Economic Comparison of the Use of Tyres, Wheel Chains and Bogie Tracks for Timber Extraction

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Abstract – Nacrtak

Many logging operators in Finland use bogie tracks and wheel chains all the year round and under all terrain conditions. The hypothesis tested here is that bogie tracks and wheel chains increase the resistance forces, and thus fuel consumption, when operating in summer conditions and on a hard-earth forest floor. Fuel consumption was measured under such conditions using the CAN bus and GPS techniques and models were generated to simulate it in different forms of terrain and types of logging work. It was found that both wheel chains and bogie tracks increased fuel consumption under all simulated terrain conditions, the difference being quite marginal for wheel chains, but much more significant for bogie tracks. A site size of 5 hectares was the break-even value reached in three out of four simulated terrain types that made the removal and re-installation of bogie tracks profitable when the average extraction distance was more than 600 metres.

Keywords: *Tyre, wheel, bogie track, wheel chain, fuel consumption, forwarder*

1. Introduction – *Uvod*

Many logging operators in Finland use bogie tracks all year round and under all terrain conditions. The common explanation for this is that the removal and re-installation of these takes a lot of time and is too costly. In addition, the following benefits of using bogie tracks and wheel chains are quoted:

⇒ improved bearing capacity because of the increased tyre contact area

⇒ better thrust

⇒ the tyres remain cleaner, which improves thrust.

All these benefits are achieved especially when operating on soft terrain, e.g. on peatlands. In addition, bogie tracks and wheel chains are often necessary in winter in order to make movement possible at all.

Bearing capacity, thrust and tyre cleaning are no problem for forest tractors on hard, mineral soil terrain, and the hypothesis to be tested here is that bogie tracks and wheel chains only increase the resistance forces, and thus fuel consumption, when operating under such conditions. This is because the mass of the tractor and its internal and external friction are increased. If this hypothesis proves to be correct, the removal of bogie tracks and wheel chains might well be profitable in some cases. I will take only the economic viewpoint into account here and ignore ecological aspects such as soil disturbance and compaction. I will, however, consider the question of the conditions under which it would be economic to take bogie tracks or wheel chains off, and analyse the behaviour of various ground contact devices under different terrain conditions, so that the reasons behind the fuel consumption models can be appreciated.

This paper starts with the review of earlier work on the topic, followed by a description of the materials and methods used, including the measuring system, test programme, test tractor and its equipments. The next part introduces the results, and the discussion section at the end of the paper reviews the results and takes a look at prospects for further studies.

List of symbols and abbreviations – *Lista simbola i kratica*:

a	acceleration – *ubrzanje*, m/s^2
A	forest stand size – *površina sastojine*, ha
$d_{average}$	average extraction distance – *srednja udaljenost izvoženja drva*, m
d_{loaded}	loaded drive distance – *udaljenost opterećenoga kretanja*, m
$d_{loading}$	loading drive distance – *udaljenost premještanja pri utovaru drva*, m
$d_{unloaded}$	unloaded drive distance – *udaljenost neopterećenoga kretanja*, m
F_T	total resistance – *ukupni otpor*, N
F_R	rolling resistance – *otpor kotrljanja*, N
F_S	slope resistance – *otpor uspona*, N
F_O	obstacle resistance – *otpor površinskih prepreka*, N
F_W	steering resistance, winding resistance – *otpor upravljanja vozilom*, N
F_L	snow resistance – *otpor snježnoga pokrivača*, N
F_I	slip resistance – *otpor klizanja*, N
h_c	height of the tractor's cabin – *visina kabine forvardera*, mm
h_{gc}	ground clearance – *prohodnost vozila*, mm
h_t	height of the tractor – *visina forvardera*, mm
i	slip – *klizanje kotača*, %
l	length of the tractor – *duljina forvardera*, mm
m	tractor mass – *masa forvardera*, kg
$n_{pulpwood}$	number of cycles for pulpwood – *broj turnusa pri izvoženju celuloznoga drva*
$n_{sawn-timber}$	number of cycles for sawn-timber – *broj turnusa pri izvoženju tehničke oblovine*
P	power, recorded gross power on drive line – *bruto snaga motora*, kW
r_R	rolling radius – *polumjer kotrljanja*, mm
S	skid – *negativno klizanje kotača*, %
t_v	vehicle tread – *trag kotača*, mm
v	horizontal velocity of the tractor – *vodoravna brzina kretanja forvardera*, m/s
V_{ha}	average volume of growing stock per hectare – *prosječna drvna zaliha*, m^3/ha
V_{load}	load volume – *obujam tovara*, m^3
V_{st}	sawn timber percentage – *obujamni udio tehničke oblovine*, %
V_{sr}	timber volume along the strip road – *obujam izrađenoga drva uzduž vlake*, [m^3/100 m]
w	width of the tractor – *širina forvardera*, mm
ω	angular velocity of the wheel – *kutna brzina kotača*, s^{-1}
CAN	Controller Area Network – *mrežni protokol*
GPS	Global Positioning System – *globalni pozicijski sustav*
VAT	Value Added Tax – *porez na dodanu vrijednost*

Definition – *definicija*:

site size	the group of forest stands, which can be operated without translocation of forest machines by truck – *skupina šumskih sastojina (radilišta) na kojima se drvo privlači bez premještanja forvardera kamionom*

2. Earlier research – *Prijašnja istraživanja*

There are a lot of studies of the performance of wheeled or tracked vehicles, but only a few compare ground contact devices under given terrain conditions. Wong and Huang (2006) evaluated wheels and tracks performance from a traction perspective, while Bygdén et al. (2004) studied rut depth, soil compaction and rolling resistance when using wheels or two models of bogie tracks, and reported that the relative rolling resistance did not increase when using bogie tracks but the mass of the test vehicle did, by 10–12%. They also reported that the rut depth decreased by up to 40% when using bogie tracks, although the ruts that they measured were relative shallow (2.2–8.0 cm). The effects of wheel chains and bogie tracks on fuel consumption of forwarders are a new research topic.

Fuel consumption is traditionally measured with flow meters, e.g. (Nordfjell et al. 2003), but new technologies, especially the CAN bus technique, allow more accurate, less expensive and easier test arrangements, e.g. (Rieppo and Örn 2003). The CAN bus technique makes it easier to analyse fuel consumption at a certain moment, which is crucial when defining the most important factors for fuel consumption. The development of more economical and ecological logging is possible only by identifying these crucial factors. Rieppo and Örn (2003) calculated that a 5% reduction in fuel consumption of forest tractors and timber extraction vehicles in Finland would yield savings of five million euros annually.

Favreau and Gingras (1998) reported that fuel costs account for about 10% of total harvesting costs in fellings carried out by the CTL method in Canada, while according to Johansson (2001) fuel costs can reach 20% in Sweden, where fuel prices are much higher than in North America. Fuel prices have in any case increased dramatically since the beginning of the new millennium, so that fuel costs as a proportion of total costs are nowadays probably even higher. Nordfjell et al. (2003) estimated that forwarders consumed 0.23–0.38 litre per 100 metres driven and that consumption increased by only 10% when loaded as compared with an unloaded vehicle. They also reported the average fuel consumption to be 13.3 litres per hour during final fellings and 10.5 litres per hour during thinning. Rieppo and Örn (2003) quoted average consumption for forwarders of 10.5 litres per hour, while Nordfjell et al. (2003) reported that 61–62% of fuel was consumed during loading and driving in connection with loading.

The results presented by both Rieppo and Örn (2003) and Nordfjell et al. (2003) are based on average parameters for a wide body of data, whereas detailed analyses of the effects of the conditions of the terrain and ground contact device on fuel consumption are practically ignored. Nordfjell et al. (2003) did assume, however, that under more difficult terrain conditions the use of bogie tracks and wheel chains would probably increase fuel consumption.

3. Materials and methods – *Materijal i metode*

3.1 Test forwarder – *Ispitivani forvarder*

The tractor was an 8-wheeled Timberjack 1110 forwarder registered in 1997, with about 6500 engine hours on its log. This model is powered by a six-cylinder turbo-charged diesel engine and has a hydrostatic-mechanical power transmission system which can generate a maximum pull of 150 kN. The maximum engine power is 114 kW at 37 s^{-1} and the maximum torque 620 Nm at 25 s^{-1}. The dimensions of the forwarder are presented in Figure 1.

3.2 Tyres, bogie tracks and wheel chains – *Gume, polugusjenice i lanci*

The forwarder was equipped with Nokian 710/45–26.5 16 Forest King F SF tyres (Nokian Tyres, No year), with an inflation pressure of 350 kPa on the front bogie and 440 kPa on the rear one.

The wheel chains were manufactured from 16-millimetre chain and had a mass of 400 kg per pair. The ECO-TRACK bogie tracks, manufactured by Olofsfors (Olofsfors, No year), had a mass of 1850 kg per pair. The wheel chains were fitted to the tyres on the second and third axles, whereas the bogie tracks

Fig. 1 Dimensions of the test forwarder
Slika 1. *Dimenzije ispitivanoga forvardera*

were placed on the rear bogie (3rd and 4th axles) and were used in conjunction with wheel chains on the tyres of the second axle.

3.3 Measuring system – *Mjerni sustav*

The measuring system consisted of a 12-channel Trimble ProXR GPS receiver with external antenna and a CAN bus data logging system. The point accuracy of the GPS receiver has been examined by Naesset (1999), who reported a mean error of 1.17 metres and a standard error of 1.07 metres below the forest canopy after a 30-minute observation period. Veal et al. (2001), who studied the suitability of the ProXR for tracking forest machines, reported a three-dimensional mean positional error of 1.26 metres in open areas and 1.77 metres under a light forest canopy. They also reported that the tractor's ground speed had only marginal effects on the positional error. It should be noted that a part of positional error is systematic, so that the accuracy of horizontal speed measurement is normally better than the absolute positional accuracy of the same instrument.

The present GPS data were collected in line generic mode in order to define the tractor velocity. The data collection rate was set at one observation per second. Post-processed differential correction was applied using a base station located at Evo about 70 kilometres from the test area.

The CAN bus data logging system, which enables simultaneous measurements from three CAN buses placed in the engine's pressure sensors, indicates the gross power on the tractor's drive line and the rotational speed of the drive motor.

A more detailed description of the measuring system and its sensitivity is presented by Suvinen and Saarilahti (2006). The accuracy of Trimble GeoXT GPS receiver used by Suvinen and Saarilahti (2006) is slightly inferior to that of the Trimble ProXR used here.

3.4 The test programme and conditions – *Mjerni postupci i uvjeti*

Field tests were carried out in September 2005 near the Jämsänkoski Forest Machine School. The test trajectory, presented in Figure 2, was levelled at intervals of 2.5 metres in order to obtain an accurate terrain profile. The leveled profile is also presented in Figure 2. This profile is in fact too accurate for the terramechanical analyses, as the test tractor was almost 10 metres long, and thus an interval of 10 metres was used to construct the terrain profile for the total resistance, motion resistance coefficient, slip and fuel consumption models. Conditions during the test period were fairly constant, the weather and terrain were dry and the temperature was above zero. Since the tests were carried out in final felling areas, the forest canopy did not disturb the GPS signal reception.

