Permissible ground pressure of wheeled forestry vehicles depending on the ground conditions

G V Grigorev*, I N Dmitrieva, E V Kotenev
Institute of Technological Machines and Forest Transportation, St. Petersburg State Forest Technical University, 5 Institutskiy Lane, St. Petersburg 194021, Russian Federation

*Corresponding e-mail: vtl-lta@mail.ru

Abstract. The aim of the work is to investigate interrelations between wheeled vehicle pressure on the ground and its cross-country ability. To comply with the requirement of ecological compatibility of the mover, which is that the rut depth after the passage of the vehicle should be less than 0.1 m, the pressure of the wheeled mover when working on moderate forest soils should not exceed 0.07 MPa (a forwarder 8x8 with a loaded weight up to 31 tons), on weak forest soils the pressure should not exceed 0.025 MPa (a forwarder 8x8 with a loaded weight up to 11 tons). On moderate soil to ensure cross-country ability, the pressure should be limited to 0.095 MPa (a forwarder 8x8 with a loaded weight up to 42 tons) (slipping ratio reaches 0.2, the depth of the rut is 0.18 m, the operating speed of the machine 1.5 m/s). To ensure the wheeled vehicle cross-country ability, the average pressure when working on weak forest soils should be limited to 0.04 MPa (a forwarder 8x8 with its loaded weight of up to 18 tons) (slipping coefficient reaches 0.136, rut depth of 0.253 m, the operating speed of the machine 2.8 m/s).

1. Introduction

Average ground pressure $p$ is one of the most important characteristic of the influence of the wheeled machine engine on the bearing surface. Ground pressure is determined by the depth of the track $h$ formed during the passage of the machine, which, in turn, depends on the ground resistance to the movement of the machine $F_r$. The value of the propulsor's pressure on the ground determines the normal stress $\sigma$ in it, this determines the tangential stress $\tau$ on the contact spot of the propulsor with the bearing surface, therefore, the adhesion force of the propulsor with the surface $F_T$ and slip ratio $S$. Taken together, the motion resistance and slipping ratio determine the operating speed of the machine $v$. The difference between the net thrust coefficient $\mu$ and the rolling resistance coefficient $\phi_r$, the drawbar pull coefficient $\phi_p$, is a characteristic of the machine's cross-country ability $P$, and it also determines the height of a single obstacle $z$ that the wheeled propeller can overcome.

The aim of the study is to investigate the relationship between the wheel vehicle pressure on the ground and the performance of the vehicle's cross-country ability.

2. Results and Discussion

As input parameters of soil we will accept: general deformation module $E$, specific cohesion of soil $C$, internal friction angle $\phi$, specific weight $\gamma$, shear module $G$, thickness of deformable soil layer $H$. Soil will be divided into three categories by physical and mechanical properties, the values of which are presented in table 1 [1-3].
To calculate the tractive performance of the wheeled mover, first it is necessary to determine the depth of the track $h$, formed when the tractor passes through the forest soil, for this purpose we use the transcendental equation [4, 5]:

$$h = \frac{\text{JpEaB}}{(p_s - p)(E(E - Jp))^0.5} \arctg \left( \frac{E(H - h)}{aB(E(E - Jp))^0.5} \right),$$  \hspace{1cm} (1)

where $J$ is a parameter that takes into account the ratio between the length and width of the tractor mover's contact with the ground, $a$ is a parameter that takes into account the thickness of the soft soil layer, $H$ is the thickness of the soft soil layer, $B$ is the width of the tractor mover, $p$ is the pressure of the tractor mover on the ground (average), $E$ is the general deformation module of the ground, $p_s$ is the bearing capacity of the ground.

**Table 1.** Physical and mechanical properties of forest soil by categories [1-3].

| Parameter | I (bearing soil) | II (moderate) | III (weak soil) |
|-----------|-----------------|---------------|-----------------|
| $E$, MPa  | 3               | 1             | 0.4             |
| C, MPa    | 0.025           | 0.011         | 0.0053          |
| $\varphi$, $^\circ$ | 16.7          | 13.7          | 11.6            |
| $\gamma$, MN/m$^3$ | 0.0096      | 0.0084        | 0.0075          |
| $H$, m    | 0.28            | 0.47          | 0.73            |
| $G$, MPa  | 0.28            | 0.24          | 0.22            |

Parameters $J, a$ we will find by formulas [4, 5]:

$$J = \frac{0.03 + LB^{-1}}{0.6 + 0.43LB^{-1}},$$  \hspace{1cm} (2)

$$a = 0.64 \frac{B + H}{H},$$  \hspace{1cm} (3)

where, $L$ is the length of the soil contact stain.

