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Field and Laboratory Research of the Rut Development Process on Forest Roads

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Abstract: The main tasks of this research are an extended analysis of the technological rut formation process's geometric, force, and energy characteristics as a result of repeated passage of a forest machine on the soil surface. Existing experimental studies of the rutting process are associated with significant material costs and disruption of the forest ecosystem. The purpose of this study is to obtain similar experimental data in laboratory conditions, as well as establishing the correspondence of these experimental results to the results of field studies. The experiments were carried out on the specialized "soil channel" stand of Technical University in Zvolen (Slovakia), as well as in natural conditions in Brody Forestry of the Lviv Region (Ukraine). Geometric track characteristics were determined by length gauges. Power and energy characteristics of the track development process were determined using dynamometers, ammeters, and voltmeters. The physical and mechanical characteristics of the soil with which the mover interacted were determined by a dynamic hardness tester, a penetrometer, and a moisture meter. The characteristics of rut development processes in natural and laboratory conditions are similar to each other. This makes it possible to carry out a wide range of studies of a wheel with soil on a specialized stand and save considerable money during the implementation of full-scale experiments. So, the process of track development can be analyzed with the help of the geometric, force, and energy characteristics of the "wheel-soil" system obtained on laboratory equipment.

Keywords: forest soils; rut development; forestry machines; tire; experimental research

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1. Introduction

Timber-harvesting machinery movement on soil surfaces generates a number of irreversible physical and mechanical processes: soil compaction with subsequent technological rut formation and development; elastic wheel non-linear deformation; and soil mass destruction in the vicinity of the area in contact with the tire. These processes ultimately cause tire and soil heating, partial soil destruction, tire wear, machine individual part heating, etc. The indicated consequences of the interaction of a pneumatic tire with the soil require energy costs, which absorb a significant part of the considered equipment engine energy, and during the movement of that equipment on a horizontal surface—the full power of the engine. The amount of engine power required to overcome the obstacles outlined above and the energy loss associated with them largely depends on the types of soil and tire, as well as the interaction model of the tires with the ground surface; in particular, the movement speed and the load on the tire.

A generally accepted way of determining engine power or traction force, taking into account the costs of overcoming obstacles [1], is the introduction of certain resistance coefficients. However, this does not make it possible to effectively predict the rational modes of the machine's movement in specific operating conditions. This can lead to excessive consumption of fuel and an unjustified increase in the level of environmental damage.

In order to clarify the considered equipment's rational mode movements, it is advisable to isolate all the components of the tire and soil interaction process [2] and to identify the theoretical dependences of the rutting intensity on the operating modes under the specified operating conditions. To clarify the integration of movement resistance factors (energy losses), an energy approach is considered [3]. However, in order to build an adequate mathematical model of such a process, it is necessary to perform a number of experimental studies, which became the goal of this work.

A number of approaches have been developed to determine the rut depth dependence on the number of technological transport passes. In particular, Byblyuk [1] concluded that the machine load capacity and its movement speed are essential for the intensity of rutting. However, this approach is too general to obtain an accessible engineering evaluation of the process.

The range of theoretical studies of rutting is quite wide. Fedorenchyk et al. [4] characterized the depth of the rut, taking into account the variability of the elasticity modulus and soil creep cores after each passage of the machine. A comparative analysis of the rut depth using similar methods for the case of paving the traffic route with auxiliary materials is presented in the paper by Fedorenchyk et al. [5]. However, obtaining results for specific cases of soil–machine interaction is quite complicated and difficult for practical application. On the other hand, the oversimplified approach using variable resistance coefficients, presented by Galactionov [6], gives only an approximate assessment of the process and is often far from reality.

In work by Shilo et al. [7], it is proposed to use the probabilistic approach of statistical physics. Despite the methodological complexity, the obtained results are suitable for the experimental data analysis of the same authors. The construction of numerical models for determining the depth of "settlement" using finite element methods [8] and numerical methods [9] are quite effective, but this approach is difficult for the practice of machine operation.

Experimental studies of the rutting process are associated with the implementation of expensive field studies in natural conditions. Byblyuk et al. [10] describe the results of various stages of field research, starting from the polygon formation to the analysis of the geometric and temporal characteristics of rutting. However, these results are descriptive in nature, which makes it difficult to predict rutting in conditions other than experimental ones. The materials presented in the work by Shilo et al. [7] also have a similar drawback.

On the basis of a comprehensive analysis, Sutherland [11] sets out the principles of recommendations for forest wetland roads operation in Canada, and Smith and Johnson [12] the risks of soil erosion due to logging in South Africa. The work by Dunston et al. [13] analyzed the general state of empirical studies of the rutting process and formulated general recommendations for the operation of freight transport on soil surfaces. A detailed analysis of research related to the study of various aspects of the impact of vehicles on forest soils is presented by Cambi et al. [14].

The main disadvantages of the above-mentioned studies are the use of empirical methods or theoretical methods based on complex mathematical models. This makes it difficult to predict the process of rutting in the general case of different types of soil under the action of forest machines or other technological transport engines, which differ in structure and load. A significant expansion of the experimental base is necessary to build the theoretical foundations of mechanical processes that occur during the contact interaction of the wheel with the contact surface of the movement. For this reason, the results of field and laboratory measurements of the rutting formation process were compared. Both natural settings in Brody Forestry of the Lviv Region (Ukraine) and the specialized "soil channel" stand at Zvolen's Technical University (Slovakia) were used for the studies. Length gauges were used to determine the features of geometric tracks. Dynamometers, ammeters, and voltmeters were used to measure the track development process's power and energy characteristics. Three instruments were used to assess the mechanical and physical properties of the soil that the mover came into contact with: a moisture meter, a penetrometer, and a dynamic hardness tester.