A cone penetrometer was used to assess the bearing capacity of the soil. As the penetrometer measurements were made after the driving tests, the test points were located less than half a metre to one side

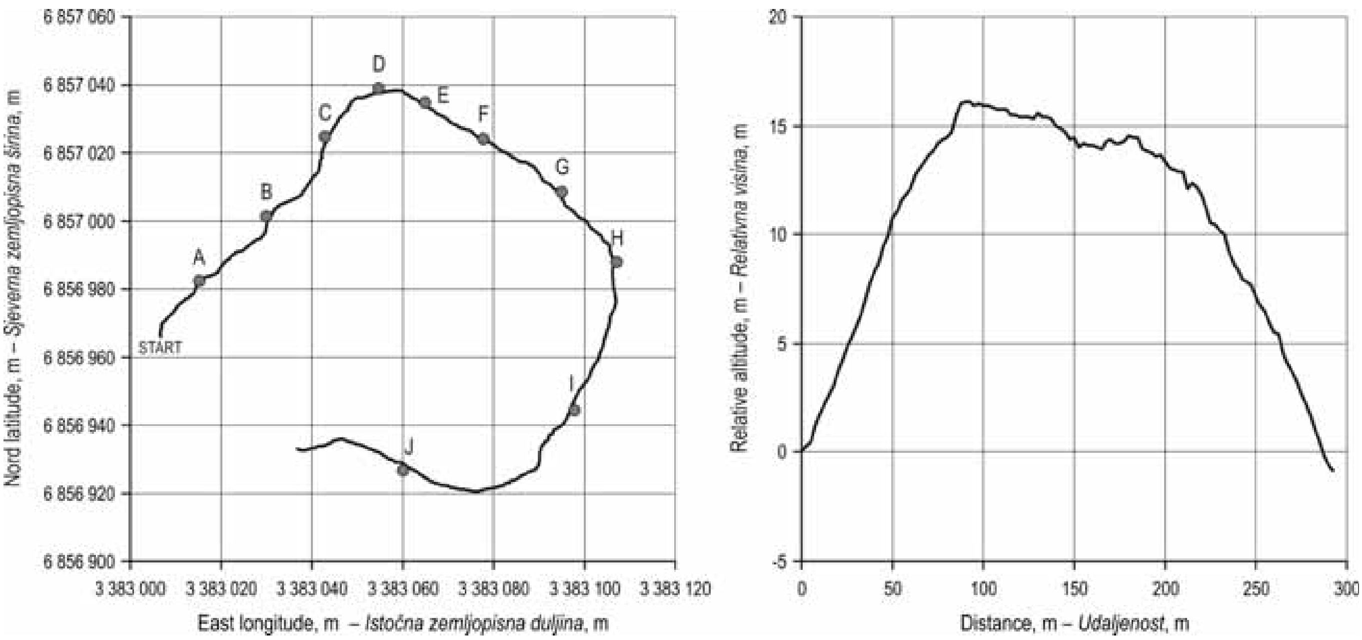

Fig. 2 Geographic position and profile of the test lane with penetrometer measurement points

Slika 2. *Zemljopisni položaj i profil ispitne izvozne vlake forvardera s mjestima izmjere penetrometrom* of the test lane, thus representing the penetration resistance on undisturbed soil. The measurements were repeated 2–4 times at each test site and the cone index values presented in Figure 3 represent average values for one test cluster. According to Murfitt et al. (1975), a cone index value higher than 662 kPa means that there will be no mobility problems for heavy earth-movers. This value, indicated with a vertical line in Figure 3, is exceeded at a depth of 10 cm everywhere except at measuring point F. On the other hand, the cone index values even at point F are very close to this limit value, so that it can be said that the bearing capacity on the test site was very high. It was in fact slightly lower on the section with an even terrain (points D, E, F and G) than on two sloping sections (points A, B, C, H, I and J), so that the cone index values support the visual observations concerning the terrain.

Based on the levelling data, penetrometer results and visual classification of the terrain, the test trajectory was split into homogeneous sections, as presented in Figure 4. This enabled more precise analysis of the influence of the terrain on the tractor mobility.

The test driver was an experienced forwarder operator who was briefed to drive through the whole

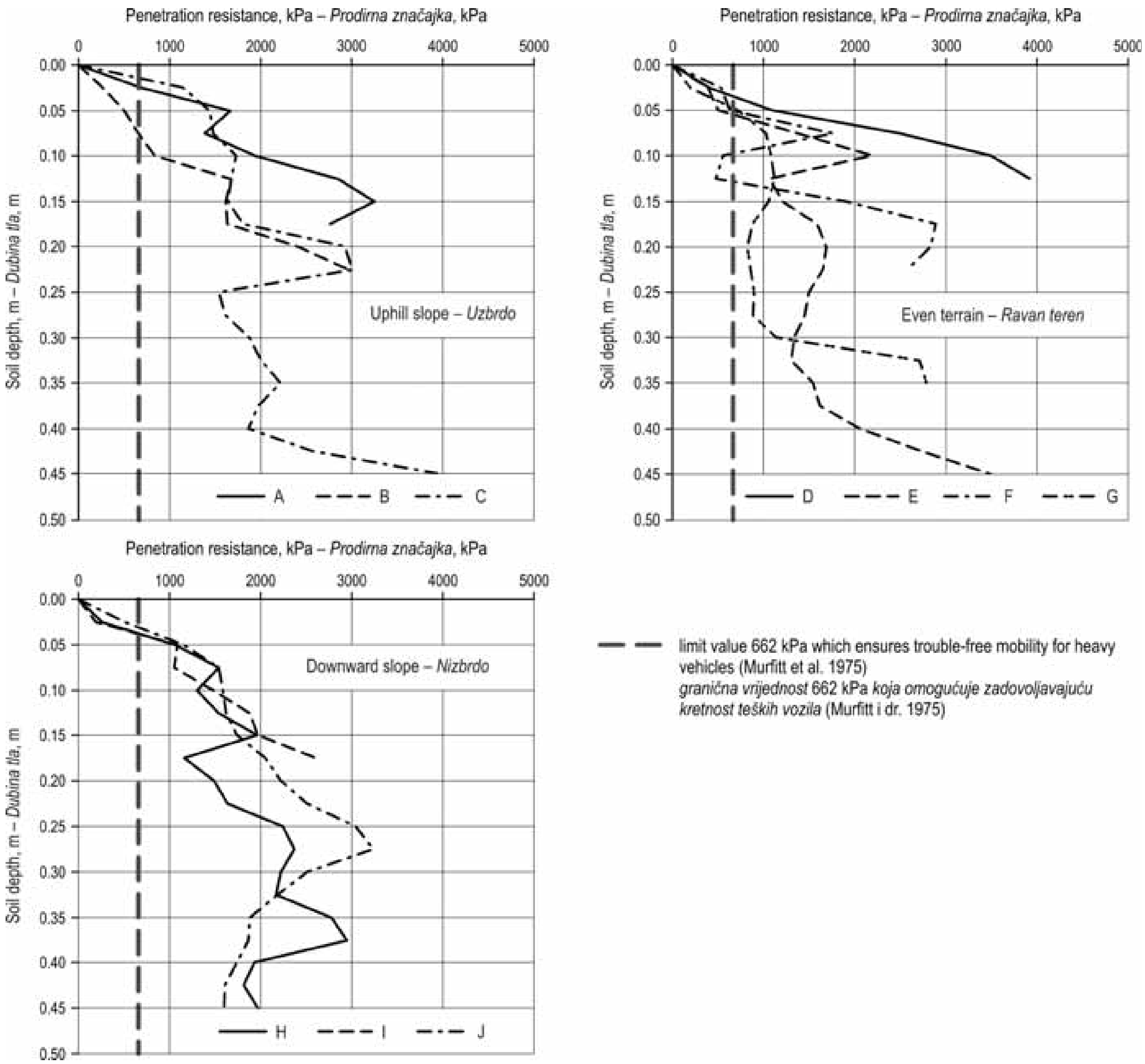

Fig. 3 Average cone penetrometer indices for ten test points

Slika 3. *Srednji konusni indeksi tla na deset mjernih mjesta* trajectory with the same gear and at the same engine speed (number of revolutions), so that the velocity during one test drive would be more or less constant. This was done with the tractor both unloaded and loaded with spruce logs (the same quantity in all tests). The tractor was weighted unloaded and loaded, but without bogie tracks and wheel chains, using an extraction vehicle weighbridge. The mass of the bogie tracks and wheel chains was determined separately (see section 3.2).

3.5 Fuel consumption factors – *Čimbenici potrošnje goriva*

Fuel consumption depends on the power on the drive line, with negative power readings implying that the fuel feed has stopped. Actual fuel consumption is not absolutely linear, however, as the efficiency of the engine varies a little depending on the power level. Since the engine efficiency curve for this tractor at different power levels was not known exactly, a constant specific fuel consumption of 240 g kWh^{-1} was used here. The actual power on the drive line is obtained four times per second from the CAN bus measurements.

The field data were used for developing fuel consumption models using the slope percentage as an explanatory variable. Fuel consumption was simulated under two sets of terrain conditions: terrain A, consisting of mild slopes (–5% to +5%), and terrain B, consisting of slopes of up to ±25%, see Figure 5.

The terrain of type A was handled by dividing the uphill and downhill slopes equally between the loaded and unloaded drives, while type B was handled in three subsets:

⇒ B1: Uphill and downward slopes divided equally between loaded and unloaded drives

⇒ B2: Unloaded drives on the downhill slope and loaded drives on the uphill slope

⇒ B3: Unloaded drives on the uphill slope and loaded drives on the downhill slope.

The other variables for the simulation model were:

⇒ forest stand size (A, ha)

⇒ average volume of growing stock per hectare (V_{ha}, m^3/ha)

⇒ sawn timber percentage (V_{st}, %)

⇒ average extraction distance ($d_{average}$, m).

The simulation models enable fuel consumption to be examined under different forest and terrain conditions using different ground contact devices. Fuel consumption is converted to monetary values by means of a fixed unit price. Once the costs of removal and installation of the wheel chains and bogie tracks have been defined, an economic comparison of the various operational models is possible.

The calculations of the total driving distance for the forwarder are based on the report by Väkevä et al. (2001). The field data consist of unloaded drives and loaded drives with 70% of the maximum load

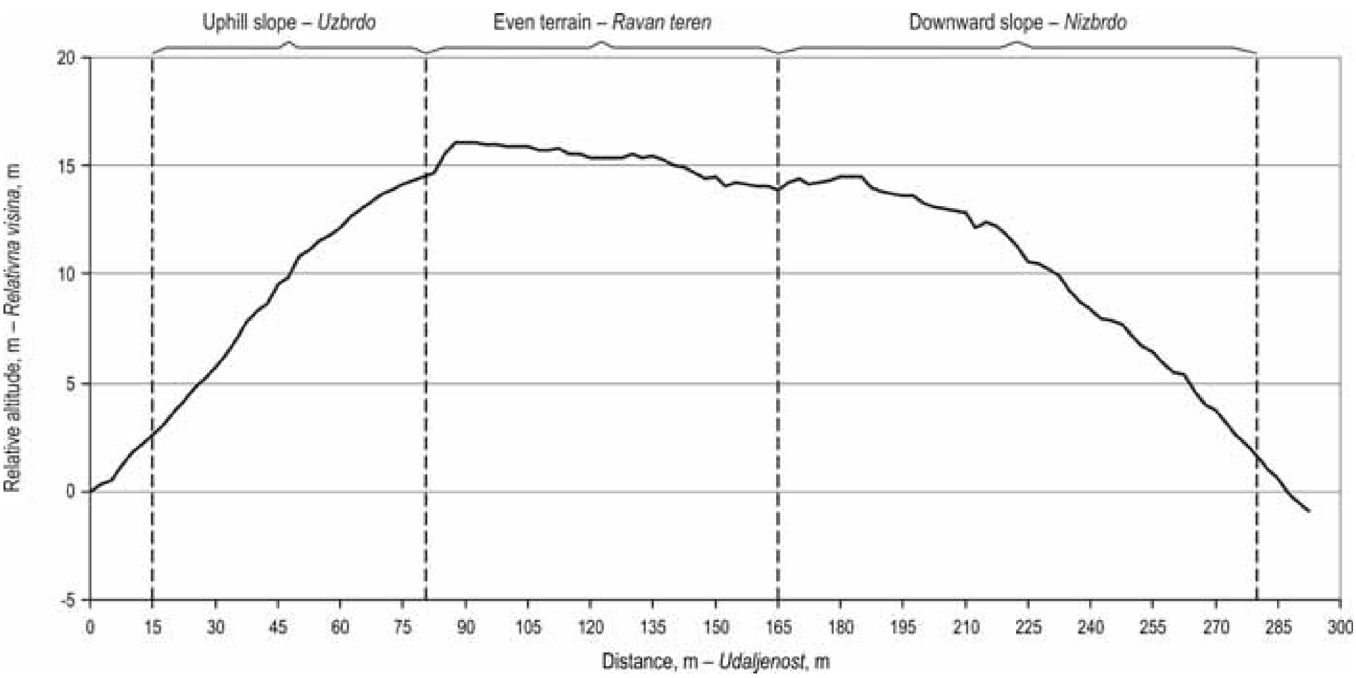

Fig. 4 Three sections of the test lane, an uphill slope, even terrain and a downward slope

