Modeling the towing properties of construction vehicles

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Abstract. This article studies the ways to increase the towing properties of propulsors and the patency of wheeled vehicles.

The characteristics of the machines running systems significantly affect the technical level of the unit. The paper justifies the advantages of wheel dwellers over caterpillar ones. The advantages include small specific metal consumption and the possibility of usage on the roads. Wheel tractors provide the best working conditions for the driver and maintenance personnel.

Analysis of the calculated coefficients shows a significant scatter of values, which causes difficulties in the calculations. For this, it is necessary to know the values at each interaction of the tractor propulsor with the soil. The same slippage values can be obtained with different values of the coefficients. The task is simplified if these dependencies have one coefficient.

The paper obtains a model for a more complete assessment of the towing properties of wheel and tracked vehicles with a minimum number of experimental coefficients, which makes it easily applicable for engineering calculations.

Keywords: towing properties, maneuverability, slipping, lug, tangential traction, traction coefficient.

1 Introduction
The studies of V.P. Boykov, V.P. Goryachkin, V.V. Guskov, G.G. Kolobov, E.E. Klubnichkin, N.K. Mazitov, M. M. Makhmutov, R.L. Sakhapov, OI Chudakov and others, made a significant contribution to the base for increasing the towing properties of wheel propulsors [1-7].

These works note an improvement in the towing properties of propulsors due to:
1) using the entire weight of the tractor as a drawbar;
2) increased tire contact with the soil;
3) the development of new design solutions;
4) the development of new technological solutions [8-13].

These measures for a tractor with two driving wheels are implemented by: turning all four wheels into driving wheels, doubling the wheels, using loaders and hydraulic grip weight increases, lugs and half tracks. However, a significant drawback of the half-track operation is the short service life of its parts, wear of the drive wheels and a slight increase in the resistance to movement [14-20].

One of the indicators that assess the towing properties of machines is the traction characteristic, built on the results of experiments or calculations. Currently, we know more than fifty mathematical models that describe the interaction of wheel propulsion with soil [1]. Most of them were created as a result of superimposing of experimental slipping curves and determination of design coefficients depending on the tractor brand, type of running system, soil condition, etc. [2].

Analysis of the calculated coefficients shows a significant scatter of values, which causes difficulties in the calculations. Therefore, it is necessary to know their values at each interaction of the
tractor mover with the soil. The same slippage values can be obtained for different values of the coefficients. The task is simplified if these dependencies have one coefficient [3].

Existing regression analysis software of the “Regress type from ENEK Group, Advanced Grapher did not allow to select a function according to the graphical dependence of the propulsor’s interaction with the soil on one experimental coefficient. However, using the capabilities of “Mathhead”, we obtained the following expression of the traction driving force of a machine-tractor unit (MTA):

\[ P_K = \frac{\delta_K \cdot G_{cl} - \delta_K \cdot (1 - a)}{a + \delta_K \cdot (1 - a)}, \quad (1) \]

where \( P_K \) is the tangent of the traction force, N; \( \delta_K \) - slip coefficient; \( G_{cl} \) – coupling weight of the tractor, N; \( a \) - experimental coefficient, depending on the tractor brand, type of running system, soil condition. The tangential traction force can also be determined by the sum of the hook load and the force of resistance to movement then the experimental coefficient “a” from expression (1) will be determined as:

\[ a = \frac{\delta_K \cdot (P_{kp} + P_f - \lambda \cdot \varphi_{cl} \cdot G_{tp})}{(P_{kp} + P_f) \cdot (\delta_K - 1)}, \quad (2) \]

where \( P_{kp} \) – hook load, N; \( P_f \) – force of resistance to movement, N; \( \lambda \) – coefficient of load distribution of the wheels, \( \varphi_{cl} \) – coefficient of adhesion of the wheel to the soil; \( G_{tp} \) – tractor weight, N.

An analysis of the equation (2) shows that the experimental coefficient “a” depends on several factors. Coefficients of adhesion and slipping depend on the type and parameters of the running system, the physical and mechanical properties of the soil, and the load conditions on the propulsor. The hook load is determined by the traction resistance of the agricultural machine and the implement. The strength of the resistance to movement depends on the parameters of the wheel, internal tire pressure, soil hardness, tractor weight. Coupling weight depends on the mass of the unit and the load coming to the driving wheels of the tractor [4, 9].

