assessment MMP.

To achieve the goal, the following tasks are set in the work:

– to build an improved Simulink-model of the movement of a four-wheel drive car off-road;

– to assess the mobility of a particular type of four-wheel drive vehicle taking into account soil deformation;

– to determine the possibilities for improving the calculation of the MMP cross-country ability assessment indicator, taking into account the peculiarities of the layout of WMV samples.

4. The study materials and methods

The object of our study is the cross-country ability of four-wheel drive vehicles under off-road conditions.

The hypothesis of the study assumes the possibility of improving the assessment of the reference cross-country ability of four-wheel drive vehicles under off-road conditions through the improvement of the appropriate methodology based on simulation modeling.

The following assumptions and simplifications were adopted during the research:

– the same resistance to the driving wheels of the left and right sides of the WMV model is assumed;

– for horizontal BSs, the dynamics of the suspension is not taken into account, which does not affect the mobility of WMV sample;

– three-axle vehicles with balanced suspension of the rear axles are reduced to an equivalent two-axle model.

The parameters and approaches for assessing the geometric cross-country ability of four-wheel-drive vehicles are fairly unambiguous and standardized in NATO member countries [7].

As for the assessment of the reference cross-country ability of four-wheel drive vehicles, it is necessary to state significant differences in the methodology of the assessment of characteristics in the studies and the normative base of almost two different scientific schools. This applies to the scientific school used by most of the countries that were part of the former USSR (hereinafter referred to as «Eastern») and the scientific school used by NATO member states (hereinafter referred to as «Western»).

Common to the existing approaches to assessing the cross-country ability of all-wheel drive vehicles of the «Eastern» and «Western» scientific schools, based on the theory of car movement, is the condition of the movement of the excess of the traction force on the wheels F_k of the total movement resistance force F_f, provided that the traction force F_k is less than the traction force of the tires with the road F_φ, because otherwise movement is impossible [8].

Hence the difference between the coupling coefficients φ and the movement resistance f, as a condition for the possibility of movement. This happens due to exceeding the value of the tire adhesion coefficient φ, the wheel resistance coefficient f corresponding to the given surface. Accordingly, in the «Western» methodology for evaluating cross-country ability, the movement coefficient μ appears, which is equal to the ratio of the difference in the corresponding values of the traction forces and movement resistance to the weight of the car G_a:

$$\mu = \frac{F_\varphi - F_f}{G_a} = \frac{G_a(\varphi - f)}{G_a} = j - f. \quad (1)$$

Similar in physical essence is the assessment of cross-country ability in the methodology of the «Eastern» scientific school, which is introduced as an indicator into the legislative framework – the so-called zone of the specific traction force on the towing hook K_T, i.e., the difference $F_\varphi - F_f$, attributed to the weight of the car while neglecting the aerodynamic component movement, insignificant at low speeds. However, according to the data of road tests, it can be stated that the threshold values of $K_T \geq 0.250$ required by the regulatory requirements are provided at the minimum allowable air pressures in the tires and correspond to speeds significantly lower than the real ones [8]. Also, when moving at the maximum possible speed, the amount of traction force on the hook goes to zero, which formally, according to the normative assessment, gives a negative assessment of cross-country ability according to the criterion K_T. Road tests of vehicles regarding the assessment of cross-country ability according to the indicator K_T also adopt a certain assumption regarding the fixation of the amount of traction force on the hook with a dynamometer in the connecting rod with the towing vehicle (trailer). However, the latter moves along the already laid track of the front car (actually, the object of assessment) and corresponds to different values and ratios of the coefficients of adhesion φ and movement resistance f.

Significant differences in the approaches to the assessment of the cross-country ability of the «Eastern» and «Western» scientific schools begin with different indicators of the support and traction characteristics of the traffic surface.

For the «Western» scientific school, the WES (Waterways Experiment Station) method, implemented by the US Army Corps of Engineers since World War II, is dominant. It allows one to evaluate the load-bearing capacity of the BS movement (soil, sand, etc.), using a standardized measurement of its resistance to deformation with a cone-shaped penetrometer. The angle of the cone is 30° with a base area of 0.5 in^2 – inch square – 3.23 cm^2, moving to a depth of 15–20 cm with a speed of movement of 3 cm/s. This procedure was reflected back in the 1970s in the ISVTV standard [9] and the ISO standard – termed the cone index CI. The CI indicator, as a basic one in NATO, is the basis of the developed method for determining the cross-country ability and assessing the mobility of WMV [8]. Approximate ranges of CI values for different types of BS are given in Table 1.