Slika 4. *Tri dijela ispitne vlake: uzbrdo, ravan teren i nizbrdo*

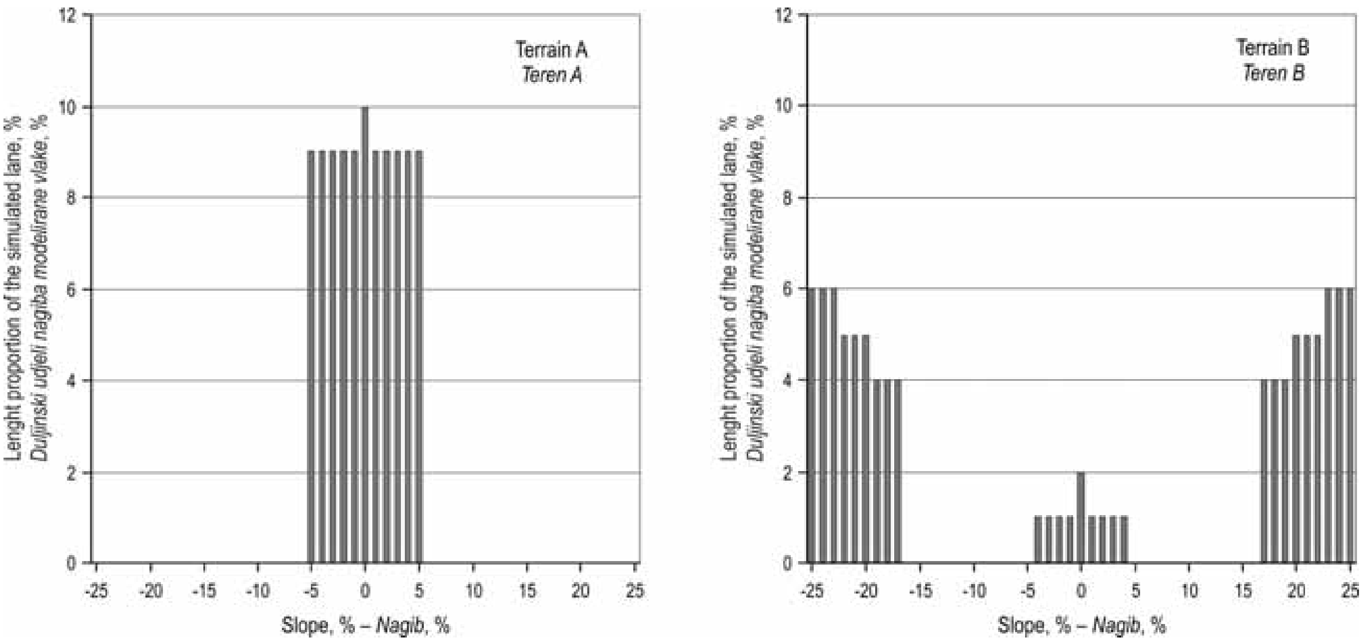

Fig. 5 Distribution of slopes between the two types of simulation terrain A and B

Slika 5. *Distribucija nagiba kod dva tipa modeliranoga terena*

mass. The maximum load mass as such is rarely reached, because the solid volume of a bunch of logs is less than the frame volume. The loading drive distance for one full load was calculated by Väkevä et al. (2001):

$$d_{\text{loading}} = V_{\text{load}} \cdot \frac{64.864}{\sqrt{V_{sr}}} \tag{1}$$

where the variable V_{load} is the load size in m^3, and V_{sr} is the timber volume along the strip road in m^3/100 m (combined volume of all roundwood assortments). Väkevä et al. (2001) reported that under average Finnish logging conditions this value is 8–25 m^3/100 m in the case of thinnings and 15–50 m^3/100 m for final fellings. For the present purpose the value was fixed at 30 m^3/100 metres.

According to Väkevä et. al. (2001) the loaded and unloaded drives can be calculated as follows:

$$d_{\text{loaded}} = d_{\text{average}} - \frac{d_{\text{loading}}}{2} \tag{2}$$

$$d_{\text{loaded}} = 2 \cdot d_{\text{average}} - d_{\text{loading}} \tag{3}$$

As the present field data do not include any information on driving with a smaller load size, no reliable information for a loading drive is available. The loading drive distance is divided in half, and one half is included in the unloaded drive and the other in the loaded drive. Thus, based on Eqs. 1, 2 and 3, the unloaded and loaded drive distances can be calculated by means of Eq. 4:

$$d_{\text{loaded}} = d_{\text{unloaded}} = d_{\text{average}} + \frac{d_{\text{loading}}}{2} \tag{4}$$

The number of driving times is obtained by dividing the total volume by the average solid volume of one load. This is calculated for both sawlogs and pulpwood. In the present case the average solid volume of one load is 12 m^3 for sawlogs and 8 m^3 for pulpwood.

$$n_{\text{sawn-timber}} = \frac{A \cdot V_{\text{ha}} \cdot V_{\text{st}}}{12} \tag{5}$$

$$n_{\text{pulpwood}} = \frac{A \cdot V_{\text{ha}} \cdot (1 - V_{\text{st}})}{8} \tag{6}$$

Using Eqs. 4, 5 and 6, the total driving distance on the site can be calculated for both unloaded and loaded drives. The total distance driven under different slope conditions can be derived by simulation, and fuel consumption per metre can be modelled based on field data. This information is enough for the fuel consumption simulations, after which the results can be converted to monetary values. This enables comparisons to be made between the fuel costs and removal and installation costs of the ground contact devices, which in turn consist of the capital and labour costs of these operations.

3.6 Handling of the GPS and CAN bus results – *Obrada GPS i CAN bus podataka*

The GPS receiver was placed on the top of the tractor's cabin, but as the tractor's centre of gravity is located about 3 metres further back (depending slightly on the load size and the length of the logs), the GPS data should be shifted to match the trajectory of the tractor's centre of gravity (Suvinen and Saarilahti 2006).

Since the measuring frequency is four times per second for the CAN data logger and once per second for the GPS receiver, every four consecutive CAN bus observations are averaged in order to synchronize these measurements.

Although Suvinen and Saarilahti (2006) reported that acceleration and deceleration cause some inaccuracy in the measuring system, these phases are ignored here as no reliable data are available on them.

For accurate analysis of the performance of various ground contact devices, momentary total resistance data are needed. This total resistance can be divided into components, which enables monitoring of the interaction between the soil and the ground contact devices.

The GPS receiver gives the horizontal velocity (v) of the forwarder, and the CAN bus system gives the gross power of the tractor's drive line (P). The total resistance to the motion of the tractor can be derived by dividing the gross power of the drive line by the horizontal velocity of the tractor:

$$F_T = \frac{P}{v} \tag{7}$$

The total resistance of a forwarder can normally be divided into seven components:

$$F_T = F_R + F_S + F_O + F_W + F_L + F_I + a \cdot m \tag{8}$$

It should be noted that the gross power of the drive line also includes some internal friction, which should be subtracted from the total resistance force before it is divided into its components.

The angular velocity of a wheel (ω) is calculated from the CAN bus data referring to the tractor's drive line. Based on the horizontal velocity of the forwarder (v), the angular velocity of the wheel (ω) and the rolling radius of the wheel, the slip or travel reduction (i) can be calculated. This indicates the extent to which the speed of the tyres differs from the speed of the vehicle, and can be calculated using the equation (ISTVS 1977):

$$i = \frac{v - r_R \cdot \omega}{v} \tag{9}$$

For a braked tyre the slip indicator is named skid (S) and can be calculated using the equation (ISTVS 1977):

$$S = \frac{r_R \cdot \omega - v}{r_R \cdot \omega} \tag{10}$$

On steep downhill slopes, when the wheels are in skid mode, the tractor adjusts its power transmission to keep the velocity suitable, which often means that the direction of hydraulic transmission is opposed. This can be seen in the CAN bus data in the form of negative values for the gross power on the tractor's drive line. In that case unfortunately, the fuel feed for the test tractor falls to zero and decreases reliabilty of consumption model at wheel skid. It is on account of this that the percentage differences in gross power on the drive line are not equal to the fuel consumption.

The components of the total resistance to the forwarder's movement are described in Eq. 8. As the present analysis does not include acceleration or deceleration parts, the inertia resistance can be omitted, as can the snow resistance, as all the tests were carried out under summer conditions. The data were not suitable for analysing the winding resistance, because the trajectory that included only a few turns and effects of the turning radius on the winding resistance could not be analysed. Thus the effects of winding resistance are considered to belong to the background noise. Eq. 8 can be reduced to the following form:

$$F_T = F_R + F_S + F_O + F_I \tag{11}$$

The main factors which cause these four resistance forces are the micro- and macrotopographies of the terrain, soil type and conditions, performance of the tractor and its equipment, and the driver's decisions. The terrain conditions were easy during the whole test route, and the test was carried out so that the driver's decisions (e.g. microrouting, acceleration and deceleration) were limited as far as possible. Thus the variation between the total resistance forces can be considered to be a consequence of the modifications made to the forwarder's equipment. Modification of the forwarder's ground contact device brings about changes in factors such as:

⇒ slip between the ground contact devices and terrain

⇒ transformation of the soil and ground contact devices

⇒ contact area between the terrain and ground contact devices

⇒ internal slip in ground contact devices

⇒ internal friction in ground contact devices

⇒ forwarder's overall mass

⇒ forwarder's kinetic energy

⇒ forwarder's turning and steerability characteristics.

Changes in the above variables can be seen in variations in the total resistance to tractor's movement.

4. Results – *Rezultati*

4.1 Total resistance, motion resistance coefficient, slip and skid – *Ukupni otpor, koeficijent otpora kretanja, klizanje*

The test trajectory consisted of three parts, as presented in Figure 4, and the total resistance in each section when driving with an unloaded tractor is shown in Table 1. It can be seen that tyres alone were better than tyres with wheel chains in every section, and that the latter were better than tyres with bogie tracks and wheel chains. The resistance force on the downward slope was as much as about 50% greater with wheel chains and bogie tracks than without them. It should be noted, however, that the absolute values for the total resistance were quite small on the downward slope, so that even small changes will affect the result substantially in percentage terms.

The total resistance forces for a loaded tractor are shown in Table 2. The results are quite similar to those with an unloaded tractor, the only significant differences being that the total resistance with bogie tracks on even terrain was 4% lower and that with wheel chains 19% lower.

