Researching impact of pressure re-distribution along the length of the track ground contacting area on resistance of the timber-hauling vehicles' travel over snow

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Abstract
The tracked timber-hauling vehicles which operate in the cutting areas having highly deforming soil, virgin snow in particular, feature significantly reduced performance due to rutting and caused frontal resistance.

Most logging enterprises harvest bulk timber in I and IV quarters of the year. However, deep snow during the second half of winter significantly reduces performance of the dragging tractors. Snow mostly affects performance of the feller-skidders and feller-bunchers which need to move from tree to tree to collect load while frequently crossing deep virgin snow.

Snow 0.4-0.6 m deep slightly resists to movement. However, when virgin snow is 0.7 m and deeper, the resistance rises sharply.

The tracked vehicle capacity to cross virgin snow can be improved in two ways: by improving friction properties and by reducing motion resistance. As is evident, more even distribution of track pressure and lack of pressure concentration under individual rollers will improve vehicle's hauling power by reducing frontal resistance.

But as researcher M.G. Bekker stated, despite the fact that pressure distribution was considered one of the most important factors determining vehicle's performance, the theoretical research and assessment of the problem was frequently neglected.

Today designers while designing new tracked dragging vehicles and assessing their performance refer to the researches made for industrial and agricultural tractors. This can be explained by few works dedicated to researching performance of the forest tracked vehicles. The design and operating conditions of the forest and non-forest vehicles are much different so that the results of research made for one type of vehicles cannot be applied to other types of vehicles.

That is why it is necessary to research the process of tracks' impact on snow and pressure re-distribution due to snow reaction to justify parameters of the tracked undercarriage of the forest vehicles, provide optimized location of the gravity center and reduce motion resistance.

Our work is aimed to develop a method to estimate pressure distribution along the length of the track ground contacting area, test the method with experiment and provide recommendations to designers on improving oversnow performance of the forest tracked vehicles.

**Keywords**: Forest tracked vehicle, Snow, Pressure distribution, Motion resistance

1. Introduction

Interaction between the tracked running gear and crushable soil have been studied by (Anisimov 1975; Bekker 1969; Bodin 1999; Cambi et al. 2015; Dhir and Sankar 1994; Dmitriev et al. 1993; Goberman et al. 2003; Horn et al. 2007; Klubnichkin et al. 2015; Kochnev et al. 2008; Kotikov 1995; Krasnenkov et al. 1984; Rakheja et al. 1992; Said Al-Milli et al. 2010; Silaev 1972; Wong 2001; Zabavnikov 1975) and others.

Interaction between the tracked running gear and snow have been reflected in the works by (Abol 1951; Bekker 1969; Kochnev et al. 2008; Wong 2009; Zabavnikov 1975) and others.

Review of the contemporary knowledge about interaction between tracked running gear and crushable soil concludes the following.
Today impact of the track width and length on the vehicle drought and qualitative impact of those parameters on the travel resistance are mostly studied.  
Out of the great number of formulas developed to determine pressure on soil and travel resistance of the tracked vehicles on different soils none can be used to calculate the above values in case of vehicle's operation on deep virgin snow.  
The least examined issue of the process of interaction between the tracked vehicle and the path bed is re-distribution of pressure along the track ground contacting area which occurs under external forces as well as impact of uneven pressure distribution per travel resistance unit.  
Considering the above, we deem it necessary to set the following researching tasks:  
- to develop a method of analytical determination of optimum displacement of the center of gravity and maximum pressure of the tracked vehicle as well as resistance to its travel over crushable soil;  
- to experimentally test the accuracy of the proposed method on the skidding tractors moving over forest virgin snow and obtain required correction factors;  
- to analyze the obtained relationships and basing on the analysis provide recommendations for reduction of resistance to travel of the tracked skidding vehicles over virgin snow.

