Improving wheeled vehicles trafficability

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Abstract. A mathematical model of multi-axle wheeled vehicle motion over the bearing surface is presented in the article. An equation system describing the vehicle motion over the snow road bed is given. The formation of resistance to motion force is considered. Dependences to calculate the basic components of external resistance are given: resistance force due to the snow road bed vertical deformation; resistance force due to excavation-bulldozer effects and dependence for the drag force calculation. Field tests allowed to analyze dependence of pressure distribution in extra-low-pressure tire flat spot with snow and to compose a stress distribution equation. Consideration of real pressure distribution in the flat spot when calculation drag force for snow-and-swamp-going-vehicles of «Кержак» (Kerzhak) family having 4x4 and 6x6 wheel-arrangement allowed to get an error of theoretical and experimental data of not more than 15%.

When moving upon the snow road bed (Figure 1) a wheeled vehicle, as a dynamic system, is affected by the snow cover, being the disturbance factor. As soon as the solid base covered with snow is a random surface, the snow road bed is a random surface too, i.e. the snow cover is a physical body, geometrically limited from above and from below by random surfaces. Moreover, a wheeled vehicle is a dynamic loop system because the disturbance factor is changed as a result of its impact (there appears a rut).

Figure 1. A model of vehicle motion over the bearing surface
The complete software implementation of the mathematical model, taking into account road micro-
profile random nature, deformability of soft surfaces and curvilinear character of wheeled vehicles
motion causes difficulties and for this reason is outside the scope of this article. Thus, when building a
mathematical model of the wheeled vehicle-to-snow interaction and estimating trafficability, the fol-
lowing basic assumptions have been made: the motion surface is smooth, i.e. the terrain microprofile
impact is neglected; wheels-to-the-vehicle-body connection is absolutely rigid in all directions, except
relative wheel rotation; the vehicle motion is steady, rectilinear.

Then the equation system describing the vehicle motion can be presented as a set of formulae:

\[ \sum_{k=1}^{n} G_k^{(nh)} - \sum_{i=1}^{2} \sum_{j=1}^{N} F_{ij} = 0, \]
\[ G - \sum_{i=1}^{2} \sum_{j=1}^{N} N_{ij} = 0, \]
\[ \sum_{k=1}^{n} M_k^{(nh)} - \sum_{i=1}^{2} \sum_{j=1}^{N} \left( M_{ij} + N_{ij} L_{cij} + F_{ij} h_{cij} \right) = 0, \]

where \( \sum_{i=1}^{2} \sum_{j=1}^{N} G_{ij}^{(an)} \) – sum of axial external forces applied to the vehicle;
\( \sum_{i=1}^{2} \sum_{j=1}^{N} F_{ij} \) – sum of axial responses of the road bed to all running gear wheels;
\( \sum_{i=1}^{2} \sum_{j=1}^{N} N_{ij} \) – sum of vertical responses of the road bed to all running gear wheels;
\( \sum_{i=1}^{n} M_{ij}^{(an)} \) – sum of external moments applied to the vehicle;
\( \sum_{i=1}^{2} \sum_{j=1}^{N} \left( M_{ij} + N_{ij} L_{cij} + F_{ij} h_{cij} \right) \) – sum of the road bed reactive moments;
\( L_{cij} \) – horizontal distance from reaction point;
\( N_{ij} \) to the mass center;
\( h_{cij} \) – vertical distance from reaction point;
\( F_{ij} \) to the mass center.

The above model allows to calculate reactions on the vehicle wheels, their values forming the basis
for calculating resistance to the vehicle motion and drag force.

The force of resistance to the vehicle motion can be presented as:

\[ P_c = P'_f + P_f, \]

where \( P'_f \) - force of resistance, due to the engine internal losses, \( P_f \) - external resistance force.

\[ P_f = P_{fc} + P_{f\beta} + P_{f\delta} + P_{f\beta} + P_{f\delta}, \]

where \( P_{fc} \) - due to the snow road bed vertical deformation,
\( P_{f\beta} \) - resistance force due to excavation-bulldozer effects,
\( P_{f\delta} \) - resistance force emerging at the engine immersion exceeding the clearance,
$P_{fr}$ - resistance force due to the hook load,
$P_{fw}$ - air resistance force.

