Simulation of the process of interaction between the vehicle and snow in the environment of DEM and MBD-systems

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Abstract: The problem of increasing the mobility of tractors on snow in our country is very important. This is due to the long duration of the snow cover, primarily in those regions that are of great national and economic importance in terms of mining. There are many methods to increase the mobility of the vehicle, but all of them are associated with increased traction, as well as bearing characteristics of the wheel. The question of calculating the resistance to movement on the part of the body parts submerged in the snow, as well as transmission and engine for a long time did not receive sufficient attention, despite the fact that their contribution to the overall resistance to movement can reach 60%. In this article the existing methods of calculation and modeling of the value of resistance to movement on the side of housing parts are considered, their advantages and disadvantages are given. The design of a soil canal to study the movement of large-scale models of cars in the snow is considered, and the conclusion is made as to the feasibility of using this method at the present time.

The paper also suggests a new method of drag calculation based on the joint use of discrete element modelling (DEM) and multibody dynamics (MBD) software packages. This approach allows both realistically simulate snow due to the discrete element modeling approach, and enter into the model the values of loads on the suspension, traction force, etc. through the use of MBD. The article deals with the technique of modeling the interaction of the body with snow in the EDEM package of DEM Solutions Ltd. The scheme of interaction between DEM and MBD-packages on the example of EDEM and MSC Adams software is described, as well as the technique of using Adams/Co-simulation Interface (ACSI).

1. Introduction

Modern economic development of Russia is connected with the increase of productivity of existing transport and technological machines. Recently customers, designers and researchers are interested not so much in passability of motor transport vehicles (MTV), as in their mobility - the integral index describing set of qualities [1]. It includes, except for cross-country ability, such parameters, as speed, fuel consumption, resource of motor transport, and also such properties, as reliability, maintainability, maintainability. There are many ways to increase mobility (Figure 1), each of which has been thoroughly studied in many works, such as [2, 3].

At the same time, there are still a number of particularly difficult cases of machine mobility loss that need to be considered in more detail. One of these problems is mobility on weak soils. They traditionally...
include marshy soils, water-saturated clay, as well as sand and snow. And if the mobility on the sands is of little relevance because of the almost complete absence of economic activity in the desert zone and is interesting rather in the defense aspect, the mobility on saturated soils is relevant in agriculture, on marshy soils - for the tasks of geology and mining.

Figure 1. Ways to increase the mobility of the MTV

2. Relevance of the research

Of the weak soils, snow is the most common in the Russian Federation. The appearance of snow varies from year to year and quite often does not differ much from the average for many years of observation. However, in some regions there may be trends towards significant time shift. In addition, in recent decades the dates of the first snowfall on the territory of Russia have fluctuated within 2-4 decades for all regions [4-9]. According to [10], about 80% of the territory of the former Soviet Union is covered by it for a long period of time. The authors of the book [10] point out that in the Far North, on the coast of the Arctic Ocean the snow cover is 8-10 months a year, and in some areas of the North (Turukhansk region) the average monthly maximum height of snow cover reaches 1.2 m. Such duration, stability and very large depth of snow cover is a significant feature of our country's climate and has a great impact on its economy and lifestyle.

The range of wheeled machines in winter is extremely wide. This includes the transportation of goods, construction and maintenance of winter roads in normal conditions, and work to combat snow drifts. There is a large volume of transportation and snow retention work in agriculture, as well as a wide range of work in forestry. At the same time, the wheeled machines themselves are not adapted to moving on weak-bearing support bases, and the experience of operation shows that the efficiency of using wheeled machines in winter time is 2...3 times lower than crawler ones, and 5...6 times lower than in summer period [11]. In such conditions of operation the movement of wheeled machines is not only difficult, but often excluded altogether. Therefore, the use of wheeled machines, equipped with means of cross-country ability, is most often the only possibility of technological operations.

Movement on deep snow [12] wheeled cars is connected with dive of wheels and running gear in snow on considerable depth. The great depth of the track laid in the snow requires overcoming great resistance to movement. At the same time, movement on the snowly virgin land is almost always associated with increased wear and tear as a propulsor [13] (tires at reduced pressure dramatically lose their life), and the car as a whole. In addition, rutting requires quite high energy consumption, which leads to increased fuel consumption. Speed of movement does not usually exceed 25 km/hour.