2. Analysis of interaction between tracked running gear of the timber harvesting machine and crushable soil

Movement of the timber harvesting machine over crushable soil is accompanied by rutting that spends work. The amount of this work and caused resistance to travel are determined by maximum pressure transferred by the vehicle to the path bed which is normally much higher that average calculated vehicle pressure on soil.  
There are two groups of reasons causing uneven pressure along the length of the track ground contacting area. The first group includes a ratio of side roller pitch and track pitch, ratio of spring arms, track tension. As a result of action of the above factors the vehicle to soil pressure diagram may have either gentle curves or pronounced peaks under rollers and valleys between them. We shall further refer to this type of irregularity as a peak irregularity. As previously noted, the peak irregularity (for this type of soil) is determined exclusively by design concept of the undercarriage.  
The second type of irregularity which shall be referred to as a longitudinal irregularity is caused by impact of external forces on the vehicle: load from working elements and travel resistance. It leads to displacement of the diagram center of gravity relative to the vehicle's center of gravity. It is natural that application of external forces cannot change the nature of peak irregularity of the vehicle's pressure on soil but it can significantly influence the value of maximum pressure and thus the travel resistance.  
Other things being equal, the vehicle's maximum soil pressure caused by peak irregularity will have the least value in most cases when the center of gravity rests on a vertical being an axis of symmetry of the ground contacting area.  
Since the work reviews impact of external forces on re-distribution of pressure along the length of the ground contacting area, then the main attention will be paid to the pressure longitudinal irregularity.  
The process of interaction between the track running gear and the crushable soils is quite complex. This is noted by many authors (Bekker 1969; Kotikov 1995; Wong 2009; Zabavnikov 1975). The track under action of vertical and horizontal reactions of the soil gets bent at the front slanting runs and gets bulged at the intervals between support rollers. With that the tracks while in contact with the soil execute complex oscillatory motion and transfer maximum pressure to the path when support rollers pass over tracks. In most cases when research is made for interaction between the track running gear and the crushable soil, it is necessary to review this process with due consideration of all details.  
However, when analyzing re-distribution of pressure along the length of the track ground contacting area (longitudinal irregularity), we may use a widely held in the tractor theory assumption that pressure is transferred to soil without peaks under rollers and the suspension of the vehicle's running gear is rigid. This assumption is admissible because it is not the form of the diagram but the position of its center of gravity, i.e. a point of application of the resultant ground reaction which is important for solving this problem.  
When reviewing equilibrium of the tracked vehicle at different positions of the center of pressure we obtain relationship between maximum pressure and value of displacement of the center of pressure from the middle of the ground contacting area this or other way:

\[
q_{\text{max}} = q_0 \left(1 + \frac{6|\epsilon|}{L}\right),
\]

\[
q_{\text{max}} = \frac{4q_0 L}{3L-6|\epsilon|},
\]

at \( \epsilon \geq -\frac{L}{6} \)

at \( \epsilon \leq -\frac{L}{6} \)
Value ε is accepted negative at displacement of the center of pressure from the middle of the ground contacting area to the side opposite to the movement direction, and positive in case of reverse displacement. So, relationship between maximum pressure and value of displacement ε of the center of pressure from the center line of the track ground contacting area will be linear until

\[ \varepsilon \geq -\frac{1}{6}L \]

Should this inequality is violated, the diagram of pressure under the bottom runs become triangular, and the relationship between \( q_{\text{max}} \) and ε becomes hyperbolic (formula 2). In other words, displacement of the center of pressure from the middle of the track to the side opposite to the movement direction by the value more than \( \frac{1}{6}L \) leads to sharp increase in maximum pressure. This pressure will define the depth of vehicle’s landing, work of deformation at rutting and hence resistance to travel.

That is why to provide movement of the tracked timber harvesting machine this or other way it is necessary that the center of pressure gets displaced from the track middle to the side opposite to the movement by the value not exceeding \( \frac{1}{6}L \).

Proceeding from these conditions, the maximum displacement of the vehicle’s center of gravity forward from the middle of ground contacting area shall be defined by the following equation

\[ \varepsilon_{0\text{max}} = \frac{1}{6}L - h_t\tan \beta \]  

(3)

Determining center of pressure. As it has noted, one of the main criteria of longitudinal irregularity of pressure distribution along the length of the track ground contacting area is a position of the center of pressure, i.e. a point of application of resultant normals to the ground reactions. By knowing the value and point of application of the total normal reactions we can find maximum pressure of the forest vehicle on the soil (with due consideration for peak irregularity), and hence resistance to travel caused by rutting. Besides, in case of necessity we can find soil reaction to support rollers.