Table 1 Total resistances in three sections of the test lane with an unloaded tractor
Tablica 1. *Ukupni otpori na tri sekcije ispitne izvozne vlake pri kretanju neopterećenoga forvardera*

Unloaded forwarder *Neopterećeni forvarder*		Tyres – *Gume*	Chains – *Lanci*		Tracks and Chains *Polugusjenice i lanci*	
Velocity – *Brzina*	m/s	1.15	1.08		1.01	
Mass – *Masa*	t	16.2	17.0		18.5	
Slope *Nagib*	Section length *Duljina sekcije*	Sum of total resistance *Ukupni otpor*	Sum of total resistance *Ukupni otpor*	Difference relative to tyres *Razlika u odnosu na gume*	Sum of total resistance *Ukupni otpor*	Difference relative to tyres *Razlika u odnosu na gume*
	m	kN	kN	%	kN	%
Uphill – *Uzbrdo*	65	4008	4373	9	5109	27
Even terrain – *Ravan teren*	85	2230	2281	4	2538	15
Downhill – *Nizbrdo*	115	850	1242	46	1280	50
Total – *Ukupno*	265	7061	7896	12	8927	26

Table 2 Total resistances in three sections of the test lane with a loaded tractor
Tablica 2. *Ukupni otpori na tri sekcije ispitne izvozne vlake pri kretanju opterećenoga forvardera*

Loaded forwarder *Opterećeni forvarder*		Tyres – *Gume*	Chains – *Lanci*		Tracks and Chains *Polugusjenice i lanci*	
Velocity – *Brzina*	m/s	0.85	0.99		0.85	
Mass – *Masa*	t	20.9	21.7		23.2	
Slope *Nagib*	Section length *Duljina sekcije*	Sum of total resistance *Ukupni otpor*	Sum of total resistance *Ukupni otpor*	Difference relative to tyres *Razlika u odnosu na gume*	Sum of total resistance *Ukupni otpor*	Difference relative to tyres *Razlika u odnosu na gume*
	m	kN	kN	%	kN	%
Uphill – *Uzbrdo*	65	6458	7093	10	8126	26
Even terrain – *Ravan teren*	85	3427	2763	–19	3286	–4
Downhill – *Nizbrdo*	115	1020	1514	48	1493	46
Total – *Ukupno*	265	10905	11370	4	12905	18

Table 3 Motion resistance coefficients in three sections of the test lane with an unloaded tractor
Tablica 3. *Koeficijenti otpora kretanja na tri sekcije ispitne izvozne vlake pri kretanju neopterećenoga forvardera*

Unloaded forwarder *Neopterećeni forvarder*		Tyres – *Gume*	Chains – *Lanci*		Tracks and Chains *Polugusjenice i lanci*	
Velocity – *Brzina*	m/s	1.15	1.08		1.01	
Mass – *Masa*	t	16.2	17.0		18.5	
Slope *Nagib*	Section length *Duljina sekcije*	Motion resistance coefficient *Koeficijent otpora kretanja*	Motion resistance coefficient *Koeficijent otpora kretanja*	Difference relative to tyres *Razlika u odnosu na gume*	Motion resistance coefficient *Koeficijent otpora kretanja*	Difference relative to tyres *Razlika u odnosu na gume*
	m	–	–	%	–	%
Uphill – *Uzbrdo*	65	0.39	0.40	4	0.43	12
Even terrain – *Ravan teren*	85	0.17	0.16	-1	0.16	-1
Downhill – *Nizbrdo*	115	0.05	0.06	39	0.06	32
Total – *Ukupno*	265	0.17	0.18	6	0.19	11

The increase in the mass of the unloaded tractor when using wheel chains was 5% and that when using bogie tracks and wheel chains was 14%, but the difference in total resistance relative to the use of tyres alone was in most cases greater than that, as can be seen in Tables 1 and 2. The motion resistance coefficients for an unloaded tractor, obtained by dividing the total resistance by the weight of the tractor and the driving distance, are shown in Table 3, where it can be seen that the motion resistance is almost the same on even terrain regardless of the ground contact device. Thus it is the increased mass that explains a higher total resistance. The motion resistance was even slightly smaller when using wheel chains and bogie tracks. On the uphill slope the total resistance increased by 4% when using wheel chains and by 12% when using bogie tracks and wheel chains, but on the downhill slope the increment was about one third of this in both cases. The general effect of the downhill slope section on the overall traction results was small, although it is clear that the increased mass does not explain the whole of the rise in total resistance on the downhill and uphill slopes.

The increase in the mass of the loaded tractor when using wheel chains was 4% and when using bogie tracks it was 11%. The results for the unloaded and loaded tractor on the uphill and downhill slopes were quite similar, and the same conclusion can be reached – that the increment in mass explains only about a half of the increase in total resistance. On even terrain, however, the total resistance was lower when using wheel chains and bogie tracks, and as can be seen in Table 4, the difference was even greater in terms of motion resistance coefficients.

The slip percentages on a different section of the test lane and with different ground contact devices are presented in Table 5. When the mass of the tractor (with all its ground contact devices) and the slip are taken into account, the total resistance coefficients on the uphill slope and on even terrain are almost the same. The difference between the results is less than 6%, i.e. less than the measurement error of the system as reported by Suvinen and Saarilahti (2006).

Slip percentages and rolling resistance coefficients for the loaded tractor, with the slip effects deducted, are shown in Table 6. The results are very similar to those in Table 5 for an unloaded tractor, the only notable differences being that wheel chains and bogie tracks reduced the motion resistance coefficient on on even terrain and that the difference was so significant when using wheel chains that it did not fit within the limits of the measurement error. Probably as a result of a greater slip and increased mass relative to the unloaded tractor, the tyres penetrated deeper into the soil, and thus the rolling resistance increased. At the same time the bearing capacity of the soil was slightly lower on even terrain than on slope sections (see Figure 3).

It should be noted that the slip was very much smaller on the uphill slope section when using tyres rather than wheel chains and bogie tracks, with both a loaded and unloaded tractor. It is likely that the slip in that case consisted mostly of slip between the tyre and the wheel chain or bogie-track, which increases as the power on the drive line becomes greater, but unfortunately these data do not allow to distinguish the slip between the ground contact device and the terrain from the internal slip in the ground

Table 4 Motion resistance coefficients in three sections of the test lane with a loaded tractor
Tablica 4. *Koeficijenti otpora kretanja na tri sekcije ispitne izvozne vlake pri kretanju opterećenog forvardera*

Loaded forwarder *Opterećeni forvarder*		Tyres – *Gume*	Chains – *Lanci*		Tracks and Chains *Polugusjenice i lanci*	
Velocity – *Brzina*	m/s	0.85	0.99		0.85	
Mass – *Masa*	t	20.9	21.7		23.2	
Slope *Nagib*	Section length *Duljina sekcije*	Motion resistance coefficient *Koeficijent otpora kretanja*	Motion resistance coefficient *Koeficijent otpora kretanja*	Difference relative to tyres *Razlika u odnosu na gume*	Motion resistance coefficient *Koeficijent otpora kretanja*	Difference relative to tyres *Razlika u odnosu na gume*
	m	–	–	%	–	%
Uphill – *Uzbrdo*	65	0.48	0.51	6	0.55	13
Even terrain – *Ravan teren*	85	0.20	0.15	–22	0.17	–14
Downhill – *Nizbrdo*	115	0.04	0.06	43	0.06	32
Total – *Ukupno*	265	0.20	0.20	0	0.21	7

Table 5 Slip and motion resistance coefficients exclusive of travel reduction and slip on three sections of the test lane with an unloaded tractor
Tablica 5. *Postotak klizanja i koeficijent otpora kretanja umanjen za otpor klizanja na tri sekcije ispitne izvozne vlake pri kretanju neopterećenoga forvardera*

Unloaded forwarder *Neopterećeni forvarder*		Tyres – *Gume*		Chains – *Lanci*			Tracks and Chains *Polugusjenice i lanci*		
Velocity – *Brzina*	m/s	1.15		1.08			1.01		
Mass – *Masa*	t	16.2		17.0			18.5		
Slope *Nagib*	Section length *Duljina sekcije*	Slip Klizanje	Motion resistance coefficient *Koeficijent otpora kretanja*	Slip *Klizanje*	Motion resistance coefficient Koeficijent otpora kretanja	Difference relative to tyres *Razlika u odnosu na gume*	Slip *Klizanje*	Motion resistance coefficient Koeficijent otpora kretanja	Difference relative to tyres *Razlika u odnosu na gume*
	m	%	-	%	-	%	%	-	%
Uphill – *Uzbrdo*	65	5.2	0.367	9.2	0.366	0	10.1	0.389	6
Even terrain – *Ravan teren*	85	7.4	0.151	2.4	0.157	4	2.6	0.160	6
Downhill – *Nizbrdo*	115	0.7	0.046	–1.4	0.066	42	–2.3	0.063	29
Total – *Ukupno*	265	3.9	0.161	2.4	0.174	8	2.3	0.181	13

contact device. The bearing capacity of the soil was slightly lower on on even terrain than on the uphill slope section, and that is probably the reason why the slip was about three times greater without wheel chains and bogie tracks.

The increment in the total resistance coefficient when using wheel chains or bogie tracks on the downward slope was greater than could be explained by the growth mass and slip. The steerability and turning characteristics of the vehicle are probably better with skid tyres than with skid tyres fitted with wheel chains and bogie tracks, and inflexibility in steering naturally means an increased resistance force. More rigid ground contact devices (i.e. tyres with wheel chains and bogie tracks) also penetrate deeper into the soil during deceleration, which increases the rolling resistance. These data cannot exhaustively explain why the motion resistance coefficient was so high on the downward slope when using wheel chains and bogie tracks as compared with tyres, but it should be remembered that the absolute value for the total resistance on the downward slope is relatively small, so that it is of relatively minor significance for the total model. Also, the low absolute values mean that even small measurement errors can cause a notable error in comparisons expressed in percentage terms.

The slip is not constant, but increases as the power increases (e.g. on uphill slopes) and asymptotically

Table 6 Slip percentages and motion resistance coefficients exclusive of travel reduction and slip in three sections of the test lane with a loaded tractor
Tablica 6. *Postotak klizanja i koeficijent otpora kretanja umanjen za otpor klizanja na tri sekcije ispitne izvozne vlake pri kretanju opterećenoga forvardera*

Loaded forwarder *Opterećeni forvarder*		Tyres – *Gume*		Chains – *Lanci*			Tracks and Chains *Polugusjenice i lanci*		
Velocity – *Brzina*	m/s	0.85		0.99			0.85		
Mass – *Masa*	t	20.9		21.7			23.2		
Slope *Nagib*	Section length *Duljina sekcije*	Slip Klizanje	Motion resistance coefficient *Koeficijent otpora kretanja*	Slip *Klizanje*	Motion resistance coefficient Koeficijent otpora kretanja	Difference relative to tyres Razlika u odnosu na gume	Slip *Klizanje*	Motion resistance coefficient Koeficijent otpora kretanja	Difference relative to tyres *Razlika u odnosu na gume*
	m	%	-	%	-	%	%	-	%
Uphill – *Uzbrdo*	65	6.3	0.454	10.8	0.457	1	9.9	0.495	9
Even terrain – *Ravan teren*	85	6.8	0.183	2.8	0.148	–19	2.2	0.166	–9
Downhill – *Nizbrdo*	115	–2.1	0.044	–2.7	0.063	44	–2.1	0.058	32
Total – *Ukupno*	265	2.8	0.195	2.4	0.197	1	2.2	0.209	7

approaches a limit value that depended on the soil conditions as well as the performance of the tractor and its equipment. On the other hand, the slip does not increase in a linear fashion depending on the gradient of the slope, but rather the increment is greater on steeper gradients. The same pattern is

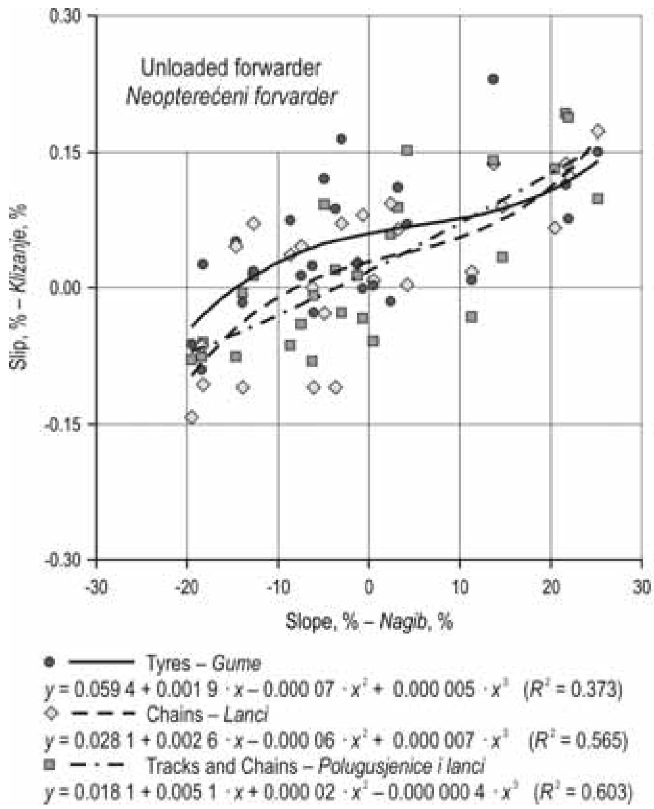

Fig. 6 Slip percentages for an unloaded forwarder as a function of the percentage gradient

