Original scientific paper

Effect of Transmission Type on Wheel Slip under Overload – Presented on the Example of the AGT 835 T Tractors

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Abstract

During their occasional work on small forest holdings, forest owners often use tractors that are, as a rule, not intended for professional forest purposes. Due to their small size, these tractors are appropriate for cultivating smaller agricultural areas and, with additional forestry equipment, also for forestry operations. This paper analyses their performance at the capacity limits, since this type of use is possible but very limited due to their low technical characteristics. Here, a comparison is made between two AGT 835 T tractors produced in Slovenia, with the same basic characteristics but different types of the engine power transmission to the forest ground (comparison between a machine with a standard mechanical transmission system and a machine with a newer version of a hydro-mechanical transmission system). The analysis focuses on the wheel slip – this time only in the last meters of skidding when the slip reaches its peak and the tractors stop because of excessively demanding working conditions. Both tractors were used for skidding timber in the same working conditions – the same skid trail and the same load size.

On the steepest section with a 27% longitudinal incline and under the load of 1 m^3, both tractors stopped due to excessively demanding working conditions. However, there was a fundamental difference between the two machines in the final section of skidding. The mechanical transmission system enabled rotation of tractor wheels, which led to a multi-fold increase in slip values (remarkable 80% in the last metre of movement). Contrary to that, the system with hydro-mechanical power transmission resulted in a substantially lower wheel slip (no more than 31%). In the latter case the tractor stopped due to excessively demanding working conditions but the hydro-mechanical steering system reduced the wheel slip. It is important to know that the selected transmission system can significantly influence the efficiency of transmitting power to the ground surface – with a smaller slip, which is also important for the forest ground and the environment.

Keywords: small forest holding, tractor harvesting, wheel slip, transmission type, overload

1. Introduction

In Slovenian forests, the majority of timber is skidded by tractors. They vary in size, technical capacities and equipment. During their development, these machines have undergone numerous changes. It all started with small adapted agricultural tractors that were later replaced by bigger skidders – mostly for operations in difficult working conditions – (Krivec 1967). They did not only differ in size, mass and engine power but also in ergonomic characteristics, forestry upgrade and, recently, in the transmission of engine power to the wheels and ground (Košir 1997, Tomašić 2006, Rebula and Košir 1988).

Skidders are mostly used for operations in difficult conditions (Košir 1997, Košir 2000, Košir and Krč 2000, Marenče 2005, Obranovič 2013), as on the majority of worksites – where this is feasible considering the terrain and the load size – smaller adapted agricultural tractors are used (Zupančič 2008). This is possible due to the technical characteristics of the latter enabling efficient and safe work on less demanding worksites. Such tractors are more affordable mainly due to their lower purchase prices. This is a particularly important factor in case of small and fragmented forest holdings, of course, provided that working conditions permit the use of smaller tractors. Most agricultural tractors that can also be used for forestry operations with additional equipment tend to have engines with less power. The data (Poje 2012) shows the prevalence of tractors with 37 kW of engine power (Fig. 1). Almost two thirds of all tractors do not exceed this engine power. The majority of these tractors are mainly used

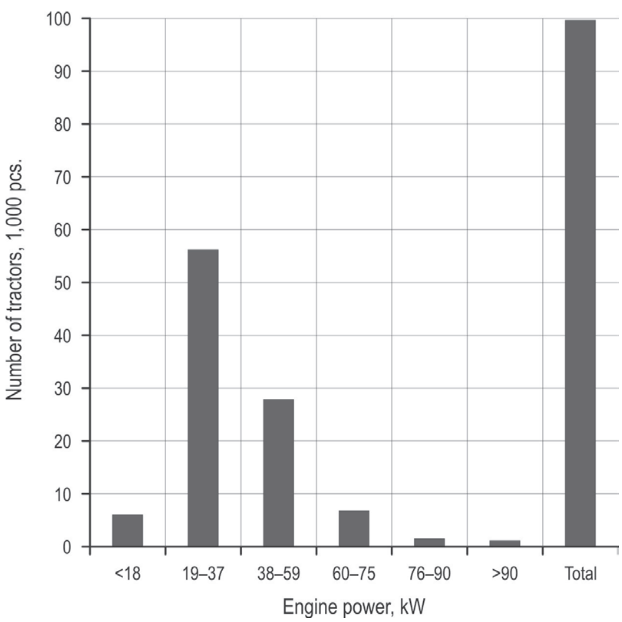

Fig. 1 Number of farm tractors according to their engine power

on the agricultural land, while some owners use them to conduct various forest operations.

It is therefore understandable that the usability of such machines is limited. They are used occasionally, mostly on smaller private forest holdings, but nevertheless, they might be interesting despite their limitations. However, to be used in forests, they need to be appropriately upgraded.