It needs to be noted that since modern tracked skidding vehicles has a speed of around 4 km/h during travel with load over crushable surface, then the entire vehicle's interaction with soil is analyzed without consideration of such forces as air environment resistance, inertial force, as well as impact of travel speed on resistance to travel. Those factors have little impact on the reviewed process and they can be neglected.

Let us review a case of irregular straight line movement of the tracked vehicle followed by rutting when it is influenced by hook effort, vertical load from drag and frontal resistance to movement. In a general case a vehicle will move with a certain longitudinal trim \( \beta \) which occurs due to action of external forces.

Sum moment of forces relative to point A (Figure 1):

\[ \sum M_A = X_{w1}(h_x + L\sin \beta) + X_p[h_z\cot g(\psi + \beta) + L\cos \beta] - G_0 \left( \frac{L}{2} + \varepsilon_0 \right) \cos \beta + G_0h_z\sin \beta + W \left( \frac{L}{2} - \varepsilon \right) - Q \left( \frac{L}{2} - \delta_0 \right) \cos \beta - P_{wp} \left( \frac{L}{2} - \delta_0 \right) \sin(\gamma - \beta) + Qh_{wp}\sin \beta + +P_{wp}h_{wp}\cos(\gamma - \beta) = 0, \]

(4)
Formula (3) suggests that the value of backward displacement of the center of pressure from the track lateral axis stands at

\[ \varepsilon = \frac{L}{6} \left( 1 - \frac{q_p}{q_0} \right) \]  

(5)

By substituting value \( \varepsilon \) into equation (4) and considering that \( X_b = \tan(\frac{\psi}{2} + \beta) \), after the transformation we obtain:

\[ X_{a1} \left[ \frac{L}{3\cos\beta} - \left( \frac{L}{2} - \delta_0 \right) \cos\beta + h_{ap}\sin\beta \right] + P_{ap} \left( \frac{L \sin\gamma}{3} + h_{ap} \right) = 0. \]  

(6)

Modern tracked timber harvesting machines while moving over soft soil and snow in normal operation conditions have a longitudinal trim angle of \( \beta \) not exceeding 8°. Horizon tilting angle of the cable assembly \( \gamma \) also lies within 8° to 10°. This allows for some assumptions without great damage to accuracy:

\[ \cos\beta = 1; \quad \cos(\gamma - \beta) = 1; \quad \sin\beta = t\gamma\beta; \quad \sin^2\beta = 0; \quad \sin(\gamma - \beta) = 0. \]

Considering those assumptions, after transformation of equation (6) we obtain:

\[ (G_0 h_0 + Q h_{ap}) \sin\beta + X_{a1} \left[ \frac{h_0(1+\cos\psi)}{\sin^2\psi(\sin\psi+\sin\psi)\sin\beta} + \frac{L(2\cos\frac{\psi}{2}+\sin\frac{\psi}{2})\sin\beta}{3\sin^2\psi+3\cos^2\psi}\right] + \frac{bq}{3} q_n - G_0 \left( \frac{L}{6} + e_0 \right) - Q \left( \frac{L}{6} - \delta_0 \right) + P_{ap} \left( \frac{L \sin\gamma}{3} + h_{ap} \right) = 0. \]  

(7)

In this equation values \( \sin\beta, X_{a1} \) are \( h_0 \)-variable and depend on the properties of the crushable soil and type of undercarriage. These values can be expressed in terms of conditional value of pressure under the front rollers \( q_n \).

Figure 1 suggests that

\[ \sin\beta = \frac{h_0-h_1}{L}. \]  

(8)

where \( h_0 \) and \( h_1 \) - depth of track under rear and front rollers respectively.