Table 1

Value of the cone index CI for different types of support surfaces

No.	Type of support surface	CI, MPa
1	Snow (fresh – firn)	0.01–0.04
2	Swampy soils, uncompacted peatlands	0.18–0.44
3	Sapropel, silt (silt) uncompacted	0.09–0.18
4	Arable land	0.13–0.20
5	Soil, loam, fluid plastic	0.4–0.9
6	Soil, loam fluid	0.3–0.4
7	Uncompacted sand (0.1–0.2 m in track)	0.013–0.03
8	Compacted sand (0.1–0.2 m in track)	0.74–1.2

The methodology for assessing the cross-country ability of the «Eastern» scientific school is based on the quantitative assessment of the resistance of indentation in the BS of the stamp, with an area of 600 to 5000 cm^2, depending on the type of BS. Then the calculation of the basic indicator – soil deformation modulus E, N/cm^2 is carried out according to Schleicher's formula, taking into account the settlement of the stamp and the load on it. In addition, two empirical coefficients are taken into account, the lateral expansion of the soil (BS) and the coefficient that takes into account the material and shape of the stamp [10].

In addition, for the assessment of cross-country ability and computer simulation – the calculation of the movement of four-wheel drive vehicles under off-road conditions, it is also necessary to determine a number of parameters of BS: the coefficient of adhesion, the angle of internal friction in the soil φ_0, and the shear modulus C_0 during the formation of a rut.

Taking into account the methodological differences in the assessment of cross-country ability by «Eastern» and «Western» scientific schools, it is necessary to emphasize the need to assess this aspect with the help of computer simulation. This approach makes it possible to more fully and accurately assess traffic parameters under difficult road conditions and off-road.

In work [11], a method for assessing the cross-country ability of WMV is proposed, which is based on the achievements of the «Eastern» and «Western» scientific schools, which is used by NATO member countries. In addition, the specified method takes into account the work experience and the database on the physical and mechanical properties of BS in the territory of Ukraine. The developed method is based on empirical dependences used by the «Eastern» scientific school and is problematic for evaluating movement mobility.

Accordingly, it is necessary to improve the Simulink model developed in [11], which makes it possible to estimate the impact of the physical and mechanical characteristics of BS on the cross-country ability and mobility of a sample of WMV on a specific type of off-road, according to the methodology of the «Western» scientific school.

5. Results of studies on the assessment of the cross-country ability of all-wheel drive vehicles under off-road conditions

5. 1. Improvement of the Simulink model of movement of four-wheel drive car off-road

Evaluation of the car's cross-country ability under off-road conditions is practically a determination of the maximum possible speed of movement, which is set by the correspondingly selected operating modes of the engine and transmission under the conditions of limited tire traction with BS.

At the first stage, the dynamic equivalent scheme of two-axle vehicles during the movement of the deforming BS was improved (Fig. 1).

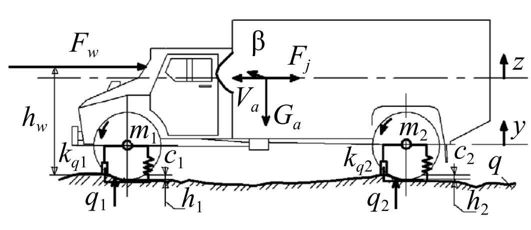

Fig. 1. Dynamic equivalent scheme of two-axle vehicles when moving on a deformable support surface

This makes it possible to take into account the movement resistance during soil deformation. This approach is applied in accordance with WES and other methods of assessing the cross-country ability of all-wheel drive vehicles of the «Western» scientific school.

The study is based on a two-dimensional equivalent model of the dynamics of a WMV sample on a deforming BS:

$$\begin{cases} M_a\ddot{z}_a = \left(k_{q1}\cdot a + k_{q2}\cdot b\right)\dot{\beta} + \\ +\left(k_{q1}+k_{q2}\right)\dot{z}_a + \left(c_{q1}+c_{q2}\right)z_a = \\ = k_{q1}\dot{q}_1 + k_{q2}\dot{q}_2 + c_{q1}q_1 + c_{q2}q_2; \\ J_a\ddot{\beta} + \left(k_{q1}\cdot a^2 + k_{q2}\cdot b^2\right)\dot{\beta} + \\ +\left(c_{q1}\cdot a^2 + c_{q2}\cdot b^2\right)\dot{\beta} = \\ = k_{q1}\cdot a\cdot\dot{q}_1 + k_{q2}\cdot b\cdot\dot{q}_2 + c_{q1}q_1 + c_{q2}q_2, \end{cases} \quad (2)$$

where M_a is the sprung mass of the car; J_a is the moment of inertia of the car body; β is the angle of longitudinal oscillations; z_a – vertical movements of the sprung mass; k_{q1}, k_{q2} – damping coefficient of the support surface at the point of contact of wheels 1 and 2 of axle; c_{q1}, c_{q2} – stiffness coefficient of the support surface; a is the distance from the front axle to the center of oscillations; b – distance from the rear axle to the center of oscillations; q – disturbance from the micro profile of the support surface.

