Researching rolling resistance of the wheeled forestry tractor at skidding

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Abstract
Off-road performance improvement remains one of the main problems in designing wheeled dragging and forestry tractors. Improvement of off-road performance of the dragging and forestry tractors is closely related to the general problem of wheeled vehicles' off-road performance, however it features a number of specific aspects which require specialized research to be made.

During tree skidding by a wheeled tractor, vertical load on a double-reduction axle greatly changes that is linked to additional load by a roundwood bundle and redistributed in-motion load. The above in-motion redistribution of load and driving moments along the axles greatly affects the vehicle's off-road performance. While skidding, the increased load on a wheel leads to increased specific pressure, track depth and rolling resistance.

This work employs simplified tire calculation model used as a base to determine relationship between load and deformation. Calculation is made successively for each elementary tire section that allows for finding diagram of pressure distribution in the contact longitudinal plane and researching rolling resistance related to rutting and hysteresis losses in the tire material. Further experimental research of the driving wheel and wheel system motion allowed for elaborated theoretical analysis and helped to justify parameters the forestry tractor wheels.

The following tasks were set during this work:
1. To make efforts to elaborate approximated method for estimating relative elongation of the rolling resistance depending on wheel parameters, vertical load and air pressure. The method is based on calculation of contact pressure distribution on the basis of simplified tire model
2. To conduct experimental research of rolling resistance for one wheel and wheel set of a tractor in the leading movement mode with due regard to tire tangential deformation.
3. To study aspects of a process of rolling resistance of a forestry tractor during tree skidding in summer time. To run comparative draw tests of a forestry tractor equipped with tires of variable size.
4. To find out possibilities to reduce rolling resistance basing on theoretical and experimental researches.

Keywords: Wheeled forestry tractor, Rolling resistance, Tree skidding, Off-road performance

1.Introduction
Today forest industry and forest management of the Russian Federation have a mission of sustainable use of the national forest wealth. This mission can be carried out through designing a set of equipment for gradual and selective cutting, clean cutting, regeneration and forestry works, as well as fire-fighting and pest management(sandu). The types of cutting feature low volume of cut wood per unit of area. It varies from 7 m³ per 1 ha at thinning from 50 to 90 m³ during gradual and selective cutting. The equipment used during such cutting and forestry works shall meet such important requirements as high mobility and less damage to undergrowth and left trees. In this condition use of wheeled tractors is more reasonable as compared to tracked vehicles.

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Performance research needs solving of a number of issues and involves examination of rolling resistance, wheel friction features and soil bearing capacity.

The most prominent researches in this field are made by Ya.S. Ageykin, V.F. Babkov, M.G. Bekker, A.K. Birulya, N.F. Bocharov, V.A. Deligovskiy, V.P. Goryachkin, V.L. Knozroza, V.M. Kotikov, A.F. Poletaev, Yu.E. Sharikyan.

A dragging tractor during ground skidding has a higher trailing weight, with that the load on the wheels greatly changes both due to bundle weight and re-distribution of weight between the vehicle axles, especially during the movement (Melekhov, 1980; Pobedinsky and Zheldak, 1989; Kotikov, 1995). During off-road movement in the forest such change in wheel loads may lead to tire overload, sharp rise in ground pressure and increased rolling resistance. Rolling resistance frequently constitutes the majority of the total movement resistance and requires priority research.

Researching impact of changes in wheel vertical load on rolling resistance demanded review of load transfer from a wheel rim to its base, its deformation and pressure distribution in the contact area. Strictly theoretical solution to this issue meets huge difficulties, and when wheel rolling mechanics are examined, use is made of approximate methods based on calculation of tire simplified models. This work reviews a model pneumatic tire which allowed finding a dependence between rolling resistance and forestry vehicle wheel parameters, tire air pressure and vertical load.

Rolling resistance research is inextricably linked with research of operation of the wheel system – in movement distribution of load between axles and related re-distribution of torques, as well as finding of optimum weight distribution of the dragging tractor. Such researches are needed for solving a whole range of practical tasks related to designing of cross-country wheeled running gear and selection of optimum design of the vehicle in general (Bekker, 1969; Wong, 2009, Horn 2007).