Values \( X_{a1} \) and \( h_x \) are revealed in function \( q_n \) after review of a diagram of interaction of the forward slanting section of a track with crushable soil

\[ X_{a1} = 2b \int_0^q f_2(q) dq. \]  

(9)

\[ h_x = \frac{0.5 h_0 f_2(q)|^q dq}{f_0 f_2(q) dq}. \]  

(10)

By substituting values of formulas (9) and (10) into equation (7) we obtain after transformations:

\[ (G_0 h_0 + Q h_{ap}) \sin\beta + \frac{bL}{2} \left[ \frac{2\cos\frac{\psi}{2}+\sin\frac{\psi}{2}}{\sin^2\frac{\psi}{2}+\cos^2\frac{\psi}{2}} \right] \int_0^q f_2(q) dq + \frac{b(1+\cos\psi)}{\sin^2\psi(\sin\psi+\sin\psi)\sin\beta} \int_0^q f_0 f_2(q) dq + \frac{bq}{3} q_n - G_0 \left( \frac{L}{6} + e_0 \right) - Q \left( \frac{L}{6} - \delta_0 \right) + P_{ap} \left( \frac{L \sin\gamma}{3} + h_{ap} \right) = 0. \]  

(11)

Equation (11) is solved relative to value \( q_n \) - one of the trapezoid sides - pressure diagram. If we consider that the second side of the trapezoid is \( q_k = 2q_0 - q_n \), then we can take that the position of the center of pressure is known to us. This equation is expressed in a general view. To obtain concrete results it is necessary to substitute required parameters of a tracked tractor and soil properties into it. The properties of the crushable soil are expressed by relationship \( h = f(q) \) between deformation and pressure which can be found experimentally.

Resistance to travel of the timber harvesting machine caused by rutting
The timber harvesting machine while moving over crushable soil and making track faces certain resistance to travel. Resistance due to soil crushing by tractor's tracks i.e. rutting constitutes the major part of this resistance. The value of this resistance is directly proportional to the amount of the pressed soil. 

For the sake of simplicity the resistance due to rutting can be viewed as two forces. One acts on the front slanting runs of the track, the other acts on the ground contacting area.

In lack of so called “bulldozer” effect, i.e. soil pushing by tracks, the resistance faced by the front slanting runs of the tracks is expressed by the equation (9):

$$X_{II1} = 2b \int_{q_П}^{q_{max}} f_2(q) dq.$$  

(12)

Similarly the resistance acting on the ground contacting area can be expressed as follows:

$$X_{II2} = 2b \int_{q_П}^{q_{max}} f_{2max} f_2(q) dq.$$  

(13)

The total resistance to travel due to rutting will be composed of two components

$$X_{II} = X_{II1} + X_{II2} = 2b \int_{q_П}^{q_{max}} f_{2max} f_2(q) dq.$$  

(14)

3. Experimental research method

The experimental research is aimed at establishing the relationships which characterize the process of rutting and equations required for and deduced in the previous section. In particular, it was necessary to establish relationship between the track landing depth and pressure, the coefficient of pressure concentration under roller, relationship between resistance to travel and position of center of gravity and center of pressure, and to obtain experimental material to check the method of calculation of pressure re-distribution along the length of the track ground contacting area.

All experiments were carried out at the tracked tractor TT-4M during its interaction with deep forest virgin snow as a form of crushable soil.

To maintain experimental integrity the tests were done on forest glades with even surface. The snow depth varied from 0.6 to 0.9 m. Measures were made in Murashinsky timber industry enterprise of Kirov oblast, Russian Federation

Numerous measurements of scow density made at different sites and in different years have demonstrated that average values of forest snow density remained within 0.23 to 0.27 g/cm³. This allowed for a conclusion that the properties of forest snow fell at stable negative temperatures and not subjected to thaw change insignificantly and those changes have no impact on the experiment results.

During the experiments the recording equipment was placed inside a cab of the timber harvesting tractor. To check the calculation method it was necessary to measure normal pressure and resistance to travel at different positions of the center of pressure of the tested tractor.