The dependence of the experimental coefficient “a” (2) obtained analytically allows us to organize experimental studies using wheeled vehicles “Belarus” of the MTZ-82, MTZ-2022 and MTZ-3022 DC-1 type with an estimated weight of 40, 70 and 100 kN, respectively [21-23].

2 Materials and methods

We have developed an active experiment while conducting the field studies. This means that the levels of variation of factors were changed purposefully depending on the conditions of each experiment. Composite B-plans (Box plans) of the second order were implemented. The following indicators were selected as variable factors: the coefficient of utilization of the grip weight \( X_1 (\varphi_K = P_K / G_{cl}) \), the coefficient of adhesion \( X_2 (\varphi_{cl}) \) and the weight of the tractor \( X_3 (G_{tp}) \) (table 1). The work was carried out according to the plan of the three-factor experiment matrix. The experiment was conducted on an unpaved road, with adhesion coefficients of 0.50 respectively; 0.65 and 0.80.

| The name of the levels | Designation | \( X_1 \), kN | \( X_2 \) | \( X_3 \), kN |
|------------------------|-------------|--------------|--------|---------|
| Lower                  | -1          | 0.3          | 0.5    | 40      |
| Central                | 0           | 0.5          | 0.65   | 70      |
| Top                    | +1          | 0.7          | 0.8    | 100     |
| The range of variation | \( \Delta X \) | 0.2          | 0.15   | 30      |

The transition of the actual levels to the coded ones was performed according to the formulas \( X_1 = \frac{\varphi_K - 0.5}{0.2} \); \( X_2 = \frac{\varphi_{cl} - 0.65}{0.15} \); \( X_3 = \frac{G_{tp} - 70}{30} \).
In order to measure and record the parameters in the study of the towing properties of the wheel propulsion device, we used a small-sized device for energy evaluation MTA - EMA-P. The device was powered by a battery. The device simultaneously records signals from eight analog and twelve discrete sensors [7, 11]. The signals during the experiment were recorded in memory and at the end of the experiment were displayed on the display. The experiment was repeated three times.

The strength of the resistance to movement was determined by towing the MTZ-82, MTZ-2022 and MTZ-3022 DC-1 vehicles in neutral gear, respectively, at different x, dynamometer. The required hook load for each experiment was determined by the formula:

\[ P_{KP} = \varphi_k \cdot \lambda \cdot \varphi_{CUC} \cdot G_{TP} - P_f, \]

(3)

The effort on the hook was changed by shifting the gears of the variable gearbox of the towed tractor, which engine worked in compressor mode. The adhesion coefficient was determined when the tractor wheels were completely braked and towed by a tractor while measuring the coupling force with a dynamometer [10]. The ratio of this effort to the full weight of the towed tractor is a traction coefficient [5].

3 Results
In order to minimize the influence of uncontrollable factors, the order of experiments was randomized as follows: 4, 5, 7, 8, 15, 6, 12, 9, 11, 1, 14, 2, 10, 13, 3 (table 2). The influence of the studied parameters on the value of the experimental coefficient "a" was evaluated after processing the results of experiments according to the developed algorithm.

| №  | Factors and levels |
|----|--------------------|
| 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
| 1  | 0,3 | 0,5 | 40 | 20 | 5,4 | 0,6 | 8 | 0,20 |
| 2  | 0,7 | 0,5 | 40 | 20 | 5,4 | 8,6 | 31 | 0,21 |
| 3  | 0,3 | 0,8 | 40 | 32 | 1,9 | 7,7 | 2 | 0,05 |
| 4  | 0,3 | 0,5 | 100 | 50 | 13,5 | 1,5 | 8 | 0,20 |
| 5  | 0,5 | 0,8 | 40 | 32 | 1,9 | 20,5 | 11 | 0,05 |
| 6  | 0,3 | 0,8 | 100 | 80 | 4,8 | 19,2 | 3 | 0,05 |
| 7  | 0,7 | 0,5 | 100 | 50 | 13,5 | 21,5 | 32 | 0,19 |
| 8  | 0,7 | 0,8 | 100 | 80 | 4,8 | 51,2 | 10 | 0,06 |
| 9  | 0,3 | 0,65 | 70 | 45,5 | 6,4 | 11,8 | 5 | 0,12 |
| 10 | 0,7 | 0,65 | 70 | 45,5 | 6,4 | 25,4 | 23 | 0,13 |
| 11 | 0,5 | 0,5 | 70 | 35 | 9,5 | 8,1 | 17 | 0,20 |
| 12 | 0,5 | 0,8 | 70 | 56 | 3,4 | 24,6 | 5 | 0,04 |
| 13 | 0,5 | 0,65 | 40 | 26 | 3,7 | 9,3 | 11 | 0,13 |
| 14 | 0,5 | 0,65 | 100 | 65 | 9,2 | 23,4 | 12 | 0,12 |
| 15 | 0,5 | 0,65 | 70 | 45,5 | 6,4 | 16,3 | 11 | 0,12 |