2. Experimental Research Planning and Implementation

2.1. Experiments in Natural Conditions

Field studies of rutting parameters were carried out in two sections of the logging area in Lagodiv's Forestry of the Brody Forest State Enterprise, and included the measurement of the rut depth in the supporting surface after the AMKODOR 2662-01 forwarder performed a certain number of research passes with a wood package with a volume of 17.1 m^3 (beech breed). The average pressure in the forwarder's tires was 94.4 kPa.

Experiments were performed to determine the real indicators of damage to the environment by forest machines, to substantiate the ecologically safe modes of operation of forest vehicles in natural conditions. Polygon studies of the rut formation processes as a result of wheeled forwarder repeated passage were performed.

The area of the landfill for testing was chosen on a surface with a slope of no more than 2–4°. Figure 1 shows a schematic representation of the test site, on which the route is laid out for the forwarder to pass two characteristic sections with branches and without branches. At each site, three measuring points were determined, the distance between which was 1.5 m.

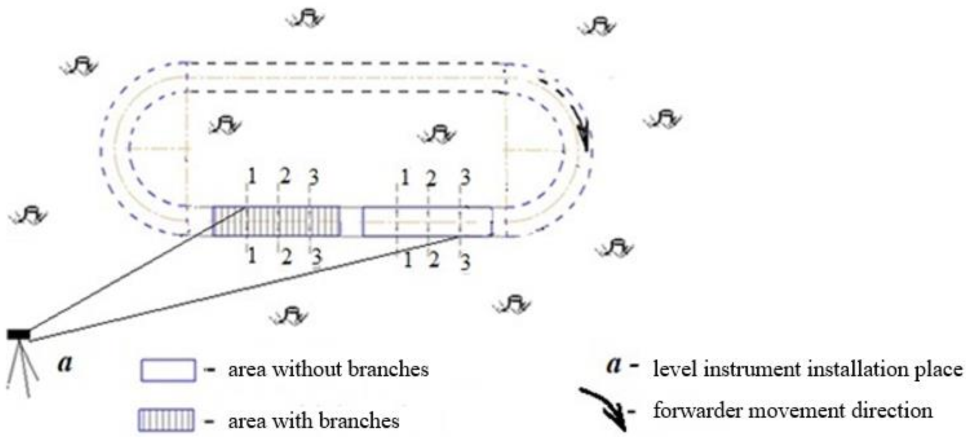

Figure 1. Scheme of the landfill for rut formation parameter field studies.

Before starting the measurements, the cruise load, the average pressure in the forwarder's tires, as well as the soil parameters of the supporting surface (moisture and density) were recorded. After each series of passes, the depths of the right and left tracks were fixed with the help of a level and measuring rails. The test site was a sandy soil surface of undisturbed structure with vegetation cover, slope—2–3°, initial density—1.40–1.51 g/cm^3, humidity—10.1%. Fragments of polygon studies to determine the depth of the rut after passing by the AMKODOR 2662-01 forwarder are presented in Figure 2.

(**a**) (**b**)

Figure 2. Photo fixation of polygon studies. Track depth measurement after 3 passes (**a**) and after 10 passes (**b**).

2.2. Scheme of the Experiment on the "Soil Channel" Stand

To study the regularities of a wheel on a pneumatic tire with the ground surface of movement interaction, the following scheme is proposed (Figure 3). The electric engine E pulls the wheel along the soil surface with a speed v by means of a cable. The weight of the total load on the wheel (including the weight of the wheel) is G. The wheel is in driven mode and rolls on the surface, pressing into the ground due to this force.

Along with the elastic compression and compaction of the soil, there is the effect of frontal and lateral squeezing. Such phenomena form a technological rut in the soil. After each wheel pass, the elastic deformations in the soil disappear, so the residual depth of the rut is slightly reduced compared to the depth under the loaded wheel. Repeated passage of the wheel leads to a step-by-step increase of the rut depth.

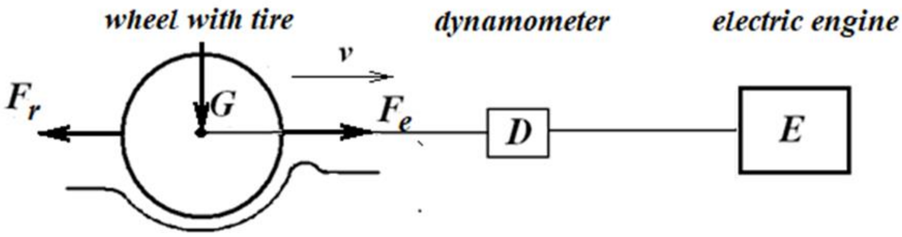

Figure 3. Scheme of the experiment on the laboratory stand.

The electric engine consumes electric energy: electric voltage U, amperage I. Then, the power consumed by the electric engine is

$$N_e = U \cdot I \quad (1)$$

The main part of this power is spent on overcoming the resistance forces during the movement of the loaded wheel. A small part of this power is heat loss in the electric motor. The loaded wheel is set in motion by the electric motor traction force F_e. On a horizontal section where the motion of the wheel is uniform, the traction force is equal to the total resistance force F_r, which covers all the mechanisms of motion resistance classified in [2]. Dynamometer D is designed to measure the traction force F_e.

Useful power, which is spent on wheel moving:

$$N = v \cdot F_D \tag{2}$$

where F_D is the force determined from the dynamometer readings. The magnitude of the force F_D coincides with the traction force of the electric engine *Fe*.

The main goal of that study is to experimentally establish the dependence of the rut depth, the height of the soil lateral squeeze, and the resistance force to movement on the number of wheel passes on the soil. In addition, we planned to determine the change in the compaction characteristics of the soil mass and some energy characteristics of the considered process. The measurements were carried out in the period April–May 2023.