To simulate forward displacement of the center of pressure the tractor was equipped with two-meter arms where a 1-ton load was secured. The arms provided for three positions of the load. Backward displacement of the center of pressure was provided by securing a load on board in three positions as well. Besides the tractor was subjected to significant backward displacement of the center of pressure as of roundwood bundle and dragging another tractor by a hoist cable with strain gauge.

Measurements were made with a pressure transmitter, a snow track landing transmitter, strain gauge system to measure torque on driving sprockets.

A special test bench was used to determine tractor's center of gravity.

4. Results of experimental research

As a result of the pressure and landing oscillograms’ processing we obtained relationships between specific pressure and depth of landing of tractor TT-4M track landing into snow 0.8 m deep.

$$q = \frac{h}{200-2,5h}.$$  

(15)

For snow 0.6 m deep this relationship is as follows

$$q = e^{0,1h-3,62}.$$  

(16)

Relationships (15) and (16) have been obtained while reviewing interaction between snow and front slanting section of the track to the first support roller. Hence, these relationships are the function of snow properties and track width. Other
factors, including type of suspension, weight parameters, tilting angle of front sections (in lack of or insignificant value of snow pushing) have no impact on them.

This brings to a conclusion that relationships between deformation and pressure obtained for tractor ТТ-4М, which track width is equal to 50 см may be applied to calculation for any tracked vehicles which feature track width range within 50 см.

By substituting values of function by equation (15) into formula (3) and considering that $\tan \beta$ can be replaced with $\sin \beta$ without great mistake, we obtain maximum forward displacement of the tractor’s center of gravity (for snow $H=0.8$ m)

$$\varepsilon_{max} = \frac{L}{6} - \frac{400bq_{0}}{(5q_{0} + 1)L}$$

(17)

Value of average specific pressure is expressed as follows

$$q_{0} = \frac{G_{0}}{2bL}$$

After revealing values $X_{p1}$ and $h_{a}$ with due consideration of dependences (15) and (16) we obtain expressions for finding values $q_{p}$ for snow of:

At $H=0.8$ m

$$(G_{0}h_{c} + Qh_{sp})\sin \beta + 21.3bL \left(\frac{2 \cos ^{2} \psi + \sin ^{2} \psi}{\sin ^{2} \psi + \cos ^{2} \psi}\right) \cdot \ln (2.5q_{a} + 1) - \frac{2.5q_{a}}{2.5q_{a} + 1} + \frac{136b(1 + \cos \psi)q_{a}}{\sin ^{2} \psi + (\sin 2 \psi + \sin \psi) \sin \beta} + \frac{bL}{3} q_{a} - \frac{P_{sp} \left(\frac{L}{6} - \varepsilon_{a}ight)}{3} + h_{sp} - G_{0} \left(\frac{L}{6} + \varepsilon_{0}\right) = 0;$$

(18)

At $H=0.6$ m

$$(G_{0}h_{c} + Qh_{sp})\sin \beta + 21.3bL \left(\frac{2 \cos ^{2} \psi + \sin ^{2} \psi}{\sin ^{2} \psi + \cos ^{2} \psi}\right) \cdot q_{a} + \frac{100b(1 + \cos \psi)q_{a}}{\sin ^{2} \psi + (\sin 2 \psi + \sin \psi) \sin \beta} + \frac{bL}{3} q_{a} - Q \left(\frac{L}{6} - \varepsilon_{a}\right) + P_{sp} \left(\frac{L}{6} - \varepsilon_{a}\right) - G_{0} \left(\frac{L}{6} + \varepsilon_{0}\right) = 0;$$

(19)

In those equations

At $H=0.8$ m

$$\sin \beta = \frac{32(G_{0}q_{a} + Q - 2bLq_{p})}{(0.4 + q_{a})[G_{0} + Q + 2b(0.4 - q_{a})]L}$$

(20)

At $H=0.6$ m

$$\sin \beta = \frac{10}{L} \ln \left(\frac{G_{0}q_{a}}{bLq_{a}} - 1\right)$$

(21)

The tracked vehicles moving over snow and experiencing no hook load normally feature insignificant longitudinal trim angle ($1 - 2\varepsilon_{max}$). This angle has little impact on calculation results and they can be neglected.

