UNIVERSITY OF FORESTRY

FACULTY OF FOREST INDUSTRY

INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

2/2022

INNO vol. XI Sofia

ISSN 1314-6149
e-ISSN 2367-6663

Indexed with and included in CABI

INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

Science Journal
Vol. 11/p. 1–98
Sofia 2/2022

ISSN 1314-6149
e-ISSN 2367-6663

Edition of
FACULTY OF FOREST INDUSTRY – UNIVERSITY OF FORESTRY – SOFIA

The Scientific Journal is indexed with and included in CABI.

Cover Design: DESISLAVA ANGELOVA

Printed by: INTEL ENTRANCE
Publisher address: UNIVERSITY OF FORESTRY – FACULTY OF FOREST INDUSTRY
Kliment Ohridski Bul., 10, Sofia, 1797, BULGARIA
http://inno.ltu.bg
http://www.scjournal-inno.com/

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EXPLOITATION RESEARCH OF A CABLE SKIDDER TAF 690 PE FOR TIMBER SKIDDING IN THE WESTERN STARA PLANINA

Dimitar Peev, Dimitar Georgiev, Konstantin Marinov
University of Forestry, Sofia, Bulgaria
e-mail: dimitar_peev@ltu.bg; dimitarg@hotmail.com; kmarinov_ltu@abv.bg

ABSTRACT

This paper presents the results of a study that was conducted to establish the basic performance characteristics of a specialized forestry tractor for skidding of a whole tree stems and long timber sections in mountainous conditions. The tractor travel speed at different gradients as well as the hourly productivity for a tree-length harvesting system in the Western Balkan Mountains region were determined. The regression analysis method was used to conduct the study and to determine the influence of various factors on the hourly productivity of the tractor, at a constant trip load volume. For this purpose, a planned two-factor experiment with three levels of variation of input factors was conducted. The time for tractor's moving in different gradients was determined by timing. Running speeds were found at range from 3,23 to 4,82 km/h, hourly productivity from 5,36 to 10,98 m^3/h with trip loads ranging from 6,9 to 8,5 m^3. Regression equations were derived and by their use could be determined the productivity for different gradients and different lengths of skidding distances.

Key words: cable skidder, skidding wood, speed of skidding, hourly productivity.

INTRODUCTION

The most widespread means of timber skidding in our country are specialized forestry tractors equipped with an articulated frame and a rope collection system with a single- or double-drum winch. These tractors are distinctive by high off-road capability, maneuverability and productivity. They are designed to work on terrains with steeper slopes – in the range of 11º-20º.

The object of the study is the wood skidding in the UOGS "Petrohan", which is located on the north-western slopes of the Balkan Mountains with predominantly beech plantations, steep terrains and relatively large skidding distances up to 1500 m. The base means of timber skidding in the area in recent years has been the specialized choker tractors LKT-81 (Slovakia). The market price and maintenance of these tractors has remained at relatively high levels, which is why the UOGS "Petrohan" has purchased and commissioned a relatively cheaper and easy to maintain TAF 690 PE tractor (Romania) at the end of 2018. A similar tractor of the same brand, the TAF 658, has been in use for more than 10 years in the coniferous forests of the UOGS "G. Avramov", Yundola and shows good results. The study of the tractor TAF 690 PE on the territory of the Western Balkan Mountains will make it possible to establish its operational qualities when skidding deciduous wood materials.

Studies on this type of tractors have been conducted and they are mainly focused on determining the performance and cost of the skidded wood under different technologies of felling and skidding, and the influence of different factors on the productivity has been determined (Klepac and Rummer, 2000; Najafai et al., 2007, Mousavi, 2009, Mousavi 2014). It has been found that the greatest influence on the productivity of skidding tools is the skidding distance (Behjou et al., 2008), the slope of the terrain and the number of stems (Jourgholami and Majnounian, 2008; Mousavi et al., 2012; Behjou et al., 2008).

The majority of studies on wood skidding productivity have considered skidding distances, with average values between 25 (Zečić et al. 2005) and 1119 m (Spinelli & Magagnotti 2012).

The results of the literature analysis show that idling and loaded travel speeds differ depending on the conditions under which the experiments have been conducted so far. Idling speeds between 4,15 km/h (Behjou et al. 2008) and 8,10 km/h (Spinelli & Magagnotti 2012) and loaded speeds between 1,33 km/h (Zečić et al. 2005) and 7,3 km/h (Spinelli & Magagnotti 2012) have been found for certain operating conditions and machines used.