2.3. Experiment Planning

This experiment can be conducted with different types of tires. In this study, two types of tires are assumed—BKT 210/95 R16 Agrimax RT 855 and Continental B3 240/70—15 IMP 8PR. For each type of tire, the measurements were carried out separately on dry ground and on wet ground. The experiments involved a one-way passage of a wheel through a soil channel: after each passage, the moving block of the wheel was lifted by special equipment and in a suspended position was transferred to the starting point of movement.

The measurement of the rut depth and the soil lateral squeeze height must be carried out after each wheel pass. Experiments were carried out until the rut depth stopped increasing. The characteristics of the compacted soil were measured once every 5 wheel passes. Before each series of measurements, it was necessary to record the initial values and characteristics: soil type; soil moisture; air temperature, pressure and humidity; air pressure in the tire; free and static wheel radii; wheel load; the width and length of the footprint of the immovable wheel pressed to the ground, the length of the measuring section; and the initial distance from the measuring bar to the undisturbed soil surface.

In the soil channel, forest soil was used, which we can characterize based on the laboratory grain size analysis as loamy sand. For a closer specification, we present in Figure 4 the grain size curve of the given soil constructed according to the Slovak technical standard STN 72 1001 [15].

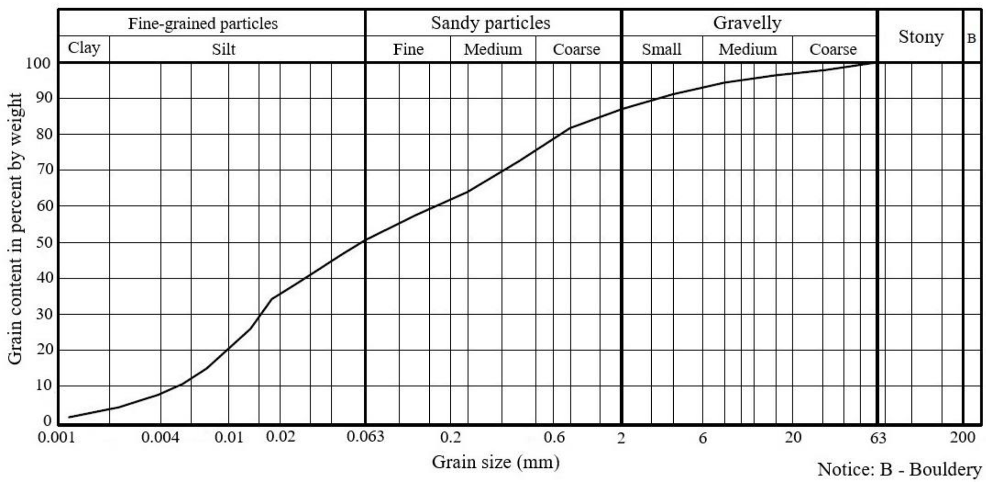

Figure 4. Soil grain size curve.

In Table 1, we present the basic mechanical properties of this soil obtained from samples taken from the upper soil horizon (0 to 0.15 m) after wetting with water to a moisture content of 23%. The stated characteristic soil values were obtained on the basis of laboratory analysis of soil samples taken at the Faculty of Civil Engineering of the University of Žilina.

Table 1. Basic characteristics of the used soil.

Property	Value
Soil type	Loamy sand
Gravel	12.90%
Sand	36.06%
Silt	46.74%
Clay	4.3%
Frictional angle	37.75°
Cohesion	11.6 kPa
Particle density	$2.650\ g \cdot cm^{-3}$
Humidity content	23.00%
Plasticity number I_p	13.26
Limit of plasticity W_p	23.55%
Liquid limit W_L	36.81%

Rut geometric characteristic measurements after passing the movement control section and the characteristics of soil compaction due to the passage of the wheel are systematized by the number of passes. During this group of measurements, it is necessary to record the travel time of the wheel between control points and determine the wheel linear speed value.

The geometrical characteristics have conditional values, since the footprints of the wheel grips and soil particles are stochastically distributed. Therefore, when establishing these geometric characteristics, it was necessary to take into account the averaged dimensions in a certain way.

In addition to the values indicated above, it was necessary to record data on the electric motor during each drive: voltage, amperage, and consumed electric power, and also the value of the traction force. These last values, due to the stochastic of the contact interaction of the tire with the soil, should be accumulated in the form of tables and graphs in Microsoft Excel with a step of 0.2 s. To determine the averaged values, it was necessary to choose a section of the movement in such a way that the transient processes of acceleration and stopping of the wheel were outside the measurement section.

Experiments were performed until the intensity of the rutting process became low. Laboratory measurements were simulated based on operating conditions.

2.4. Equipment Used in Experiments

The "soil channel" stand developed at the Department of Environmental and Forestry Machinery, Zvolen's Technical University (Figure 5) was used for experiments conducted to determine the interaction peculiarity of a wheel on a pneumatic tire with the ground surface of movement. This stand is designed to simulate the dynamic interaction of a pneumatic wheel with a deforming soil. This makes it possible to carry out experiments that reproduce the real interaction processes of the wheel drive with soil surface that have given parameters (moisture, density, granulometric composition, etc.). The stand makes it possible to carry out repeated consecutive passes of the wheel on the soil support surface with a given amount of weight that falls on the wheel under test. In addition, the stand makes it possible to perform research into wheel movement during successive wheel passes in driven and leading modes, as well as to perform experiments for successive forward and reverse directions of movement.

To ensure the movement of the stand carriage with the wheel mounted on it in driven mode along the soil support surface, a traction rope was used, which was set in motion with the help of a 4 kW electric motor drive Siemens 1LA7 113-4AA (Figure 6a). During the experiments, the power on the electric motor of the drive, which was created to ensure traction, was measured by an electronic wattmeter Metrel MI 2893 Power Master XT (Figure 6b). This made it possible to collect the energy parameter data of the process in real time.