2. Researching a process of rolling resistance of a forest vehicle wheel with pneumatic tire

Air pressure forces and tire external load may be simply taken up by the cord threads located in one radial plane. We call this form of carcass radial-balanced. Material reactions in the planes different from a radial one can take up air pressure in case of disordered radial-balanced form of the shell, which is used to define them and consider in the calculations. Proceeding from this provision, the tire calculated model represents a carcass where the cord threads are located strictly in radial plane, with that the model carcass dimensions are reduced from radial-balanced form to the dimensions of similar to the calculated tire through the action of a breaker strip (Fig. 1) (Kotiev et al. 2009; Primazarov et al. 2015).

![Figure 1. Calculation diagram](image)

The given in this work solution of differential equations of flexible thread tension by action of air pressure and widely known experimental data determine that the flexible thread is deformed over constant radius (Goberman et al. 2003; Kochnev and Bocharov et al. 1974). Let us review an equilibrium of forces and reactions in an elementary section. A sum of vertical components of forces of air pressure and external load on the X-X section is equal to \( P_0(B+\Delta B) - \Delta Q \). Vertical reactions of the flexible thread tension along X-X axis are equal to \( 2R P_0 \). For the given section the width in length units is not considered in the calculation. The following dependence is obtained from the condition of equilibrium of forces and reactions:

\[
P_0(B+\Delta B) - \Delta Q = 2R P_0,
\]

\( \Delta Q = P_0(B+\Delta B - 2R) \) (1)

Calculation of loading consists in calculation of a tire side curvature radius \( R \) and increase of width \( \Delta B \). We initially assume that the elementary section (Fig. 2 a) is cylindrical (hose section), rimless, absolutely flexible, inextensible, the perimeter width is even and equal to the length unit (1 cm), the tangential forces – reactions of carcass tension, perpendicular to radial, are absent. For our purpose we call the section a separate flexible thread. External load is transferred to flexible thread via two horizontal planes \( M, N \).

Since load is transferred via parallel planes and the thread is deformed along the radius, the side form represents a semicircle.
Ideally an elementary section has a form of circle (hose section), is absolutely flexible, inextensible, tangential forces are absent. For our purpose we call a section a separate flexible thread. External load is transferred to a flexible thread via two parallel planes. For the assumed conditions \[2R = H - \lambda\], and the section width increase under load and length of thread contact length \(L\) are found on the assumption that the thread is inextensible and its height is equal to width \(H = B\).

Relationship between the load and deformation becomes as follows

\[\Delta Q = \frac{\pi}{2} P_0 \cdot \lambda\]  
(2)

According to equation (2) relationship between the load and deformation is straight-line and may be expressed through specific rigidity. When the load is taken by tire air pressure only (carcass effect is not considered), the load taken by the section can be found by the volume of compressed air, passing through calculation of area and form of contact surface or base rigidity. Then pressure distribution is determined by section areas in contact.

Hence, specific pressure shall be equal to air pressure. However, specific pressure is equal to air pressure only when the section between parallel planes is deformed. In this case equation (2) becomes as follows

\[\Delta Q = P_0 \cdot L\]  
(3)

If the contact surface is curvilinear (Fig. 3), then specific pressure is not equal to air pressure. Such deformation of a shell occurs under influence of the tire tread or when a section is deformed on the crushable soil. Definition of relationship between load and radial deformation reduces to calculation of a radius of the side curvature and impact of the carcass on the tire specific rigidity that allows for finding distribution of specific pressure both on the hard foundation and crushable soil.

Through sequential consideration of impact of a rim, tread on the tire side curvature radius, as well as impact of tangential forces and carcass rigidity we find relationship between load on radial section and deformation, which is used to calculate specific rigidity. In case of hard foundation, the value of deformation of each wheel section in contact is easily calculated, hence pressure profile along contact length can be found.
of sides of the tire radial element.

Thus, even if the rigidity of the entire tire depends on rigidity of the foundation, it can be recalculated to specific rigidity which within the certain limits can be taken as a tire parameter not dependent on foundation rigidity in calculating on-soil rolling.

3. Analytical calculation of rolling resistance on solid crushable foundation

The force of rolling resistance on solid foundation can be found by energy loss in the course of movement. The rolling load is taken by a carcass and air. Let us accept that energy losses for air volume compression can be omitted. In case uniform rolling the tire air volume does not change and its movement is insignificant. Contact friction shall be considered by coefficient $K \approx 1.1$ of the main energy losses for hysteresis. Hysteresis energy losses shall be found by energy taken by the tire carcass in the course of rolling and a hysteresis loss coefficient.