In NATO countries, the assessment of the cross-country ability of WMV is based on the assessment of the load-bearing properties of the vehicle based on the empirical determination of VCI (vehicle cone index), which is also the basis of the improved method. In addition, in the improved Simulink model, the results of the conducted research on the quantitative and correlational assessment of the relationship between the values of the cone index VCI and the deformation modulus E, as well as the existing empirical base of the physical and mechanical characteristics of soils in Ukraine [12] were used.

The main differences of the improved Simulink model are:

– calculation of the technically possible maximum movement speed V_{max} of a specific model of WMV on a given BS with defined physical and mechanical deformation characteristics;

– specification of the engine characteristics in the form of a two-dimensional numerical tabulated array with interpolation in the ENGINE subprogram of the current values of the engine operating mode according to the methodology;

– automatic gear selection in the transmission for the determined traction force and driving speed (including modes of maximum fuel supply to the engine) – by logical setting of a selection of load variants of the engine operation mode brought to the ENGINE drive wheels.

The variant of the simulation model according to the WES method differs by the introduction of the characteristics of the same BSs based on the assessment of CI – the cone index with the option of recalculating the values of the deformation modulus – Young's modulus E by correlation dependence in CI. In addition to reproducing the set speeds and determining the maximum possible speed of a specific four-wheel drive vehicle for a given BS, VCI and MMP are calculated [8, 11].

The calculation of the maximum possible speed of movement for the given parameters of BS and loading the car, including the trailer, is performed under the conditions of achieving 10–20 % slippage of the driving wheels and the maximum tire grip with almost all types of BS.

The structure of the construction of the movement model according to the research of the «Western» scientific school was based on the analysis of publications on the given topic and was formed from the following stages:

– setting (determining) the numerical value of CI (MPa) for a specific type and state of BS;

– the calculation of the cross-country ability index MN for the known value of the cone index CI of BS and a specific type of four-wheel drive vehicle is calculated according to the procedure given in [13].

The cross-country ability index MN is an indicative indicator, the value of which is used to assess the cross-country ability of this BS and to further calculate the depth of the rut, coefficients of rolling resistance and tire adhesion to the road. The rut depth was calculated on the basis of the empirical dependences defined in [11].

Also, the coefficients of resistance to deformation of BS – movement resistance *f* and the coefficient of adhesion of the tire to BS μ for snow-covered BS and those close to them in the CI of dry sandy deserts were calculated according to [8]. Taking into account the vertical load on the wheel of the car, the motor resistance force at the specified BS and the tire adhesion force with the surface, and accordingly, the necessary traction force close to the wheel slip limit $S=0-0.2$, are determined. This ensures the maximum possible speed of movement V_{max} at the maximum possible higher gear for the required traction force on the wheels and, accordingly, a kinematically higher speed.

Separately, according to the WES methodology, the cross-country ability indicator of all-wheel drive vehicles was determined – the cone mobility index VCI [13]. According to the British RARDE method, the so-called maximum effective pressure on the BS – MMP was determined [14].

BS compaction, depending on the number of axle passes, is estimated by the corresponding increase in the CI value by 1.85 times when 10 axles pass and up to 2.80 when 50 axles pass [8].