Then for vehicles with similar load diagram equations (18) and (19) will take the following form:

At $H=0.8$ m

$$42.7b \\cot \psi \frac{2}{2} \ln (2.5q_{a} + 1) - \frac{2.5q_{a}}{2.5q_{a} + 1} + \frac{136b(1 + \cos \psi)q_{a}}{1 - \cos \psi + 2.5q_{a}} + \frac{bL}{3} q_{a} = G_{0} \left(\frac{L}{6} + \varepsilon_{0}\right)$$

(22)

At $H=0.6$ m

$$q_{a} = \frac{G_{0}\left(\frac{L}{6} + \varepsilon_{0}\right)}{13.3b \\cot \psi \frac{2}{2} \ln (2.5q_{a} + 1) + \frac{100b(1 + \cos \psi)q_{a}}{1 - \cos \psi}}$$

(23)

Basing on formula (14) with due consideration of relationships (15) and (16) we obtain expressions for finding travel resistance due to rutting:

At $H=0.8$ m

$$X_{n} = 64b \left\{\ln \left(2.5q_{max} + 1\right) - \frac{2.5q_{max}}{2.5q_{max} + 1}\right\}$$

(24)

At $H=0.6$ m

$$X_{n} = 20bq_{max}$$

(25)

Determining pressure concentration coefficient. The oscillograms of normal pressure recorded during movement of the skidding tractor over snow clearly show the peaks under the rollers and valleys between rollers where pressure drops almost to zero. This concentration (peak irregularity) of pressure under rollers depends on physical and mechanical
properties and depth of snow, pitch of support rollers, pitch of track links, type of suspension, towing and other factors. For each specific case it can be evaluated by pressure concentration coefficient $k$, equal to ration of average pressure during peaks to average calculated pressure $q_0$

$$k = \frac{\sum q_i}{nq_0} \tag{26}$$

where $\sum q_i$ – a sum of pressures in peaks under rollers; $n$ – number of rollers on one side of the tractor.

Experiments have established that during movement of the tracked vehicle with ration of roller pitch to track link pitch of $\lambda = 4.5$ (TT-4M and LP-18K) over snow 0.8 m deep, coefficient $k$ is equal to 1.95, during those vehicles’ movement over snow 0.6 m deep - 2.45. This suggests that due to peak irregularity the true pressure exceeds calculated one 2 - 2.5 times.

Calculating maximum pressure. Finding a coefficient of pressure concentration allowed for consideration of peak irregularity during calculation of maximum pressure. For calculating maximum pressure it is first necessary to determine value $q_n$ by equations (18) or (19) depending on snow depth. If value $q_n$ exceeds average calculated pressure $q_0$, then maximum pressure shall be described in terms of the following relationship

$$q_{\text{max}} = k \cdot q_n \tag{27}$$

If value $q_n$ is less than $q_0$, then maximum pressure expression shall take the following form

$$q_{\text{max}} = k \cdot (2q_0 - q_n) \tag{28}$$

Comparing experimental values of maximum pressure with calculated one by formulas (27) and (28) demonstrates that maximum deviation of the calculated values from the experimental data does not exceed 5%.

Relationship between resistance to travel and maximum pressure. As a result of processing of oscillograms of recording torque of driving sprockets we obtain resultant circumferential force $P_0$. The total resistance to vehicle’s travel $P_{vt}$ is determined as a difference between resultant circumferential force $P_0$ on driving sprockets and drawbar force $P_{kp}$

$$P_{vt} = P_0 - P_{kp} \tag{29}$$

In its turn the total resistance to travel $P_{vt}$, is composed of resistance to travel due to rutting $X_n$, internal losses in the undercarriage $P_i$ and losses due to rubbing of the vehicle’s bottom and protruding parts against snow, entry of snow inside a track, increased tension of tracks and other factors.

$$P_{vt} = X_n + P_i + \Delta P \tag{30}$$

Going to the coefficients, we can write

$$f_{vt} = f_{it} + f_r + \Delta f \tag{31}$$

Isolating all losses which comprise value $\Delta P$, from the total resistance to travel is a complex task. This value depends on the type of undercarriage, depth and properties of snow as well as load on the vehicle. However, for certain types of undercarriage, snow depth and specific load on a tractor value $\Delta P$ will be more or less constant. For this, to obtain an experimental value of force $X_n$, losses in undercarriage $P_i$ were subtracted from total resistance to travel $P_{vt}$.

