Comparison between skid trail soil penetration characteristics and tractive performance of adapted farm tractors

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COMPARISON BETWEEN SKID TRAIL SOIL PENETRATION CHARACTERISTICS AND TRACTIVE PERFORMANCE OF ADAPTED FARM TRACTORS

USPOREDBA PENETRACIJSKE ZNAČAJKE TLA TRAKTORSKE VLAKE I VUČNE ZNAČAJKE ADAPTIRANOGA POLJOPRIVREDNOG TRAKTORA

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This paper describes the analysis for determining the possibility to estimate the tractive performance of an adapted farm tractor (AFT) based on soil penetration characteristics measured by cone penetrometer. It has been established by research carried out to date at the Faculty of Forestry in Zagreb that such assessment is possible for friction-cohesive soils, but not for sand so that further target investigations should be conducted.

With that purpose, a simplified investigation of tractive performance of the adapted 4x2 farm tractor was carried out with the measurement of the horizontal tractive force and simultaneous wheel slip. Granulometric soil content was completely determined as well as skid trail inclination, its moisture and soil penetration characteristics. Gross tractive coefficient was calculated on the basis of the measured tractor dimensions and the dynamic model of its load during skidding.

The research was carried out on the skid trail of silty loam granulometric soil content with two moisture degrees. The analysis of the results obtained by exponential regression model showed that the difference between the penetration characteristics of dry and wet soil correspond to the changes of the tractor tractive performance. The difference was also observed in view of forwarder tractive performance determined by some previous investigations on the soil of the same granulometric content.

Key words: wood skidding, adapted farm tractor, tractive performance, cone penetrometer characteristics, exponential regression model

INTRODUCTION
UVOD

Mechanized extraction of the so-called small wood is very significant in Croatia especially for the part of industrial timber produced in forest thinning because the share of small wood ranges between 10 % and 60 % in the annual cut, depending on different forest administrations and forest offices (Tomičić, 1986, Štefančić, 1989). Significant use of mechanized transportation of wood started in early 1960s when the use of farm tractors started. At the beginning they were applied for extraction or transport of wood and in silvicultural operations mainly in establishing the plantations of Euro/American poplar. At that time they were not provided with special technical adaptations, which could have improved their characteristics and eleminate some deficiencies caused by their inadequate original purpose. Up to late 1980s, the existing driving machines were mostly large-series farm tractors, adapted to forest operations or not. Arisen and ever growing problems with malfunctions and spare parts especially when using imported machines and special devices, were caused by insufficient strength of machine components, low safety factor and inadequate distribution of front/rear load.

By the introduction of specialized machines, skidders and forwarders, in the Croatian forests in 1970s (Beđula & Slabak, 1974), work mechanization, as a simple replacement of human and animal work, entered into a period of creating and modelling up-to-date work technologies in forest silvicultural and harvesting operations. The ways of performing these operations depend primarily on natural features of the forest area and methods of growing the stands. As a result the technology was established of performing specific degrees of forest-production operations such as cutting, processing, skidding/forwarding and transport as well as the closely related choice or implementation of a specific technique.

In shelterwood felling of low-lying forests, where pedunculate oak prevails as the most valuable species, forwarders are used almost exclusively with the applied cut-to-length method wherever the load bearing capacity of soils is satisfying, since wood forwarding on wheels causes much less damage to young growth than skidding. Similarly, tractor assemblies – farm tractors with trailer and crane as well as those equipped with winch are used in thinning these forests.

On sloped terrain of mountainous areas, wood skidding is usually applied in shelterwood felling of even-aged forests and in selective felling along with the application of cut-to-length, semi and full-length methods. Medium-sized skidders and adapted farm tractors with winch are also used in thinning operations of these forests.

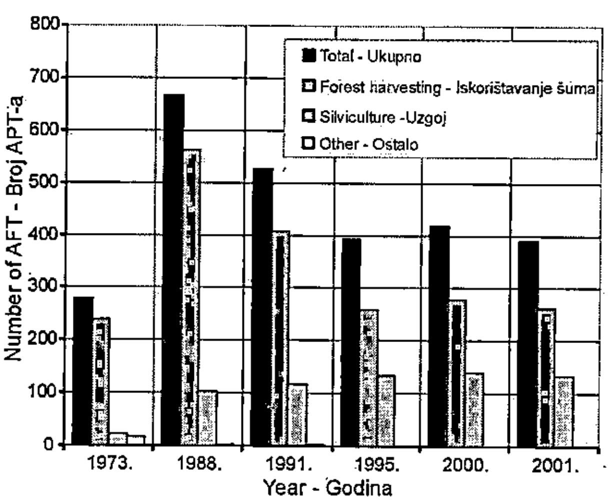
Consequently the tractors designed for the extraction of wood in mountainous conditions are equipped with forest winches for timber skidding, usually double-drum winches for winding the pulling rope and the tractors designed for the extraction of wood in low-lying areas are additionally equipped with the forest trail with crane - the so-called tractor assemblies. In this way, by assembling the farm tractor, the shock protective frame and the coupling device for forest equipment the adapted farm tractors (AFT) are made or in other words farm tractors adapted to forest operations.

As they were originally designed for a completely different purpose, regardless of the adaptations, they could not meet the basic requirements of the thinning vehicles:

- small dimensions, especially width;
- good manoeuvrability, especially low turning radius and
- good longitudinal/lateral stability and rear axle load capacity.

Among these requirements, due to the possibility of using separate left/right brakes, farm tractors only meet the requirement related to a relatively satisfying turning radius, Horvat (1983, 1996a). According to Horvat (1996b and 2001) and Sever & Horvat (1997) providing such tractors with forest equipment (winch, anchoring board, protection cabin, etc.) lowers the vehicle stability especially the longitudinal one and hence skidding up the slope very often causes lifting of the front part. During skidding in mountainous conditions energy characteristics as well as tractive efficiency and maximum winch force must not be too low.