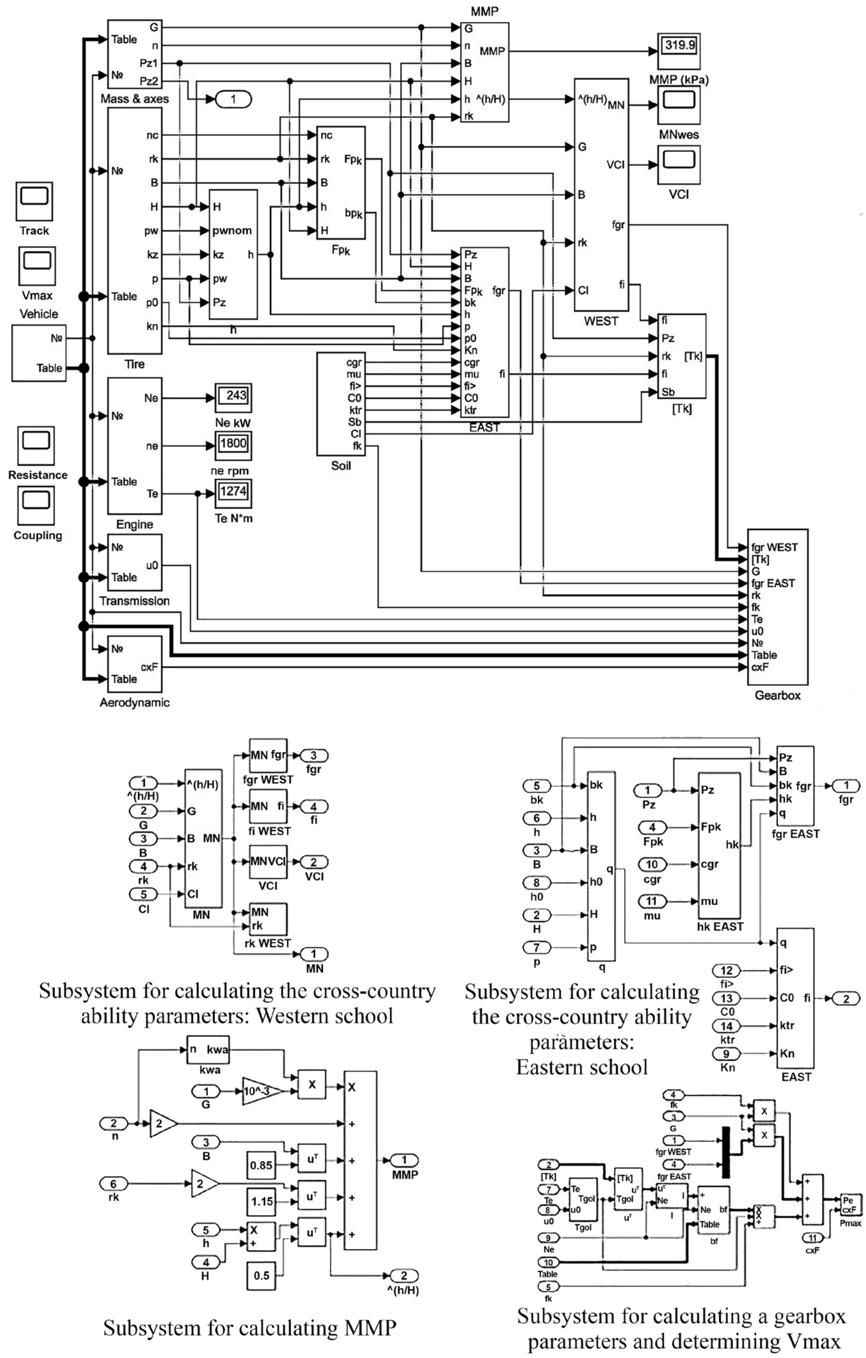

Fig. 2. Improved Simulink model for determining V_{max} and other cross-country ability parameters based on empirical data from the «Eastern» and «Western» scientific schools (built using the model given in [15])

In the development of Simulink model [15], an improved model was built, which allows determining the maximum possible speed of movement V_{max} on specific off-road roads due to the introduction of a calculation block for selecting transmission gears, taking into account the physical and mechanical properties of a specific off-road road.

The improved Simulink model of the movement of a sample of WMV off-road in the MATLAB Simulink software environment based on the empirical dependences of the «Eastern» and «Western» scientific schools is shown in Fig. 2.

In this way, the procedure for assessing the cross-country ability of WMV sample has been improved, which takes into account the achievements of the «Eastern» and «Western» scientific schools and allows comparing the results of simulation modeling and experimental studies [12].

5. 2. Results of assessing the cross-country ability of a specific type of four-wheel drive vehicle, taking into account soil deformation

Assessment of the adequacy of the proposed off-road model of the KamAZ-4310 all-wheel drive vehicle developed in the MATLAB Simulink software environment requires thorough experimental studies that would allow obtaining the appropriate parameters of the movement of various types of BS.

According to the classification of types of roadless terrain, which is typical for the territory of Ukraine and actually generally accepted (with certain deviations of the numerical values of the characteristic parameters), the following measuring areas were selected:

– site No. 1: sandy loam with a natural moisture content of 15.3 %, soaked to a depth of 0.1 m, with a change in the profile value of ±0.1 m, 115 m long (Fig. 3, *a*);

– site No. 2: sandy loam with a natural moisture content of 14.8 %, soaked to a depth of 0.1 m, with a change in the profile value of ±0.3 m, 98 m long (Fig. 3, *b*);

– site No. 3: light sandy loam with a natural moisture content of 23.5 %, soaked to a depth of 0.1 m, with a change in the profile value of ±0.1 m, 118 m long (Fig. 3, *c*).

a *b* *c*

Fig. 3. General appearance of sites for conducting experimental studies: *a* — sandy loam; *b* — sandy loam; *c* — light sandy loam

The experimental assessment of the deformation characteristics of BS of the test areas was carried out according to the procedure for assessing the conic index CI, adopted in the standards, and the assessment of the cross-country ability of NATO armies. The resulting CI values for a specific type of BS make it possible to determine the corresponding values of the soil deformation modulus *E* (Young's modulus) according to known dependences [8]. Numerical values of the basic indicators of the load-bearing capacity of the soil elasticity module *E*, MPa, and cone index CI, MPa, of BS according to the specified methodologies are given in Table 2.