Slika 6. *Postotak klizanja neopterećenoga forvardera u ovisnosti o nagibu terena*

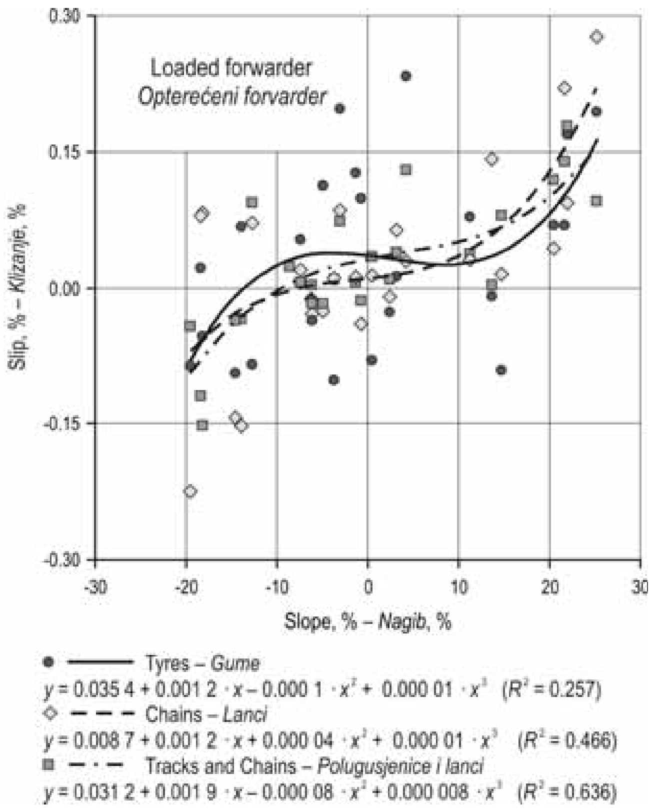

Fig. 7 Slip percentages for a loaded forwarder as a function of the percentage gradient

Slika 7. *Postotak klizanja opterećenoga forvardera u ovisnosti o nagibu terena*

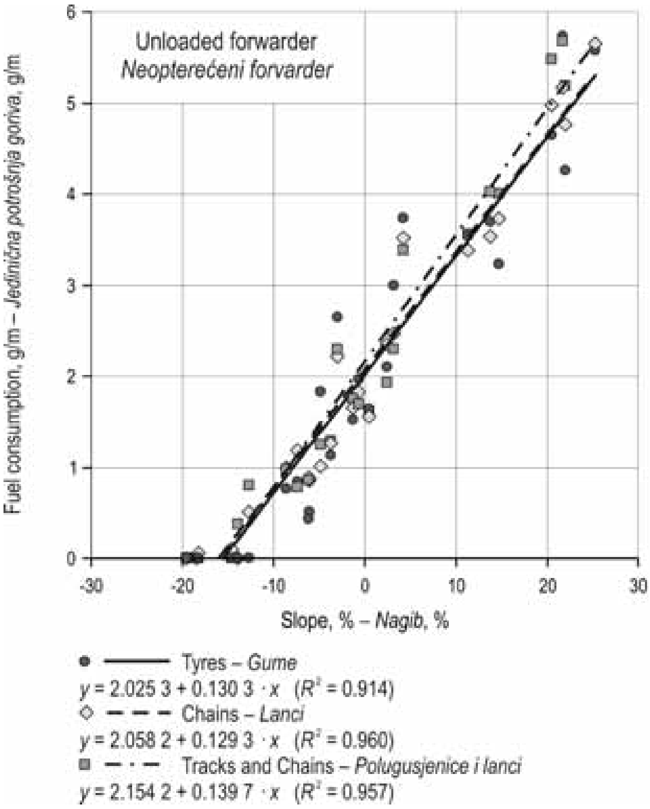

Fig. 8 Fuel consumption for an unloaded forwarder as a function of gradient

Slika 8. *Jedinična potrošnja goriva neopterećenoga forvardera u ovisnosti o nagibu terena*

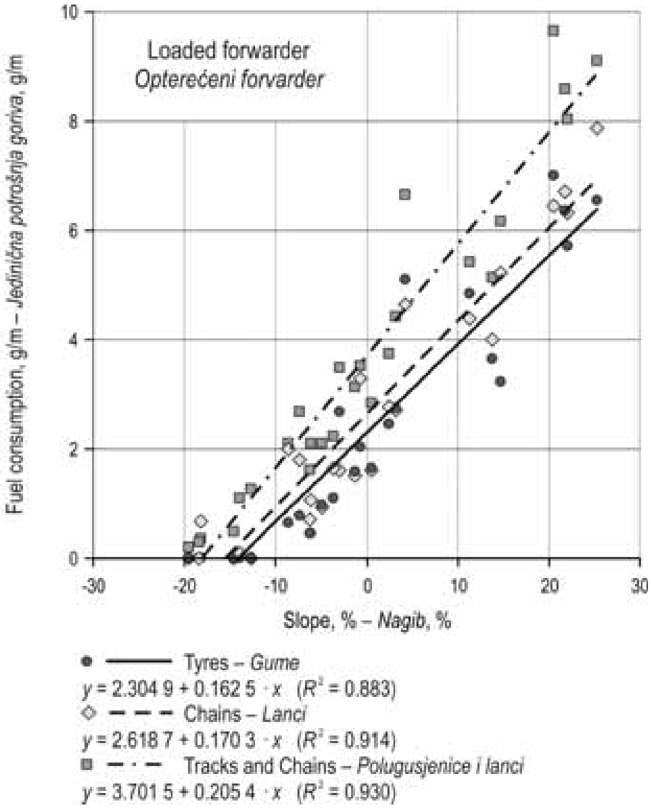

Fig. 9 Fuel consumption for a loaded forwarder as a function of gradient

Slika 9. Jedinična potrošnja goriva opterećenoga forvardera u ovisnosti o nagibu terena

recognized for negative slip or skid on the downward slope. On the other hand, slip does not give way to skid until the gradient is steep enough to compensate for the traction. Thus the relationship between gradient and slip or skid can be described best by means of a third-degree polynomial function.

Third-degree functions are fitted to the slip measurements in Figures 6 and 7, where it can be seen that the slip on even terrain was low when using wheel chains and bogie tracks but the difference evened out on the uphill slope, although admittedly the coefficients of determination for tyres are lower. The performance of wheel chains on the loaded tractor become progressively worse as the slope became steeper.

When using wheel chains on an unloaded tractor the slip turns to skid almost immediately as the gradient becomes negative, whereas the turning point for a loaded tractor with wheel chains is at a gradient of about –10%. When using bogie tracks the turning point is at about –10% for both an unloaded and loaded tractor. With tyres alone the slip turns to skid only at a gradient of about –15%, and this turning point is almost the same for a loaded and unloaded tractor. This is probably one of the reasons why the total resistance is much higher for bogie tracks, and especially for wheel chains, than it is for tyres alone on a downward slope – since skid may affect the resistance to the tractor's movement more than does a minor amount of slip.

4.2 Fuel cost analysis – *Analiza troškova goriva*

4.2.1 Consumption models – *Modeli potrošnje goriva*

An interval of 10 metres distance was used to define the terrain profile, and as the power sums and times for these 10-metre intervals were known and specific fuel consumption was set at 240 g/kWh (see section 3.5), the fuel consumption per metre could be modelled based on the gradient data. The fuel consumption figures per metre for the unloaded and loaded tractor based on measured wattages for different slope conditions, together with linear models based on these measurements, are presented in Figures 8 and 9. The coefficients of determination attached to these figures are very high. For an unloaded tractor the fuel consumption is almost the same for tyres with wheel chains as for tyres alone, but it is about 6–7% higher for tracked tyres on an uphill slope. In the case of a loaded tractor the differences are clearer, tracked tyres in particular being substantially worse, with a difference of about 40–60% relative to tyres alone on uphill slopes. On downhill slopes the difference is still greater in percentage terms, but as the absolute fuel consumption is less, this is not so critical as far as total fuel consumption is concerned.

The linear models presented in Figures 8 and 9 can be used to calculate the fuel consumption for four types of terrain introduced in Chapter 3.5. (A, B1, B2, B3), the other variables in the sensitivity analyses being the size of the site (*A*, ha), average volume of growing stock on the site (V_{ha}, m^3 ha^{-1}), the percentage of sawlogs (V_{st}, %), which depends on the average volume of growing stock and the average extraction distance ($d_{average}$, m).

4.4.2 Consumption when using tyres – *Potrošnja goriva pri primjeni guma*

The total fuel consumption per hectare when using tyres is presented separately in Figure 10 for four terrain types as a function of extraction distance and average volume of the growing stock (in this simulation the percentage of sawlogs is taken to vary between 50% and 80% depending on the volume of the growing stock). Here the figure is seen to be about 10% higher on terrain type B3, about 20% higher on