When estimating vehicles over-the-snow movability, basic components of external resistance were considered: resistance force due to the snow road bed vertical deformation; resistance force due to excavation-bulldozer effects.

Using the obtained dependence (4) of the snow vertical deformation on the basic load it is possible to calculate the snow resistance to compression taking into account critical parameters of the snow cover: depth $H$, snow density $\rho$ and its initial hardness $\gamma$.

$$q = (k_1 e^{-k_2 h_{max}(H)} + \gamma) h^{[a_1 n_1(H) + b_1]},$$

Resistance force due to the snow road bed vertical deformation can be calculated by direct integration:

$$P_{fc} = b \int_0^{h_{def}} q(h) dh$$

Using dependence (4):

$$P_{fc} = \frac{bq_{max}}{n + 1} \left( \frac{q_{max}}{k_1 e^{-k_2 h_{max}} + \gamma} \right)^{1/n}$$

Resistance force of excavation-bulldozer effects:

$$P_{f\phi} = b \sum_{i=1}^{m} \int_{hi - \Delta hi}^{hi} q(h) dh$$

Using dependence (4):

$$P_{f\phi} = b \sum_{i=1}^{m} \frac{k_1 e^{-k_2 h_{max}(H)} + \gamma \left[ h_{i}^{n+1} - (h_{i} - \Delta h_{i})^{n+1} \right]}{n + 1}$$

where $\Delta h$ – snow depth, displaced from the contact zone to inter-wheel space, due to excavation-bulldozer effects.

The basis of determining the drag force according to traction is the dependence of soil shear strength (Coulumb- Mohr equation) and the shear diagram. However, using the dependence appears difficult for theoretical calculations or generates an error of up to 70% for snow calculations.

The experimental research of forces distribution when extra-low-pressure tires interact with the bearing surface, allows to draw stress distribution curves of extra-low-pressure tire (Fig.2) lengthwise and edgewise contact with snow and to obtain contact stress distribution surface (Fig.3) and compose a stress distribution equation (9).
Figure 2. Stress distribution along the contact stress contact length

Figure 3. Contact stress distribution surface

\[ q_{xy} = k_{x1} r x^5 - k_{x2} r x^4 + k_{x1} r x^3 - k_{x3} r x^2 + k_{x4} r x^2 + k_{y1} b y^5 - k_{y2} b y^4 + k_{y1} b x^4 + k_{y3} b x^3 - k_{y3} b x^2 + k_{y4} b x \]

where \( q_{xy} \) kPa – stresses;

\( x, m \) – distance from the tire-to-bearing-surface contact starting point to the contact point;
\[ y, \text{ m} \] – distance from the tire-to-bearing-surface contact starting point edgewise to the contact point;
\[ r, \text{ m} \] – wheel radius,
\[ r_a, \text{ m} \] – wheel rim seat radius,
\[ b, \text{ m} \] – wheel width,
\[ k_x, k_y \] – approximation coefficients.

Shear stress:
\[ \tau = C + q_{xy} \tan \varphi \quad (10) \]

where \( C \) – connectivity coefficient,
\( \tan \varphi \) – friction coefficient

Then drag force of one wheel will be the following:
\[ P_t = \int_0^L \int_0^B \tau \, dz \, db \quad (11) \]

Comparing the obtained experimental data of drag force values for snow-and-swamp-going-vehicles of «Kerzhak» family having wheel-arrangement 4x4 and 6x6 with the data obtained by numerical methods generates an error of not more than 15\%, which at the design stage allows to calculate to high precision drag force values of the extra-low-pressure tired vehicle motion along the snow cover.

Comparison of the obtained experimental data of drag force for snow-and-swamp-going-vehicles of «Kerzhak» family having 4x4 and 6x6 wheel-arrangement with the data obtained by numerical methods generates an error of not more than 15\%, which at the design stage allows to calculate with high precision the drag force values of the extra-low-pressure tired vehicle motion along the snow cover.

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