Figure 1. Number of AFT in Croatian forestry
Slika 1. Broj APT-a u hrvatskome šumarstvu



In spite of all deficiencies, adapted farm tractors have had a historical role in up-grading the degree of mechanization of thinning wood extraction. Based on their current number it can be said that their role is still significant. The survey of the number of adapted farm tractors in use over a 40-year period in the Croatian forestry given by Horvat and Šušnjar (2001) has been completed with some data related to 2001 thanks to some new sources and monitoring methods and it is shown in Figure 1.

RESEARCH ISSUES
PROBLEMATIKA ISTRAŽIVANJA

Some machines, such as heavy skidders, forwarders, etc. are basically used in final felling but also in thinning operations causing often damage to soil and remaining trees due to inadequate technical characteristics, Sever & Knežević (1989). Soil compactness caused by vehicle passage is systematically measured by cone penetrometer at the Faculty of Forestry Zagreb. Bojanin et al. (1976) were the first to describe such measurements performed by use of a penetrometer with the so-called energy penetration and Sever (1980) gave the description of the first statistical analysis of the results of such investigations. Cone penetrometer produced in Croatia has been used since early 1980s and in view of its drive/method of data collecting it makes part of BUSCH penetrometer group. It was thoroughly described by Sever and Horvat (1985). Hitrec and Horvat (1987) developed a programme for exponential regression analysis aimed at processing the data related to soil penetration characteristics determined by cone penetrometer as well as for defining the vehicle tractive performance.

Right this programme for the exponential regression analysis provided the possibility for making a better interpretation of the measurement results and for comparing different penetration characteristics. Thus Horvat (1994a) set forth that the penetration characteristics can be well described by the exponential correlation model of the form:

$$CI = A_{CI}\left(B_{CI}^{Z} - 1\right)$$

which is shown for a measurement in Figure 2. The characteristic point in which the horizontal asymptote intersects the tangent from the 0 point ($\mathbf{T}_{CI}$) has then the following coordinates:

$$T_{CI}\left(\frac{-1}{\ln B_{CI}}; -A_{CI}\right)$$

The same author (1994b) showed that the change of soil compactness after multiple vehicle passage could be observed by measurement of the penetration char-

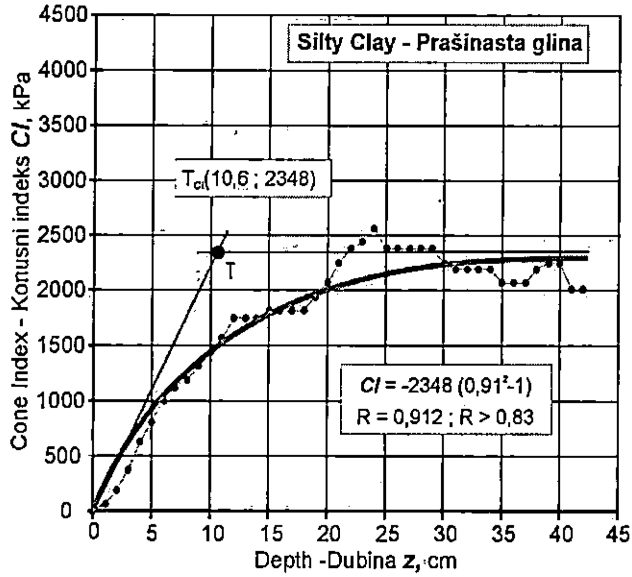


Figure 2. Penetration characteristics analysed by exponential regression analysis and the characteristic point (Horvat, 1994a)

Slika 2. Penetracijska značajka analizirana eksponencijalnim regresijskom modelom s ucrtanom karakterističnom točkom (Horvat, 1994a)

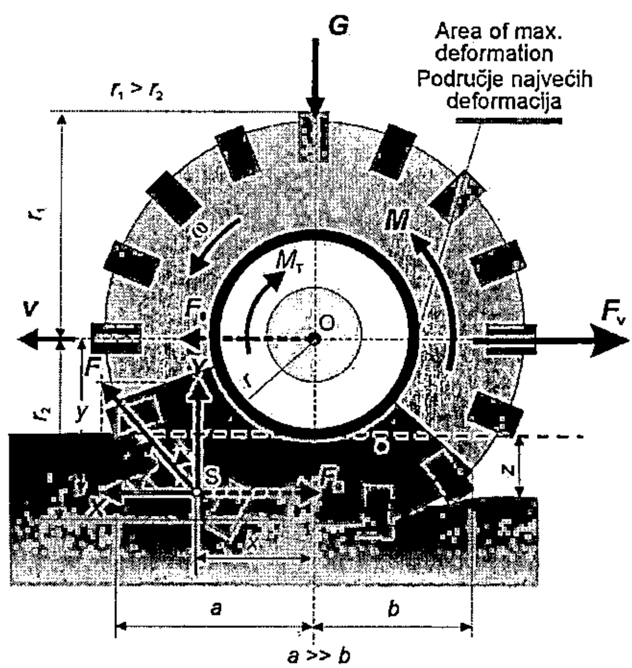


Figure 3. Model of driven wheel of AFT

Slika 3. Model vučnog kotača APT-a

acteristics, as well as the natural soil regeneration 10 years after compaction (Horvat, 1995).

The analysis of driven wheel model travelling on deformable ground, as shown in Figure 3, can be used for the analysis of the wheel load.