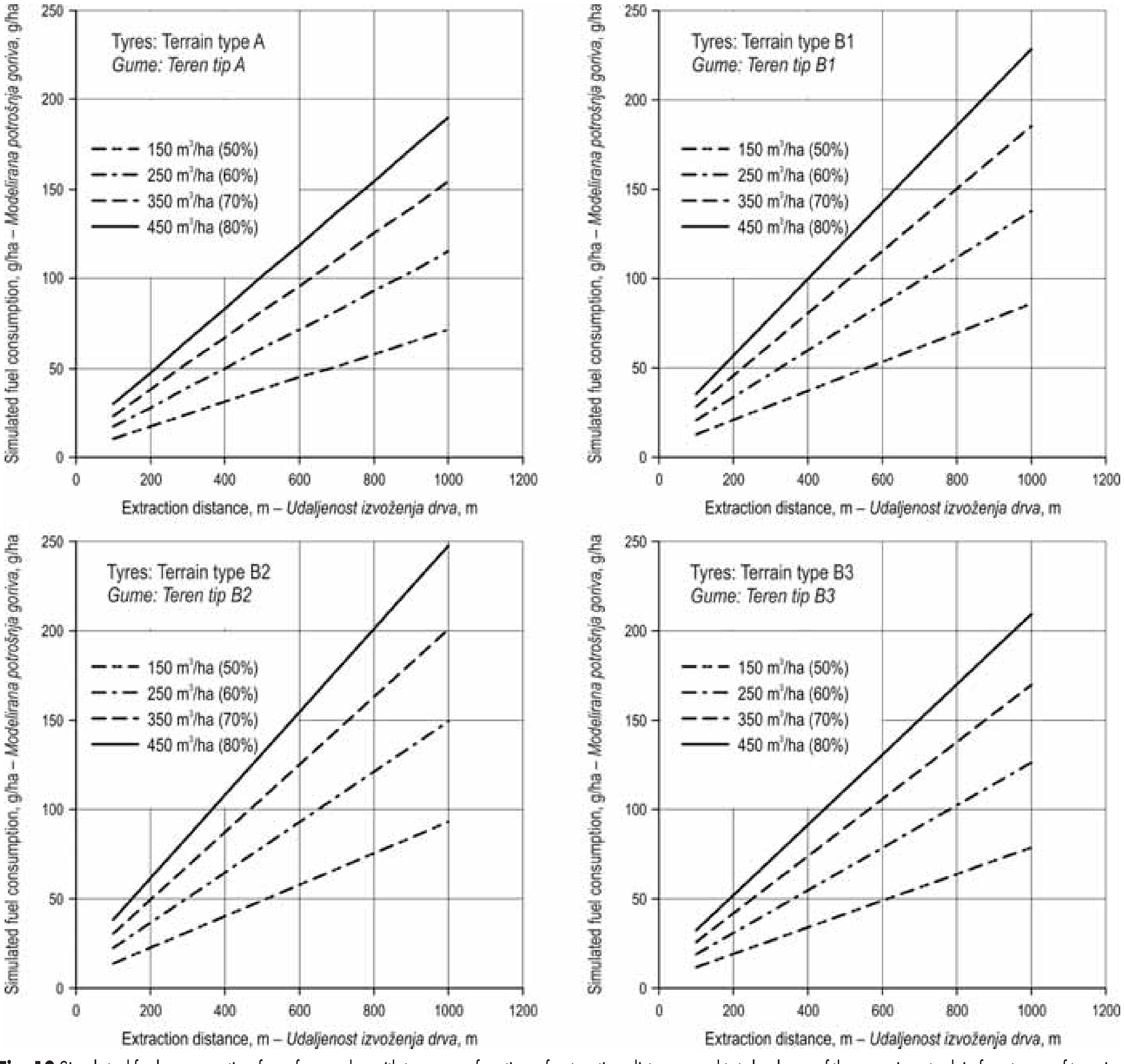

Fig. 10 Simulated fuel consumption for a forwarder with tyres as a function of extraction distance and total volume of the growing stock in four types of terrain
Slika 10. *Modelirana potrošnja goriva forvardera bez lanaca i polugusjenica u ovisnosti o udaljenosti izvoženja i drvnoj zalihi na četiri vrste terena*

type B1 and 30% higher on type B2 than on terrain type A. Steep terrain, and especially driving on uphill slopes when loaded, will naturally increase fuel consumption substantially.

4.2.3 Fuel consumption using wheel chains and/or bogie-tracks in relation to tyres alone – *Potrošnja goriva pri primjeni lanaca i/ili polugusjenica u odnosu na primjenu guma*

The differences in total fuel consumption relative to tyres when using wheel chains or bogie tracks and wheel chains are presented in Figures 11 and 12. It can be seen that these combinations increase fuel costs in all simulated terrain types, the extra costs being about four times greater when using bogie tracks and chains than with chains alone.

The increase in costs is greater when driving on even terrain (A) than on steep terrain (B1), because as it was previously mentioned, fuel consumption measurement is false on steep downward slopes when it falls to zero. The absolute value for the total resistance on the downward slope is relatively small and has relatively minor significance for the total model. On the other hand, loaded driving on uphill

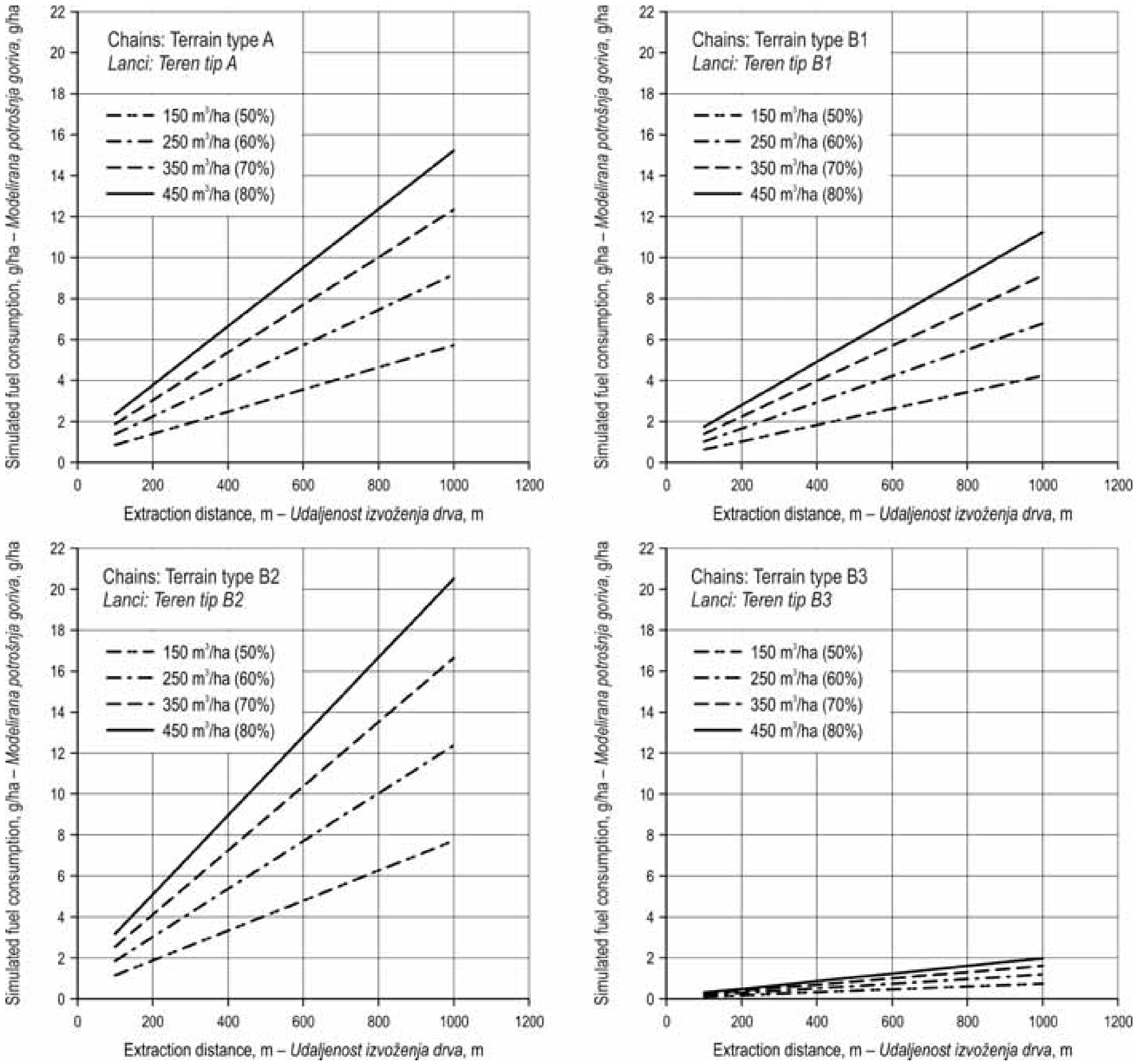

Fig. 11 Differences in simulated fuel consumption when using wheel chains relative to tyres alone in four types of terrain
Slika 11. *Razlike u modeliranoj potrošnji goriva forvardera s lancima u odnosu na primjenu guma na četiri vrste terena*

slopes (B2) notably increases the costs. If the forwarder is loaded when driving downhill and unloaded when driving uphill (B3), the increase is only marginal relative to other terrain types. The conclusion is that the use of bogie tracks greatly increases fuel costs when the extraction distance is relatively long, the quantity of timber handled is high (the volume per hectare is high and/or the site is large) and loaded driving takes place on even or uphill terrain. Wheel chains have only a marginal effect, as do bogie tracks when the forwarder is loaded on its downhill runs.

4.2.4 The size of the site depending on break-even point – *Ovisnost veličine sječine o prekretnici troškova*

The analysis was carried out employing an exchange rate between the euro and the United States dollar of 1.28 (1 € = $1.28) and an average light fuel oil price in Finland in June 2006 of $0.876/litre (= 0.684 €/litre), implying a price to the entrepreneur of about $0.718/litre (= 0.561 €/litre) exclusive of the statutory 22% VAT.

Similarly, the following estimates are used for the reductions in the tractor's effective work time

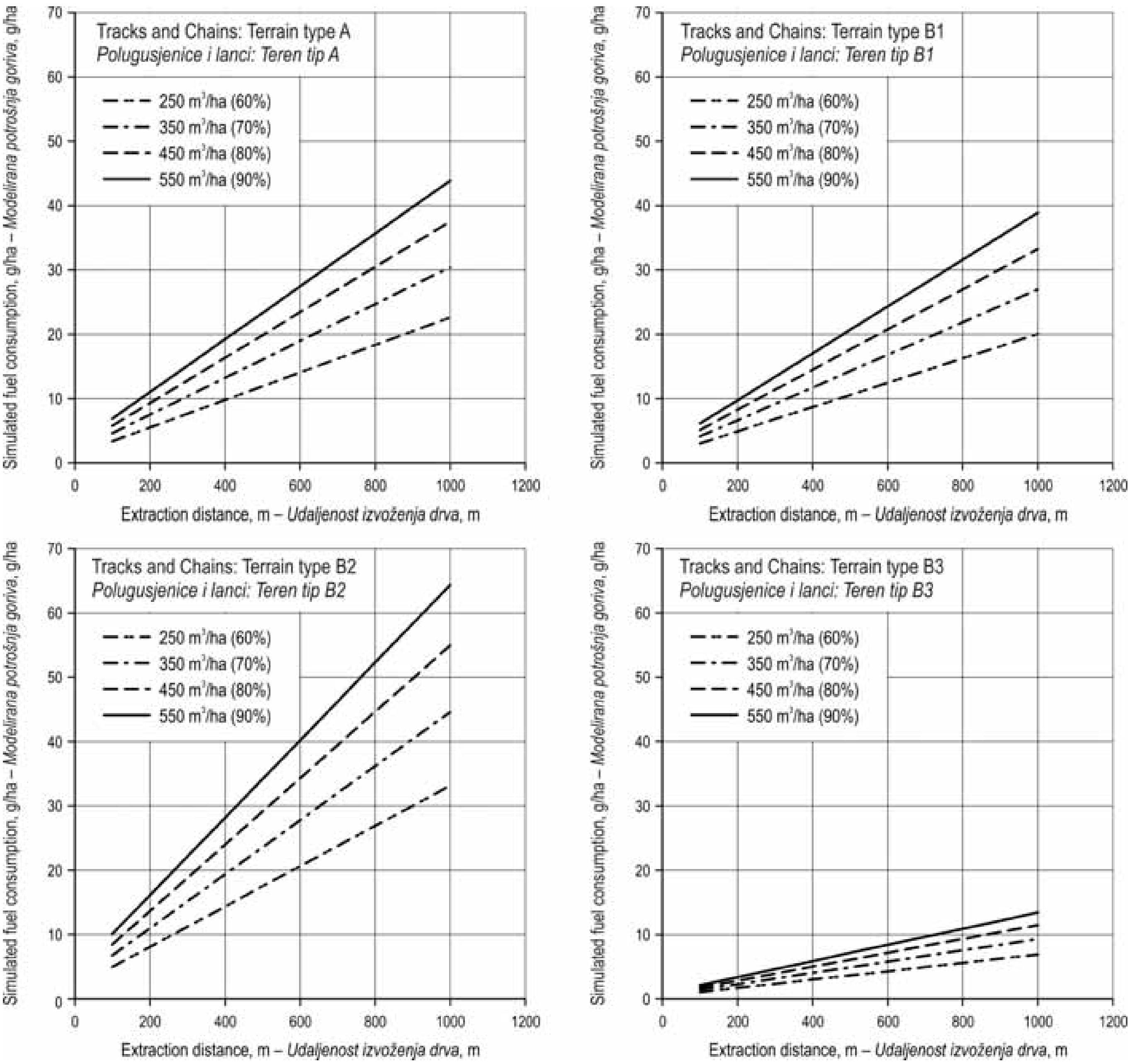

Fig. 12 Differences in simulated fuel consumption when using bogie tracks relative to tyres alone in four types of terrain

Slika 12. *Razlike u modeliranoj potrošnji goriva forvardera s polugusjenicima u odnosu na primjenu guma na četiri vrste terena* caused by the removal and re-installation of wheel chains and bogie tracks:

⇒ for wheel chains (on the tyres of the 2nd and 3rd axles), 1 hour 15 minutes

⇒ for bogie-tracks and chains (chains on the 2nd axle and tracks on the rear bogie), 1 hour 30 minutes.