The aim of this work is to carry out an experimental study and to establish the main performance characteristics of a specialized forestry tractor TAF 690 PE for the skidding of whole tree stems and long timber sections.

OBJECT, MATERIALS AND METHODS

Study area

The study was conducted in the area of the Western Balkan Mountains on the territory of the UOGS Petrohan, Barzia village. The observations were carried out in a deciduous natural plantation of Common beech (*Fagus sylvatica*) in the locality "Gavanishchitsa" in section 136, sub-section "a" and section 135, sub-section "b", which are located in the land area of the Barzia village.

Object of the study

The object of the study is a specialized forestry tractor TAF 690 PE (cable skidder) – Figure 1. It is equipped with a double-drum winch with mechanical drive and a winch tractive force of 70 kN, maximum cable length of 70 m and cable diameter of 13 mm. The transmission is a 5-speed mechanical transmission box with forward speed in range from 2,5 to 32,6 km/h and reverse speed in range from 2,74 to 4,79 km/h. The maximum permissible semi-suspended load weight is 5000 kg and the maximum capacity load weight is 9300 kg.

Figure 1: Tractor TAF 690 PE at a temporary forest storage site at UOGS "Petrohan", in the locality "Gavanishchitsa"

The tractor TAF 690 PE is an improved version of the older 690 OP model, to which a number of technical changes have been made. The 690 PE model is equipped with a Perkins engine, rated at 70 kW (95,2 h.p) effective power at 2300 min^{-1} and maximum torque of 410 N.m at 1600 min^{-1}. The tractor's weight is 7500 kg, of which 4285 kg is on the front half-frame and 3215 kg on the rear half-frame.

The experimental sites and polygons for the experimental observations were determined by the crawling method, based on the experimental plan and the levels of variation of the input factors.

The timber used for the study was Common beech (*Fagus sylvatica*), in the form of whole tree stems and long timber sections, which were skidded from the clearing site to a landing area.

The technology for skidding of the timber is as follows:

- Movement of the tractor without load (idling) – from the landing area until arrival at the felling site;
- Maneuvering and position selection – starts after the tractor arrives at the felling site and ends after the assistant tractor driver starts pulling the winch rope;
- Load forming (loading) – starts from the rope pull and finishes once the load is placed on the tractor;
- Movement with load (work move) – starts from the tractor leaving with the load and ends when the load arrives at the landing area;
- Unhitching (unloading) – from the arrival of the tractor at the landing area to the release of the load and it’s alignment, if necessary.

All observations were carried out without external interference to the work of the tractor operators, ensuring real working conditions.

The regression analysis method was used to carry out the study and to find out the influence of the slope of the terrain and the size of the skidding distance on the hourly productivity of the tractor, at a constant trip load volume. For this purpose, a planned two-factor experiment with three levels of variation of the input factors was conducted.

The first factor, X_1, is the slope of the terrain and the second factor, X_2, is the skidding distance. The parameter under study is the hourly productivity – Y of skidding beech timber on a straight slope.

The time for the execution of the individual operations, including the tractor's movement in the road sections with different slopes, according to the methodology for conducting the experiment and the above-mentioned technology of operation, was determined by the timing method. The slope of the road was determined by inclinometer and the volume of the trip load was determined by cubing the stems.

The following levels of variation of the investigated factors were assumed for the conditions of the UOGS “Petrohan”, including slope and average skidding distance:

$$X_1 = 10, 15, 20^o;$$

$$X_2 = 500, 1000, 1500 \text{ m.}$$

Baseline parameter:

$\bar{Y}$ – hourly productivity, m^3/h.

Since the factors allow their level to be maintained, a planned experiment of the 3^m type was conducted, where m is the number of factors. All possible combinations of three levels are implemented, where the number of experiments is $N = 9$. To determine the variance of the equivalent disturbance, 4 parallel trials were conducted at each point in the experimental plan.

Checking for the influence of individual factors was performed by multivariate analysis of variance, which is particularly effective when investigating the simultaneous influence of several factors or groups of factors.

Due to the different nature of multifactorial objects, their factors have different dimensionality and different intervals of variation. This leads to differences in the scale and dimensionality of experimental designs (Bojanov and Vuchkov 1983).

