Investigation of the slope angle influence on the loading imbalance of the wheeled vehicle sides and the change in the center of gravity vector direction

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Abstract. The article deals with the inclination angle influence of the support surface on the vertical deformation of the wheeled vehicle tire, as well as the relationship of transverse stability with the air pressure in the tire and its deflection.

1. Introduction.
One of the main operational characteristics of wheeled vehicles is the stability of movement, which provides high-quality and safe performance of transport and technological processes in agriculture as well as determines the equipment use effectiveness \cite{1,2}. The stability of the wheeled vehicle movement is influenced by such factors as: speed, bearing surface area state, longitudinal and transverse slopes, longitudinal base, wheel track, center of gravity coordinates and others \cite{2}. Violation of straightforwardness, particularly on slopes and hillsides results in reduction of the technological process quality, the loss of speed and performance by lengthening the actual passable route, increasing fuel consumption, worsening of traffic conditions on the curvilinear sections and rollover \cite{2,3}. Therefore, ensuring stability when moving wheeled vehicles on surfaces with a complex profile is one of the important ways to improve the efficiency and safety of equipment.

2. Analysis of publications and research.
A large number of works \cite{1,2,3,4,5,6,7,8} are devoted to the problems of increasing the wheeled vehicles stability when driving on the slopes.

In these works the analysis of the reasons leading to wheeled vehicles overturning is given, engineering devices for this problem solution are offered (figure 1) \cite{7}.

The proposed engineering solutions allow, to a certain extent, to solve the problem of increasing the wheeled vehicle stability but they have some disadvantages: reduced geometric patience, complexity of the design, soil compaction and more.

The analysis of publications on the potential efficiency of wheeled vehicles operation in agricultural production showed that the problem of improving the stability on the slopes has no final solution and remains relevant. As a result of existing scientific and technical solutions review aimed at improving the efficiency and safety of wheeled vehicles operation in the performance of technological operations, in particular the improvement of transverse stability, it is reliably established that one of
the most promising and rational ways is to control the direction of the wheeled vehicle center of gravity vector [1,2,6].

Figure 1. Main ways to improve the transverse stability of wheeled vehicles

3. Purpose of research.
Determination of the changes effect in air pressure in the wheels tires on the wheeled vehicle stability when moving across the slope.

To achieve this goal, the following research tasks are formed:
1) To describe the process of wheeled vehicle transverse stability loss when operating on a surface with a slope.
2) To obtain the dependence of the tires deformation on the wheeled vehicle sides on the slope angle and the vertical load at different air pressures in the tires.

4. Method of research.
At horizontal rectilinear movement of the wheeled vehicle on the hard level road forward speed of wheels of the left and right sides (at all equal conditions) is identical, i.e.

\[ V_{ls} = V_{rs}. \]  \( (1) \)

In this case, the weight of the vehicle is distributed over the axles and wheels in accordance with its design. For vehicles and tractors with a 4x2 vehicle's weight is distributed like this: on the front axle – 1/3G; on the rear one – 2/3 G. For the cars with the wheel formula 4x4 it is: on the front and rear axle - 1/2 G. It is assumed that the redistribution of weight at the wheels on a level road does not occur, collapse (deflection) of the tire meets certain standards depending on tires design and pressure in them [9,10,11,12].

Under these conditions, any of the wheels velocity of translation is determined by the expression:
V_w. = S/ t, \hspace{1cm} (2)

where S - the path traversed by the vehicle, m; t-time, s.

Classically, the path traversed by the vehicle will be determined as:

S=2\pi r_n n, \hspace{1cm} (3)

where n - the number of wheel revolutions; r_n - free wheel radius, m.

We assume that at the horizontal vehicle movement the static r_st wheel radius determines the amount of tire deflection and depends on the tire model and the pressure in it.

Then the translational wheel speed will be determined as follows:

V_w. = 2\pi r_st n / t. \hspace{1cm} (4)

When the machine moves across the slope, the decisive factor of deviation from the working (rectilinear) trajectory is the redistribution of loads (weight) on the wheeled vehicle sides [9, 13, 14]. In this case, the side wheels tires deflection located closer to the base of the slope will be greater than that of the opposite side due to its unloading. With this in mind, the static wheels radii will be as follows:

right (more loaded) side r_st - \Delta r_st;
left (unloaded) side r_st + \Delta r_st, \hspace{1cm} (5)

where \pm \Delta r_st - the value of the tire deformation (deflection) when loading or unloading the sides of a wheeled vehicle located on a slope, mm. It should be noted that the magnitude \pm \Delta r_st is a function of the slope angle values, tire pressure and load on the wheel (\Delta r_st = f(\alpha, \rho, G)). For fixed angle values \alpha, \Delta r_st will take the corresponding values: \Delta r_st, \alpha_1, \Delta r_st, \alpha_2 ... \Delta r_st, \alpha_n.