This paper was drafted on the basis of the above stated fact that these smaller tractors are relatively frequently used but at the same time limited in the scope of operations, and therefore it presents some characteristic principles of uphill skidding. By doing so, the engine power transmission to the forest ground is analysed with an exclusive focus on the section when working conditions become excessively difficult for such tractors. At this point the longitudinal incline of skid trail and the load size become too big an obstacle to continue skidding. In demanding working conditions, the tractor can no longer operate, and therefore it stops. This is a limit point that cannot be surmounted.

2. Problem definition

Most studies have so far examined the equipment used for measuring different technical parameters (Jejčič et al. 2003), and their interrelations and interdependencies (Horvat 1996, Košir et al. 2005, Marenče and Košir 2006, Wong 2001). By doing so, those parameters were analysed in various working conditions, mostly by using different sizes of loads skidded and by changing longitudinal inclines of the skid trail. The studies dealt with different machines used for transporting timber. In most cases the entire timber transportation route was covered, from the stump to the truck road, focusing on the environmental impacts (Wasterlund 1992, Šušnjar 2005, Najafi 2009).

Few are studies that only cover a single segment of harvesting (e.g. the moment when the machine stops due to excessively demanding working conditions). These studies focus on changes in technical parameters (slip, weight distribution, torque, winch pulling forces) only occurring in the last meters of timber skidding before the machine stops (Marenče and Košir 2008). The quoted study examined a skidder with a hydro-mechanical transmission gear. The focus was on its technical parameters in the period immediately before the machine stopped, i.e. when the tractor was still moving along the skid trail but operated at its maximum capacity.

The present paper does not examine the machines used for professional purposes but rather focuses on tractors operated by private forest owners during their occasional forestry operations. The aim is to upgrade the present tractors skidding at their capacity limits by comparing the operation and performance of two tractors that have identical basic characteristics but different types of transmission gear or different ways of power transmission to the ground. For this purpose, the results were used of field measurements of two tractors – one with a standard mechanical transmission system and the other with a newer version of a hydro-mechanical transmission system.

At present, the following three types of transmission systems installed in tractors prevail: mechanical, hydrostatic and hydro-mechanical. The selected type depends on the designated use of a tractor; however, it also influences its price and operation. The mechanical version comprises a standard cogwheel transmission with the highest efficiency rates and a finite number of gear ratios. The hydro-mechanical version, however, combines the advantages of mechanical transmission (high efficiency rate) and of hydrostatic transmission (lower efficiency rate, but an infinite number of gear ratios). This study does not deal with the hydrostatic versions.

The data analysis mainly focuses on the wheel slip, which is one of the most important factors of the environmental impact assessment (forest ground). However, the energy consumption is also considered here as an important factor. During timber skidding, both tractors operated in the same working conditions, i.e. loads of the same size were skidded on the same skid trail. As expected, the biggest slip occurred in the most difficult section of skidding. The above stated different types of transmission have substantially influenced the value of the slip. Hence, the slip does not only depend on working conditions (mostly longitudinal incline and load size) but can also be influenced by the type of tractor or transmission.

Today, tractors with mechanical transmission still prevail. There are no substantial differences between private owners and professional providers. The important fact is that the selected transmission system notably influences the efficiency of the power transmission to the ground. At low tractor speeds, minimum slips are desired. Slips do not only cause energy losses, but also damage the upper layers of the ground. Therefore, when working in forests, it is not only important to select the appropriate tractor, but also the right transmission type.

The study aims at presenting:

⇒ the work involving tractors with less power and tractive force that are appropriate for forestry operations under certain conditions,

⇒ the efficiency of engine power transmission via the wheel to the ground,

⇒ the analysis of their operation at the capacity limit when skidding becomes impossible due to the excessive longitudinal incline.

It is important to answer the following questions: to what extent are such tractors appropriate for forestry operations considering their technical characteristics and how acceptable are they for the environment in the most difficult working conditions considering different wheel slips? Many authors have recommended the ways for selecting the appropriate mechanisation for forest operations, especially on the soft forest ground. In this regard, they emphasise that all forest operations need to be conducted with the most suitable machinery and technology at the most convenient time (Owende et al. 2002). In the studies dealing with the slip (Horvat 1993, Wasterlund 2003), the authors established values between 10 and 30% for wheel tractors. Horvat (1193) indicates that tractive forces are comparatively small when the slip values are small. The largest tractive forces occur with higher slip values, which however depend on the characteristics of the ground. Sever (1980) and Saarilahti (2002) mention the slip threshold value of 40% – higher values cause a dramatic drop of effective power of wheels and subsequently cause excessive damages to the ground, mainly due to the ground shifting and deep, long ruts. Horvat (2003) states that with slip values exceeding 33%, the rut depth also increases significantly (by 60%). The approach to this kind of issues is always multifaceted: in terms of energy, the tractive forces necessary for timber skidding are observed, while in terms of environmental protection, the wheel slip value should be kept as low as possible. Wheel slip also represents a loss of energy that decreases the machine speed. Therefore, the aim is to find a sort of optimum value that would be acceptable in terms of energy and environment.