Methods of calculation of wheeled cars cross-country ability on snow without taking into account excavating and bulldozing effects and interaction of the car bottom or protruding parts of the body do not reflect the real picture observed in operation [14]. When calculating by these methods the machine has a reserve of traction force when moving on any snow and, therefore, the cross-country ability is provided in any conditions of movement, which is in sharp contrast to practice. Taking into account the real character of interaction between the wheeled mover and the snow cover significantly clarifies the
prediction of cross-country ability of the machine. In this case, for each type of snow there is a certain depth of occurrence, at which there is a loss of cross-country ability due to the fall of the reserve of traction force.

3. Analysis of publications

If the carrying capacity of the "snow-machine" system is such that the wheel is immersed in the snow by an amount exceeding the ground clearance, the probability of loss of cross-country ability of the machine sharply increases due to changes in both resistance and traction forces. On the one hand, there is a sharp increase in resistance to movement, and on the other hand, the traction force, which can be realized by the engine when interacting with snow, is significantly reduced [15]. Despite the presence of studies [11, 14, 16], which propose methods for calculating the value of resistance to movement from the bottom and body elements, this question is difficult to call solved. Available methods do not allow to predict the flow of snow masses along the machine, the influence of structural features of the body on the value of resistance.

Of particular importance is the problem of increasing mobility when moving on weak-bearing support bases is for small-size robotics, mainly operating in difficult conditions (Figure 2). Due to the scale effect, the requirements for their mobility are much higher than for vehicles of traditional size. The best known example of the importance of this problem is the Mars rover, immobilized due to hitting the sand dune. This was the reason why the Mars Exploration Rover mission worth several hundred million dollars ended in 2009.

The reason for this phenomenon is that the classical methods of terra-mechanics (engineering science studying the interaction between vehicles and deformable landscape) were developed mainly for large, heavy (more than a ton of weight) vehicles and were not originally intended for use on small, lightweight robots [17]. To date, there has been a boom in the development of small (less than 50 kg in weight and less than 1 m in length) robotic systems designed to address a wide range of both military and civilian tasks [18]. Traditional calculation methods based on the theory of Becker and other founders of terramechanics [19] are not always applicable to them, which actually leads to the creation of a new science – micro-terramechanics.

The proposed article sets a task to search for a method that allows you to predict the value of resistance when moving on the snow for small automatic, stand-alone automatic telephone exchanges. This research will allow to create more mobile, reliable and economical robotic systems.

Let's consider different methods used to determine the resistance force of movement in the snow. Their number is relatively small in comparison with the methods used for solid soils, the accuracy is relatively low. The reason for this is that the number of snow types and conditions is much higher than the variety of soils. Additional difficulties are added by the snow metamorphism, the prevailing effect of temperature, greater heterogeneity and porosity. The shear process takes place over time and, naturally, the physical state of snow changes [4-9]. The limit of snow compressive strength changes in time, and there is no long-term limit of tensile strength [22].

![Figure 2. Test of a combat robotic complex in winter conditions [20]](image-url)
It is most obvious to use methods similar to those used in snowplow calculations to determine resistance. Their traction and energetic calculations are made with the help of conditional snow resistance coefficient for cutting \( k_{res} \) [23]. On the physical side, cutting resistance is the total resistance of elementary types of deformation, covering the resistance to compression, tearing, adhesion and friction (internal and external). Quantitatively, it expresses the force required to cut a layer of snow with a cross section equal to one 1 m².

According to the results of studies by A.L. Gorbunov, the values of the cutting resistance coefficient for different types of snow were obtained [23]. Tests of snow in its natural state (undisturbed, without compaction) were carried out on "frontal cutting", where the cutting edge was perpendicular to the direction of movement of the knife, delivered at a cutting angle of 37°. These data were obtained when cutting the layer with \( s=0.02 \text{ m}^2 \text{ section 0.4 m wide and 0.05 m thick.} \) According to the experiments of A.A. Kungurtsev and other researchers [244], the value of snow resistance to cutting is significantly influenced by cutting speed.

The analysis of literature sources shows that little attention was paid to the issue of snow cutting process earlier and that there are a number of contradictions in published works. Cutting forces calculated using well-known methods of V.M. Gusev, A.L. Gorbunov, V.F. Kulepov have values that differ significantly from each other [25].

The practice of designing the working equipment of snow plows shows that the available data on cutting forces are not enough [26, 27]. The cutting resistance coefficient does not take into account the influence of chip thickness, cutting width and cutting angles. The cutting resistance coefficient is determined experimentally and does not take into account the physical basis of the fracture process.

F.M. Zakirov [28] notes that the use of empirical dependencies in determining the cutting resistance of soil and snow becomes an obstacle to the improvement of dumps and other working bodies of earthmoving and snow-plow machines [29].