One of the analysis methods was applied with this model and namely the introduction of imagined forces acting in the centre of gravity of the surface of contact. Their values are equal to the product of multiplication of the surface and the relative stress (tangential or radial) at the point of contact between wheels and the ground. As the basic balance equation is defined as follows:

$$X = F_v; Y = G; M_k = F \cdot r,$$

The result of balance condition is the following:

$$F_v \cdot y + G \cdot x + M_t = F \cdot r.$$

Torque M_k can be replaced by the action of imagined coupling of forces $F_o y$ and then the following applies:

$$F_0 \cdot y = F \cdot r, \text{ and then as follows } F_0 = F\frac{r}{y}.$$

If the expression for the resultant force is introduced in the equation and the moment arm – r is substituted with the distance between the wheel centre and the line of action of the force F:

$$r = \frac{y + x \cdot tg\alpha}{\sqrt{1 + tg^2\alpha}} = \frac{y + x \cdot \dfrac{G}{F_v}}{\dfrac{1}{F_v}\sqrt{F_v^2 + G^2}}$$

The final expression for the circumferential force is obtained:

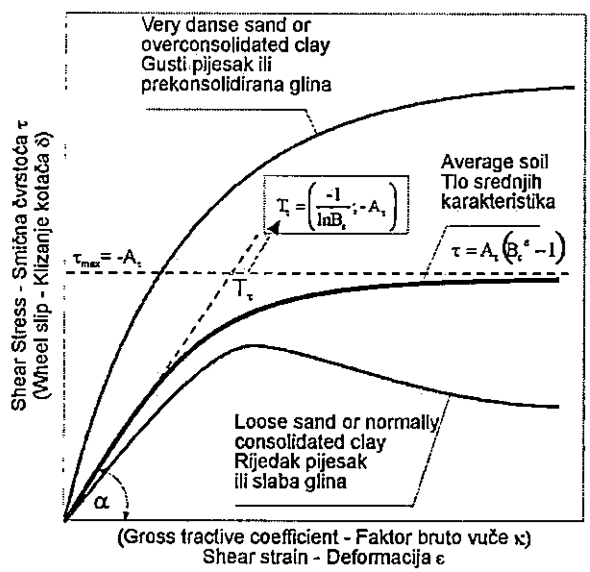
$$F_0 = \sqrt{F_v^2 + G^2}\,\frac{y + x \cdot \dfrac{G}{F_v}}{\dfrac{1}{F_v}\sqrt{F_v^2 + G^2}} = F_v + G\frac{x}{y} = F_v + F_r.$$

F_o is the circumferential force and y is the dynamic wheel radius often marked as r_d. If the latter is divided by vertical load, the known expression for the gross tractive factor is obtained:

$$\kappa = \mu + f$$

If the wheel of the vehicle moves on the soil, i.e. on a deformable base, the force will be transfered from the wheel to the soil causing stress and shear strain to the soil in tangential direction provided that there is friction between the tyre and the soil. As the tyres of forest vehicles must also have the ribs, tangential strain will surely be present. In that case, shear-strain ($\varepsilon - \tau$) is the most significant soil characteristic, as the forces are realized based on the soil shear strength. When measured by triaxial test or direct shear-strain device its trend is as shown in Figure 3. As early as 1960 Bekker suggested that the exponential form with horizontal asymptote should be used for this soil characteristic in order to investigate the off-road drive of the vehicle. The so-called wheel-slip curve (δ–κ) derives directly from shear-strain soil characteristics and it connects the gross tractive coefficient (κ) and wheel slip (δ) and it has, therefore, the same trend. Consequently gross tractive coefficient and wheel slip are also plotted on coordinates in Figure 4.

Figure 4. Strain-stress soil characteristics
Slika 4. Značajka tla deformacija-naprezanje



Considering similar trend of penetration soil characteristics and strain-stress (wheel slip curve) soil characteristics, Horvat (1996a and 1996b) started developing the correlation between these characteristics with regard to published investigations of forwarder tractive characteristics and penetration characteristics of soils on which the investigations were carried out. Based on these research and made analysis, the conclusions of the author are as follows:

- there are pretty good indications that the vehicle tractive performance on silty clay, silty clay loam and silty loam, i.e. on mostly cohesive soil, can be assessed as satisfying subject to the penetration test;
- the assessment related to friction soil, such as Dense Sand, is not satisfying;
- further target investigations are required, and
- good knowledge of forest vehicle dynamic model is required for making this assessment.

Further to previous research, soil penetration characteristics and tractive performance of the adapted farm tractor are correlated in this paper.

SCOPE AND METHOD OF INVESTIGATION
OBJEKT I METODE ISTRAŽIVANJA

According to Balady (1987) the approach to solving the complex issue of investigating the wheel – soil system, i.e. vehicle – soil, with the purpose of assessing the vehicle tractive performance, can be divided into three basic groups:

1. Empiric approach, which requires the basic soil data (granulometric content, moisture), terrain description (slope, vegetation), penetration test and tractive experiment. The results of such approach are based on measurements but they are restricted to the conditions under which the experiment was carried out.
2. Analytic approach, which involves simple, basic patterns obtained on the basis of the main soil indicators, cone penetration test, penetration-rotational plate test (bevameter test) and the device for direct strength measurement. Unlike the empiric approach, in this case no tractive experiment is carried out and tractive performance is estimated based on known loaded vehicle dynamic model and they apply only under optimum conditions.
3. Numerical approach is the most complex. It contains complex mathematical models developed by three-dimensional finite elements analysis based on data obtained by laboratory research of soil content and by triaxial test.

