Stationary simulation method of road conditions in the problem of interaction prediction of the wheel of the vehicle support surface

N Volskaja\textsuperscript{1,2}, M Zhileykin\textsuperscript{1} and A Zakharov\textsuperscript{1}

\textsuperscript{1}Bauman Moscow State Technical University

\textsuperscript{2}E-mail: volskaja52@mail.ru

Abstract. A method for estimating the deformation properties of the support surface of the operation proposed area of a four-wheel drive wheeled vehicle is presented. These properties influence the vehicle efficiency. The method is based on the use of physical characteristics of soils specified in the probabilistic form. The estimation of the vehicle movement efficiency is carried out on the average probabilistic speed on the reference route. Features of vehicle rectilinear and curvilinear movement are considered.

Introduction
There are methods for calculating the wheeled vehicles patency (WV) with different wheel formulas \cite{1--17}. One of the main traction indicators is the track depth. At the same time it is important to be able to calculate its numerical value depending on the passes number when the wheels move “track to track” \cite{2}. The more specific are the expected road-ground conditions (RGC) of the movement surface, the more accurate the calculated forecast of this indicator. Thus it is possible asking the RGC by varying the propeller parameters, the calculations to find the preferred combination of effective design solutions for the evolving pilotless vehicle with high cross (PVWHC). An effectiveness indicator of the developed design PVWHC is a higher value of the probabilistic speed on the calculated reference route.

In this regard, it is relevant to solve the problem of patency assessment PVWHC on the ground surfaces of the intended operation region in General, taking into account the heterogeneity of the soil, surface roughness and the curvilinear trajectories possibility.

The purpose of the study: increased permeability of PVWHC for heterogeneous, uneven dirt surfaces and changing the deformation properties trajectory-based prediction of the intended area of operation RGC.

Problem statement
1. Develop a method for evaluating the deformation properties of the intended area of operation soil surface, providing a patency rates prediction (primarily the depth of the rut after the wheel passage) at the design stage PVWHC.

2. Development of a methodology for assessing the effectiveness of KM traffic for a specific operation area.

The tasks decision should be based on the unified approach to the soil physical-mechanical condition assessment of any type, taking into account seasonal operation PVWHC.
Stationary modelling RGC held in conjunction with the separately solved problems of pneumatic wheel interaction modeling with deformable ground (straight and curved types of motion).

Method of mechanical properties evaluation of the proposed area soil surface of operation PVWHC

Evaluation method of the deformation properties of the intended area soil surface of operation PVWHC based on the use of soils physical characteristics are presented in probabilistic form; as information sources are used long-term observations at meteorological stations, topographic and soil maps, results of field experiments, the technical literature [3]–[6].

Well-known vehicle movement mathematical models on soft soils differ from each other by different characteristics of soil deformation properties. The main requirement for them - independence from the wheel characteristics. In this study, the soil characteristics are selected: wetness \( W \), volumetric density of soil \( \rho \), modulus of deformation \( E \), internal friction angle \( \phi \), internal cohesion in the soil \( c_0 \), soft layer thickness \( H_f \). They fully correspond to the soil mechanics characteristics [7–12].

Soils are heterogeneous primarily in wetness and density. Long-term observations on soil moisture and density are conducted at weather stations. It was found that the humidity varies by month according to the normal law with a fluctuation relative to the mathematical expectation not exceeding 6 %. Therefore, for different country regions it is possible to predict the physical and soils mechanical characteristics in probabilistic and statistical form. Soil type distribution boundaries can be determined from soil maps. The weather station location is also known according to weather reports.

Depending on the type and physical condition of soils, their graphical calculation models give a different response under vertical loading and shear (fig. 1, a: — porous soil, 2 — dense soil; 3 — soil with a solid base; fig. 1, b: 1 — soil with low internal adhesion; 2 — soil with high internal coupling properties.