3. Methods

The study examined two AGT tractors produced in Slovenia. All tractors of this brand are equipped with less powerful engines (from 13.2 to 26.4 kW); they are classified as adapted agricultural tractors, and have four equal-size wheels and a two-axle drive system. Being small, they can be used on smaller agricultural areas and, with additional forestry equipment, also for forestry operations in worksites with smaller longitudinal inclines and load sizes appropriate for skidding. Such working conditions were also selected for this study. The AGT tractors are available with the mechanical and hydro-mechanical types of transmission (Jejčič 2001), both of which are examined in the study (Fig. 1). Both tractors have identical dimensions, mass and 16-inch pneumatic tyres. They have a water-cooled, three-cylinder diesel engine of 26.4 kW produced by Lombardini. The tractors fall into the category of adapted agricultural tractors with front-wheel steering.

The mechanical transmission system has 6 gears for driving forward and 3 gears for driving backward, with a maximum speed of approximately 20 km/h.

The hydro-mechanical transmission system is based on the consecutive operation of a diesel traction engine, an oil pump and a hydro engine, connected by

Fig. 2 Adapted agricultural tractor AGT 835 T with measurement equipment

mechanical transmission. The mechanical part of transmission covers three ranges, selected with a gear-shift lever, with infinitely variable transmission ratio (Jejčič 2001).

Both tractors were upgraded with the following equipment: a safety cab, a front and rear blade, a single-drum winch Krpan with pulling force of 30 kN and wheel chains. A tractor equipped like this can also be used for forestry operations.

The skid trail used in the test was selected with regard to the capacities of the tested tractor and was divided into several sections depending on its longitudinal incline. It was concave in shape, 191 m long, with an increasing incline that reached its maximum value just before the trail end (Fig. 3), thus meeting the trial conditions that, when skidding the selected load, the tractor would stop due to excessively demanding working conditions. The analysis of developments on the entire skid trail has already been presented in other papers (Marenče and Košir 2006b, Marenče and Košir 2007); this time the focus will be strictly on the developments from profile No. 7 onwards. This section of the skid trail (20.8 m) is the steepest (27%) and, with the selected load (1 m^3), it was too big of an obstacle for the tractor, so it stopped.

As already stressed, the tractor is intended for operations in less demanding working conditions, the level of difficulty being determined by the longitudinal incline and the load size. Based on the experiences gathered by operating such tractors, it was assumed that, on the selected skid trail, the load size of 1 m^3 would be an insurmountable obstacle for the tractor. This assumption was confirmed during the test. The load was a single fir 8 m log, with bark. In both cases (hydro-mechanical and mechanical version) the load was skidded with butt-end forward in the driving direction. This paper does not deal with different load orientations because this issue has already been presented in other publications (Marenče 2005, Marenče and Košir 2007). Before the measurements took place, the test load was weighed (Fig. 4). Its weight was 770 kg (1 m^3).

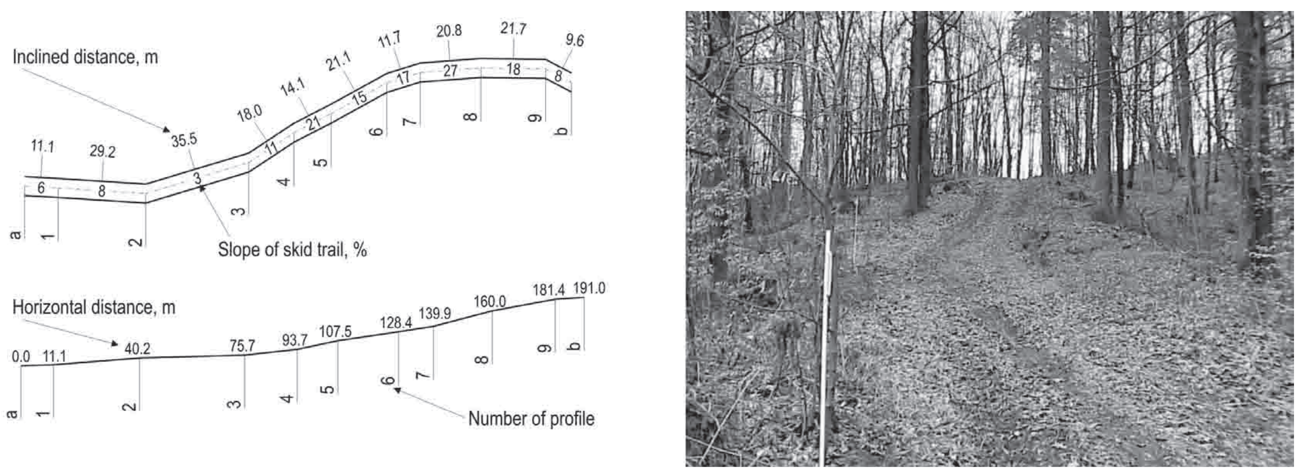

Fig. 3 Data on the test skid trail and a photo of the skid trail upper part where it is the steepest