Figure 5. Research stand "soil channel".

(**a**) (**b**)

Figure 6. Electric drive of the traction rope (**a**) and wattmeter (**b**).

An electronic dynamometer HBM S9M-10kN was used to measure the traction force on the traction rope. This made it possible to study the number of passes on the traction parameters at different wheel loads and different levels of moisture of the supporting surface influence.

During the experiments, the movement of the carriage with a wheel on the ground was carried out cyclically in one direction. This made it possible to obtain more homogeneous and comparable results. A 5-ton crane beam was used to return the carriage with a wheel to its initial position in a suspended state.

Two types of tires were used in the research (Table 2). The free and static radii of the wheel as well as air pressure in the tire was measured (Figure 7), and the dimensions of the soil wheel imprint (Figure 8) were determined, based on its footprint.

Table 2. Technical characteristics of the tires used in the experiments.

Tire Parameters	BKT 210/95 R16 Agrimax RT 855	Continental B3 240/70–15
Tire diameter, mm	806	710
Tire width, mm	214	229
Tire weight with rim, kg	35.40	29.90
Construction	Radial	Diagonal

Figure 7. Measurement of the static wheel radius using an electronic ruler.

Figure 8. Setting the dimensions of the wheel track on the supporting surface of the ground.

The carriage with a wheel weight was measured using an electronic scale: Crane Scale OCS-3-X, max. capacity 3000 kg (Figure 9).

Figure 9. Measuring the mass of the carriage with a wheel.

The soil plot was prepared for conducting two stages of experiments for different humidities (2.4%–24.3%). The soil was previously prepared by loosening and leveling the surface. Humidity was measured with an electronic hygrometer Imko HD2 with sensor Trime PICO 64/32 (Figure 10).

Figure 10. Electronic hygrometer Imko HD2 with sensor Trime PICO 64/32.

The measurement area of the wheel movement was 2 meters with two or three measurement points 1 meter apart. The wheel passage time measurement on measuring area was carried out with the help of an electronic stopwatch. After each pass, the rut depth (Figure 11) and the size of the soil lateral squeeze were measured.

Figure 11. Rut depth measuring.

The rut depth compared to the undamaged soil surface was measured using a bar that showed a zero line and the ruler. Measurements were made after each pass until a stable rut depth was reached, when the value of the rut depth hardly changed after the pass. Usually, this happened after about 10 passes for dry soil and 17–18 for wet soil.

The classical DORNII weight impactor [16] was used to determine the dynamic density. It consists of a cylindrical rod with a cross-section of 1 cm^2 (for wet soils of 10%–20%) and a cross-section of 2 cm^2 (for dry soils with a moisture content of up to 10%). A weight of 2.5 kg with a central hole is stuck on the rod (Figure 12). Falling from a height of 0.4 m, the weight hits the thrust washer on the rod, causing rod to sink into the soil. The density of the soil is estimated by the number of hits of the weight or, equivalently, by the work of sinking the rod by 10 cm. The process takes place until the tip of the density tester is completely immersed in the soil. The density rating is determined by the scale [17].

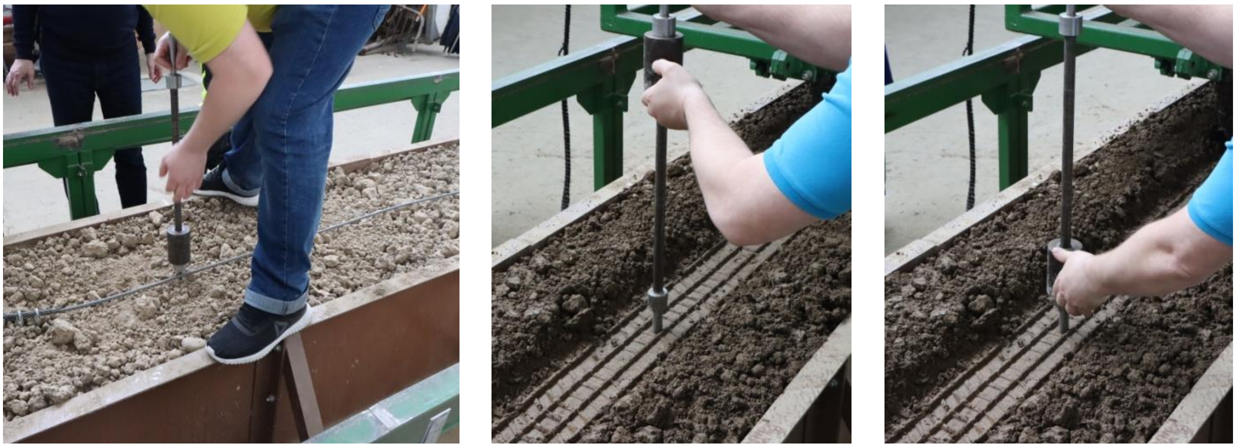

Figure 12. Determining the dynamic density of the soil using the DORNII device.

An Eijkelkamp manual penetrometer (Figure 13) was used to determine penetration resistance (bearing capacity) and soil compaction.

Figure 13. Hand penetrometer Eijkelkamp.

2.5. Measurement Results—Field Conditions

The results of the experimental data obtained under the natural conditions described in paragraph 2.1 of this article are given in graphical form. The rut depth after the number of the forwarder passes dependences is presented in Figure 14.