According to this division, the estimated content of the said research would be mostly related to the first, empiric group. The possibility of developing simple, basic patterns, i.e. an analytic-empiric approach by the application of the dynamic load model of the adapted tractor in skidding was provided by the increase of the research volume obtained by measuring a higher number of soil characteristics and vehicle-soil effects.

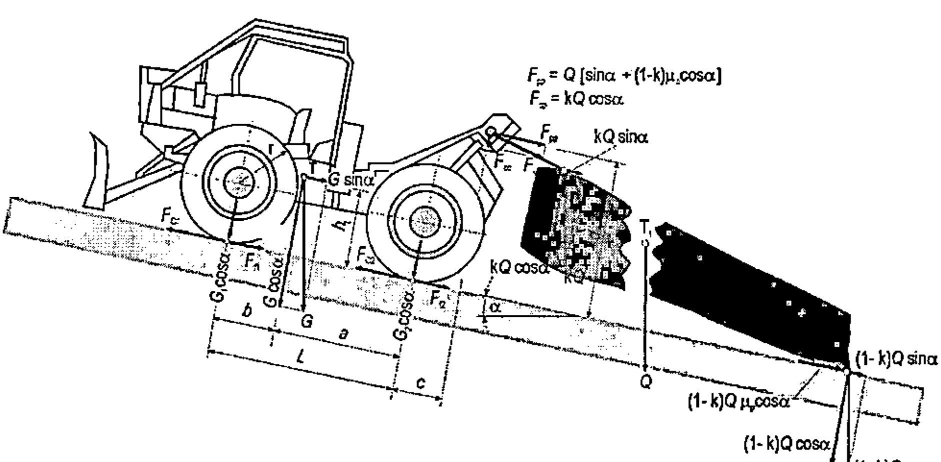
These target investigations were carried out through a simplified testing of tractive performance of the adapted farm tractor involving the measurement of horizontal components of the tractive force, terrain slope and wheel slip. The measurement of all values required for calculating the APT gross tractive coefficient were carried out and they were as follows:

- overall dimensions;
- distance between front and rear axle;
- track width;
- position of the lead point;
- mass;
- center of gravity.

The calculation was carried out based on dynamic load model of the adapted farm tractor during skidding as shown in Figure 5 in conjunction with the basic definition of the gross tractive coefficient as the quotient between peripheral force and adhesive mass:

$$\kappa = \frac{F_0}{G_{ad}} = \frac{F_H + F\sin\alpha}{F_B}$$

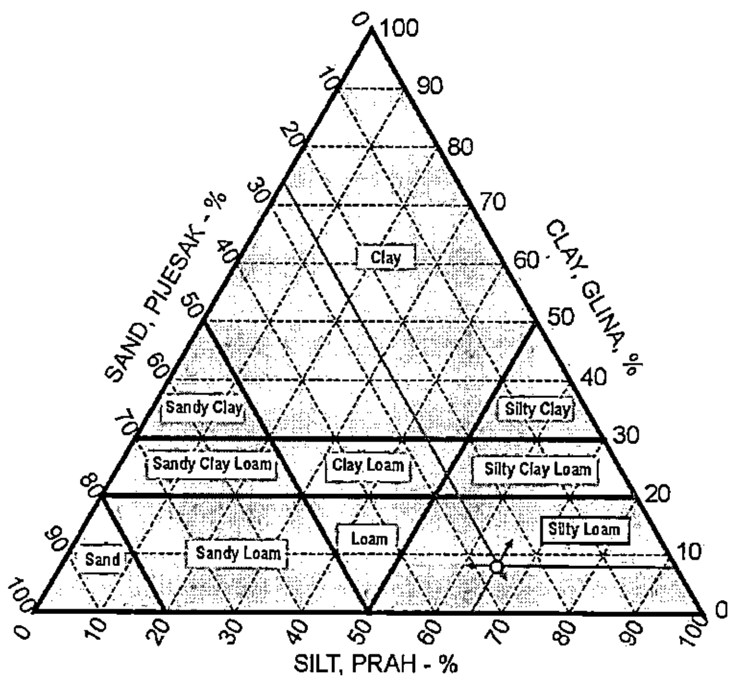
Figure 5. Dynamic weight distribution of AFT at wood skidding
Slika 5. Dinamička preraspodjela opterećenja APT-a tijekom privlačenja



Penetration characteristics were measured by the penetrometer of the Faculty of Forestry Zagreb, which can be classified as Busch penetrometer according to its drive/data processing. The resistance was measured by tensometric method – manual force and its shear strain – penetration depth by passing of the indented lever close to the spiral. The measurement results were then processed by a software programme developed for exponential regression analysis at the Faculty of Forestry Zagreb.

Skid trail inclination was measured by clinometer and moisture was determined as the weight share. Granulometric soil content was determined in the pedological laboratory of the Faculty of Forestry Zagreb and it is shown in Figure 6. It can be seen that the soil was silty loam.