Then the translational wheels speeds will be:

right side V_{rs} = 2\pi (r_st - \Delta r_st)n/t; \hspace{1cm} (6)
left side V_{ls} = 2\pi (r_st + \Delta r_st)n/t. \hspace{1cm} (7)

The analysis of the equations shows that the translational speed of the left unloaded side wheels is greater than the wheels of the right side, which leads to a violation of the vehicle course movement across the slope. From the above it can be concluded that the alignment of the wheels sides static radii when the vehicle moves across the slope would result in a more stable wheeled vehicle movement.

We determine the equilibrium condition of the moments of forces acting on the wheeled vehicle, when it is located on the slope (in a static state) (Fig.1). To determine the reaction \mathbf{R}^l on the wheels of the right (loaded) and left \mathbf{R}^u (unloaded) sides of the wheeled vehicle, we use the expression of the vehicle tilting moment value with respect to the point O \hspace{1cm} [9,11,15,16]:

\Sigma M_0 = G \cdot \cos\alpha \cdot 0.5 \cdot B - G \cdot \sin\alpha \cdot h_{mc} - \mathbf{R}^l \cdot \mathbf{B}, \hspace{1cm} (8)

where G is the wheeled vehicle weight, kN; \alpha is the slope angle (static), deg.; B - track width, m; h_{mc} - height of the wheeled vehicle mass center, m.

To study the magnitude of the imbalance on the wheeled vehicle sides, we find the forces acting on the vehicle when it is on the slope. From equality (8) we find that:

\mathbf{R}^l = (G \cdot \cos\alpha \cdot 0.5 \cdot B - G \cdot \sin\alpha \cdot h_{mc})/ B \hspace{1cm} (9)

Provided \mathbf{R}^l \to 0, the rollover of the vehicle can occur (\mathbf{R}^l=0). In this case, the reaction force acting on the right side wheels will be the maximum value and at a certain moment it will reach G value.

The nature of normal load (weight) redistribution on the sides can be considered on the example of the tractor MTZ-80 (G=3700 kg; B=1.35 m; h=0.805 m) \hspace{1cm} [17]. It is necessary to take into account the weight distribution between the front and rear axle. The results of the calculation according to the formula (9) are shown in figure 2.

The graph shows that as the static angle of the slope increases (\alpha_0), the right side (1,2 lines) is loaded, and the left side is unloaded (3,4 lines) almost according to a straight-line correlation. When reaching \alpha=40^\circ (static critical rollover angle for wheeled tractors [9]), the reaction on the left side wheels approaches zero and it is possible to separate the left side wheels from the bearing surface (rollover moment).
Figure 2. Scheme of changing the MG vector direction and the values of the wheels static radii (tire deflection) due to the load redistribution when changing the angle of the slope

Figure 3. Distribution of weight G on the wheels of the right and left sides depending on the slope angle: 1, 2-right (loaded) side of the rear and front wheels load, respectively; 3,4-left side of the rear and front wheels load
Based on the data obtained, we determine the normal tires deflection of the tractor MTZ-80 front and rear wheels, depending on the load on each side (wheel). For example, we consider the rear wheels tires of size-15.5R38 (brand f-2A) and the front wheels tires 9.0 – 20 (brand VL-45) [18]. The value of the normal tire deflection, depending on the load on the wheel and the air pressure in the tire, is determined by the dependence proposed by V. L. Biderman [19]:

\[
h = \frac{C_2 \cdot G}{2 \rho} + \left(\frac{C_2 \cdot G}{2 \rho}\right)^2 + C_1 \cdot G,
\]

(10)

where \( h \) - normal deflection, m (we believe that \( h = \Delta r_{st} \)); \( \rho \) - tire pressure, MPa; \( C_1 \) and \( C_2 \) - constant coefficients determined empirically for each tire type. In our case for tires 15.5R38: \( C_1 = 0.0028 \times 10^{-5} \) m²/N, \( C_2 = 0.3 \) m⁻¹; for tires type 9.0 – 20: \( C_1 = 0.0012 \times 10^{-5} \) m²/N, \( C_2 = 0.6 \) m⁻¹ [18]. The calculations carried out by the formula (10) are presented in figures 4 and 5.