In the developed model, the calculation of cross-country ability indicators for the selected four-wheel drive vehicle, taking into account its mass during experimental studies and tire characteristics, was performed according to the procedures by the Eastern and Western scientific schools. These procedures are described in detail in [8, 11]. The values of cross-country ability indicators obtained in this way for the corresponding types of BS are given in Table 3.

Table 2

Main characteristics of research BS

No.	Basic indicators of the bearing capacity of BS	Moist sandy loam with a depth of <1 m	Moistened sandy loam with a depth of >1.5 m	Moist loam, light
1	Modulus of soil elasticity *E*, MPa	1.17	0.82	1.25
2	Cone Index *CI*, MPa	0.57	0.4	0.61

Table 3

Cross-country ability indicators of the KamAZ-4310 all-wheel drive vehicle according to NATO procedures for experimental sites of BS

No.	BS type	Moist sandy loam with a depth of <1 m		Moistened sandy loam with a depth of >1.5 m		Moist loam, light		MMP, kPA
	Value	MN	VCI_1	MN	VCI_1	MN	VCI_1	
1	KamAZ-4310	8.4	16.39	5.9	16.73	8.95	16.36	328

In order to assess the adequacy of the empirical dependences of the description of the effect of compaction of BS during subsequent passes along the already laid track, the corresponding runs were conducted for 3 types of BS. Experimental studies are averaged by 4–5 times duplication on each of the 3 types of experimental plots and the laying of the first track.

Fig. 4 shows the results of the specified studies on determining the maximum possible speed of the KamAZ-4310 all-wheel drive vehicle.

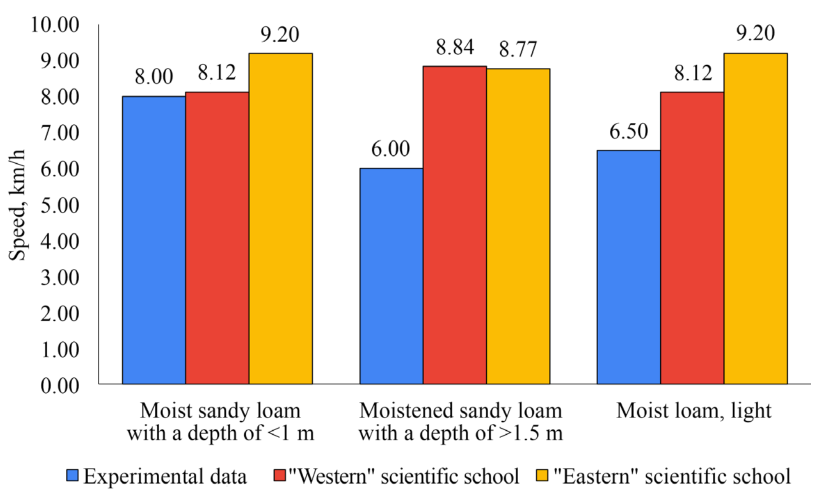

Fig. 4. Calculated and experimental evaluations of the speed modes of the KamAZ-4310 vehicle for specified support surfaces [15]

First of all, it should be noted that with modern multi-stage transmissions, the subjective factor of the driver's qualifications plays a big role in choosing a gear and engine operation mode for a specific section of BS.

This explains the difference in the obtained results of potentially possible high-speed modes of movement, calculated by the method of simulation modeling and the program for selecting the transmission and engine operating modes and experimental data. The second significant aspect of the results is the dissonance of the qualitative assessment of the potential and experimental estimates of the speed of movement when the type and state of BS is changed, which is more characteristic, in fact, of the methodology by the «Eastern» school.

5. 3. Improving the calculation of the MMP cross-country ability assessment indicator, taking into account the features of the layout of WMV samples

It has been experimentally confirmed that the real reference cross-country ability with a comparable gross weight is somewhat better in vehicles with a hood layout, which is proven by the results of research on the identical UrAL-4320 and KamAZ-4311. The same situation is repeated for MAZ-6317 and KrAZ-6322. However, according to the MMP indicator, these machines are identical (Table 4).

The front axle of the car actually forms the supporting cross-country ability and technically the maximum speed of off-road movement, which practically lays a track, the depth of which depends primarily on the load on this axle and the dimensional characteristics and tread of the tire. Therefore, when calculating the MMP indicator, the feature of the layout in the model must be taken into account. But at the same time, enter the data of the partial weight of the car W_a with empirically determined coefficients of the number of axles k, and directly the load on the front wheel or front axle W_k. Also, at the same time, it is necessary to take into account the distribution of pressure on 2 wheels.