Figure 6. Granulometric soil content
Slika 6. Granulometrijski sastav tla

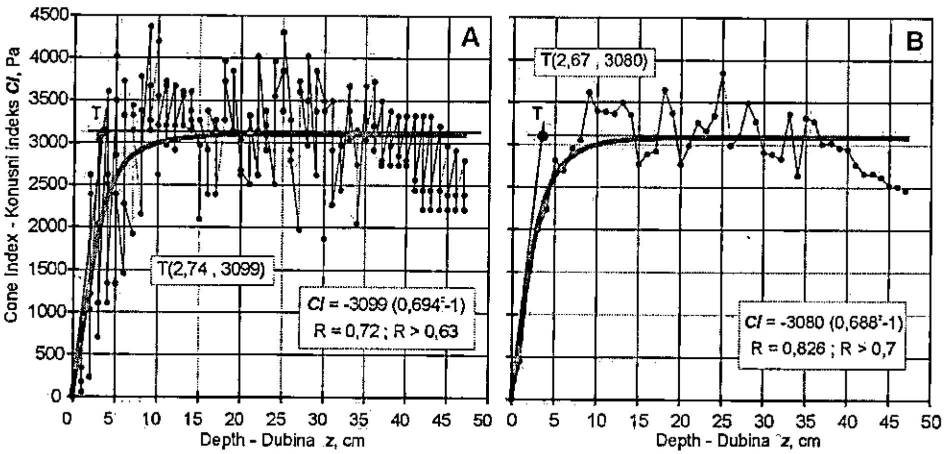


The investigated part of the skid trail was divided into three 20-m segments with a slope gradient of 1.6 %, 8.6 % and 18.1 %. Measurements of soil tractive characteristics and the penetration test were carried out at two soil moisture degrees and specifically 24 % - dry soil and 44 % - wet soil.

INVESTIGATION RESULTS
REZULTATI ISTRAŽIVANJA

The analysis of measurement results of penetration characteristics by the exponential regression model was performed by use of mean values of individual penetration tests, as suggested by Horvat (1994a) – Figure 7.

Figure 7. Method of regression analysis of repeated penetration tests (Horvat, 1994a)
Slika 7. Penetracijska značajka mokre traktorske vlake prije privlačenja



Due to the simplicity of the graphic report, in further presentation of research results, the penetration tests for individual skid trail segments are shown in diagrams only through the regression exponential curve.

The measurements of penetration characteristics were performed before and after skidding, on dry and wet skid trail with the aim of analysing soil compaction caused by timber skidding carried out by use of an adapted farm tractor. The results of these measurements are shown in the form of diagrams in Figure 8, 9, 10 and 11.

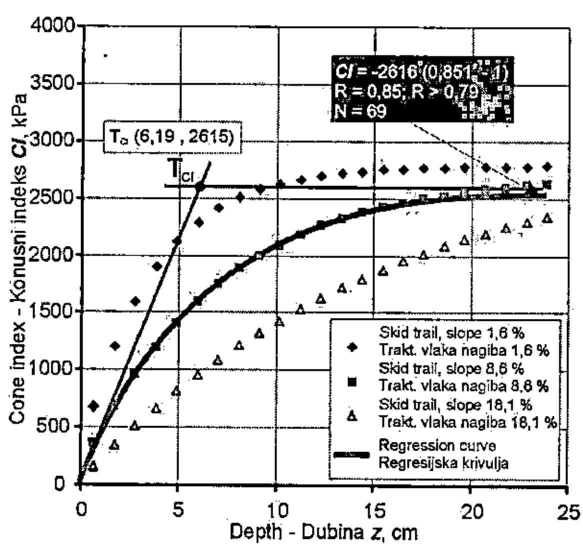


Figure 8. Penetration characteristics of wet skid trail before skidding
Slika 8. Penetracijska značajka mokre traktorske vlake prije privlačenja