Fig. 4 Weighing the load before the test

Recording was carried out with the measuring instruments connected to a measuring chain. The required equipment was installed on the tractor. The detailed description of data collection and of the measurement equipment has already been presented (Jejčič et al. 2003).

For both tractors, the distance driven was measured by using the fifth wheel (Fig. 5). In general, the application of this method for measuring uneven and longer sections could be questionable. However, in the present case, the skid trail on the measured section was straight and short (8.9 or 11.2 m). In this way the measured section could be subdivided into 1 m sections, within which the analytical tasks set for the test were carried out. Particular attention was devoted to the last few metres, where the tractor gradually stopped.

The slip occurs when the force applied to the wheel exceeds the cohesion force of the ground surface (Sever 1980). Its size also critically depends on the type and characteristics of the surface. In this research the measurements with both tractors were carried out in the same conditions: on the same skid trail and with the same soil moisture.

Fig. 5 The fifth wheel used on the front part of the tractor

The wheel slip value derived from the research can be defined in different ways: Košir (Košir 1997) defines it as follows:

$$\delta = \frac{(s_t - s_s)}{s_t} \tag{1}$$

Which can also be expressed as:

$$\delta = 1 - \frac{s_r}{s_t} \tag{2}$$

Where:

δ wheel slip coefficient,
s_s, s_r actual distance travelled,
s_t theoretical distance travelled.

The wheel slip can be expressed as a relative number or as a percentage. In this research it is expressed as a percentage.

The distance travelled by the tractor was measured by using the above mentioned fifth wheel, whereas the path travelled by a tractor wheel was measured with special sensors individually mounted on the axle of each wheel (Marenče 2000, Marenče 2005). By doing so, the distance travelled by a wheel, including the slip, was measured (Fig. 6). Pressure in the pneumatic tyres was equalized before the test started.

Both tractors were equipped with chains on all four wheels. In this research, the Tempo chains produced by CMC System, d.d., Lesce, were used – Fig. 7.

4. Results

In the analysis of this kind, the data on the tractor mass distribution is also important, i.e. it is important