To describe the stress-strain state in the contact patch "of the tire-soil" can be selected calculation model proposed by J.S. Ageikin [13]:

\[
q_\beta = \left[ \frac{(H_f - z)}{b(1+1.75\varphi_0)} (k_{p2} \cdot b \cdot \rho \cdot X_1 + k_{p3} \cdot \rho \cdot X_2 + \varphi_0 \cdot c_0 \cdot X_3 \cdot z \cdot \cos \beta) + \frac{a \cdot b \cdot \arctg (H_f - z)}{E \cdot z} \right]^{-1};
\]

\[
\tau = \left[ q_\beta \cdot \tan \varphi_0 + c_0 \left(1 - \frac{S_0}{S_f}\right) \right] \left[ 1 - \exp \left( -\frac{S_0}{k_\tau} \right) \right],
\]

where \( k_{p1} = \frac{\pi - 4 \cdot \beta \cdot \tan \varphi_0}{\pi + 4 \cdot \beta \cdot \tan \varphi_0} \),

\[ k_{p2} = k_{p3} = \frac{3 \cdot \pi - 2 \cdot \beta}{3 \cdot \pi + 2 \cdot \beta}, \]

\[ X_1 = \frac{1 - X^4}{X^6}; \quad X_2 = \frac{1.3 \cdot X^2 + 1}{X^4}; \quad X_3 = \frac{1}{X^6}, \]

where \( q_\beta \) — the pressure in the contact patch; \( \tau \) — shear stress; \( z \) — track depth; \( a \) — coefficient characterizing the stresses attenuation in the ground; \( b \) — the tire contact width with the ground; \( k_\tau \) — the soil tangential elasticity coefficient; \( S_f \) — the grouser step; \( S_0 \) — grouser shift lug; \( \beta \) — angle between load vector and normal to ground surface. These dependences are confirmed by experiments conducted on sand or sandy loam.

The equations include the soil mechanical parameters \( \varphi_0, c_0, E, H_f \). Statistics on these parameters are limited. At the same time, there is great potential for the statistical data accumulation on the soils physical parameters for specific regions. In order to use these opportunities, relationship studies between the physical and soils mechanical parameters were carried out. As a result, the following equations are obtained:

\[
E = K_{E1} \cdot \frac{W_T \cdot \rho c^2}{(W - 0.05)} - K_{E2} \cdot (W \cdot W_T)^2; \quad \varphi_0 = K_{\varphi1} \sqrt{\frac{K_{\varphi4}}{W_T}} - K_{\varphi2} \cdot \left(1 - \frac{\rho c}{\rho_T}\right) - K_{\varphi3} \cdot W \cdot \sqrt{\frac{W_T}{K_{\varphi4}}};
\]
\[ c_0 = K_{C1} \cdot \frac{W_T}{W} \rho_C - K_{C2} \cdot W \cdot W_T, \]

where \( K_{E,\phi} \) — coefficients; \( W_T \) — the wetness of yield point; \( \rho_c \) and \( \rho_T \) — the density of a skeleton of soil solid particles.

Therefore, it is possible to predict the numerical value of mechanical parameters of connected and disconnected soils depending on changes in soil moisture (seasonal forecasting) [18]–[21].

\[ q_\beta = q_0 \cdot k_\beta, \quad k_\beta = \frac{1}{1 + \frac{l \cdot n}{V}}, \quad t = \frac{l \cdot n}{V}, \]

where: \( l \) — the contact length; \( n \) — number of passes per track (or number of axle); \( V \) — speed of PVWHC; \( t \) — the duration of the load.

When driving even a single KM is characterized by cyclic soil loading. When loading the soil, there is a change in its density and humidity, i.e. its mechanical properties. The loading cyclicity can be identified with the time of single load action, but with a large effect, which can be reflected by the corresponding coefficient of transition from the time of its action to the cycles number.

Example of loading cyclicity influence (number of passes) and load action time \( t \) to the track depth \( z \) shown in fig. 2, a, b. Track depth is determined by dynamic pressure \( q_\beta \), fig. 2, a on the set \( V, l, \theta_0 \) and \( q_\beta = f(z) \). The values are then determined \( \phi_0 \), \( c_0 \) and \( E \) for connection equations.

The method of database presentation on the physical and mechanical characteristics of each soil type distributed in the intended area territory of vehicle operation is as follows:

1. According to soil maps, the main soils types are determined (it can be one or two soils). Soils are classified into: clay, loam, sandy loam, sand, snow.

2. According to the weather stations materials the wetness is statistically represented \( F(W) \), \( \rho(W) \) for a specific month (for example, the time of the thaw is April).