Figure 9. Penetration characteristics of dry skid trail before skidding

Slika 9. Penetracijska značajka suhe traktorske vlake prije privlačenja

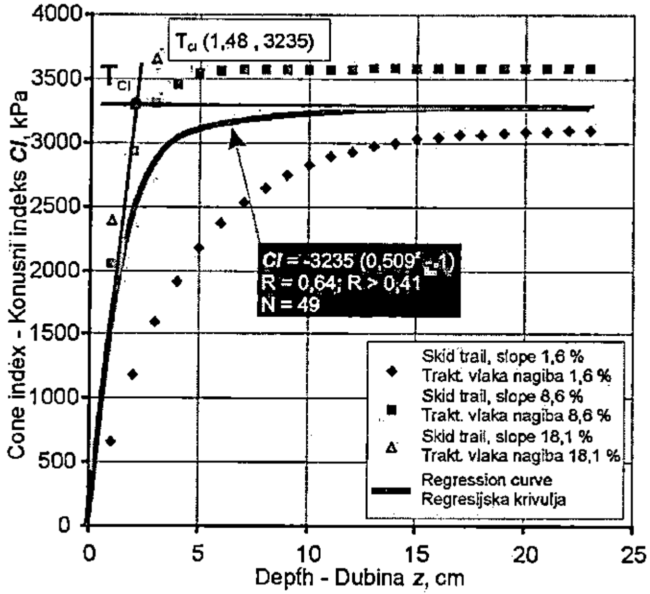


Figure 10. Penetration characteristics of wet skid trail after skidding

Slika 10. Penetracijska značajka mokre traktorske vlake poslije privlačenja

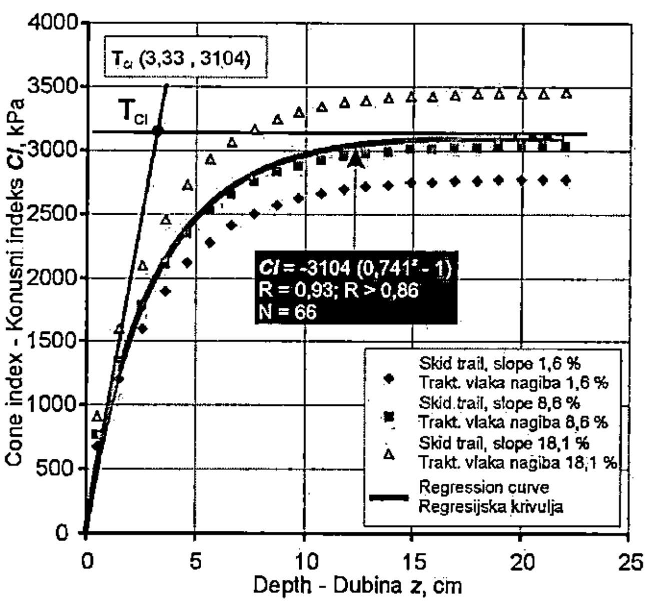
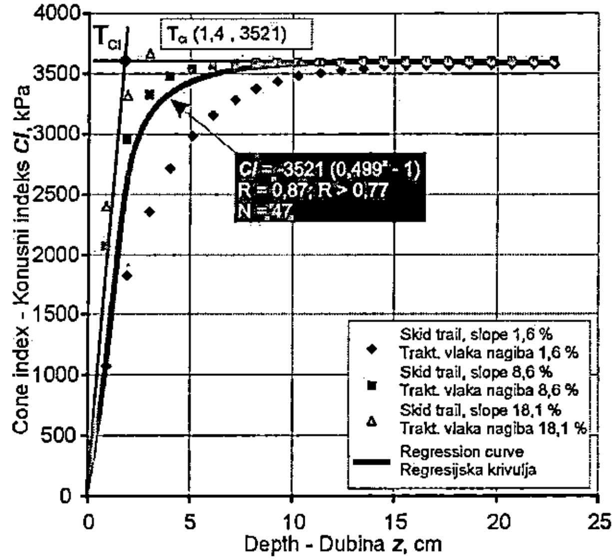


Figure 11. Penetration characteristics of dry skid trail after skidding

Slika 11. Penetracijska značajka suhe traktorske vlake poslije privlačenja



Tractive characteristics during timber skidding were determined by a simplified method of measurement of the horizontal component of tractive force and gross tractive coefficient was calculated on the basis of these measurements and measured tractor dimensions by use of the skidder dynamic load model during skidding as shown in Figure 5. Figure 12 and 13 show drive-wheel slip curves of the adapted farm tractor on dry and wet skid trail.

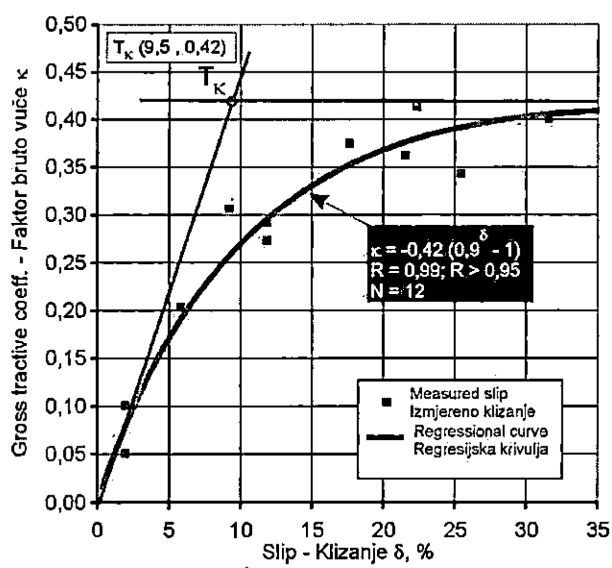
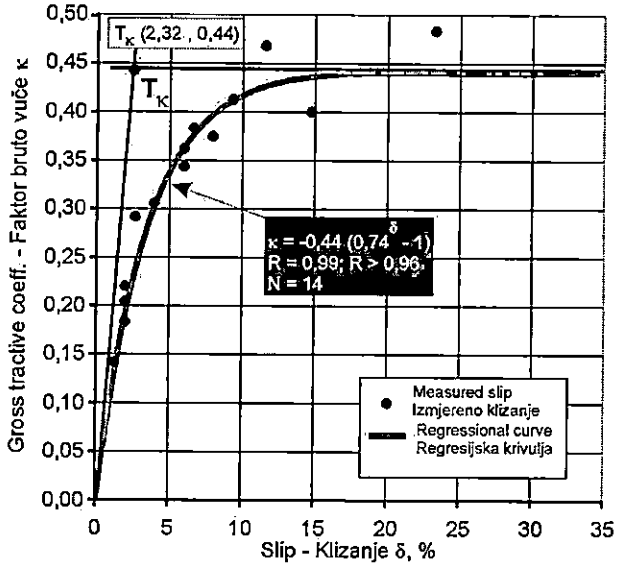


Figure 12. Tractive characterics of AFT on wet skid trail

Slika 12. Vučna značajka APT-a na mokroj traktorskoj vlaci

Figure 13. Tractive characterics of AFT on dry skid trail
Slika 13. Vučna značajka APT-a na suhoj traktorskoj vlaci