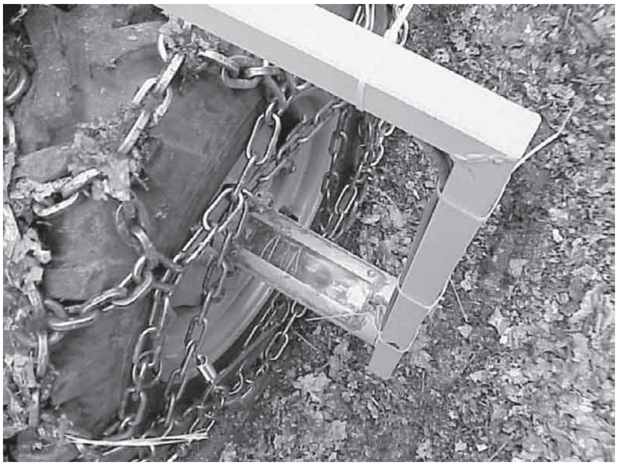

Fig. 6 Sensor (rotary optical generator) mounted on the wheel axle

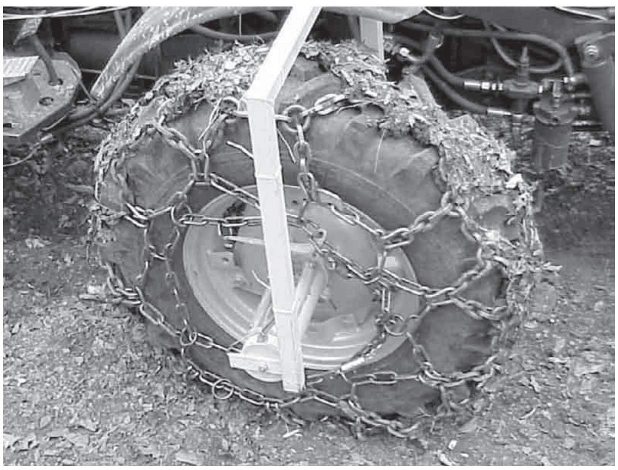

Fig. 7 Chains on a tractor drive wheel

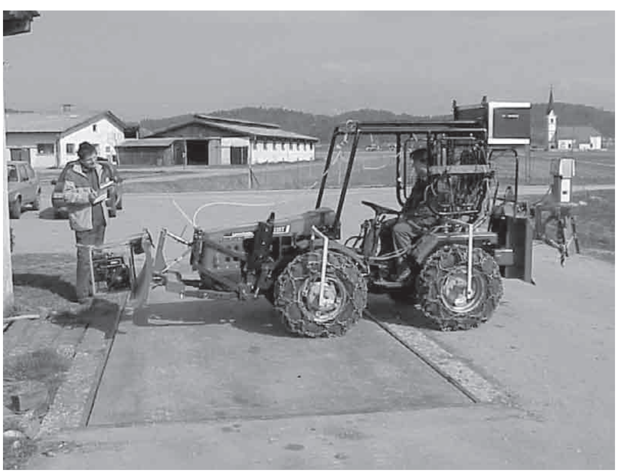

Fig. 8 Weighing the front part of the AGT 835 T tractor

to determine the front axle load and the rear axle load. This is of crucial importance for the transmission of engine power to the forest ground. For this purpose, both tractors were weighed on a weighbridge together with the entire measurement equipment. The established mass ratio between the front and rear axles was 64:36 (Fig. 8). This means that when the tractor was in a horizontal position and unloaded, the front axle carried almost two thirds of the total mass. The data was identical for both tractors examined in this paper.

Table 1 presents the values obtained on the weighbridge and during the operation on the steepest section of the skid trail. Just for comparison and as a point of interest: if unloaded, the front part of the tractor carries more mass that the rear one, even in the steepest section of the trail. However, when skidding the biggest load (1 m^3) in the steepest section (27%), with its front part leaning against the tractor, the ratio substantially changes. The front axle carries approximately one third of the entire load. It must be stressed here that, when skidding with these tractors, there is no disburdening and consequently no lifting of the tractor's front. Therefore, the transmission of engine power to the ground is ensured even in the most difficult working conditions. Thus, the tractor longitudinal stability and the tractor driver's safety are never jeopardized in any of the skidding sections.

Table 1 Tractor mass distribution when operating on the steepest section of the skid trail

	Front axle : Rear axle
Weighed in a horizontal position	64:36
Operating unloaded (at an incline of 27%)	52:48
Operating loaded (at an incline of 27%)	34:66

This paper deals with the agricultural tractors with similar weight distribution as articulated tractors. This feature enables them to be more successful in uphill skidding operations. Due to this unique characteristic, these two tractors are more suitable for forest operations that other tractors from this group. All obtained data are related to the last segment of skidding, which is the most difficult section of the skid trail due to its longitudinal incline. During the test, the distance travelled by tractors was different. The one with the hydro-mechanical transmission stopped at the 9th meter, whereas the one with the mechanical transmission made it further (to the 12th meter). It must be stressed that the measurements of the tractor with mechanical transmission ended at the moment when the wheel reached the maximum slip value (100%), which means that the wheel was still rotating, but the tractor was no longer moving. As mentioned above, in both cases the skidding conditions were the same: measurements were carried out on the same skid trail, with the same ground conditions and load mass, the only difference was in the tractor transmission systems.

The analysed values are presented for each individual meter of skidding, with particular attention on the last two meters of the skid trail, where the biggest changes were expected due to the tractor limitations. The majority of published papers dealing with a selected tractor, examined the tractor operation on the entire skid trail, and they never particularly focused on the final part of skidding, when the tractor is overloaded.

The speed analysis of both tractors shows that their average speed in the measured section ranged from 3 to 4 km/h (Fig. 9). There were no substantial changes of these values in the first part of the examined section - they remained on the similar level. The tractor with mechanical transmission was somewhat faster (on average by 0.5 km/h).

In the last meters of movement, the machines gradually stopped. The tractor with hydro-mechanical transmission came to a stop relatively quickly in the last meter. Namely, the hydro-mechanical transmission system no longer enabled the excessive rotation of wheels at the bottom limit of the machine movement. In case of the tractor with the mechanical transmission, the situation was quite different: here the speed started reducing already 2–3 meters before stopping and the tractor was still able to proceed on the steep slope while operating at its capacity limit. By doing so, the tractor was able to travel a longer distance, and therefore the stopping time was longer, too. This analysis focused exactly on the section where the tractor was coming to a stop, because it was expected that the substantial changes of some technical parameters of the machine would occur in this section.