A comparison of the regression coefficients for factors calculated according to the second-order plan with the corresponding confidence interval shows that the coefficient of adhesion has an effect on the value of the coefficient “a”. The remaining parameters do not affect the values of the coefficient “a” (table 3). The effects of squares and factors in pairwise interactions of the regression coefficients, in
the conditions of experimental studies, had values below the confidence interval and therefore are excluded from the equation.

Table 3. Coefficients of the regression equation of the experimental coefficient «a».

| №  | The name of the coefficients | Designation | Value coefficient.    |
|----|------------------------------|-------------|-----------------------|
| 1  | Free term                    | B₀          | + 0,125               |
| 2  | Coupling weight utilization factor, φₖ | B₁          | 0                     |
| 3  | Coefficient of adhesion, φ₅₆  | B₂          | - 0,175               |
| 4  | The weight of the tractor, G₆₇ | B₃          | 0                     |
| 5  | Coefficients of squares for factors |          |                       |
| 6  | Coupling weight utilization factor, φₖ | B₁₁         | +2,5 10⁻⁸             |
| 7  | Coefficient of adhesion, φ₅₆  | B₂₂         | +2,5 10⁻⁸             |
| 8  | The weight of the tractor, G₆₇ | B₃₃         | +2,5 10⁻⁸             |
| 9  | The coefficients of the factors in pairwise interactions | |                       |
| 10 | φₖ и φ₅₆                      | B₁₂         | 0                     |
| 11 | φₖ и G₆₇                      | B₁₃         | 0                     |
| 12 | φ₅₆ и G₆₇                    | B₂₃         | 0                     |

Thus, a model that reflects the influence of significant factors on the value of coefficient “a” in the encoded form will look like:

\[ a = 0,125 - 0,075 X₂. \]  

Moving from the encoded form of the equation (4), we obtain the final formula of the experimental coefficient "a" for wheeled vehicles depending on the coefficient of adhesion:

\[ a = 0,45 - 0,5φ₅₆. \]  

(5)

With an increase in the coefficient of adhesion by 0.1, the experimental coefficient "a" for wheeled vehicles decreases in proportion to 0.05 (figure 1).

![Figure 1. The effect of adhesion coefficient on the experimental coefficient "a": 1 – wheeled; 2 – tracked.](image)

Having substituted the equation (5) in the formula (1), we obtain the following equation of the propulsing force of the wheeled tractor traction:

\[ Pₖ = \frac{\deltaₖ \cdot λ \cdot φ₅₆ \cdot G₆₇}{(0,45 - 0,5 \cdot φ₅₆) + \deltaₖ \cdot (0,55 + 0,5 \cdot φ₅₆)}. \]  

(6)
Similarly, after conducting research on tracked vehicles, we obtained the following formula for the experimental coefficient “a” for tracked vehicles depending on the adhesion coefficient:

\[ a = 0.17 - 0.13 \varphi_{sc} \]  

(7)

### 4 Discussions

Experimental studies have found that with an increase in the coefficient of adhesion by 0.1 units, the experimental coefficient "a" for wheeled vehicles decreases in proportion to 0.05 units, and for tracked vehicles to 0.02 units.

Having substituted equation (7) into formula (1), we obtain the following equation of the driving force of traction of the caterpillar (tracked) tractor:

\[
P_K = \frac{\delta_K \cdot \lambda \cdot \varphi_{cil} \cdot G_{TP}}{(0.17 - 0.13 \cdot \varphi_{cil}) + \delta_K \cdot (0.83 + 0.13 \cdot \varphi_{cil})}.
\]

(8)

Thus, the resulting equation has a minimum number of experimental coefficients, which makes it easily applicable for engineering calculations and gives a more complete assessment of the towing properties of wheeled and tracked vehicles.

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