As a result of the analysis of the received data, it was established that:

- The intensity of rutting significantly depends on the bearing capacity of the soil, which is largely determined by the geomorphological structure of the terrain;
- The depth of the rut after the first 5–7 passes is about 70% of the rut depth after 30 passes, which corresponds to practically the greatest compaction of soil particles. In the future, the growth of the rut depth occurs mainly due to the protrusion of soil particles from the rut by the tires of the forwarder;
- The presence of a floor made of branches significantly (by 1.47–1.52 times) reduces the depth of the rut; the grass cover and the tree root system also affect the reduction in the intensity of rut formation;
- The maximum rut depth due to 30 passes of the loaded forwarder AMKODOR-2662-01 on the section without branches was 13.1 cm.

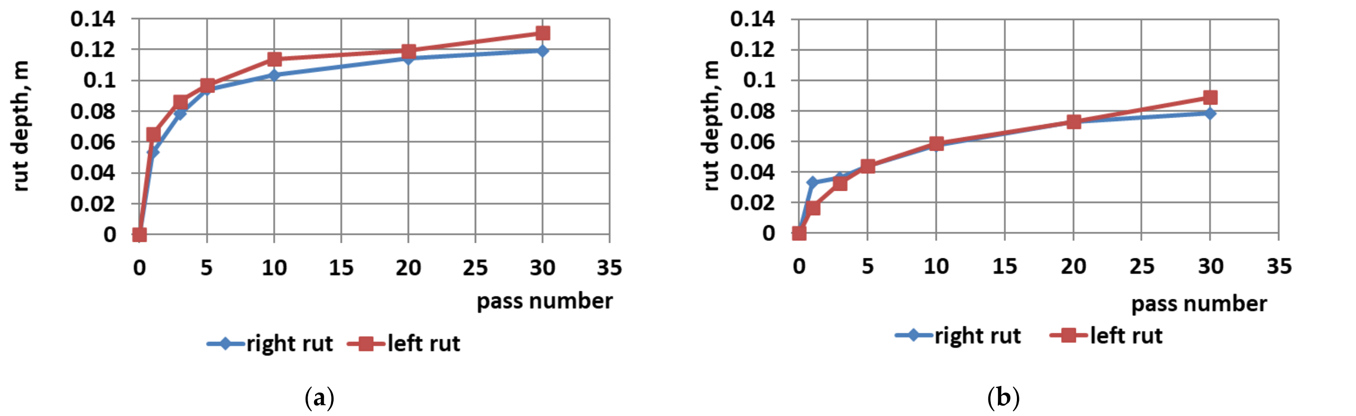

Figure 14. Dependencies of rut depth on the forwarder number of passes: (a) area without branches; (b) area is reinforced with branches.

2.6. Measurement Results—"Soil Channel"

Establishing the consequences of driving a wheel over a soil surface took place for a wide range of test conditions. Tests were performed separately for different types of tires—BKT and Continental, for soils with different humidity and for different external loads. This made it possible to analyze the general regularities of the rutting process and related phenomena. The conditions of the experiments are systematized in Table 3.

Table 3. The conditions of the experiments.

No	Tire Type	Condition Type	Humidity, %	Total Load on the Wheel, kg
1	BKT	W1	2.4	727
2	Continental	W1	3.9	727
3	BKT	W2	18.7	578
4	Continental	W2	24.3	557

Figures 15 and 16 show the obtained empirical dependences of the depth of the rut and the height of the lateral squeeze of the soil on the number of wheel passes (in driven mode) on the soil support surface.

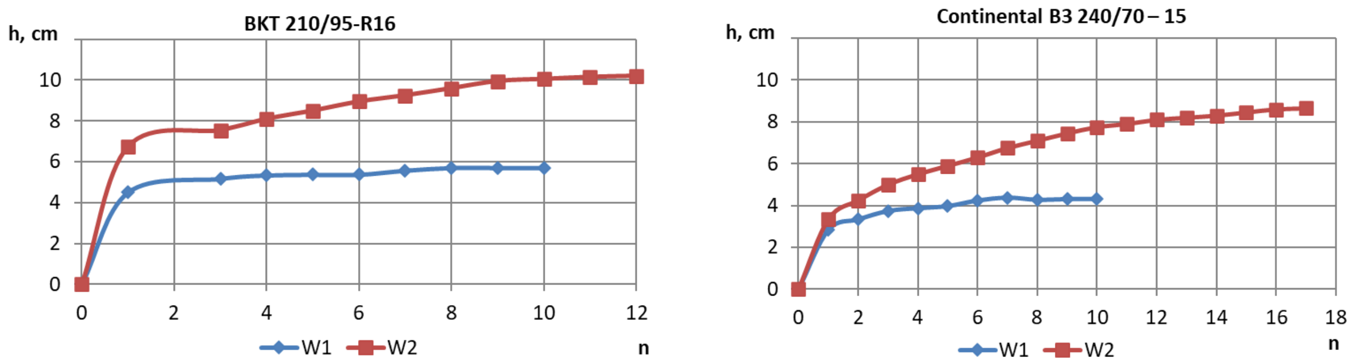

Figure 15. Rut depth dependence (h) on the pass number (n) at different levels of support surface humidity.

At the first stage of research (humidity 2.44%–3.9%), the characteristic of the change in the depth of the rut from the number of passes through dry soil was analyzed. Both for one and for the other tire, the maximum increase in rut depth was observed during the first 2 passes, which was 1.7 (BKT)–2.0 (Continental) times more than in subsequent passes. This may be due to the fact that the dominant factor in total resistance is rolling resistance, which mainly depends on the design features of the tire and the weight on the wheel. The BKT tire has a ridged tread with pronounced protrusions; the contact with the supporting surface occurred exclusively through the total contact area of the tops of the tread ridge. For soils with low moisture and incomplete penetration of ridged tread into the soil, this contributes to a low intensity of rutting. Continental tires have a tread with a more saturated pattern, which accordingly increases the real contact area and, as a result, reduces the intensity of the rut formation process. Similar conclusions regarding the effect of tire characteristics on wheel rolling resistance are given by Di Maria et al. [18]. At the second stage of research (humidity 18.74%–24.3%), similar effects were observed.