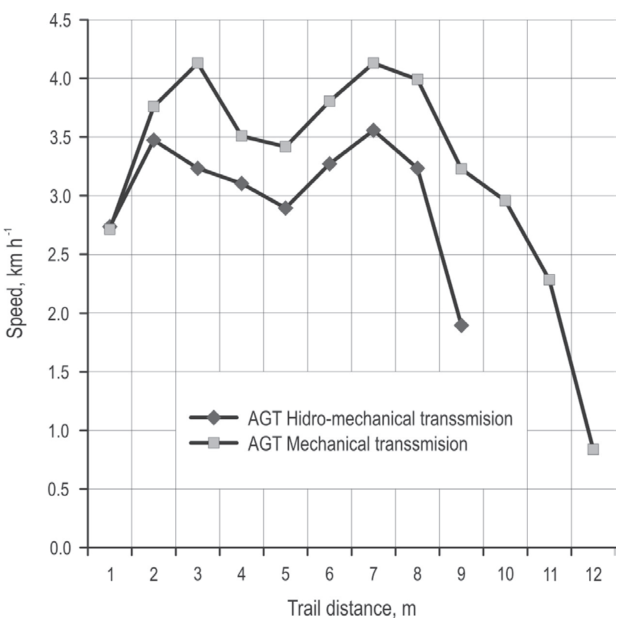

Fig. 9 Driving speed of both tractors in the test skid trail section

In the forefront, the size of the wheel slip demonstrated the efficiency of the engine power transmission to the ground. Many authors have examined the occurrence of wheel slip and its impact on the forest ground. However, very limited data is available on what is going on between the wheel and the ground surface in extreme working conditions, i.e. in a few meters where a machine is operating at its capacity limit. Do the slip values change substantially in this case? Does the transmission type make any difference and what is its role? Can the machine selection by foresters influence the scope of harmful environmental impacts in such cases?

The answers to the set questions were sought by a thorough analysis of the wheel slip of both tractors. In the first part, some principles of the slip occurrence were analysed for each tractor separately, whereas in the second part, the comparison was made between the two of them. According to the assumptions, and supported by experiences gathered while operating such tractors, substantial increases in the wheel slip values were anticipated just before the tractor comes to a halt. The tractor transmission type was expected to play a crucial role in this increase.

The tractor with the hydro-mechanical transmission travelled a distance of 9 meters in the last section of the skid trail. The wheel slip values were established separately for each driven meter and ranged from 10 to 25% (Fig. 10A). It is assumed that, with the same longitudinal incline and ground surface, it was the microrelief that caused the differences established during the test. This assumption is also supported by the fact that similar value oscillations were recorded for both tractors, i.e. in the same sections. The highest slip value was reached in the last metre of movement (30 to 32%, Fig. 10A). It was also established that the slip value was always somewhat higher on the front axle. This means that the higher the load on the rear axle of the tractor, the more effective the transmission moment to the ground surface (the mass ratio in this skidding section was 34:66). The last two metres of skidding were the crucial segment of the analyses. The