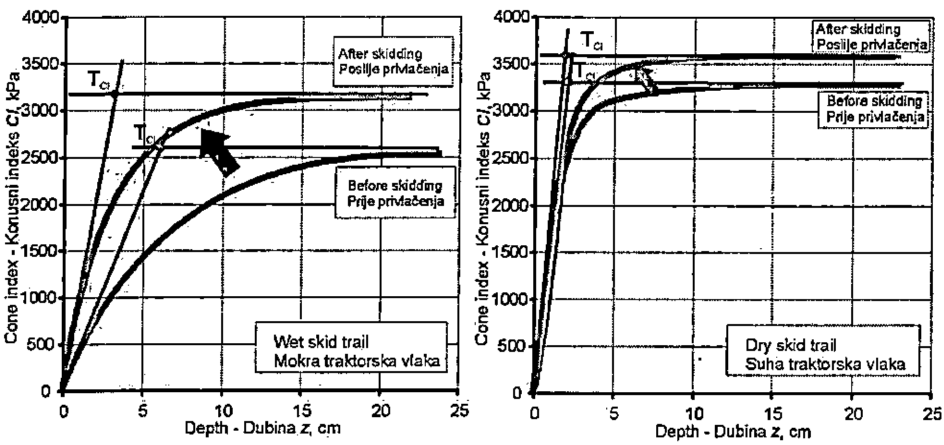


ESTIMATION OF SOIL COMPACTION BASED ON PENETRATION CHARACTERICS
PROCJENA ZBIJANJA TLA TEMELJEM PENETRACIJSKE ZNAČAJKE

This analysis requires the correlation between penetration characteristics shown in Figure 8 and 10 – wet skid trail before and after skidding and Figure 9 and 11 – dry skid trail before and after skidding. With that purpose the diagram was plotted as shown in Figure 14 from which it can be seen that the penetration characteristics changed, i.e. soil compaction occurred with both moisture contents after the passage of AFT with logs. Subject to these measurements, it can also be observed that the degree of increase of penetration soil/soil compactness is higher on wet soil. The characteristic point T (intersection of horizontal asymptote and tangent from the coordinate system 0 point) changes its position after soil compaction towards left and upward, i.e. in the area of lower depths and higher cone indexes.

It should also be noted that the penetration characteristics of the wet soil show that its load bearing capacity gets lower with the increase of moisture. This also implies that with some types of soil it is not enough to use the penetrometer to make the assessment of the soil load bearing capacity. Similarly if the basic penetration characteristics are known for a specific moisture degree, load-bearing capacity can also be assessed only by measuring its moisture.

Figure 14. Changes in penetration characteristics after wood skidding
Slika 14. Promjene penetracijske značajke nakon privlačenja

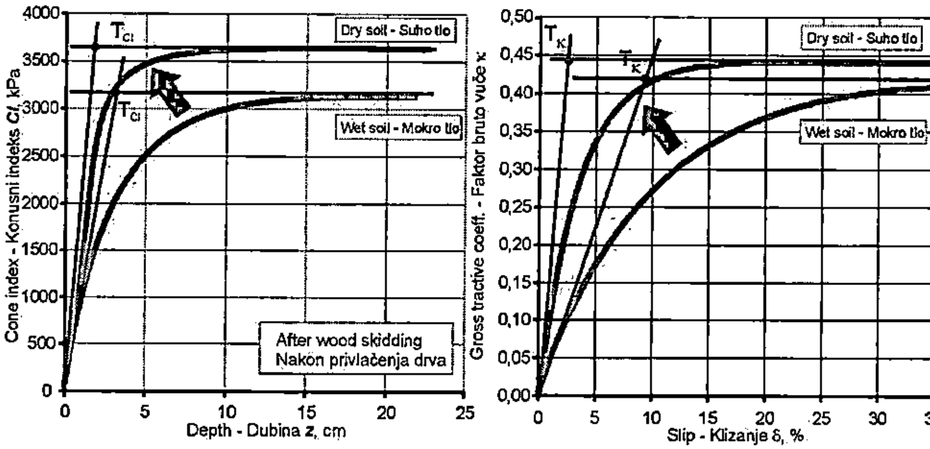


TRACTIVE PERFORMANCE OF AFT AND SOIL PENETRATION CHARACTERISTICS
VUČNA ZNAČAJKA APT-A I PENETRACIJSKA ZNAČAJKA TLA

For this analysis the data were used obtained by measurement of penetration resistance after skidding, as the tractive experiment was carried out by graded traction of different load repeatedly over the same skid trail. Many authors established in their studies, and so did Horvat (1994b), that the highest degree of compaction occurred at the very first vehicle passage. Figure 15 on the left shows the penetration characteristics of dry and wet skid trail and on the right the AFT tractive performance also on dry and wet soil.

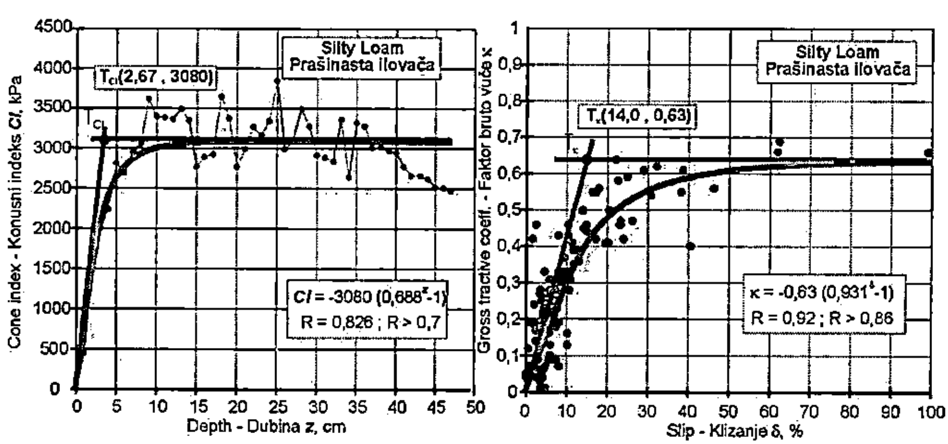
Correlation between these two diagrams shows that dry soil with better load bearing capacity (soil of higher penetration resistance) also has better tractive characteristics. Consequently the trend of the characteristic point is similar – left and upward i.e. towards lower depths and higher cone indexes i.e. towards lower slip and higher gross tractive coefficient. It can be, therefore, said that there are serious indications that silty loam tractive characteristics can be assessed based of soil penetration characteristics.

Figure 15. Penetration and tractive characteristics for two moisture contents of silty loam
Slika 15. Prodirne i vučne značajke za dva stanja vlažnosti prašinaste ilovače



In his past research, Horvat (1996a, 1996b) established the similarity between penetration characteristics and forwarder tractive performance by measuring these features on 4 types of soil. This research on silty loam is shown in Figure 16. It can be seen that the penetration characteristics of silty loam in dry condition are similar to characteristics measured in new experiments.