Basing on the experimental data a diagram (Fig. 2) of relationship between resistance to travel of tractor TT-4M and maximum pressure on snow was built. Analytical curve 1 is plotted by equation (24). Experimental values points of value $X_n$ do not match this curve and lie above it. This can be explained by that when calculating value $X_n$ no consideration was made for value $\Delta P$, which was found significant for snow 0.8 m deep. The major part of this resistance belongs to bottom rubbing against snow as with snow depth of 0.8 m the track depth of the loaded tractor TT-4M exceeds clearance by 0.10 — 0.15 m.
Figure 2. Relationship between resistance to travel of tractor TT-4M and maximum pressure:
1 – curve by equation (18) – for snow $H = 0.8$ m;
2 – curve by equation (19) – for snow $H = 0.6$ m;
3 – experimental curve for snow $H = 0.8$ m.

Curve 2 (see Fig. 2) is plotted by formula (25) for snow depth of 0.6 m. As seen, all experimental points slightly deviate from the curve. In fact when tractor TT-4M interacts with snow 0.6 m deep, its bottom does not contact the snow surface, the rest factors have no major impact on resistance to travel. This suggests that if the bottom does not press snow the value of additional losses $\Delta P$ is insignificant and it can be easily neglected.

Ordinates of curve 1 (see Fig. 2) are inevitable part of resistance to travel caused by rutting by tracks which a vehicle is subjected to when on the snow at this or that maximum pressure. Curve 3 connecting experimental points of resistance $X_n$ shows that actual values of this resistance are above calculated ones by 10 – 14%. This increase of resistance mainly caused by snow pressing by a vehicle bottom is a reserve of reduction of frontal resistance which may be implemented for an identical vehicle on the snow if its bottom does not contact the snow surface.

On the other hand, curves 1 and 2 offer an opportunity to visualize the effect which can be gained by eliminating the peak and longitudinal irregularities of pressure. Thus, under ideally uniform distribution of pressure tractor TT-4M moving with a load shall transfer to snow a pressure $q \approx 0.5$ kg/cm².

Relationship between resistance to travel and center of pressure displacement. When developing a curve of relationship between resistance to travel and displacement of center of pressure, it is more convenient to describe resistance to vehicle’s travel in terms of coefficient of travel resistance, and displacement of center of gravity and a center of pressure, in terms of fractions of length of ground contacting area. Such diagram for snow depth of 0.6 m is given in Fig. 3a. Experimental points of resistance coefficient $f_n$ coincide with a theoretical curve satisfactory (deviation does not exceed 6%).

Fig. 3b shows the same diagram for snow depth of 0.8 m. All experimental points lie above the theoretical curve. As it has been already noted, this is a result of interaction of the tractor with snow as the track landing depth is more than its clearance by 140 mm.

However, as it is seen on the diagram, with center of pressure displacement back from the middle of the ground contacting area by value $\varepsilon \geq 0.02L$ the difference in ordinates between theoretical and experimental curves is almost constant and stands at 14%, in average With center of pressure displacement back by value $\varepsilon < 0.02L$ and forward from the middle of the track, this difference rises sharply and reaches 28%.
а) Н = 0.6 m;  
b) Н = 0.8 m.

1 — theoretical curve; 2 — a curve connecting experimental points.

**Figure 3.** Relationship between travel resistance coefficient and displacement of center of gravity and center of pressure of tractor ТТ-4М for snow depth of:

This can be explained by that with displacement of center of pressure back from any point (in this case it is 0.02 L) a vehicle experiences longitudinal trim. With that the bottom compacts the snow, rubs against its surface thus creating almost constant additional resistance. Displacement of center of pressure forward from the given point leads to practical disappearance of a trim as a result of which the front head part of the bottom pushes the upper layer of snow thus forming a snowbank which sharply increases resistance to travel.