There is a problem of collecting a sufficient base of experimental data and statistical generalization of the influence of the number of leading axles k on the formation of a logically modified MMP cross-country ability indicator:

$$MMP_k = \frac{k_1 w_1}{2nwid^{0.85} d^{1.15} \sqrt{\delta/h}}, \quad (3)$$

where k_1 is the coefficient of axles; W_k – load on the front axle, kN; n – the number of axles, wid – the width of the tire in the area of the tread profile; δ/h – specific deformation of the tire on an undeformed hard surface ($\delta/h=0.18$ at the rated tire pressure for the rated weight and speed of vehicles for the highway, $\delta/h=0.25$ at a pressure of 70 % of rated for four-wheel drive SUVs with a full weight, 0.35 – similarly when the tire pressure is reduced to 30 % of rated).

In addition, an appropriate study is obviously needed regarding the possible adjustment of the values of the empirical coefficient k_1 in comparison with the known values of k. The regulatory framework, in addition to the requirements for the necessary threshold minimum permissible values of the profile and reference cross-country ability of wheeled WMV, should also regulate the procedure for assessing the compliance of specific samples of WMV with these requirements. The load-bearing capacity, physical and mechanical characteristics of even one type of soil, loam or sandy loam and others, have the same range of fluctuations in the values of the estimated parameters CI or the modulus of soil deformation E depending on humidity, fractional composition, etc. Therefore, the experimental assessment of the compliance of BS cross-country ability indicators should be carried out on an experimental off-road section with a clear quantitative assessment of the indicator – CI characteristics.

6. Discussion of the analysis of studies on the assessment of the cross-country ability of four-wheel drive vehicles under off-road conditions

A feature of the improved cross-country ability assessment methodology developed in the work is the development of the approaches to assessing the mobility of off-road traffic defined in works [4, 6]. The results make it possible to determine the speed regimes of all-wheel drive vehicles when moving off-road in real time, which is absolutely necessary for planning their routes under the conditions of military operations. In addition, the specified procedure allows making certain adjustments to the car's design to increase its cross-country ability already at the stage of design work.

In comparison with the testing centers of WMV in Europe, including the US Army in Lauterbach (Germany), Ukraine is characterized by a large part of the territory with chernozems (mainly Central and Eastern Ukraine), peatlands (Volyn, Northern Ukraine) and sandy BS (Kherson and Mykolaiv oblasts). One and a half to three times the ranges of fluctuations in CI values at the same humidity for the above-mentioned BSs predetermine the expediency of introducing typical test plots (plowed chernozem and earthy peat) into the list of normative types of BSs.

The purpose of these tests is an experimental assessment of the maximum possible technical speed of movement of a specific sample of WMV on the relevant categories of BS, as well as a comparison with similar indicators of other WMV models.

In addition to fixing the technically possible maximum speed for these typical BSs, an important evaluation indicator is the track depth, which is significantly correlated with the axle load and tire size. It is fixed after the tested sample of WMV has driven over it.

Table 4

Indicators of the structural support cross-country ability MMP of WMV

Model	UAZ-3151	GAZ-66	ZIL-131	URAL-4320	KamAZ-4310	KrAZ-5233	MAZ-6317	KraZ-6322
Full weight, kg	2,440	7,770	10,185	13,215	15,205	17,300	25,150	22,800
Tire type	215/90R15	12.00R18 320x80R457	12,00R (320R508)	390/95R20	IP-184 1220x400-533	550/75R21	530/70R21	530/70R21
MMP, kPA	304	406	408	470	539	466	545	526
MMP_k, kPA	236	414	344	441	524	430	483	438

Our results in the work are explained by the fact that the improved Simulink model (Fig. 2) was used to determine V_{max} and other vehicle cross-country ability parameters based on empirical data from the «Eastern» and «Western» scientific schools. In particular, it should be stated that there is a sufficient convergence of the obtained simulation and experimental results for the KamAZ-4310 truck in the range of 0.12–2.84 km/h depending on the type of BS (Fig. 4). The largest deviations are characteristic of a drier section of sandy loam, with greater fluctuations in the height of micro profile irregularities. The latter was set in the form of a tabulated array of data, which led to a decrease in the calculated speed of movement according to the «Western» school, which also corresponds to a certain decrease in speed according to experimental data. At the same time, this is not taken into account by the empirical dependences in the methodology by the «Eastern» scientific school, which caused, on the contrary, an increase in the corresponding calculation speed. This is due to a decrease in the humidity of BS and a corresponding change in the value of the deformation modulus E.