These estimates are based on observations during the test arrangements under assumption that the removal and installation work are done by two experienced workers. Given that the hourly cost of the forwarder is $64 (= 50 €) and the hourly wages for the workers are $19.2 (= 15 €) per person, the total costs of the removal and re-installation work will be:

⇒ wheel chains: $128 (= 100 €)

⇒ bogie tracks and chains: $154 (= 120 €).

The sizes of site required for the removal and re-installation to be profitable, as functions of extraction distance and volume of the growing stock

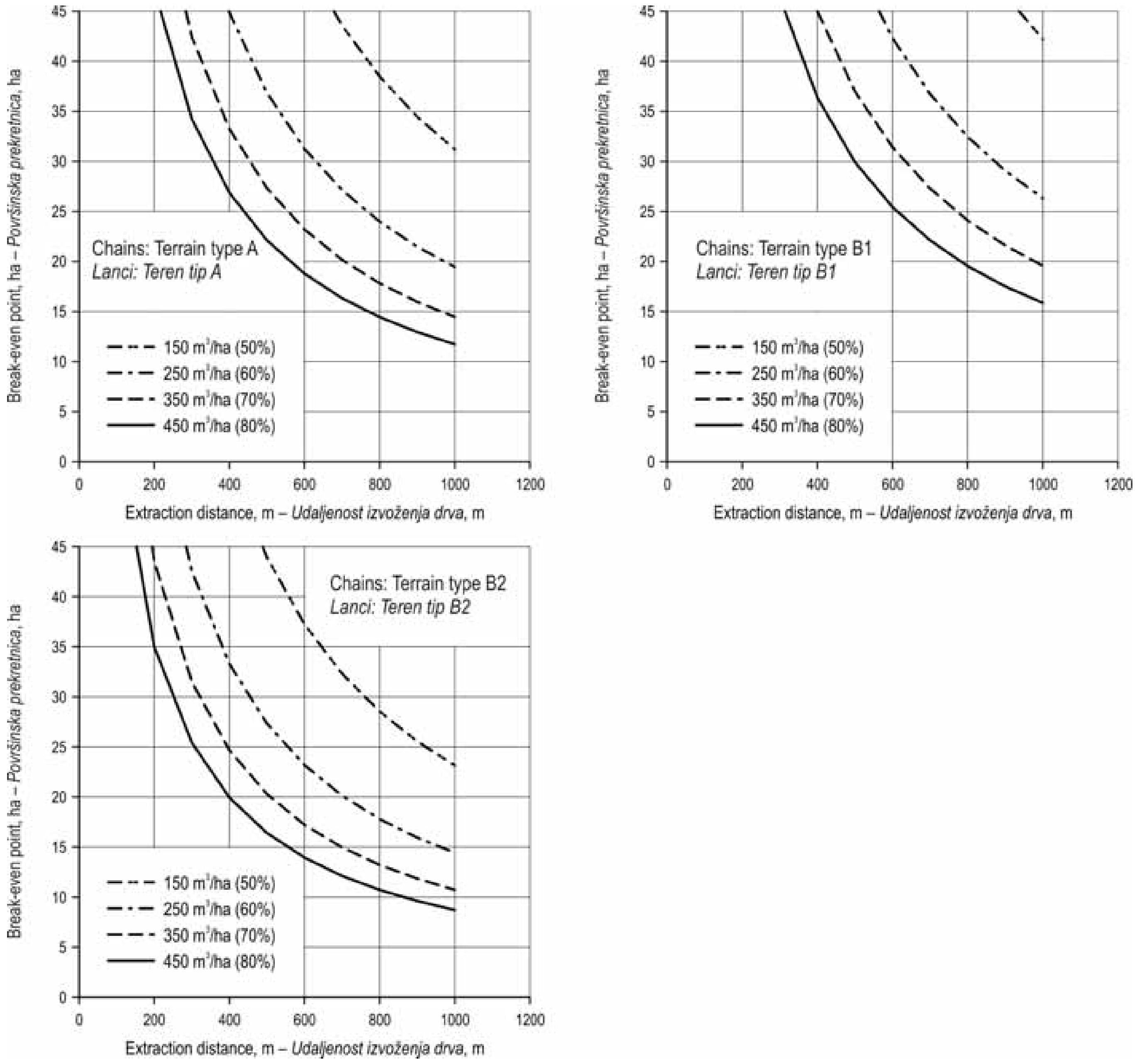

Fig. 13 Break-even points for the profitability of the removal and re-installation work of wheel chains as a function of average extraction distance and total volume of the growing stock

Slika 13. *Površinska prekretnica isplativosti skidanja i postavljanja lanaca u ovisnosti o srednjoj udaljenosti izvoženja i drvnoj zalihi*

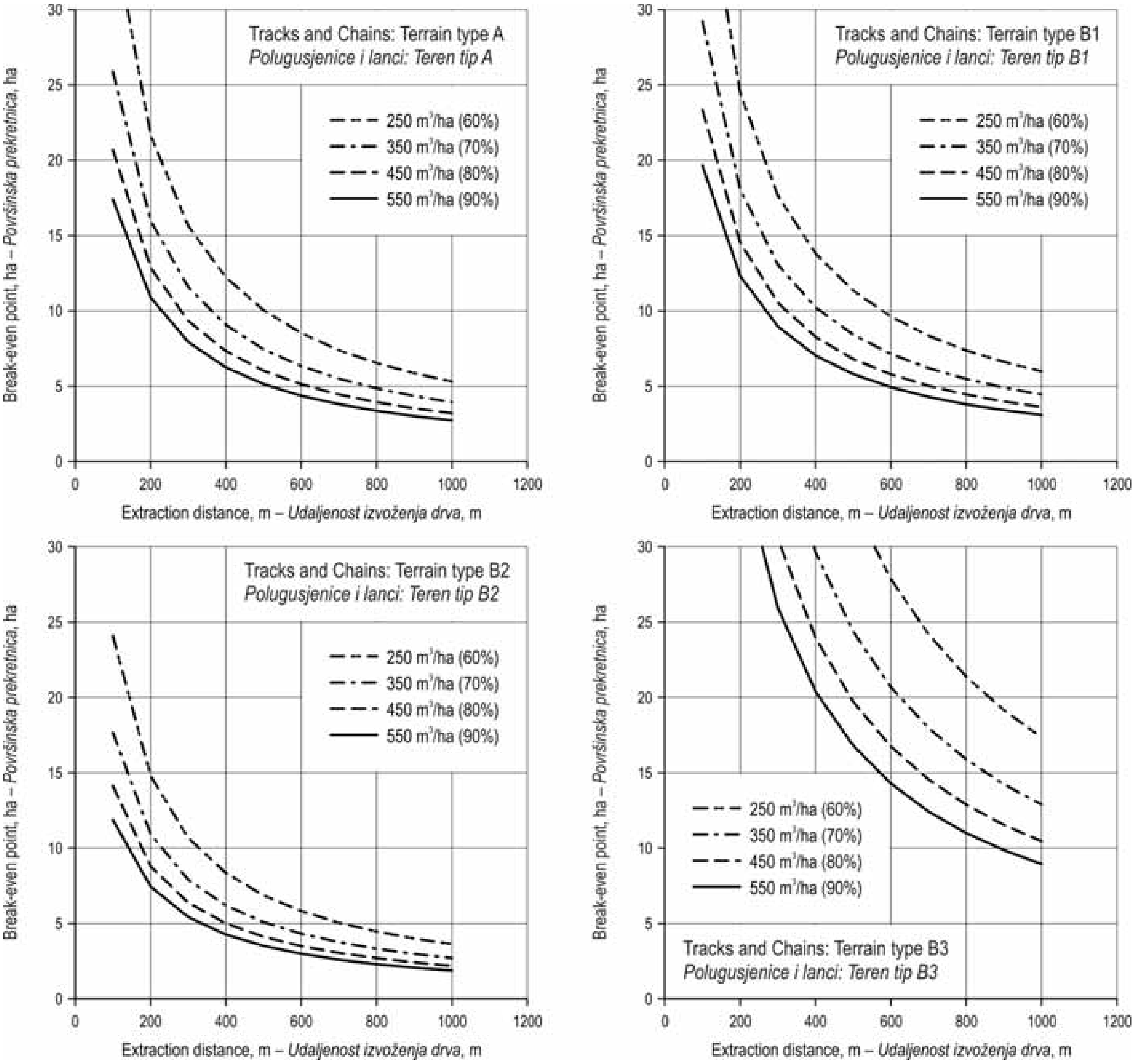

Fig. 14 Break-even points for the profitability of removal and re-installation of bogie tracks and chains as a function of average extraction distance and total volume of the growing stock

Slika 14. *Površinska prekretnica isplativosti skidanja i postavljanja polugusjenica u ovisnosti o srednjoj udaljenosti izvoženja i drvnoj zalihi*

per hectare, are presented in Figures 13 and 14. As can be seen in Figure 13, these break-even points are relative high for the removal of wheel chains. For terrain type B3 the break-even point for a growing stock of 450 m^3/ha and an extraction distance of 1000 metres is as much as 90 hectares, so that the values do not even fit on the same scale and have had to be left out of Figure 13.

The abandonment of bogie tracks (Figure 14) becomes profitable at much smaller site sizes than the abandonment of wheel chains. On terrain type B2, for example, the five-hectare break-even point is reached at an extraction distance of less than 500 metres if the average volume of growing stock is more than 350 m^3/ha. On the other hand, the break-even values for terrain type B3 are relatively high in every alternative. On even terrain the five-hectares break-even point is reached at extraction distances between 500 and 1000 metres depending on the volume of the growing stock.

As any percentage changes in the fuel price devolve directly on total fuel costs, it is easy to calculate the impacts of fuel price on these break-even points. If the fuel price increases by 15%, for example, the original break-even point will be 15% higher than that calculated using the new, higher fuel price.

5. Discussion – *Rasprava*

The hypothesis examined here was that wheel chains and bogie tracks increase the fuel consumption of a forwarder on soils with a high bearing capacity. Models based on the field tests described in this paper prove that the hypothesis is true. The extra fuel consumption was fairly marginal in the case of wheel chains, but the economic effects of using bogie tracks were considerable.

On even terrain the measured fuel consumption was around 2 grams per metre for an unloaded tractor regardless of its ground contact devices, while for a loaded tractor it was just over 2 grams per metre with tyres and wheel chains and almost 4 grams per metre with bogie tracks. Nordfjell et al. (2003) reported that forwarders consumed 0.23–0.38 litre per 100 metres of driving and that the difference between an unloaded and loaded vehicle was only 10%. They carried out their measurements without bogie tracks, however. The present results support their findings, although the difference in fuel consumption between an unloaded and loaded tractor is clearly greater when using bogie tracks.

The most important factors behind the rise in fuel consumption when using wheel chains and bogie tracks seem to be:

⇒ increased tractor mass

⇒ slip on uphill slopes.

The data obtained here did not enable us to analyse whether the latter was a matter of slip between the soil and the ground contact devices or internal slip within the ground contact devices. A significant result, however, was that the slip turns to skid on a much more gentle downhill slope when using wheel chains or bogie tracks than with just tyres. This was probably the reason why the extra total resistance and fuel consumption were so high when using wheel chains or bogie tracks on downward slopes.

The conclusion to be reached here is that the removal and reinstallation of wheel chains is not an economic proposition under normal logging conditions, although the removal of bogie tracks may become profitable on relatively small sites if:

⇒ the bearing capacity of the soil is high throughout

⇒ the total volume of the timber to be harvested is high

⇒ the extraction distance is long.