**Figure 4.** Deformation dependency of the right (loaded) side tire (\( \Delta r_{st} \)) on the vertical G load at various air pressures in the tires \( \rho \): 1 – at a pressure of 0.08 MPa; 2 - at a pressure of 0.11 MPa; 3,4 – at a pressure of 0.014 MPa; 5 – at a pressure of 0.20 MPa; 6 – at a pressure of 0.25 MPa(a - rear wheel, b - front wheel)
Figure 5. Deformation dependency of the left (unloaded) side tires $h(\Delta r_{st})$ on the vertical G load at various air pressures in the tires $\rho$: 1 – at a pressure of 0.08 MPa; 2 - at a pressure of 0.11 MPa; 3,4 – at a pressure of 0.014 MPa; 5 – at a pressure of 0.20 MPa; 6 – at a pressure of 0.25 MPa ($a$ - rear wheel, $b$ - front wheel)

Analyzing the data obtained on the deflection magnitude of the right and left sides’ tires, it can be noted that the deformation (deflection) is significantly influenced by the amount of air pressure in the tire. For example, when the air pressure in the rear tire of the right side is reduced from 0.14 MPa to 0.08 MPa, with an increase in the load on the wheel (from the horizontal position of the tractor), the deflection increases by an average of 30...40 mm (Fig.4-a). Unloading of the tractor rear wheel (Fig. 5-a), leads to a change in deflection $(\Delta r_{st})$ (with increasing pressure) from 20 mm to 5 ... 8 mm. In this
case, the static radius of the \( r_e \) wheel approaches the free radius \( r_0 \). A similar situation is observed in the front wheels, only the amount of deflection varies within smaller limits (15...20 mm for the loaded wheel (Fig 4-b); 12...4 mm for the unloaded (Fig 5-b)).

The given calculations on deflection for MTZ-80 tractor tires are confirmed by the data of other researchers. So for conventional tires the deflection value at the maximum recommended radial load and corresponding to its internal air pressure is in the range of 10 ... 14%, tires for tractors and agricultural machinery 14...18%. The developed cleats tires amount of deflection is 22 ... 27% [18,19].

The amount of tire deflection can be determined experimentally as the difference between the mean radius in the free state (without radial load) and the static radius of the \( r_e \). For example, in a 1000x650 tire, an increase in internal pressure from 0.5 kg/cm² to 2 kg/cm² leads to a decrease in deflection from 43 mm to 23 mm at a load of 500 kg and from 140 to 84 mm at a load of 3000 kg [18,19].

Analyzing these data, it can be noted that the value of the internal pressure in the tire has a significant impact on the amount of tire deflection. At the same time, the disproportionate change in deflection, depending on the change in internal pressure, under different loads is also explained by the change in tire stiffness depending on the deflection value.

The increase in the relatively greater magnitude of the deflection at low loads can be explained by the fact that the deflection does not involve the side tire elements which have increased stiffness.

5. Research results.

Depending on the slope angle, the changes in the load on the sides of the wheeled vehicle, the changes in the radii of the wheels (tire deflection), the displacement of the center of gravity vector direction are determined.

Based on the analysis of the above material, it can be assumed that the forced change in the values of the static radii of the wheels (when the wheeled vehicle is on a slope) can be controlled (within certain limits) by changing the direction of the center of gravity vector, and therefore increase the transverse stability of the vehicle. The analysis of literary sources shows that the tires deflection \( \pm \Delta r_{st} \) adjustment at the wheeled vehicle on the slope can be realized by using air (gas) (increase, decrease pressure) in the respective sides of the wheeled vehicle tires. For this purpose, the authors of the article developed a tracking automatic system of "pumping-reducing” air pressure in the sides of a wheeled vehicle tires moving across the slope or down-up the slope [20,21].

6. Summary.

Depending on the slope angle, due to the redistribution of the vehicle weight on its sides, there is a change in the center of gravity vector direction by changing the radii of the wheels (deflection);

A more stable position of the vehicle on the transverse slope can be achieved by automatically adjusting the air pressure in the wheels tires.

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