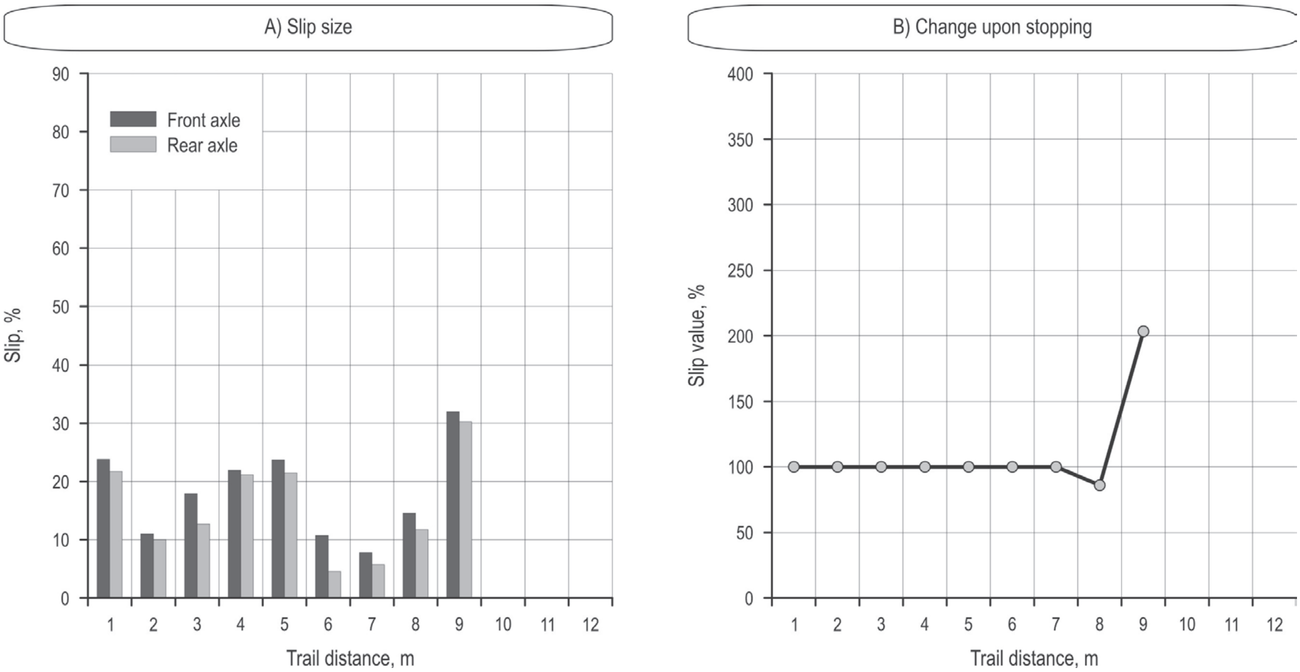

Fig. 10 AGT tractor (hydro-mechanical transmission)

biggest change in case of the hydro-mechanical transmission occurred in the last meter. To illustrate the development and to compare values, the average value in the analysed section from the first to the seventh metre was taken into account (to simplify, this value was marked as level 100). This value was compared with the values in the last two meters of load skidding. An approximately twofold increase in the slip value was recorded in the last meter of movement (Fig. 10B). At this point the tractor stopped.

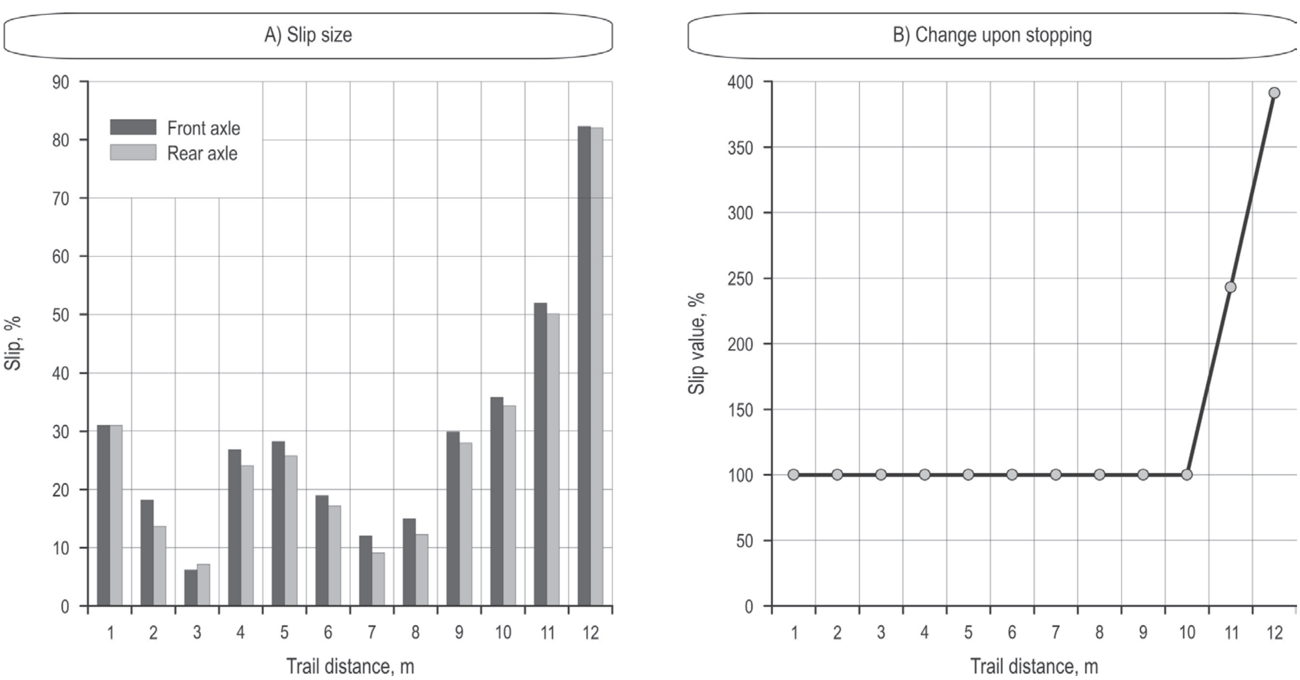

Fig. 11 AGT tractor (mechanical transmission)