3. Graphs are represented by the above dependencies \( F(W) \), \( \rho \), \( E \), \( \phi_0 \), \( c_0 \). A graphical view of the statistical database on soil type silt is shown in figure 3.
Figure 2. An example of the cyclical loading effect

Figure 3. Graphical view of the statistical database on soil (Silt)

Mathematical model of RGC operation area

It is proposed to assess the heterogeneity of the RGC operating area using a virtual reference route. The mathematical model of the route consists of several sections. Soil maps determine the boundaries and areas of main types of soils distribution of the operation intended area (one or more types of soils). Taking the hypothesis of the equal probability of movement PVWHC at any terrain point, it is possible
to determine the density of the distribution of soil types: \( P(j) = \frac{S_j}{S_{\text{total}}} \), where \( S_j \) — distribution area of \( j \)-th soil; \( S_{\text{total}} \) — region area in question. As a result of analyzing soil maps to assess the prevalence of soil type, a decision is made to introduce it into the characteristics of the sites.

Reference route — a set of sections, each of which is characterized by a "weighting factor" — the relative length \( P_i \) (selected by analyzing soil, topographic and road maps). The prevailing soil type (or several soils) is assigned to the parcel number \( s \). Each site is characterized by probabilistic characteristics of soil parameters, slopes, degree of evenness. On one of the sites in the probabilistic form is given curvilinear motion. The average probabilistic speed on the reference route is determined by:

\[
V_{cp} = \sum \frac{1}{P_i} V_{eci}^{i-p},
\]

where \( P_i \) — relative length of the section in the reference route; \( V_{eci} \) — probabilistic average speed on \( i \)-th site.

Mathematical model of PVWHC interaction wheel mover with soil in rectilinear motion

For determining \( z \) — track depth and \( h \) — tire deformation is used, the above equation models from J.S. Ageikin and the calculated scheme of interaction between wheel and soil (fig.4).

![Design scheme of wheel-ground interaction](image)

**Figure 4.** Design scheme of wheel-ground interaction
Determining rut depth and deformation of the tire for the front axle PVWHC for subsequent axes, with the condition of a constant gauge, determine the parameters of the contact problem of a wheel-soil, but the physical and mechanical characteristics of the soil are recalculated according to the number of the axis (or passage) in the dependencies\( \rho_n = f(n; q_0; \rho_m); \quad E_n = f(n; W_m; W) \).

After determining \( h \) and \( z \) for each vehicle wheel are defined: tire rolling resistance coefficient, \( f_{W1} \); the rolling resistance coefficient of soil, \( f_r \); total rolling resistance coefficient \( f \); free relative thrust force on the hook \( \psi_T \):

\[
f_{W1} = 1.75 \cdot P_x \cdot \psi_1 \cdot h^2 \left( B^2 + 1.5H^2 \right) \frac{B - 0.3h}{P_x \cdot H \cdot B^2}; \quad f_r = q \cdot z \cdot 0.3 \left( \frac{b + b_k}{P_x} \right); \quad f = f_{W1} + f_r; \quad \psi_T = \left[ k_H \cdot \psi_1 + \left( 1 - k_H \right) \left( \tan \varphi_0 + \frac{c_0}{q} \right) \right] - f_r,
\]

where \( B, H \) — width and height of tire profile; \( E_1 \) — the tangential modulus of soil deformation; \( k_H \) — coefficient of saturation of the tread pattern; \( \mu_1 \) — coefficient of friction of rubber on the ground; \( \psi_1 \) — coefficient of hysteresis losses in the rubber-cord bus sheath.

The calculations results show that if we solve the problem of patency estimation (for example, when determining the engine optimal parameters in the given RGC), then in the probabilistic formulation a solution significantly different from the final result in the averaged formulation will be obtained.

**Assessing patency of PVWHC when moving along a curved path on a deformable surface**

For the case of curvilinear motion developed: 1) the mathematical model of rolling elastic wheels on rigid and deformable grounds; 2) mathematical model of PVWHC motion on deformable soil.

In assessing the pneumatic wheel kinematic and power parameters of the curvilinear motion takes into account its more complex loading and change in the nature of the movement in comparison with the rectilinear.

The wheel power balance is recorded as follows:

\[
M_{k_0} \omega_k = P \omega_k r_k + P \omega_k r_k \omega_k + P \omega_k (r_k^2 - n_k) + K \delta^2 \omega_k r_k + M_{k_0} \omega_k,
\]

where \( M_{k_0} \omega_k \) — power supplied to the drive wheels from the transmission; \( P \omega_k r_k \) — power spent on performing useful work; \( P \omega_k r_k \omega_k \) — rolling resistance losses due to radial tire deformation in free mode; \( P \omega_k (r_k^2 - n_k) \) — rolling resistance losses from tangential deformations and sliding in the contact spot in the longitudinal direction; \( K \delta^2 \omega_k n_k \) — losses due to lateral withdrawal; \( M_{k_0} \omega_k \) — losses in acceleration.