For wheeled tractor [6, 7]:

$$L = \frac{d}{2},$$  \hspace{1cm} (4)

where, $d$ is the diameter of the wheel.

Ground bearing capacity is calculated by the formulas [8]:

$$p_s = p_s0\alpha_z;

p_{s0} = 0.5K_1N_1\gamma B + N_2\gamma h + K_2N_3C

K_1 = \frac{L}{L + 0.4B}; K_2 = \frac{L + B}{L + 0.5B}

N_1 = \frac{1 - S^4}{S^5}; N_2 = \frac{1}{S^2}; N_3 = \frac{2(1 + S^2)}{S^3}; S = \tan\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)

\alpha_z = 1 + \frac{H'h}{2H'\cdot(H - h - 0.25H')}; H' = 0.707\exp\left[\frac{\pi^2}{4} + \frac{3\varphi^4}{4}\right] \tan\frac{3\varphi}{4} \cdot B \cos\frac{3\varphi}{4},$$  \hspace{1cm} (5)

where $p_{s0}$ is the load-bearing capacity of the ground at the unlimited thickness of the soft layer, $\alpha_z$ is the coefficient of account of the thickness of the soft layer of the ground, $K_1, K_2$ are the coefficients of account of the ratio of length and width of the spot of contact of the mover with the ground, $N_1, N_2, N_3$.
are the coefficients of account of the angle of internal friction of the ground, \( C \) is the specific cohesion of the ground, \( \gamma \) is the specific weight of the ground, \( S, H^* \) are auxiliary designations.

Force of soil resistance to tractor movement is according to the formula [9]:

\[
F_r = B \int_0^h p dh .
\]

(6)

The force of cohesion of the mover with the ground is according to the formula [9, 10]:

\[
F_\tau = \frac{BG^2 L (p \tan \phi + C)}{(G - C)^2} - S \cdot \frac{BCGL^2}{2t_g (G - C)} - \frac{1}{S} \cdot \frac{(p \tan \phi + C)^2 BG^2 t_g}{(G - C)^3} \ln \left(1 + S \frac{L(G - C)}{t_g (p \tan \phi + C)}\right),
\]

(7)

where, \( S \) is the slip ratio, \( t_g \) is the grousers spacing.

Let us calculate the coefficient of resistance to tractor movement by the formula [9, 10]:

\[
\phi_r = \frac{F_r}{BL},
\]

(8)

where, \( \phi_{r0} \) is a correction for power loss caused by tyre hysteresis, soil stickiness and other factors not directly related to rutting.

We will find the coefficient of tractor's traction with the ground using the formula [9, 10]:

\[
\mu = \frac{F_\tau}{BL},
\]

(9)

and in determining \( F_\tau \), the slipping factor \( S \) is a variable.

Let us define the coefficient of traction by the formula [9, 10]:

\[
\phi_p = \phi_r - \mu.
\]

(10)

A negative traction factor indicates a loss of the vehicle's passability.

We will find the height of the threshold single obstacle that the mover can overcome at \( \phi_p > 0 \) by formula [8]:

\[
z = \frac{d}{2} \left(1 - \frac{1}{(1 + \phi_p^2)^{\frac{5}{2}}} \right).
\]

(11)

The operating speed of the wheeled mover is determined by the formula [9, 10]:

\[
v = \frac{N \eta}{\phi_p G_w n},
\]

(12)

where, \( N \) - engine power of the machine, \( \eta \) - transmission efficiency, \( G_w \) - related load per wheel, \( n \) - number of wheels of the machine.