As a result of the review of studies in the field of fracture mechanics and theory of the limit state of bulk and bonded media, a qualitative commonality of the process of snow destruction by cutting with the process of destruction of ice, frozen soil and rocks was established [28, 30]. It is known that the mechanical characteristic of the material is the envelope of the limiting circles of the Sea, the shape of which depends only on the properties of the material. If the envelope of limiting circles for the material is set, then at any stress state it is possible to determine the safety margin, or to solve the problem of minimizing the energy intensity of the process of material destruction [31]. For a number of continuous media such as soils, rocks, snow and ice, there is a quality community of material destruction process. This qualitative generality consists in the fact that compression of a constricted volume of the material creates a compacted core, under the influence of which there are and spill cracks in inclined directions, there is a cyclic separation of the sliding bodies from the array [32].

According to A.N. Zelenin's method, the envelope of fracture is tangential to the tensile limit circle, and tilted to the \( \alpha \) axis at \( \varphi \) of internal friction. Under this condition, the full identity of calculation and experimental data for a wide range of anisotropic materials is achieved. However, for the application of A.N. Zelenin's idea it is necessary to have the limits of compressive, tensile and internal friction strength of the material. Due to the variety of types and states of snow, obtaining these characteristics is associated not only with a large volume of laboratory tests, but also with the need to identify the type and current state of snow in real conditions.

In M.F. Zakirov's article [27] it is proposed to construct a line of snow destruction not by the main stresses but by the components of the medium resistance vector, which are associated with energy consumption for snow destruction. This allows to simulate the forces of resistance that occur when towing any snow plow. The proposed method is confirmed by experimental material, confirming the theory of the author.

4. Description of the model

Modeling the simulation of the interaction of automatic telephone exchange with the snow cover to determine the value of resistance to the movement of real automatic telephone exchange is complicated
by the fact that its shape is very different from a plough snowplow, it is very complex, therefore, this
method is clearly not applicable. The problem is solvable if we divide the surface of the MTV model
interacting with snow into separate elementary surfaces, "facets" (Figure 3). In this approach, each of
the facets having an area, the coefficient of friction, depending on the material, the angle of interaction
with snow, can be calculated by the method of plough snowplow. The total resistance is the sum of the
resistance of all the facets. This problem is insoluble manually, but quite in the power of modern
personal computers.

To implement such a hybrid model, it is necessary to create brand new software, which makes the
method expensive. The simplest way to determine the value of resistance to the MTV movement in
snow is suggested in [16]. The method suggests reducing all submerged in snow or other weakly-bearing
ground parts of automatic telephone exchange (suspension, transmission, engine crankcase, housing
structures, etc.) to a generalized body (Figure 4).

Figure 3. The faceted representation of the body

Figure 4. Side and frontal MTV projections (Generalized body is shown on the projections with red line)

The proposed method allows to qualitatively compare the cross-country ability of cars on the snowy
virgin land, but does not allow to assess the mobility. For this purpose it is necessary to calculate the
value of resistance provided to the MTV movement by snow, which requires to take into account the
shape of structural elements immersed in the snow. Obviously, cars with the same area of the front
projection, but with a different shape of the bottom will have different mobility.

Historically, the first way to test the MTV were runs - long runs between different climatographic
zones in its course. For all the proximity to the real road conditions this method has serious
disadvantages - firstly, the lack of opportunity to conduct a serious repair or modification of the MTV
during the passage of the route and secondly, significant time and money costs to organize the mileage [32].

Therefore, by the middle of XX century, the mileage was abandoned in favor of specially prepared polygons that have sections of roads with imitation of different surfaces, as well as simulations of obstacles. This made it possible to significantly reduce the testing time, facilitate the testing of new designs and commissioning of new machines.

But the test site is quite expensive in construction and operation. Often, to test individual elements of the design it is redundant, so use a highly specialized stands that reflect this or that aspect of the PBX. One of them is a soil canal, used mainly to determine the parameters of interaction between the wheel and the road [33]. The scheme of one of such stands is shown in Figure 5. Stand includes: test object; propulsor 1, propulsor drive 2; soil canal 3; load simulating normal load 4; cart 5; dynamometer to measure the traction force 6; drive 7; adjustable brake mechanism 8. In addition, can be used to measure torque, angular and linear movement of the wheel, tire deformation, ground deformation, normal contact pressures, specific tangential forces in contact.