In the evaluation of pneumatic wheel kinematic and force parameters of curvilinear motion on deformable soil deformation is considered in three directions as the wheels and the ground. In contrast to the pneumatic wheel deformability, the soil deformability in the normal, tangential and lateral directions is considered in the relationship (fig.5).

**Method of calculating the average probabilistic speed of the PVWHC on a route that includes typical sections of paved roads, dirt roads and terrain**

As an example of a reference design route, consider the road-ground conditions, which are characterized by the main soil (background) — loam. RGC of wheeled vehicle movement are represented by seven characteristic sites (fig. 6). The sections length and the RGC of each section are given in probabilistic form. Methods for determining the maximum possible speed of movement in the areas are different and depend on the deformation properties of the support surface and its roughness.
The cumulative distribution function of velocities $F(V)$, RMS values of the dynamic suspension $h_{dc}$ and vertical vibration acceleration $\ddot{Z}_c$ depending on the vehicle speed in question on each of the sections of the route are presented on fig. 6.

Figure 5. The design scheme of the tire interaction with the ground in curvilinear motion

Figure 6. Example of forming the structure of the reference route
In section 1, the speed is determined from the vehicle power balance equation. On the other six sites according to special developed methods. The average probabilistic speed on the route is determined taking into account the possible variability of the nature of the trajectory and types of RGC.

Probabilistic characteristics of seven sections of the reference route: $F(i)$, $F(V)$, $F(W)$, $F(H_R)$, $F(f)$ — integral functions of slope distribution, velocity, humidity, soft layer thickness, rolling resistance coefficient, respectively. The table shows an example of the reference route structure formation.

### Table

| Section number | Surface plot characteristics | The relative length, $P(N)$ |
|----------------|-------------------------------|-----------------------------|
| 1              | Paved road, smooth            | 0.3                         |
| 2              | Dirt road, flat               | 0.05                        |
| 3              | The road is paved, uneven     | 0.3                         |
| 4              | Dirt road, uneven             | 0.2                         |
| 5              | Unpaved surface smooth (clay loam) | 0.1                     |
| 6              | Ground surface, uneven        | 0.025                       |
| 7              | Curved sections of ground surfaces, smooth | 0.025                   |

The results reliability was confirmed by assessing the adequacy of mathematical models of the elastic wheel interaction with the deformable soil and the calculation results of the moving PVWHC permeability to the results of the field experiment. Experimental studies were carried out using wheeled vehicle of high permeability on loamy and sandy soils in the floodplain of the Oka river, on muddy and sandy soils of the ZIL landfill in Feodosia.

**Conclusion**

1. The basic principles of mathematical models formation that allow the estimated by evaluating the deformation properties of a soil surface area exploitation for developing wheeled vehicle. The method allows in stationary simulation by calculation to predict the expected numerical values of permeability. Calculations can be carried out for both unmanned and manned wheeled vehicle.

2. It is offered to estimate efficiency of PVWHC in the area of intended operation by means of the settlement reference route. An appropriate methodology has been developed. Route sections with a certain relative length are divided depending on the type of road-ground surface, the degree of roughness, ruggedness, soil parameters. Each site is represented by statistical characteristics. The criterion of efficiency of BT SVP is a probabilistic average speed at each site and probability speed of traffic on the route.

**References**

[1] Bekker M.G. Introduction to terrain-vehicle systems. — Ann Arbor: University of Michigan Press, 1969. — 520 p

[2] Volskaya, M.M. Zhileykin and A.Y. Zakharov. Mathematical model of rolling an elastic wheel over deformable support base. IASF-2017. IOP Conf. Series: Materials Science and Engineering 315 (2018) 012028 doi: 10.1088/1757-899X/315/1/012028.

[3] Rybansky, M. The impact of terrain on cross-country mobility geographic factors and their characteristics / M. Rybansky [et. al] // 18th International Conference of the International Society for TerrainVehicle Systems, ISTVS 2014. — Seoul, 2014.
[4] Shaheb M.R., Grift T., Godwin R., Dickin E., White D., Misiewicz P. Effect of tire inflation pressure on soil properties and yield in a corn - soybean rotation for three tillage systems in the Midwestern United States. — 2018. doi: 10.13031/aim.201801834.