At the same time, there is a certain dissonance of speed modes when switching to moist, light loam. According to the simulation results, a higher speed is observed than obtained according to experimental data. This is explained by the fact that the calculation using the Simulink model was carried out in a higher gear. However, during experimental studies, the driver used a lower gear of the car, compared to the theoretically and technically possible higher gear. Under such conditions, its technical capabilities were not fully realized.

A comparative analysis of the cross-country ability assessment indicators used by the «Western» scientific school – *MN*, *VCI*, *MMP* (Table 4) with the results of computer simulation and experimental studies proves the comparability of the assessment and the model's operability for practical use [12]. Based on approximately the same values of MMP for both samples of WMV, a difference in the experimental values of speeds on the sandy BS of 11–12 % was obtained, depending on the tire pressure. To a certain extent, this correlates with the difference in the assessment of the passing of these models of WMV according to the MN, VCI indicators.

From the analysis of research, it follows that in the European countries of NATO, the determining structural indicator of the cross-country ability of wheeled armored personnel carriers is MMP, put into practice by the center of scientific and research work in the field of armaments of Great Britain.

Along with the fact that the results of analysis and research, including experimental ones, proved, the MMP indicator is based on the usual for European NATO armies, the same type of composition of vehicles of the same class. In Ukraine today, the military uses different models of the same class of WME, which differ in layout and, accordingly, uneven distribution of loads on the axles. As an example, KamAZ-4310 with hoodless layout and UrAL-4320 with hood layout, or respectively MAZ-6317 and KrAZ-6322, were used.

The MMP indicator, unlike MN and VC, is «insensitive» to the hood or hoodless layout of WMV samples, i.e., the unevenness of the distribution of the identical total mass of the car along the axles. This is confirmed by the above-mentioned results of comparative studies – assessment of dry sand permeability of BSs that are practically identical in terms of total weight and power drive and UrAL-4320 and KamAZ-4310 tires (Table 4). With equal MMP values for both samples of WMV, the difference in the front axle load of 470 kg in the hooded UrAL-4320 with the corresponding additional load of both rear axles by 630 kg due to a greater equipped mass by 130 kg compared to the hoodless KamAZ-4310 caused the difference in the experimental determined possible speeds on sandy road surface from 11 % at reduced pressure to 0.1 MPa to 12 % at nominal tire pressure. In a certain way, this correlates with the difference in the assessment of the passage of these models of WMV according to the MN, VCI indicators.

The indifference of the MMP indicator to the uneven distribution of loads on the axle is also confirmed by the results of an experimental assessment of the roadworthiness of almost the same type of KamAZ-4310 and UrAL-4320 vehicles with the same values of the MMP indicator, but the obvious maximum speed achieved on the sandy BS actually in the UrAL-4320 due to the lower load on the front axle, despite the corresponding increase on both rear axles, which move on an already compacted track. The same situation is repeated for KrAZ-6322 and MAZ-6317.

For soils characteristic of Ukraine, the research must be carried out both at the rated air pressure in the tires and at reduced to 30 % of the rated with the corresponding recalculation of MMP (MMP_k).

Research results are limited by the accepted types of BSs, their characteristics, and car models.

The shortcomings include an insufficient information array of data, primarily experimental, regarding the values of the empirical coefficient k_1 (3) for various car wheel designs. Therefore, the further development of research necessitates the collection of a certain base of empirical data on BS typical for Ukraine, primarily chernozem. This will make it possible to form a complete database for the assessment of cross-country ability according to the MMP_k indicator, which requires separate experimental studies for different layout schemes. Therefore, the development of this research may consist in the further improvement of the developed methodology with the transition to a spatial 3D model and possible deviations of the BS characteristics for the left and right wheels of the vehicle. The issue of introducing restrictions on speed modes of off-road traffic, taking into account the threshold values of vibrational loads [12], is also relevant.

7. Conclusions

1. An improved Simulink model has been proposed for the movement of a four-wheel drive vehicle off-road for determining V_{max} and other parameters of cross-country ability based on the empirical data of the «Eastern» and «Western» scientific schools. The specified model differs in that it makes it possible to determine parameters of reference cross-country ability of four-wheel drive vehicles, in particular the maximum possible speed of movement, taking into account the physical and mechanical properties of the soil and the potential cross-country ability according to the MMP indicator. Also, it makes it possible to evaluate and make the necessary adjustments to the characteristics of the power drive, tires, and general layout solutions already at the stage of design work.

2. The operability of the improved Simulink model was confirmed by the sufficient convergence of simulation results

and experimental studies. In particular, it can be stated that the difference in the speed of the sample of WMV according to the results of modeling and experimental research is within the range of 0.12–2.84 km/h.