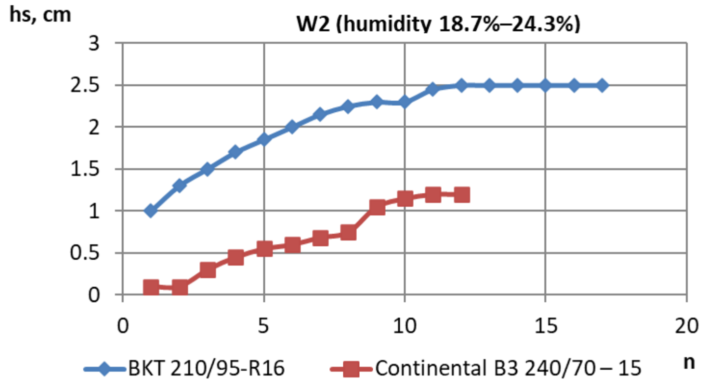

Figure 16. Height of the lateral squeeze dependence (*hs*) on the pass number (*n*).

Figures 17–19 show some of the energy characteristics accompanying the movement of the wheel on the soil surface: the electrical energy consumed, the traction force, and the linear speed of the wheel.

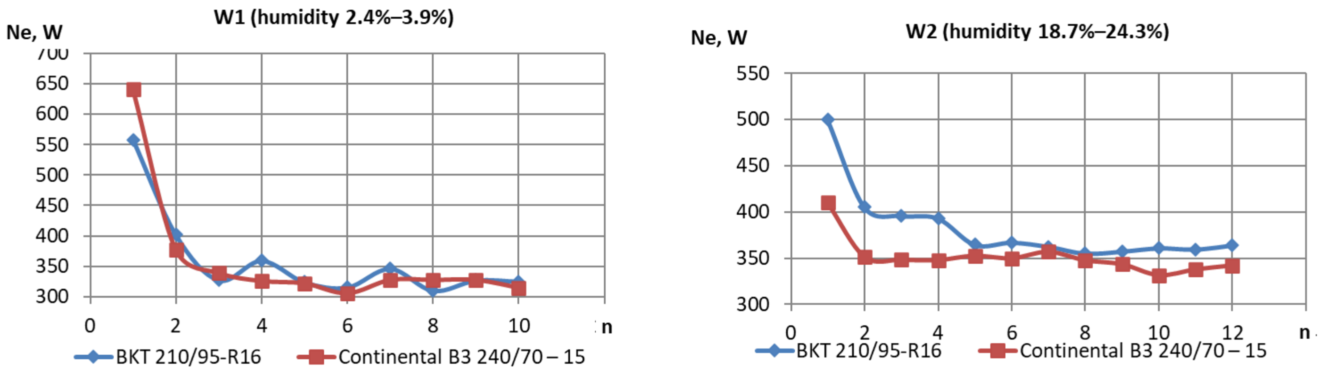

Figure 17. Electric drive power dependence (*Ne*) on the pass number (*n*) at different levels of support surface humidity (*W1*, *W2*).

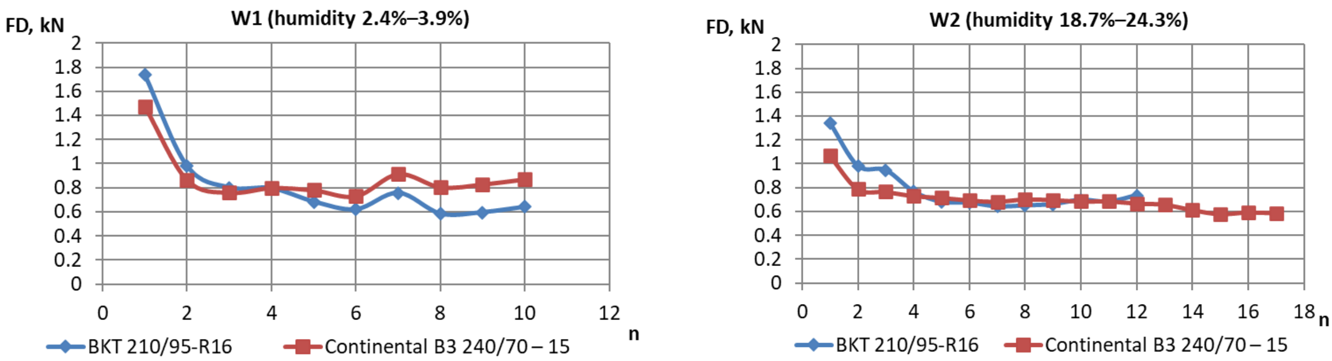

Figure 18. Traction force dependence (*FD*) on the pass number (*n*) at different levels of support surface humidity (*W1*, *W2*).