To avoid this inconvenience, factor coding or standardization is widely used in theory and practice, whereby a factor $\tilde{Xi}$ is replaced by a new Xi.

$$X_1 = -1, 0, 1; \quad X_2 = -1, 0, 1.$$

Coding as a form of transformation of input factors is mainly used when conducting a planned (active) experiment (Bojanov and Vuchkov 1983).

Stepwise regression analysis is used starting from a full quadratic equation for the two factors X_1 and X_2 of the form:

$$Y = b_0 + b_1x_1 + b_2x_2 + b_{12}x_1x_2 + b_{11}x_1^2 + b_{22}x_2^2. \quad \textbf{(1)}$$

The CranR program is used to determine the most appropriate model for the investigated machine under study. The Akaike's Information Criterion (AIC) is used as the basis for this, according to which the model with the lower AIC criterion is more appropriate and sufficiently simplified in terms of stepwise regression analysis (Crawley 2007).

The adequacy of the model as well as the significance of the individual coefficients is determined according to Fisher's F_T criterion and its corresponding probability p (statistical significance). The critical cut-off for statistical significance in the study of most experiments, as well as this particular one, was set at p = 0,05. If the significance level α = 0,05 is preset, then for the model or an individual coefficient to be adequate or significant, the probability $p \leq \alpha$ must be set.

The individual regression coefficients are tested for statistical significance using the Student's t criterion and a significance level of p. For a given t value, if p < 0,05 means that the coefficient of interest is statistically significant.

RESULTS AND DISCUSSION

The tractor running times for the technology described in the previous section were determined and are listed in Table 1.

Table 1: Execution times of different operations of the technological process

Technological operations	***Slope***	***10º***			***15º***			***20º***		
	Skidding distance	*500*	*1000*	*1500*	*500*	*1000*	*1500*	*500*	*1000*	*1500*
Movement without load (idling)		*382*	*763*	*1145*	*440*	*880*	*1320*	*568*	*1136*	*1703*
Maneuvering and position selection		*300*	*300*	*300*	*300*	*300*	*300*	*300*	*300*	*300*
Load forming (loading)		*900*	*900*	*900*	*900*	*900*	*900*	*900*	*900*	*900*
Movement with load (work move)		*382*	*763*	*1145*	*440*	*880*	*1320*	*568*	*1136*	*1703*
Unhitching (unloading)		*540*	*540*	*540*	*540*	*540*	*540*	*540*	*540*	*540*

From Table 1 it can be seen that the maneuvering and positioning times, the load forming times and the load unhitching times are relatively constant values due to the fact that they are not affected by the slope of the terrain and the skidding distance.

Cable skidders are operated by two workers, a tractor driver and a tractor assistant.

When working on steep gradients, the tractor idling and loading times are almost identical due to the difficulty of climbing boundary gradients.

The average volume of the trip load for the individual observations was 7,60 m^3. The tractor running speeds are given in Table 2.

Table 2: Tractor travel speed on different ground gradients

Slope, °	*Movement speed, m/s*	*Movement speed, km/h*
10	*1,34*	*4,82*
15	*1,15*	*4,13*
20	*0,90*	*3,23*

The data shows that as the slope of the terrain increases, the speed of movement decreases, which is logical and has been proven in other studies.

The straight slope and idling were performed in second gear with reduction (slow). According to the tractor technical data, the speed achieved in this gear is 4,84 km/h.

Based on the timing data, the performances of the TAF 690 PE specialized forestry choker tractor were determined. The data are shown in Table 3.

Table 3: Coded values of the two factors and the determined capacities for the cable skidder TAF 690 PE, m^3/h

№	X_1	X_2	Y_1	Y_2	Y_3	Y_4	$\bar{Y}$
1	*-1*	*-1*	*10,98*	*10,16*	*11,21*	*11,45*	*10,95*
2	*0*	*-1*	*10,23*	*10,39*	*11,03*	*10,16*	*10,45*
3	*1*	*-1*	*10,09*	*9,63*	*8,69*	*9,75*	*9,54*
4	*-1*	*0*	*8,43*	*7,50*	*8,71*	*9,00*	*8,41*
5	*0*	*0*	*7,58*	*7,76*	*8,49*	*7,50*	*7,83*
6	*1*	*0*	*7,43*	*6,95*	*6,00*	*7,07*	*6,86*
7	*-1*	*1*	*6,85*	*5,95*	*7,13*	*7,42*	*6,84*
8	*0*	*1*	*6,02*	*6,19*	*6,90*	*5,95*	*6,27*
9	*1*	*1*	*5,88*	*5,43*	*4,58*	*5,55*	*5,36*

To determine the estimates of the regression coefficients in model (1), the experimental data were processed with the STATISTICA program. The results obtained are shown in Table 4.