The found relationship between the load taken by the carcass, its deformation, deformation of the cord thread tread is used to find the energy taken by carcass, the losses and then the rolling resistance

$$f_t = \frac{3\eta h \cdot 2\sqrt{DA}}{8D} \cdot \left( \frac{8}{3} \left( \frac{E_p h}{2n \cdot s E_k \cdot \cos \beta} + \frac{E_p \cdot \varepsilon h \cdot 2\sqrt{DA}}{Q} \right) + \frac{2}{3} \cdot \frac{\lambda E_k n \cdot h^2 \cdot 2\sqrt{DA}}{Q} + \frac{1}{2} \cdot \frac{\lambda E_k n \cdot h^2 \cdot 2\sqrt{DA}}{Q} + \frac{2}{2} \cdot \frac{\lambda E_k n \cdot h^2 \cdot 2\sqrt{DA}}{Q} \right).$$

The rolling resistance of the wheel with pneumatic tire rises with increasing hysteresis loss coefficient $n_1$, carcass rubber elastic coefficient $E_p$, carcass width $b$, tread width $h_0$. Increased rigidity of the cord layers $n \cdot E_k \cdot \cos \beta$ leads to reduced loss in the carcass rubber, cord threads, but increased bending loss of the tire sides. The rolling resistance reduces with increased: tire diameter $D$; tire width $B_t$; tread width $B_t$; elastic coefficient of the tread rubber $E_p$; as well as tread design ratio $\psi_{nt}$. The wheel load and air pressure also cause change in the rolling resistance.

The research of tire deformation impact on rolling resistance of the wheel with pneumatic tire on the soil is performed comparison movement by moving an equal in size rigid wheel and applying coefficient $\psi$. Coefficient $\psi$ shows what fold load $Q$ on the wheel with tire is higher than load $Q_{rig}$ on the rigid wheel at rolling with equal in depth and shape gauge.

$$\psi = \frac{Q}{Q_{rig}}$$

In experimental research the rolling characteristics of the rigid wheel can be obtained during tests with high tire air pressure when its deformation is insufficient and it can be considered by interpolating the research data. A wheel with a rigid rim is considered as a special stamp which defines the soil capacity to bear vertical loads for the given wheel parameters.

Let us successively review interaction between the wheel elements and soil during rolling flowed by rutting. In this case it is possible to define two specific zones for the contact longitudinal plane: front curvilinear and rear planes. The load in the front area successively borne by the wheel sections is increased and depends on the depth of their penetration into soil. The load in the rear plane successively borne by the sections is reduced and depends on the tire parameters and its capacity to distribute contact load.

Basing on the found tire specific rigidity we calculate a relative value - a coefficient $\psi$ which in equal soil conditions describes tire impact on on-soil operation as compared to a similar rigid wheel.

$$\psi = \sqrt{\frac{1}{3Q_t} + \psi}$$

Relationships for the wheel with pneumatic tire are found with use of coefficient $\psi$ and presented in Table 1.

| Description | Wheel with rigid rim | Wheel with pneumatic tire |
|-------------|----------------------|--------------------------|
| Wheel load, $Q$ | $\frac{2}{3} b \cdot c \cdot h \cdot \sqrt{DA}$ | $\frac{2}{3} b \cdot c \cdot h \cdot \sqrt{DA} \cdot \psi$ |
| Gauge depth, $h$ | $\frac{3}{\sqrt{b \cdot c \cdot \sqrt{DA}}} \left( \frac{1.5 \cdot Q}{b \cdot c \cdot \sqrt{DA}} \right)^2$ | $\frac{3}{\sqrt{b \cdot c \cdot \sqrt{DA}}} \left( \frac{1.5 \cdot Q}{b \cdot c \cdot \sqrt{DA}} \right)^2 \frac{1}{\psi^2}$ |
| Rolling resistance force, $P_f$ | $0.86 \cdot \frac{Q}{b \cdot c \cdot D^2}$ | $0.86 \cdot \frac{Q}{b \cdot c \cdot D^2} \cdot \frac{1}{\psi} + P_{f \psi}$ |
| Rolling resistance, $f$ | $0.86 \cdot \frac{Q}{b \cdot c \cdot D^2}$ | $0.86 \cdot \frac{Q}{b \cdot c \cdot D^2} \cdot \frac{1}{\psi} + f_t$ |
Coefficient $\psi$ considers impact of the tire deformation on rutting, internal, hysteresis losses are considered by value $f_t$ and $P_{ft}$ defined during rolling with the same load on a hard surface.