The complex criterion of cross-country ability is estimated on the equation [9, 10]:

\[
P = \frac{\phi_p \phi_0 v}{\phi_0 \phi_p v^0},
\]

(13)

where the "0" index means an indicator defined in reference conditions (in reference conditions \( P = 1 \), the closer the \( P \) value is to zero, the lower is the machine's passability assessment).
The pressure range is set into intervals with a given step $\Delta p$. At each pressure $p$ value the system of equations (1) - (4) is numerically solved. As a result, we obtain the table of correspondence of pressure $p$ and track depth $h$. From the table, using the trapezium method, we find an approximate value of the integral by formula (6), then we calculate the resistance coefficient $\phi_r$ by formula (8). Then, for each value of $p$, we numerically determine the maximum function (7) and the corresponding value of the slipping factor $S$. We find the coefficient of adhesion by the formula (9). We calculate the coefficient of traction by formula (10), then we determine the height of the threshold obstacle by equation (11). The working speed of the machine is based on expression (12). Using the formula (13) we get a complex assessment of the vehicle's cross-country ability.

For calculation in our study we will take the following initial data: wheel width $B = 0.7$ m, wheel diameter $d = 1.6$ m, pitch $t_g = 0.14$ m, vehicle ground pressure $p = 0.01 \ldots 0.1$ MPa, pressure step $\Delta p = 0.01$ MPa, energy loss factor not related to rutting $\phi_{r0} = 0.03$, engine power $N = 0.15$ MW, transmission efficiency $\eta = 0.97$ MW. For reference conditions: machine speed $v^0 = 6$ m/s, driving resistance coefficient $\phi_{r0} = 0.03$, thrust coefficient $\phi_p^0 = 0.97$. The results of calculation are presented in figures 1-8.

![Figure 1. Rut depth as a function of vehicle ground pressure and soil category.](image1.png)

![Figure 2. Rolling resistance coefficient as a function of vehicle ground pressure and soil category.](image2.png)
Figure 3. Slip ratio at which maximum traction is achieved as a function of vehicle ground pressure and soil category.

The slip ratio, which provides the maximum adhesion of the propulsor to the ground, almost linearly depends on the average pressure of the propulsor on the ground, its value varies from 0.1 at a pressure of 0.02 MPa (machine weighing 9 tons) to 0.18-0.21 at a pressure of 0.1 MPa (machine weighing 45 tons).

Figure 4. Maximum speed of the machine as a function of vehicle ground pressure and soil category.
Figure 5. Net thrust coefficient as a function of vehicle ground pressure and soil category.

Figure 6. Drawbar pull coefficient as a function of vehicle ground pressure and soil category.

For a quantitative assessment of the vehicle cross-country ability the graphs of the complex parameter of cross-country ability, allowing to compare the stock of the vehicle traction factor in specific conditions in comparison with the reference conditions - figure 7, 8.
Figure 7. Complex parameter of cross-country ability as a function of vehicle ground pressure and soil category.

Figure 8. Threshold height of a single obstacle overcome by the mover as a function of vehicle ground pressure and soil category.

The height of a single threshold obstacle that the wheeled propeller is capable of overcoming drops sharply as the average ground pressure of the propeller increases. For this reason, it is advisable to equip wheeled vehicles with removable cross-country vehicles such as mono-trackers on cluttered logging sites.

3. Conclusion
Analysis of the calculation results allows us to draw the following conclusions and recommendations for the selection of wheeled mover (on the example of wheeled forwarder 8x8, with another configuration of the mover should be recalculated in proportion to the change in the ratio of the number of wheels):
To comply with the requirement of environmental friendliness of the vehicle, which is that the rut depth after the passage of the machine should be less than 0.1 m [11, 12], the wheeled vehicle pressure when working on soils of medium strength (II category) should not exceed 0.07 MPa (weight of the machine with a load of 31 tons), on a weak-bearing soil (category III) - no higher than 0.025 MPa (weight of the machine with a load of 11 tons). On firm soils of I category pressure limitation on depth of a track is not actual.

On soils of II category, to ensure cross-country ability, the pressure should be limited to 0.095 MPa (weight of the machine with a load up to 42 tons) (slipping coefficient will be 0.2, track depth 0.18 m, operating speed of the machine 1.5 m/s). To ensure the wheeled propulsor support cross-country ability, the average pressure when working on soils of III category should be limited to 0.04 MPa (the weight of the machine with a load of up to 18 tons) (slipping coefficient will be 0.136, the depth of the track 0.253 m, the operating speed of the machine 2.8 m/s). On soils of the first category the pressure on cross-country ability is not limited.

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