Table 4: Results of the regression analysis to determine the productivity of the cable skidder TAF 690 PE

	TAF 690 PE R^2 = 0,93575613 F_T (5,30) = 87,394; p < 2,2e-16			
N=36	Regression coefficients - b_i	Standard deviation	Student's *t* criterion	*p* - level
Intercept	7,82833	0,194898	40,1664	0,000000
x_1	-0,73917	0,106750	-6,9243	0,000000
x_2	-2,08000	0,106750	-19,4848	0,000000
x_1x_2	-0,01688	0,130741	-0,1291	0,898162
x_1^2	-0,19000	0,184896	-1,0276	0,312351
x_2^2	0,53250	0,184896	2,8800	0,007272

The results show that the coefficient of determination R^2 = 0,936, indicating that 94% of the variation in Y is described by the second-degree model. The Fisher's criterion F_T (5, 30) = 87,394 and its corresponding likelihood p < 2,2e-16 < 0,05 indicate that the model is adequate. At α = 0,05 level of significance, the coefficients b_0 = 7,83; b_1 = -0,739, b_2 = -2,080 and b_2^2 = 0,533 are significant.

The full regression model that best describes the function and has the best predictive values has the following form:

$$Y = 7{,}828 - 0{,}739x_1 - 2{,}080x_2 - 0{,}017x_1x_2 - 0{,}190x_1^2 + 0{,}533x_2^2. \quad \textbf{(2)}$$

Using stepwise regression analysis, factors with insignificant coefficients (b_{12} и b_1^2) were excluded. According to the CranR program and Akaike's Information Criterion (AIC), the model with smaller AIC was the best fit:

$$\boldsymbol{Y = b_0 + b_1x_1 + b_2x_2 + b_{22}x_2^2}. \quad \textbf{(3)}$$

The results of the regression analysis after excluding the X_{12} и X_1^2 factors are shown in Table 5.

Table 5: Results of regression analysis to determine the productivity of the cable skidder TAF 690 PE when factors X_{12} и $X_1^2$are excluded

	TAF 690 PE R^2 = 0,93345914 F_T (3,32) = 149,64; p < 2,2e-16			
N=36	Regression coefficients - b_i	Standard deviation	Student's *t* criterion	*p* - level
Intercept	7,70167	0,148763	51,7712	0,000000
x_1	-0,73917	0,105192	-7,0269	0,000000
x_2	-2,08000	0,105192	-19,7734	0,000000
x_2^2	0,53250	0,182197	2,9227	0,006322

After accounting for the non-significant influence of the X_{12} и X_1^2 factors, the model can be written as follows:

$$Y = 7{,}702 - 0{,}739x_1 - 2{,}080x_2 + 0{,}533x_2^2. \quad \textbf{(4)}$$

The results of the regression analysis show that the greater influence on the performance of the TAF 690 PE tractor is the length of the skidding distance, since the coefficient in front of this factor is greater in absolute value than the coefficient in front of the slope factor.

The surface of response $Y = f(x_1x_2)$ and the lines of equal response $f(x_1x_2) = Y = const$ are shown in the following Figs. 2 and 3, respectively. Each figure has a quadratic equation with the values of the regression coefficients in front of each of the factors and the free term describing the full model due to the specificity of the STATISTICA program.