Wheel load corresponding to a specific rolling resistance is found by the following formula

$$Q = 1.56(f - f_t)^3 \cdot b \cdot \alpha \cdot E \cdot D^2 \cdot \psi^4$$  \hspace{1cm} (8)

Let us convert this relationship by taking all the members which characterize the wheel parameters to the left part, we find

$$\frac{Q}{b \cdot D^2 \cdot \psi^2} = 1.56(f - f_t)^3 \cdot E$$  \hspace{1cm} (9)

Analysis of this formula allows for an important conclusion that by observing constant value of relation of the following parameters $\frac{Q}{b \cdot D^2 \cdot \psi^2}$ and rolling resistance on a solid foundation $f_t$, we can select wheels of different design which in similar soil environment will feature almost similar rolling resistance. By comparing this relation with its value of the forestry vehicles which meet the specified operation requirements we can evaluate rolling resistance of different forestry vehicles when analyzing their cross-country performance and capability to operate on soil.

4. Experimental research

Unlike agricultural tractors a skidder performs its transportation operation by drawing and by transporting part of load inside a vehicle. A rolling resistance force of the loaded vehicle is frequently more than drawing force used for skidding. Non-uniform distribution of load and torque which occurs during movement with load leads to increase of specific pressure on the track bedding and increase of the rolling resistance. With that the rolling resistance force of the loaded vehicle in the off-road forest environment can be several times more than its value of the empty vehicle.

It is necessary to evaluate parameters of the skidders and equipment considering full efforts and energy costs for load transportation utilized both at rolling and drawing. The relation between full efforts or energy costs for load transportation to general cost of movement is estimated by efficiency of the forest tractor. It can be used to analyze and evaluate operation of a forestry vehicle in view of providing minimum efforts and energy costs for transportation of one cubic meter of timber.

Tractors efficiency $\eta_T$ is a relation between power used for effective output for load transportation and the engine power:

$$\eta_T = \frac{\eta_{fe}}{\eta_{ne}} = \eta_m \cdot \eta_e \cdot \frac{Qf_{fg}^{'} \cdot \alpha}{270 \cdot N_{pe}}$$  \hspace{1cm} (10)

The power used for transportation of onboard load at rolling is taken proportional to the load weight and forest tractor’s weight. The efficiency of the forest tractor takes the following form:

$$\eta_T = \eta_M \cdot (1 - \delta) \cdot (1 - \frac{f_{fg} \cdot Q}{f_{fg}^{'} \cdot \alpha})$$  \hspace{1cm} (11)

Efficiency is a complex indicator which characterizes coupling parameters, rolling resistance and impact on operation mode of the forestry vehicle on the transportation capacity.

To consider full costs both for rolling and drawing of tree bundle, the tractor’s towing performance is based not depending on drawbar force but on wheel full circumferential force. The main evaluation values are respectively: relationship between coefficient of use of hitch weight and skidding, traction coefficient, coefficient of used traction, coefficient of specific trust, as well as rolling resistance for inhaul and outhaul. The above specific coefficients are calculated with due regard to increase of forest tractor hitch weight by tree bundle.

Experimental data allow tracking impact of the wheel load re-distribution at skidding on the rolling resistance.

In the test conditions the tractor’s front axle in-motion load was reduced from 2,320 kg to 1,580 kg when skidding a 1.5-m³ bundle. The rear axle load was increased from 1,580 to 3,140 kg. Front axle unloading coefficient $J_f = 0.64$, rear axle loading coefficient $J_f = 2.11$. Weight distribution of the forest tractor from 60% at outhaul has changed to 32% at inhaul. Rolling resistance increased by 1.84 times as compared to outhaul. Tests over crushable soil have uncovered that use of tires 15-24 significantly reduces rolling resistance and improves drawbar-pull properties. The efficiency of the tractor’s running gear has improved in the experimental environment from 44 to 55% that is an increase of 11% as compared to operation with use of tires 15-20.

Thus, the rolling resistance of the wheeled skidder during its off-road movement with re-distribution of weight and torque between the axes is largely dependent on the forest tractor load and its distribution between the wheels. Its inhaul values significantly differ from the outhaul or slave movement values and they shall be reviewed separately in the analysis of the forest tractor operation.