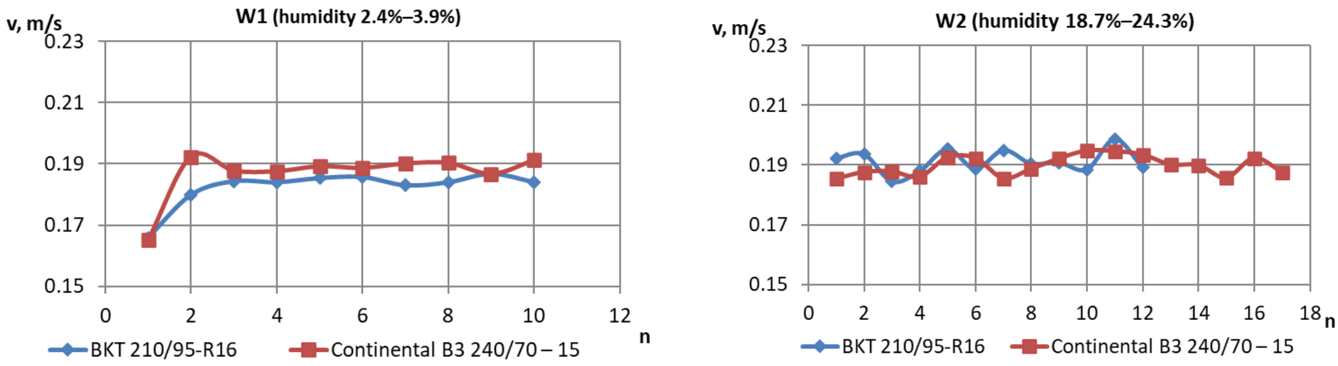

Figure 19. Wheel movement speed dependence (*v*) on the pass number of (*n*) at different levels of support surface humidity (*W1*, *W2*).

The development of a technological rut as a result of repeated passage of the wheel leads to certain structural changes in the surrounding soil mass. Figure 20 shows dynamic density (*DD*) and penetration resistance (*RP*) histograms. A DORNII device and hand penetrometer Eijkelkamp were used for measuring as mentioned in Section 2.4.

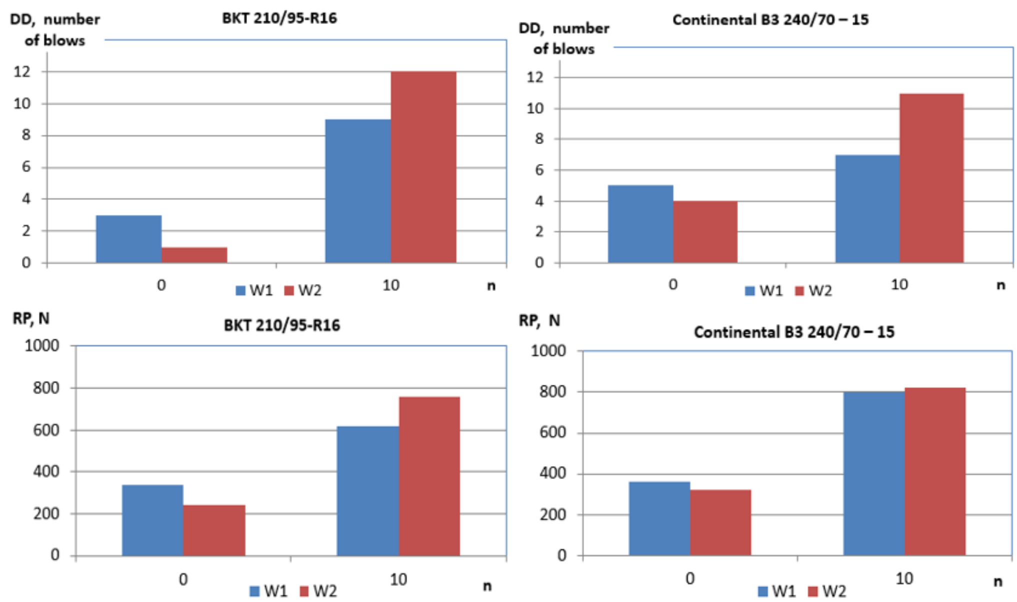

Figure 20. Dynamic density (*DD*) and resistance of penetration (*RP*) dependence on the pass number (*n*) at different levels of support surface humidity (*W1*, *W2*).

Summarizing the obtained experimental data, we will compare the graphs of the track depth in natural conditions in pass number dependences (Figure 14a, for the right track) and in laboratory conditions on the "soil channel" stand (Figure 15 for the BKT 210/95 R16 tire). The comparison results presented in Figure 21 indicate the complete similarity of the results obtained in natural and laboratory conditions. Minor differences in the graphs at the initial pass are explained by the fact that under natural conditions at the initial passes, the growth of the rut is slowed down by the root system of the grass cover. And the intensive growth of the rut during the first passage of the wheel in the soil channel is due to the fact that initially the soil in the channel was somewhat loosened. However, from the time of further passes, the intensity of rutting for both cases became close to each other.

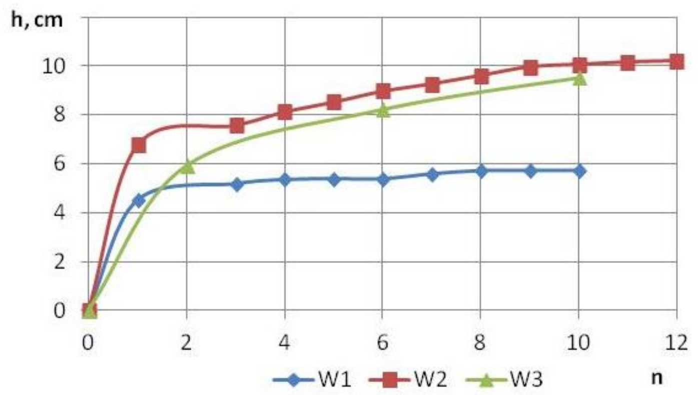

Figure 21. Comparison of rutting processes in field and laboratory conditions; *W3*—field measurements (Figure 14. Area without branches, right track).

The range of results obtained in laboratory conditions is much wider; in particular, such results cover not only the geometric characteristics of the process, but also the power and energy characteristics. Therefore, further in-depth study of the process of rutting is possible in laboratory conditions on a stand of the "soil channel" type.