Figure 16. Comparison between soil penetration characteristics and forwarder tractive performance (Horvat 1996a, 1996b)
Slika 16. Usporedba penetracijske značajke tla i vučne značajke forvardera (Horvat 1996a, 1996b)



On the other hand, the forwarder tractive performance (Figure 16) differs considerably from the AFT tractive performance. The reason can lie in the fact that the tractive experiment for the forwarder was carried out by complete measurement, while the AFT tractive performance was determined by simplified measurement with the calculation by use of dynamic load model of AFT load.

CONCLUSIONS
ZAKLJUČCI

Based on the analysis of soil penetration resistance by cone penetrometer and the measured/calculated tractive performance of the adapted farm tractor it can be concluded as follows:

- Silty loam soil penetration characteristics show considerable difference depending on its moisture content - 24 % and 44 %;
- penetration characteristics can be used for the assessment of soil compaction after vehicle passage and it gets higher with higher moisture content;
- it has been confirmed that there are serious indications for making the assessment of the vehicle tractive performance based on soil penetration characteristics; the use of exponential regression model is highly suitable for determining both characteristics;
- in order to provide further verification of this thesis, it is necessary to carry out target investigations on different soils with different forest vehicles.

Certainty of this assessment can be increased by conducting the measurement of the highest gross tractive coefficient (maximum tractive force). Dependability of the assessment can also be increased by widening the volume of target investigations. Anyway, the correlation between the penetration and tractive characteristics must be thoroughly investigated so as to replace expensive, comprehensive and time-consuming tests of measuring the vehicle tractive performance by less demanding investigations of soil penetration characteristics in conjunction with a reduced research of the vehicle tractive performance as well as of some vehicle characteristics related to its size and mass. Dynamic weight distribution of the vehicle should, of course, be taken into consideration.

Efforts should also be focused on the development of new penetrometers whose use should not be more complicated than that of cone penetrometers and they should be better adapted to forest soil and their results should be more reliable. For example the round ribbed-plate penetrometer could meet such requirements.

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USPOREDBA PENETRACIJSKE ZNAČAJKE TLA TRAKTORSKE VLAKE I VUČNE ZNAČAJKE ADAPTIRANOG POLJOPRIVREDNOG TRAKTORA

SAŽETAK

U radu je opisana jedna metoda procjene vučne značajke adaptiranoga poljoprivrednog traktora temeljem prodirne značajke tla traktorske vlake. U dosadašnjim je takvim istraživanjima provedenim na Šumarskome fakultetu u Zagrebu utvrđeno da je ovakva procjena moguća za frikcijsko-kohezijska tla, ali ne i za pijesak, te da se i nadalje trebaju provoditi ciljana istraživanja.

U tu je svrhu obavljeno pojednostavljeno istraživanje vučne značajke adaptiranoga poljoprivrednog traktora pogona 4x2, s mjerenjem vodoravne vučne sile i istodobnoga klizanja kotača. Granulometrijski su sastav tla, nagib traktorske vlake, njena vlaga kao i penetracijska značajka tla određeni u potpunosti. Bruto faktor vuče je proračunat temeljem izmjerenih dimenzija traktora, vučnoga pokusa i dinamičkoga modela njegova opterećenja tijekom privlačenja.

Istraživanje je provedeno na traktorskoj vlaci koja je po granulometrijskome sastavu tla pjeskovita ilovača, s dva stupnja vlažnosti. Analiza je dobivenih rezultata eksponencijalnim regresijskim modelom pokazala da razlike penetracijske značajke suhoga i vlažnog tla odgovaraju i promjenama vučne značajke traktora. Uočena je i razlika prema vučnoj značajki forvardera dobivenoj ranijim istraživanjima na tlu istoga granulometrijskog sastava.

Na temelju provedene analize penetracijskog otpora tla konusnim penetrometrom i mjerene/proračunate vučne značajke adaptiranoga poljoprivrednog traktora može se zaključiti:

- penetracijska značajka tla, koje je po sastavu pjeskovita ilovača, razlikuje se bitno za njegovu vlažnost od 24 % i 44 %,
- penetracijskom se značajkom može dobro procijeniti zbijanje tla nakon prolaska vozila, koje je veće za vlažnije stanje,
- potvrđeno je da postoje dobre naznake za procjenu vučne značajke vozila temeljem prodirne značajke tla, pri čemu je posebno pogodno koristiti eksponencijalni regresijski model za obje značajke,
- u svrhu daljnje potvrde ove postavke nužna su ciljana istraživanja na različitim tlima, s raznim šumskim vozilima.

Pouzdanost ove procjene vučne značajke temeljem prodirne značajke povećat će se povećanjem opsega ciljanih istraživanja. U svakom slučaju, vezu između penetracijske i vučne značajke treba dobro istražiti da bi se skupi, opsežni i dugotrajni pokusi mjerenja vučnih svojstava vozila zamijenili kraćim i jeftinijim istraživanjem

penetracijske značajke tla, uz reducirano istraživanje vučne značajke, te nekih dimenzijskih i težinskih značajki vozila. Jasno da pri tome treba voditi računa o dinamičkom opterećenju vozila.

Također se treba raditi na razvoju novih penetrometara čija uporaba nije složenija od konusnih, da su pogodniji za šumska tla, a rezultati pouzdaniji, kakav je primjerice penetrometar s okruglom pločom i rebrima.

Ključne riječi: privlačenje drva, adaptirani poljoprivredni traktori, vučna značajka, konusni penetrometar, eksponencijalni regresijski model