3. In the army, samples of the same class of wheeled heavy-duty vehicles are used, which differ in layout and, accordingly, uneven distribution of loads on the axles. The examples are KamAZ-4310 hoodless layout and UrAL-4320 hood layout, or respectively MAZ-6317 and KrAZ-6322. It has been experimentally confirmed that the real reference cross-country ability with a comparable gross weight is somewhat better actually in vehicles with a hood layout, where there is less load on the front axle. As an example, the results of studies are identical in terms of total weight and power drive and tires for UrAL-4320 and KamAZ-4311. At the same time, the layout scheme caused a difference in the experimentally determined possible speeds on sandy BS from 11 % to 12 %. Accordingly, the evaluation parameter of the MMP cross-country ability was refined (taking into account the layout schemes of the vehicle and the uneven distribution of loads on the axle), as well as the methodology for evaluating the speed characteristics of movement.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Mastinu, G., Ploechl, M. (Eds.) (2014). Road and Off-Road Vehicle System Dynamics Handbook. CRC Press. https://doi.org/10.1201/b15560
2. Dawid, W., Pokonieczny, K. (2020). Analysis of the Possibilities of Using Different Resolution Digital Elevation Models in the Study of Microrelief on the Example of Terrain Passability. Remote Sensing, 12 (24), 4146. https://doi.org/10.3390/rs12244146
3. Zhu, Y., Li, X., Zhang, X., Li, S., Liu, Q., Yuan, S. (2022). Research on Tire–Road Parameters Estimation Algorithm for Skid-Steered Wheeled Unmanned Ground Vehicle. Machines, 10 (11), 1015. https://doi.org/10.3390/machines10111015
4. Dawid, W., Pokonieczny, K., Wyszyński, M. (2022). The methodology of determining optimum access routes to remote areas for the purposes of crisis management. International Journal of Digital Earth, 15 (1), 1905–1928. https://doi.org/10.1080/17538947.2022.2134936
5. Ayers, P., Rice, M. (2017). Analysis of vehicle platoon movement and speed-spacing relationships during military exercises. Journal of Terramechanics, 73, 37–47. https://doi.org/10.1016/j.jterra.2017.05.001
6. Pundir, S. K., Garg, R. D. (2021). Development of rule based approach for assessment of off-road trafficability using remote sensing and ancillary data. Quaternary International, 575-576, 308–316. https://doi.org/10.1016/j.quaint.2020.07.017
7. Chen, J., Jia, K., Wang, Z., Sun, Z. (2021). A Data Acquisition Method for Vehicle Geometry Passability Measure. 2021 China Automation Congress (CAC). https://doi.org/10.1109/cac53003.2021.9728519
8. Hrubel, M. H., Krainyk, L. V., Kuprinenko, O. M. (2019) Metodolohiya otsinky opornoi prokhidnosti kolisnoi viyskovoi avtomobilnoi tekhniky. Ozbroiennia ta viyskova tekhnika, 4 (24), 22–31. Available at: http://nbuv.gov.ua/UJRN/ovt_2019_4_4
9. International society for terrain-vehicle systems standards (1977). Journal of Terramechanics, 14 (3), 153–182. https://doi.org/10.1016/0022-4898(77)90013-1
10. Bezborodova, G. B. (1969). Issledovanie prohodimosti avtomobiley. Kyiv, 483.
11. Hrubel, M., Krainyk, L., Bodnar, M. (2019). Otsinka tiahovo-shvydkisnykh kharakterystyk viyskovoi avtomobilnoi tekhniky za umov rukhu bezdorizhzhiam metodamy imitatsiynoho modeliuvannia. Ozbroiennia ta viyskova tekhnika, 3 (23), 46–52. Available at: http://nbuv.gov.ua/UJRN/ovt_2019_3_6
12. Hrubel, M. H., Krainyk, L. V. (2023). Prokhidnist viyskovykh avtomobiliv. Kyiv: Profesional, 182.
13. He, R., Sandu, C., Mousavi, H., Shenvi, M. N., Braun, K., Kruger, R., Els, P. S. (2020). Updated Standards of the International Society for Terrain-Vehicle Systems. Journal of Terramechanics, 91, 185–231. https://doi.org/10.1016/j.jterra.2020.06.007
14. Rowland, D. (1975). A Review of vehicle for soft ground operation. Proceedings of the 5th International Conference of the Society of Terrain – Vehicle Systems, 179–219.
15. Hrubel, M., Krainyk, L., Khoma, V. (2020). Simulation modelling of wheeled military automotive equipment movement in off-road conditions and assessment of its adequacy. Avtoshliakhovyk Ukrayiny, 2 (262), 21–28. https://doi.org/10.33868/0365-8392-2020-2-262-21-28