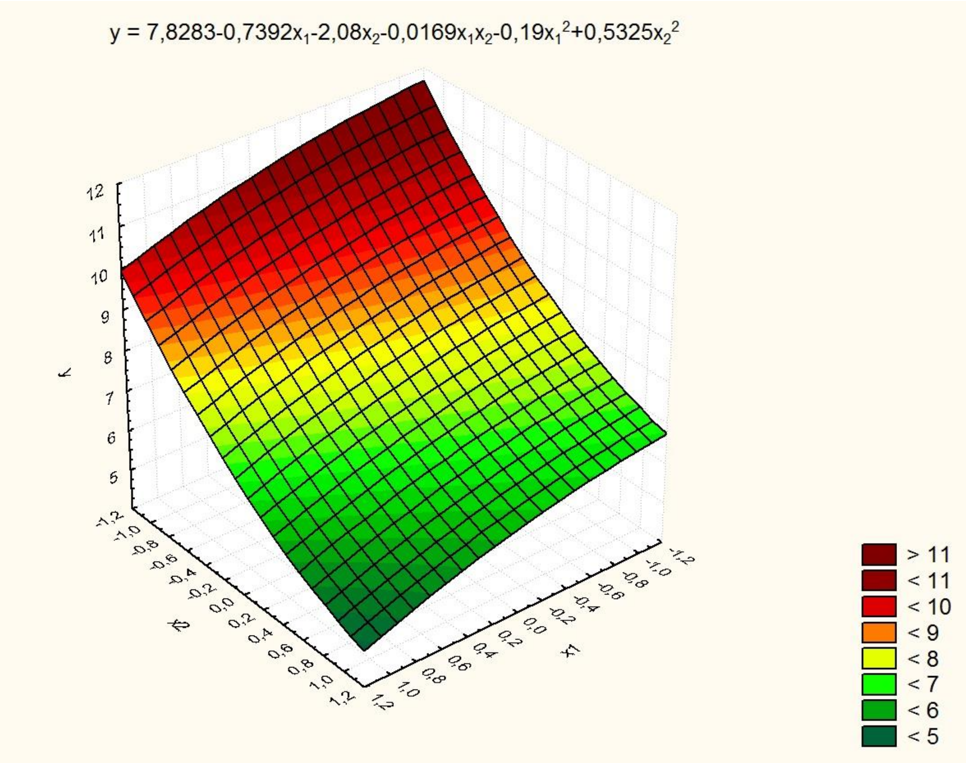

Figure 2: Surface of response Y = f(x1x2) for the productivity of a cable skidder TAF 690 PE

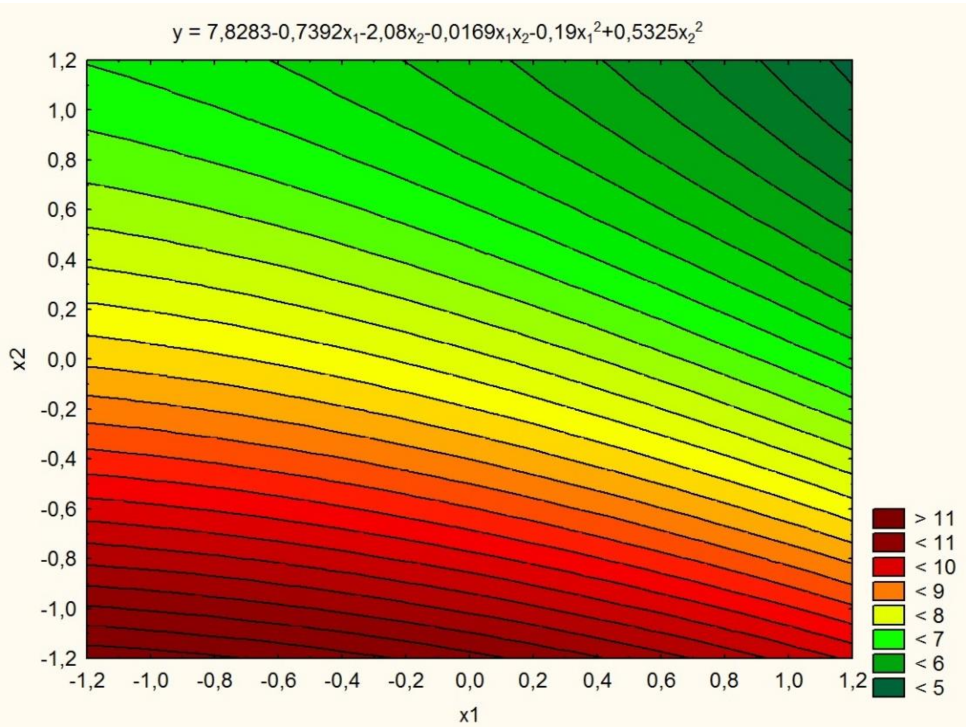

Figure 3: Lines of equal response *f(x₁x₂)* = *Y* = *const* for the productivity of a cable skidder TAF 690 PE

From Figures 2 and 3, it can be seen that the surface response and the lines of equal response has a maximum when skidding whole tree stems at slopes from 10º to 16º (x_1 from -1 to 0,2) and at skidding distances up to 550 m (x_2 less than -0,9). The tractor achieves a minimum hourly productivity at ground slopes of 17 to 20º (x_1 of 0,4 to 1) and a skidding distance in the upper level of the range 1300 to 1500 m (x_1 of 0,6 to 1).