If the forwarder is loaded when driving uphill the removal of bogie tracks becomes even more profitable. In any case, the removal of bogie tracks does not allow a single operator to achieve any huge cost savings and savings are in general restricted to certain soil types, but it should be remembered that even small cost reductions in logging operations can amount to significant savings at the national level. Rieppo and Örn (2003) have estimated, for example, that a reduction of 5% in the fuel consumption of forest tractors and timber extraction vehicles in Finland would yield annual savings of five million euros. Reduced fuel consumption also means more sustainable wood harvesting.

The present data were collected on soils with a high bearing capacity and within a relatively small area, so that the work has its limitations. The finding that the removal of bogie tracks is profitable cannot be extrapolated to soils of low bearing capacity, as bogie tracks are still necessary on soft terrain and under winter conditions. Further research will be needed to define exactly what the limit values for the break-even points are. The limit value for the cone index at which removal is profitable, for example, cannot be specified exactly on the basis of the present results. This study nevertheless provides clear evidence that the use of bogie tracks is not always justified. It has also been shown that it is not only the selection of a suitable forest tractor but also the selection of suitable ground contact devices on certain logging sites that is needed in order to achieve economies in wood harvesting.

A larger data bank on the effects of ground contact devices on fuel consumption would enable this information to be combined with digital maps, which would then allow logging operators to choose suitable ground contact devices. An off-road routing method which supports this kind of approach has been presented by Suvinen (2006), for example.

The measuring method presented here is suitable for other terramechanical research, except measuring of fuel consumption at wheel skid. A comparison of tyre types, for example, is easy to arrange, and can serve as a useful development tool for tyre, wheel chain and bogie track manufacturers. In addition, logging operators and timber procurement companies can use these results in their planning work, and can exploit them to find the best logging order for forest stands and to gather together forest stands with similar soil conditions to form a work site on which logging is possible with a single type of ground contact device.

Acknowledgements – *Zahvala*

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Sažetak

Usporedba ekonomičnosti primjene guma, lanaca i polugusjenica pri izvoženju drva forvarderom

U Finskoj se pri izvoženju drva forvarderima vrlo često tijekom cijele godine, neovisno o uvjetima terena, koriste polugusjenice na bogi ovjesu. Osnovni razlog tomu su povećani troškovi rada zbog utroška vremena na skidanju i postavljanju polugusjenica. Prednosti se uporabe polugusjenica i lanaca ističu pri radu na slabo nosivim tlima. Primjena polugusjenica ili lanaca smanjuje dodirni tlak vozila na tlo povećavajući dodirnu površinu između gume i tla, pri čemu se između rebara gume ne nakuplja blato.

Postavka se istraživanja odnosi na rad forvardera na čvrstim tlima, pri čemu primjena polugusjenica i lanaca jedino povećava otpore te time i potrošnju goriva. Pri tome bi skidanje lanaca ili polugusjenica s kotača s ekonomskoga gledišta bilo isplativo, ako zanemarimo okolišnu pogodnost (oštećivanje tla). U radu se analiziraju uvjeti ekonomske opravdanosti skidanja polugusjenica i lanaca s kotača te njihov utjecaj na radne značajke forvardera pri različitim terenskim uvjetima.

Istraživanje je provedeno na forvarderu Timberjack 1110 (slika 1) koji je bio opremljen na tri načina:

⇒ *1. gumama Nokian 710/45–26.5, pri čemu je tlak zraka u gumama prednjega bogi ovjesa iznosio 350 kPa, a u stražnjima 440 kPa,*

⇒ *2. lancima na kotačima koji su pri istraživanju bili postavljeni na stražnje kotača oba bogi ovjesa. Ukupna masa para lanaca iznosi 400 kg, dok je njihova debljina 16 mm,*

⇒ 3. polugusjenicama ECO-TRACK proizvođača Olofsors, koje su bile postavljene samo na stražnjem bogi ovjesu uz lance na stražnjim kotačima prednjega bogi ovjesa.

Mjerni sustav čini GPS uređaj Trimble ProXR s antenom i CAN bus sustav za prikupljanje podataka koji omogućuje mjerenje izlazne snage i broja okretaja motora pri radu. Nagibi su terena na izvoznoj vlaci forvardera određeni metodom niveliranja. Konusnim je penetrometrom izmjerena nosivost tla na 10 mjernih mjesta uzduž izvozne vlake nakon prolaska forvardera. Radi određivanja stanja nosivosti tla mjerenja su obavljena konusnim penetrometrom na neizgaženom tlu pored mjernih mjesta na izvoznoj vlaci. Tijekom istraživanja nije bilo oborina, temperatura se kretala oko 0 °C te je tlo bilo suho i čvrsto.

Vozač je tijekom izvoženja održavao stalni broj okretaja motora u istom prijenosnom stupnju transmisije kako bi brzina kretanja forvardera bila više ili manje stalna. Mjereno je pri više prolazaka neopterećenoga i opterećenoga forvardera s tri opreme voznoga sustava. U svakom se prolasku izvozio isti tovar smrekovih trupaca. Masa neopterećenoga i opterećenoga forvardera bez polugusjenica i lanaca određena je pomoću kolne vage. Masa je polugusjenica i lanaca preuzeta iz podataka proizvođača te pribrojena masi neopterećenoga i opterećenoga forvardera ovisno o njihovoj primjeni tijekom istraživanja.

Ukupni su otpori definirani kao suma otpora kotrljanja, otpora uspona, otpora klizanja kotača, otpora površinskih prepreka, snježnoga pokrivača, otpora upravljanja i otpora inercije (izraz 8). Ukupni je otpor određen dijeljenjem izlazne snage motora i brzine kretanja forvardera izmjerene GPS uređajem (izraz 7). Istraživanje je provedeno pri vožnji forvardera stalnom brzinom kretanja u ljetnom razdoblju te su stoga iz ukupnih otpora izbačene veličine otpora snježnoga pokrivača, otpora inercije i otpora upravljanja (izraz 11).

Izvozna vlaka forvardera podijeljena je u tri dijela (uzbrdo, ravan teren i nizbrdo) te su ukupni otpori za svaki dio puta neopterećenoga i opterećenoga forvardera prikazani u tablicama 1 i 2. Vidljivo je da su ukupni otpori najmanji pri vožnji neopterećenoga forvardera bez lanaca ili polugusjenica u svim dijelovima. Kod opterećenoga forvardera jedino je na ravnom terenu manji otpor pri primjeni polugusjenica i lanaca.

Koeficijent je otpora kretanja određen dijeljenjem ukupnoga otpora s težinom forvardera i udaljenosti izvoženja. Za prazni forvarder koeficijent je otpora kretanja pri kretanju uz nagib veći za 4 % kod primjene lanaca odnosno za 12 % kod primjene polugusjenica u odnosu na primjenu guma. Pri kretanju niz nagib koeficijenti su mnogo veći pri primjeni lanaca ili polugusjenica (tablica 3). Osnovni razlog leži u znatnom povećanju mase forvardera primjenom lanaca ili polugusjenica. Pri primjeni lanaca i polugusjenica kod opterećenoga forvardera veći su koeficijenti na nagnutnom terenu te manji na ravnom terenu, pri čemu su razlike značajnije nego pri usporedbi ukupnih otpora (tablica 4).

Mjerenjem brzine okretaja motora ustanovljena je kutna brzina kotača, tj. množenjem s dinamičkim polumjerom kotača, i obodna brzina kotača. Usporedbom obodne brzine kotača i brzine kretanja forvardera određen je postotak klizanja (izrazi 9 i 10).

Postoci klizanja kotača neopterećenoga i opterećenoga forvardera prikazani su u tablicama 5 i 6. Klizanje je kotača neznatno manje pri kretanju uz nagib bez primjene lanaca ili polugusjenica i kod neopterećenoga i kod opterećenoga forvardera. Pri tome se klizanje najviše odnosi na unutrašnje klizanje između lanaca ili polugusjenica i gume kotača. Veće vrijednosti ukupnoga otpora pri primjeni lanaca i polugusjenica pri kretanju niz nagib ne mogu se samo objasniti većom masom i klizanjem kotača, već lanci i polugusjenice dublje prodiru u tlo, što povećava otpor kotrljanja. Nosivost tla na ravnom terenu bila je manja nego na nagnutnom terenu, što je razlog većega klizanja kotača bez primjene lanaca i polugusjenica.

Izjednačene vrijednosti (slika 6 i 7) pokazuju da je klizanje kotača na ravnom terenu malo pri primjeni lanaca i polugusjenica. Opterećeni forvarder s lancima na kotačima ima znatno povećanje klizanja s rastom nagiba terena. Pri primjeni polugusjenica negativno klizanje kotača neopterećenoga i opterećenoga forvardera počinje pri nagibu terena od –10 %, a bez lanaca i polugusjenica negativno klizanje kotača počinje pri nagibu terena –15 %.

Na osnovi mjernih podataka određen je model potrošnje goriva, pri čemu je korištena specifična potrošnja goriva od 240 g/kWh. Izvozni je pravac s obzirom na nagib terena podijeljen u 2 razreda: teren s blagim nagibom A (–5 % do 5 %) i teren B s nagibom većim od 25 % uzbrdo i nizbrdo. Na terenu B su razmatrana 3 načina vožnje forvardera s obzirom na smjer kretanja: natovareni se forvarder kreće podjednako uz nagib i niz nagib (B1), natovareni se forvarder kreće uz nagib (B2), natovareni se forvarder kreće niz nagib (B3). Ostale varijable korištene u modelu su površina šumske sastojine, drvna zaliha, obujam izrađenoga drva uzduž traktorskoga puta, udaljenost izvoženja drva te postotni udio tehničke oblovine u sortimentnoj strukturi. Udaljenosti su vožnje forvardera izračunate prema izrazima 1, 2 i 3.

Potrošnja goriva po prijeđenom metru prikazana je na slikama 8 i 9. Za prazan forvarder potrošnja je približno jednaka potrošnji forvardera s lancima i bez lanaca, dok je s polugusjenicama potrošnja za 6 do 7 % veća pri kretanju uz nagib. Kod opterećenoga forvardera potrošnja je goriva za 40 do 60 % veća pri primjeni polugusjenica u odnosu prema primjeni guma pri kretanju uz nagib.

Modelirana potrošnja goriva po površini (slika 10) za forvarder bez lanaca i polugusjenica najveća je pri kretanju opterećenoga forvardera uz nagib. Razlike u potrošnji goriva po površini pri primjeni lanaca i polugusjenica u odnosu na gume prikazane su na slikama 11 i 12. Lanci na kotačima i polugusjenice povećavaju potrošnju goriva pri kretanju forvardera na tlima velike nosivosti, pri čemu je značajno veća potrošnja pri primjeni polugusjenica na ravnom terenu ili uzbrdo.

Površinska prekretnica isplativosti skidanja lanaca i polugusjenica određena je na temelju prosječne cijene goriva u Finskoj (0,684 €/L), potrebnoga vremena i troškova rada dvaju radnika za skidanje i postavljanje lanaca (100 €) i polugusjenica (120 €) te cijene sata rada forvardera (50 €). Na slikama 13 i 14 prikazana je veličina sječine s različitim drvnim zalihama pri kojoj je ekonomski isplativo skidanje lanaca i polugusjenica na kotačima bogi ovjesa forvardera.

Rezultati istraživanja jasno pokazuju da je skidanje lanaca i polugusjenica ekonomski isplativo u slučaju velike nosivosti tla, velike drvne zalihe i velike udaljenosti izvoženja. U slučaju izvoženja uz nagib skidanje polugusjenica postaje još isplativije. Za postizanje veće ekonomičnosti radova privlačenja drva nije samo bitan pravilan odabir mehaniziranoga sredstva rada već i izbor dodirnoga sredstva između kotača i tla.

Ključne riječi: *guma, kotač, bogi ovjes, polugusjenice, lanci na kotačima, potrošnja goriva, forvarder*

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