3. Discussion

Reducing the risks of soil surface destruction in forest areas is possible by regulating various natural and anthropogenic factors. In particular, this is taking into account hydrological data, seasonal natural phenomena [19], increasing the efficiency of management [20], improving the types of logging operations, and rationalizing operational modes, as is possible using the research presented in this work. The formation of a rut depends on the distribution of stresses in the soil from the applied load. It is a consequence of repeated compression and shear consequence, which leads to soil compaction and its squeezing [21,22]. The obtained results confirmed the specific character of rut formation on support surfaces with different initial moisture. Thus, at humidity *W1* (*W1* = 2.4%–3.9%), the most intense rut formation occurred during the first 2–3 passes. At the same time, after two passes with the BKT tire and after three passes with the Continental tire, the rut depth reached 87%–90% of the total value of the rut depth after the final number of passes. Further growth of the rut occurred with a lower intensity in the range of 10%–13%. At the same time, lateral bulging at *W1* was not observed, or it was insignificant (in the range of 0.4–0.6 mm), in contrast to the second stage of research on soil with moisture *W2* (*W2* = 18.7–24.3%). The formation of a rut on soil with moisture content *W2* has a different character. Thus, after the first 2–4 passes, a rut formed, which was about 75% (BKT tires) and 50% (Continental tires) of the total rut depth at the end of the experiment. During further passes of the wheel, the intensity of the growth of the rut depth gradually decreases and almost stops on the last passes. Our results were confirmed with Vennik et al. [23], where the rut depth formed after one pass was 58% of the total rut depth formed after 10 passes. A significant lateral squeezing of the soil is essential for the study of the consequences of wheel travel for the area with moisture *W2*. Thus, during the study of the BKT tire, the maximum soil squeezing was 2.5 mm, and experiments with the Continental tire showed a maximum lateral squeezing of up to 1.8 mm. Figure 16 shows the average values of the lateral squeezing depending on the number of passes. As can be seen from the graph, the intensity of lateral squeezing begins with the cessation of growth of the rut depth after 3–5 passes (Figure 15). In our opinion, this is due exclusively to the type of tread, the construction of the tire cord, and the little-studied process of soil behavior, which contributes to its lateral squeezing. The processes of formation of the lateral squeezing of the soil and its qualitative and quantitative characteristics require further study.

The nature of the change in the traction force (*FD*) depending on the number of passes (*n*) (Figure 18) is as follows: the absolute value (*FD*) on the first pass is the largest and is

48%–50% of the stable values of the traction force, which stabilize to a constant value from 3–4 passes until the end of the experiment. This phenomenon is typical for both stages of research on soils with moisture content *W1* and *W2*, as well as for different test tires with a gradual decrease in traction force until equalization to a constant value within the margin of error.

The speed of moving the cart during the experiments was maintained within 0.19 m/s, which is satisfactory for this type of experimental research (Figure 19).

The assessment of changes in soil physical properties was carried out by measuring dynamic density (*DD*) and soil penetration resistance (*RP*). The obtained results of the study indicate that for both types of wheels and for different experimental areas prepared by moisture, the dynamic density and resistance to penetration of the soil at a depth of 0–10 cm increases with the number of mover passes along the track. This finding is consistent with the results of other studies [14,24–26]. According to the results, the main factors that ultimately affected the degree of compaction were the initial moisture and condition of the soil surface and the design features of the tire. Thus, for BKT, the increases in dynamic density after 10 wheel passes were 3 times (for soil with moisture *W1*) and 12 times (for soil with moisture *W2*). For the Continental tire, the increases in dynamic density were 1.4 and 2.75 times, respectively. The growth of soil resistance to penetration, for similar conditions after 10 wheel passes, amounted to 1.8 and 3.2 times for the BKT tire and 2.2 and 2.5 times for the Continental tire, respectively (Figure 20). A significant increase in soil compaction with moisture content *W2* is partly due to the preparation of the soil surface before the experiments; namely, for artificial moistening of the soil, partial loosening with subsequent compaction of the studied area was carried out. According to research by Gheshlaghi and Mardani [27], the maximum stress at a depth of 20 cm increased with increasing soil moisture, as well as with a high level of tire load. In contrast, sequential movement showed a decreasing effect on soil loading. Loose soils contain a large number of macropores, which are easily compacted. However, the resulting smaller pores exhibit greater resistance to compaction with Berli et al. [28]. Thus, an additional machine pass over already compacted soil results in very limited additional impact [29,30]. However, the obtained results of changes in soil density correspond to similar field studies [31], where the impact of soil structure, mass, and number of tractor passes on soil compaction was recorded.

Also, a significant difference in the results for the same soil type is based on the specifics of each of the tires' designs. BKT is a tire with increased permeability, which significantly affected the degree of compaction. Its characteristic feature is the presence of a ridged tread. According to our opinion and other researchers [32,33], it is ridged tread that creates additional pressure and compacts the areas of the soil where the contact occurred.

4. Conclusions

The formation of ruts on the surface of forest soils during the movement of forestry machines has become an important issue because it affects processes leading to significant damage to forest soils. In addition to damage to the forest floor when deep ruts are created, there are also significant energy losses in wheeled forestry mechanization equipment, mainly due to an increase in rolling resistance. In the future, the presented research will enable us to assess more closely the effects of each of the main factors of contact interaction of the tire with the forest soil. We assume that the created experimental model will lead to the creation of proposals and measures to ensure the rational operation of forestry wheeled mechanization equipment and at the same time ensure the minimization of damage to the soil environment. Based on the results, it can be concluded that Continental B3 240/70–15 IMP 8PR, with no arrow pattern, had better values compared to BKT 210/95 R16 Agrimax RT 855. An arrow pattern is important for traction characteristics of the drive tire on wetter soil and thus we recommend this type of tire for forest machines. The type of soil depends on many factors, but the granulometric composition and humidity are the most important, so it is better to work with the soil in dry periods of the year.

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