![Figure 5](image.png)

**Figure 5.** Stand to study the interaction of the wheel with deformable soil [33]

Basically, the ground channel is used for modeling the interaction between the wheel and the ground, but its application by M.G. Becker is known [34] for the task of finding the optimal propeller in the conditions of the Moon surface. Unlike traditional ground channels, which use a life-size wheel, he created reduced models, which allowed to simplify modeling by accelerating and reducing the cost of creating the models themselves. Unfortunately, it is currently unknown which soil simulator Becker used in his experiments half a century ago, but judging by the preserved photo (Figure 6), it is a loose material that resembles flour or starch, imitating a weakly-bearing soil in the form of moon dust.

![Figure 6](image.png)

**Figure 6.** Test of lunar rover models in the Becker soil canal [35]
5. Research stand
In this paper, at the first stages of the experiments, a scaled ground channel was used to physically model the interaction of MTV models with weakly-bearing soil. The scale of the tested MTV models has been chosen equal to 1:43 due to the compactness of the testing installation, low cost, wide range of the models of this scale presented on the market.

The experimental installation was made, including the soil channel on the basis of a small wooden box, towed in it the MTV model (Figure 7), microwind on the basis of the collector electric motor (Figure 8). Measuring the traction force on the microwind was carried out by indirect method on the size of current strength, measured with milliammeter, programmed in grams. The towed model of automatic telephone exchange was equipped with a cargo platform, allowing to place on it cargoes of the attachment, bringing weight of model in proportional conformity with prototype. A specially selected mixture based on starch was used as a soil simulator.

The use of the first version of the stand showed the fundamental possibility of using the ground channel to simulate the MTV movement in the snow with the measurement of resistance from the ground simulator. Its main disadvantage was low force measurement accuracy. Replacing the soil simulator was complicated by the fact that the mixture had to be poured into the box and poured out of it.

At the second stage of the experiment, the second modification of the stand was made, which eliminated these drawbacks. Trays with soil imitator were made replaceable, installed in an aluminum frame mounted on a wooden shield. The micro winch was mounted hinged (Figure 9), the force from it was transferred to the grammeter, which directly measured the towing force. The resulting single traction-dynamometer module significantly improved the measurement accuracy.

The main disadvantage of the stand version 2 was the ability to measure only instantaneous force values without fixing its change over time. Also, due to the rather small scale of the models being tested, the spread of values even when testing one model exceeded 50%. There was also a lack of detail of the models on the market, which reliably simulated only the top part of the body without a detailed study of the bottom.

The third modification of the stand was designed to improve measurement accuracy. It was planned to reduce friction in the joint of the traction-dynamometer module by installing rolling bearings instead of sliding bearings, as well as add a sensor that removes the instantaneous value of the force with the transfer to a PC to record and plot the force dependence on time. This modification was not carried out, as it would not give a noticeable result because of the small scale of the models. The supposed transition to the use of larger scale models (1:35 or even 1:24) was canceled due to the extremely high cost of these models both in case of their purchase and 3d-modeling with subsequent 3D printing.
Despite the fact that the ground channel method has its limitations (it allows to remove only one parameter from the scale model - the towing force), it can be used for rough comparative analysis of the drag value of different structures when moving on weakly-bearing soil. If there are sufficient automated computational capabilities, its use is unprofitable as it requires the cost of producing physical models and selecting a soil simulator for each real soil.

6. Virtual simulation

The obvious solution in this situation is to use virtual simulation of soil interaction with the PBX. Until recently, the finite element method (FEM) remained actually the only method for high-precision modeling of terramechanics problems [36]. As applied to vehicle movement, it allows, for example, to calculate ground stresses during wheel rolling [37]. The method allows considering the ground as a solid body consisting of a finite number of elements. When the destruction condition is specified, the elements with stresses exceeding the specified value are excluded from the task space.

Therefore, FEM is not applicable for solving problems related to soil transfer after its destruction - for example, optimization of bulldozer knife design to reduce energy consumption. With the development of computational power and software products, it became possible to use the discrete element method (DEM) [38]. In it, the soil is represented as an array of particles connected to each other by ties. By changing the mass, shape (it may be different from a sphere), size and character of bonds between particles, it is possible to simulate almost any soil. The soil may consist of different types of particles, in which case the nature of the relationship is defined individually for each particle pair.

DEM is very demanding for computational resources, because the number of interactions, and, consequently, the resource intensity of the calculation increases with the number of particles. This method supports specialized calculation packages such as AMBER, Chute Maven (Hustrulid Technologies Inc.), PFC2D and PFC3D, EDEM (DEM Solutions Ltd.) GROMOS 96, ELFEN, MIMES, PASSAGE®/DEM, Bulk Flow Analyst, Rocky. Discrete elemental modeling is also possible in finite element packages such as LS-Dyna [39].