Research of the skidder running resistance shall include measurement of the wheel torque and bundle drawing force. This allows approaching to evaluation of improvement of parameters of the tractor running gear and skidding equipment against minimum energy cost for load transportation via efficiency of the tractor and its components. It is necessary to separate forces and required power needed for load transportation by skidding and onboard a tractor as well as of the tractor itself from the total movement costs.
5. Conclusion
Rolling resistance at timber skidding with butt end first constitutes (for off-road capacity limited conditions) the major part of the total circumferential load of the vehicle’s wheels.

During timber skidding the rolling resistance depends on the amount of tree bundle that is linked with rise of vertical load and torque on the forest tractor wheels, as well as changed distribution of load and torque between the wheels at inhaul movement.

Tire specific rigidity marginally depends on the foundation rigidity and load and is found theoretically and experimentally by the tire contraction properties on a solid foundation.

Basing on the found tire specific rigidity it has been determined what fold the taken load of the wheel with pneumatic tire is higher as compared to the similar rigid wheel under the same wheel load on the track surface. This value is expressed by coefficient $\psi$. Value of coefficient $\psi$ for the same soil environment can serve an evaluation characteristic of tire capability to run over crushable soil.

We have derived equations to find relationship between rolling resistance and wheel parameters, air pressure and load (Table 1), applied torque both for a single wheel and wheel system.

It is recommended to justify parameters of the skidder running gear basing on the on-soil tire capacity. On-soil capacity is determined basing on relationship between load and rolling resistance and provides for its necessary value for the given type of forestry vehicles.

Experimental research has found out that optimum weight distribution in the experimental environment was correspondent to the 0.43-0.45 load on the front axle of the tractor’s full weight, the rest weight was on the rear axle. Skidding of the front and rear wheels corresponding to the wheel maximum efficiency is different: front wheel skidding is 2-3% more than of the rear wheels which follow the front wheel track.

Increase in load on the skidder wheels by the weight of processing equipment and drawn tree bundle which is 60-80% weight of the running gear as well as specific nature of applied load by the drawn bundle to the tractor pose requirement for a special design of its running gear.

Parameters of the skidder running gear shall be evaluated with due regard for provision of minimum effort and energy costs for skidding.

Experimental tests of the forestry tractor in summer environment on sandy-loam cutting area have found out that during skidding of a 1.5 m³ bundle the front axle unloading coefficient stood at 0.64, rear axle load coefficient stood at 2.11, in-motion weight distribution on the front axle was 32%, the rest weight was on the rear axle. Under this condition the rolling resistance has increased 1.84 times as compared to the outhaul movement.

Nomenclature

| Symbol | Definition | Unit |
|--------|------------|------|
| $B$    | width of elementary section without load along the carcass internal surface | mm |
| $sB$   | increase in the elementary section width under load | mm |
| $P_0$  | tire air pressure | bar |
| $R$    | radius of elementary section side curvature in points along axis X-X over carcass internal surface | mm |
| $sQ$   | external load on elementary section | N \cdot m |
| $sQ_{\lambda}$ | lifting capacity of elementary section with deformation $\frac{1}{3}\lambda$ | N |
| $l \cong 2\sqrt{D\lambda}$ | length of tire contact with foundation | mm |
| $\gamma$ | tire specific rigidity | - |
| $Q_0, \lambda$ | load and respective tire deformation | N |
| $\eta$ | hysteresis loss coefficient | - |
| $E_p$ | carcass rubber elastic coefficient | - |
| $h$ | carcass width | mm |
| $b_0$ | tread width | mm |
| $D$ | tire diameter | mm |
| $B_0$ | tread width | mm |
| $E_{\text{tire}}$ | elastic coefficient of the tire rubber | - |
| $\psi_{\lambda}$ | tread design ratio | - |
| $Q_{\text{rig}}$ | load of the wheel with tire and equal rigid wheel at rolling with similar gauge | N |
| $\psi$ | coefficient considering impact of tire deformation on load increase at equal specific wheel pressure on the foundation | - |
| $b$ | width of wheel in the gauge | mm |
| $E$ | soil deformation module | MPa |
| $\forall$ | coefficient which defines soil characteristics for the given wheel parameters | - |
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