In normal operation a center of pressure of the skidding tractor is displaced backward by a value exceeding 0.02 L. That is why to estimate passability of the modern skidding vehicles which clearance is about 500 mm, over virgin snow 0.8 m deep, it is necessary to increase estimated value $X_p$, obtained against expression (18), by 14%.

The performed analysis and experience of the skidding vehicle's operation in deep virgin snow demonstrate that snow pressing by a bottom causes significant reduction of their passability. In addition to increase of resistance to travel due to bottom rubbing against snow, the vehicle's adhesion weight reduces and this reduction reaches 19% in case of tractor ТТ-4М. In case of track's skidding the vehicle's landing depth increases and a vehicle "sits" on its belly.

That is why the vehicles designed for operation in deep snow shall have a clearance which value is more or equal to track depth made in snow during movement under full load.

5. Conclusion

The proposed method of determination of the value of maximum forward displacement of the center gravity, maximum pressure and resistance to travel of the tracked vehicle is proved experimentally and can be used in designing new and evaluating existing vehicles from the point of their passability in deep virgin snow.

Assessment of the peak irregularity of pressure transfer along the length of the track ground contacting area can be checked with use of pressure concentration coefficient $k$ equal to ration of the average peaks pressure $i$ to average estimated pressure of the vehicle. This coefficient depends on ration $\lambda$ of the support roller pitch to track link pitch and snow depth and properties.

For the skidding vehicles made by Altay tractor plant with value $\lambda = 4.5$ coefficient $k$ is equal to 1.95 for snow depth of 0.8 m, and 2.45 for snow depth of 0.6 m.

When a modern tracked skidding vehicle moves with a load over forest virgin snow 0.8 – 0.9 m deep, the value of tracks' landing into snow exceeds clearance by 0.10 – 0.15 m. The bottom rubbing against snow leads to sharp increase of resistance to travel, especially when a center of pressure is displaced forward from the track middle, due to snow pushing by the tractor's bottom front part.
Analysis of calculated relationships and experimental data demonstrates that:

a) leveling of the pressure diagram by eliminating peak irregularity reduces resistance to travel of the modern skidding tractors with snow depth of 0.8 – 0.9 m twofold, and with snow depth of 0.6 m, in 2.5 times;

b) eliminating longitudinal irregularity (displacement of a center of pressure with lateral axis of symmetry of the track ground contacting area) may reduce resistance to travel in 1.5 – 1.8 times.

Increasing the length of the ground contacting area significantly increases capacity of the tracked skidding vehicles during operation on virgin snow.

The calculations found that increasing the length of the ground contacting area of tractor TT-4M by 10% leads to increase of maximum truck load by 28%, and increasing the length of the ground contacting area and clearance by 10% provides increase of truck load by 44%.

The proposed general analytical equations may be used for calculation of interaction of variable types of tracked undercarriage with different crushable soils. To do so it is necessary to expand the given equations using relationships between deformation and pressure obtained under the proposed method.

### Nomenclature

| Symbol | Description |
|--------|-------------|
| $q_0 \frac{b_0}{2bL}$ | average specific pressure of the track ground contacting area on the soil [kg/cm$^2$] |
| $b$ | width of a track [m] |
| $G_0$ | vehicle weight [N] |
| $L$ | length of track ground contacting area [m] |
| $h_c$ | vertical coordinate of the center of gravity |
| $\beta$ | angle of vehicles' longitudinal trim [$^\circ$] |
| $Q$ | vertical load by drag [kN] |
| $P_{hook}$ | hook load [kN] |
| $X_{n1}$ and $X_{b}$ | horizontal and vertical components of resultant soil reaction to frontal area of a track respectively |
| $W$ | resultant normals to ground reactions |
| $h_{hook}$ | height of application of hook force |
| $\beta$ | angle of longitudinal trim [$^\circ$] |
| $\gamma$ | angle of inclination to cable assembly horizon [$^\circ$] |

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