[5] Shoop S., Kestler K., Haehnel R. Finite element modeling of tires on snow // Tire Science and Technology. 2006. Vol. 34, no. 1. P. 2–37.

[6] Botero J., Gobbi M., Mastinu G. A new mathematical model of the traction force in pneumatic tire snow chain systems // Associazione Italiana Per L’Analisi Delle Sollecitazioni / Dipartimento di Meccanica, Politecnico di Milano. 2005. 10p. www.aiasonline.org/AIAS2005/Articoli/art084.pdf.

[7] Belousov, B., Ksenevich, T.I., Vantsevich, V., Komissarov, D. 8×8 platform for studying terrain mobility and traction performance of unmanned articulated ground vehicles with steered wheels (2013) SAE Technical Papers, 9.

[8] Belousov, B.N., Shelomkov, S.A., Ksenevich, T.I., Kupreyanov, A.A. Experimental verification of a mathematical model of the wheel-supporting surface interaction during nonstationary rolling motion (2009) Journal of Machinery Manufacture and Reliability, 38 (5), pp. 501–505.

[9] Keller, A.V., Gorelov, V.A., Vdovin, D.S., Taranenko, P.A., Anchukov, V.V. Mathematical model of all-terrain truck (2015) Proceedings of the ECCOMAS Thematic Conference on Multibody Dynamics 2015, Multibody Dynamics 2015, pp. 1285–1296.

[10] Benes L., Hermanek P., Novak P. Tensile resistance of wheeled combine harvester. Engineering for Rural Development // MM Science Journal, Volume. — 2018, pp. 2481–2483; doi:10.17973/mmsj.2018_10_201848.

[11] Špokas L., Adamčuk V., Bulgakov V., Nozdrovický L. The experimental research of combine harvesters. Res. Agr. Eng., 62: (2016): p. 106–112.

[12] Kaneko, T. and Kageyama, I. 2003 A study on the braking stability of articulated heavy vehicles, JSAE Review, Vol. 24, pp. 157–164

[13] Ageikin J.S. The flow of cars. — M.: Mashinostroenie, 1981. — 232 pp.N.S.

[14] Gorelov, V.A., Komissarov, A.I. Mathematical model of the straight-line rolling tire - Rigid terrain irregularities interaction (2016) Procedia Engineering, 150, pp. 1322–1328. DOI: 10.1016/j.proeng.2016.07.309

[15] Gorelov, V.A., Komissarov, A.I., Miroshnichenko, A.V. 8×8 wheeled vehicle modeling in a multibody dynamics simulation software (2015) Procedia Engineering, 129, pp. 300–307. DOI: 10.1016/j.proeng.2015.12.066.

[16] Keller, A.V., Gorelov, V.A., Anchukov, V.V. Modeling truck driveline dynamic loads at differential locking unit engagement (2015) Procedia Engineering, 129, pp. 280–287. DOI: 10.1016/j.proeng.2015.12.063

[17] Kotiev, G.O., Padalkin, B.V., Kartashov, A.B., Diakov, A.S. Designs and development of Russian scientific schools in the field of cross-country ground vehicles building (2017) ARPN Journal of Engineering and Applied Sciences, 12 (4), pp. 1064–1071.

[18] Kupreyanov, A.A., Morozov, M.V., Belousov, B.N., Ksenevich, T.I., Vantsevich, V.V. Experimental research of tire elastomer-surface tribological properties(2014) Proceedings of the ASME Design Engineering Technical Conference, 3.

[19] Klubnichkin, V.E., Klubnichkin, E.E., Kotiev, G.O., Beketov, S.A., Makarov, V.S. Interaction between elements of the track ground contacting area with the soil at curvilinear motion of the timber harvesting machine (2018) IOP Conference Series: Materials Science and Engineering, 386 (1), article № 012016.

[20] Wong, J.Y. Theory of Ground Vehicles / J.Y. Wong. — New York: Wiley IEEE, 2001. — 560 p.

[21] Sarach, E., Kotiev, G., Beketov, S. Methods for road microprofile statistical data transformation (2018) MATEC Web of Conferences, 224, article № 04009.