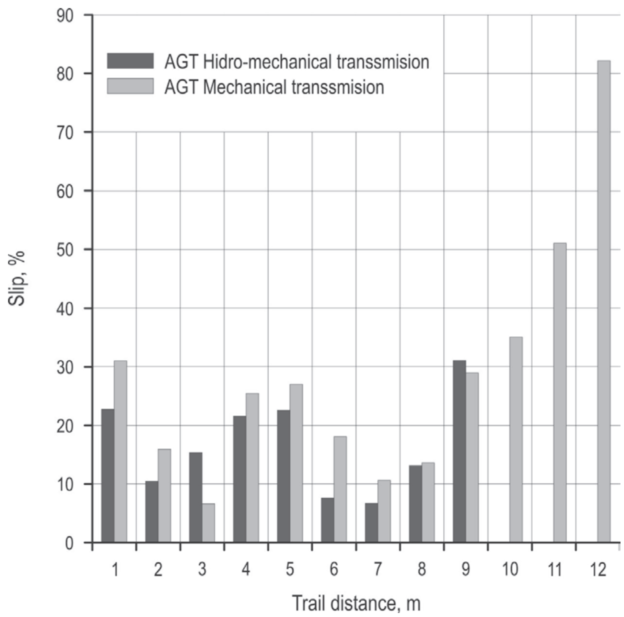

Fig. 12 Comparison of wheel slip between tractors

It must be stressed that this was not a laboratory test. The section where measurements took place was a part of a skid trail on a selected worksite, otherwise used for regular forest operations.

On the same skid trail section, the tractor with the mechanical transmission travelled a distance of 9 meters, i.e. a longer distance than in the first case. In this case, the wheel slip values measured in the predominant part of the analysed section ranged from 10 to 30% (Fig. 11A), and were again higher on the front axle, which was less loaded. Substantial changes were explicitly recorded in the last few meters of skidding. This time, the development was very much different than in the first case. In this part, the speed of movement was gradually decreasing, while the slip values were increasing. Just before stopping, the slip value was close to 80%. The measurement was interrupted when the tractor stopped. An additional comparison presented in Fig. 11B shows that the mechanical transmission substantially increased the slip. Compared to the increase in the last ten meters, a fourfold slip increase was recorded immediately before stopping.

5. Conclusion

When harvesting timber, foresters often wonder which tractor is the most appropriate for use. An equally important question is when and under what working conditions their use is most appropriate.

Studies like this can help provide at least partial answers to these questions. The analyses made so far, mostly for uphill timber skidding on longer sections (Marenče and Košir 2006, Šušnjar 2005), have revealed that tractors with the hydrostatic transmission are more appropriate because they cause less environmental damage in forests. The main goal of this paper was to present two machines that only differ in the type of engine power transmission, and to compare them when operating under the same working conditions. The study does not particularly cover changes in the skid trail and removing of the ground due to the wheel slip. It is only focused on the wheel slip itself. By comparing the two tractors (Fig. 12), some similarities and some crucial differences between them can be highlighted.

There were no substantial differences in the wheel slip between the two tractors at the beginning of the analysed section. In most cases, the slip value for the mechanical transmission system was somewhat higher. The values reached by this tractor mostly ranged between 10 and 30%. However, with gradual speed reduction of the tractor in the last 2–3 m, the slip considerably increased. The crucial differences between the two tractors were observed in this final part of skidding. The mechanical transmission system enabled a continued rotation of tractor wheels and slow movement of the machine, but this was accompanied by a multi-fold increase in the wheel slip values. The measurement ended when the tractor stopped (at the 100% slip), the average slip value in the last meter being close to 80% (Fig. 12). Consequently, the tractor with mechanical transmission was able to travel 3 m longer under the same working conditions.

Quite the opposite, the hydrostatic transmission system, and other settings on the respective tractor, prevented its wheels from rotating and therefore the machine stopped. This also resulted in proportionally smaller shear forces transmitted from wheels to the forest ground. In this case, contrary to the tractor with mechanical transmission, no substantially increased wheel slip was observed. Its value in the last metre, just before stopping, was 31%. The tractor stopped due to overload and the hydrostatic steering system prevented an increased slip. The measurement results showed that the hydro-mechanical transmission system was more successful in preventing overloading of the tractor and thereby reduced the impact on the forest ground and environment.

This type of data clearly demonstrates the differences between individual machines that can be used for forestry operations, as well as their appropriateness. It is very important and necessary to know these differences when selecting tractors. Besides, it is also inevitable to question the appropriateness of using machines at their capacity limit in general. Is this really appropriate and, above all, necessary? The case examined in this paper has clearly demonstrated that, from a strictly technical point of view, the mechanical type performed better. However, this is surely not enough. From the perspective of energy, the increase of slip up to a certain point also means a higher skidding efficiency. However, from the environmental point of view, it is not preferable as it causes the ground shifting and track prints. In order to assess the suitability of forest operations, the energy and environmental issues need to be considered, i.e. the optimum wheel slip interval of the forest operation must be determined.

To conclude, considering their technical capacities, the presented tractors can also be used for forestry operations. They are mostly appropriate for work on small forest holdings, i.e. for occasional forestry operations in less difficult working conditions. However, they should not be operated at their capacity limit, because of the excessive wheel slip and thereby intolerable environmental impact. This is particularly true for the mechanical transmission system.

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