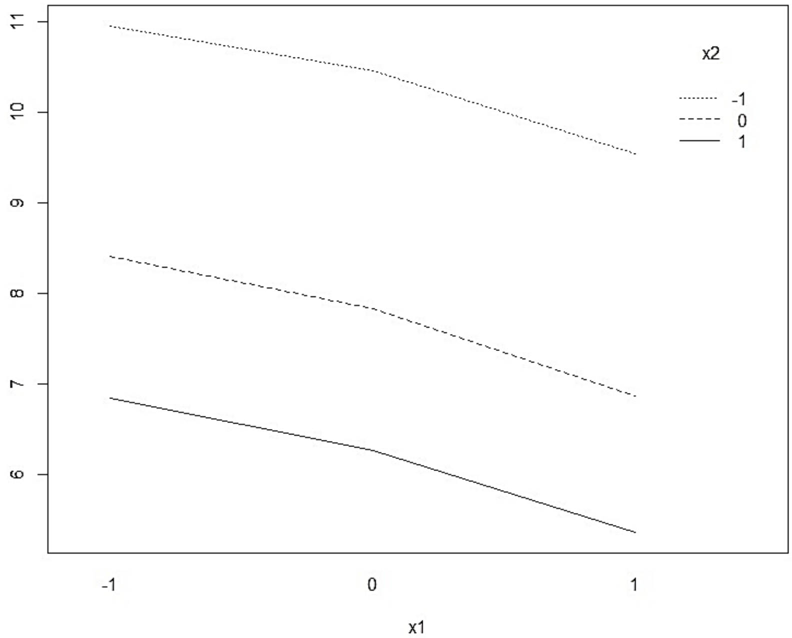

Figure 4: Relationship between productivity and the factors of ground slope and skidding distance when working with a tractor TAF 690 PE

The influence of the investigated factors on the productivity of the tractor TAF 690 PE is shown in Figure 4. It can be seen that as the skidding distance increases, the productivity decreases, which is confirmed by other authors. It is observed that within the factor space, the rate of change of productivity is not uniform. For a slope of 10º, as the skidding distance increases from 500 to 1000 m, the tractor's productivity decreases from 11 m^3 to 8,5 m^3/h, which represents almost 30% lower productivity, i.e. 2,5 m^3 less wood skidded per hour. Increasing the skidding distance from 1000 to 1500 m results in a decrease in productivity from 8,4 to 6,8 m^3/h, which represents 23% or 1,6 m^3/h less wood skidded.

This pattern of reduction in productivity with increasing skidding distance is also maintained for the remaining gradients of 15 and 20º (Figure 4).

The figure also shows that the influence of the slope of the terrain is similar for the different skidding distances, but the rate of change in productivity is smaller, which is confirmed by the regression analysis and the mathematical model derived (3).

It can be seen that as the slope of the terrain increases from 10 to 15º, irrespective of the skidding distance, the productivity decreases on average by 0,55 m^3/h, and as the slope increases in the interval 15 to 20º, the decrease is on average by 0,93 m^3.

CONCLUSIONS

It was found that the highest productivity under the operating conditions considered was achieved with a slope of 10 to 16º and a skidding distance of up to 550 m.

The skidding time of the timber with the specialized forestry tractor, which depends on the skidding distance and on the slope of the terrain, occupies the largest relative share (on average 18 min per trip) of the time for one trip. A comparison of the tractor maneuvering, load forming and load release times at the temporary storage site shows that the load forming operation takes the longest time (on average 15 min per trip). While the maneuvering and load release times are relatively constant, the load forming time depends most on the type and concentration of the cut, as this determines the average volume and number of stems to be attracted to form a suitable trip load.

The regression analysis carried out to determine the productivity of the tractor TAF 690 PE confirms the results of studies by other authors for different farm and specialized tractors.

The derived mathematical models allow to determine the tractor productivity at different ground slopes and different skidding distances. This is a significant contribution and considerably eases the work in technological design in timber harvesting. Considering that the major share of the cost of timber extraction is accounted for by skidding, the determination of the skidding performance makes it possible to make an economic evaluation and selection of an appropriate harvesting technology.

A methodology has been developed that allows similar studies to be carried out with other tractors for timber skidding in mountain conditions.

In order to more fully establish the performance and operational capabilities of the tractor TAF 690 PE, it is also necessary to conduct experimental studies in coniferous wood skidding.

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