When using DEM the soil (in this case snow) is represented as an array of separate interrelated elements, in which an absolutely rigid body moves with some speed (Figure 10). In this case, each virtual element of the ground is a material point having a mass but not a size. Each element is connected with other links (Figure 11), the nature and force of which determine the type of material [40]. These can be both elastic and inelastic connections. In addition, electrostatic, thermal, friction force, etc. can be introduced. Dimensional correspondence of the virtual element of the soil to the real one is set by specifying the so-called contact radius - the distance between material points at which the bonds begin to operate. Under the influence of external growing force, the virtual elements can approach or stretch
to a certain distance, which is influenced by the nature and force of the connection, and then the connection breaks.

**Figure 10.** Setting the task of solid body movement in snow in DEM

**Figure 11.** Interaction of two separate soil elements

Let us consider the elementary area of interaction between a moving body and snow elements (Figure 12): On the body side, each element is affected by a pressure force $F_t$, which is balanced by an equal resistance force from the neighboring $R$ elements. Also, the element is affected by the force of gravity $G$ and the force of normal reaction of the support $N$, which is played by the underlying element. After the force under the action of force from the side of the body, the connection of the element with the neighboring elements is torn, the element is detached from the snow mass and starts its own movement. In this case, it continues to be affected by the force of friction on the side of the body, the force of pressure on the side of the body, the force of friction on the side of other elements, the force of normal support reaction. In this case, the relationship with the neighboring elements becomes different, episodic.

**Figure 12.** Elementary area of interaction between body and snow

In order to solve the task of modeling the MTV movement in the snow, the EDEM system was chosen, because at present it is actively developing, has a visual interface and is equipped with training materials from the manufacturer. It is important that DEM Solutions Ltd. provides an academic license, which was obtained by the author specifically for this research.

Discrete-element at the moment seems to be the most adequate to the task of all considered, at the same time, it is not without drawbacks. The main one is that DEM-packages, including EDEM, are not originally intended for solving terra-mechanics problems, and body movement in them can be set only with a certain fixed or variable speed.

But to fully simulate the movement of the MTV in the snow requires a different approach - to set the engine power, then virtually "bring" it to the wheels to assess the adequacy of power to overcome the
obstacle. For this purpose specialized MBD-packages (Multi body Dynamics) such as MSC Adams, LMS VL Motion are used.

The solution is a connection of MBD and DEM packages. In this case DEM supplies realistic values of ground loads to the common solution space, and MBD controls kinematics (Figure 13). Such approach will allow to model the terra-mechanical system in full, because the modeling of suspension, transmission, etc. is performed in MBD - package, and the soil model in the resulting calculation provides discrete-element modeling software. MSC Adams was chosen as MBD - package, as its licenses are available in the Center of Engineering Competences of NSTU n.a. R.E. Alekseev.

**Figure 13. Structure of software interaction for solving terra-mechanics problems.**

For joint calculations in EDEM the Coupling Server unit is used, and Adams has a special Adams/Co-simulation Interface (ACSI) module. The sequence of actions to create a joint calculation is as follows: first, prepare a model in EDEM, which includes both 3D model of the MTV, and the soil with all its interactions.

Then, the same model as used in EDEM is loaded into Adams, but instead of soil, kinematic interactions between the parts are defined on it. A *.adm file describing all fixations and interactions within the model is generated as well as a *.asf file describing the duration of the simulation and its discreteness. After that, in the ACSI interface the interactions between the corresponding parts of EDEM and Adams - models are alternately established, and on the basis of these data a *.cosim file is formed (Figure 14). After starting the EDEM Coupling Server, it is possible to run a joint simulation in the ACSI window. In this case, the result of the simulation will be displayed in the EDEM window (Figure 15).

**Figure 14. The ACSI interface window.**
Figure 15. EDEM result window

7. Results and future work
Thanks to the use of the DEM+MBD bond, it is possible to simulate terramechanical interactions relatively cheaply and fairly accurately with minimal use of natural experiments. In the future publications it is planned to give the results of such tests on the basis of the test stand created by the students of Moscow Politech within the framework of the subject "Design activity".

Acknowledgment
This study was conducted in continuation of the research conducted by "Nizhny Novgorod scientific and practical school of snow vehicles" and with financial support of the grant of the President of the Russian Federation No. MD-226.2020.8.

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