Influence of soil and tire parameters on traction

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Abstract: The drawbar pull, travel reduction (slip), and rolling resistance are the main criteria to describe the traction behaviour of off road vehicles. Besides the engine performance, the drawbar pull is influenced by the traction conditions such as soil and the tire parameters. These traction conditions have to be described by a limited number of parameters which can be easily determined. Empirical equations were used to analyse roughly 850 traction curves measured and published by Steinkampf. As a result, the important parameters to describe the traction conditions are three tire parameters (radius, width, inflation pressure) and five soil parameters (soil cover, upper soil strength, lower soil strength, clay content, moisture content). These parameters with relative values between 0 and 100% are used to establish the equations for the traction prediction. Main steps to achieve this goal are the extension of the traction slip equation by a linear term of slip, and the description of this curve by 4 meaningful characteristic coefficients: the x- and y-coordinates of the κ-maximum ($\sigma_{\kappa max}$, κ_{max}), the y-axis intercept ρ_e, and the gradient of κ at zero slip (κ'(0)).

Keywords: tire; traction; wheel-slip

The tire and soil parameters influence the traction performance of farm tractor tires (Schreiber 2006). In 1956, Bekker laid the foundation for scientific investigation of soil-wheel interaction mechanism and extended his model in the following years (Bekker 1956, 1960). Numerous attempts followed to quantify the soil-traction device interaction in order to set up models for the traction prediction (Upadhyaya & Wulfsohn 1990).

Wismer and Luth (1973) used the Cone Index CI as the only soil parameter and considered the tire width d and tire diameter b in the wheel numeric

$$C_n = \frac{Cl \times d \times b}{F_z} \qquad (1)$$

where:
F_z – wheel load

and established the following equation for the gross traction ratio μ with the travel reduction (slip) σ

$$\mu = 0.75\ (1 - e^{-0.3\ Cn \times \sigma}) \qquad (2)$$

where:

$$\mu = \frac{M_T}{r_{dyn}\ F_z} \qquad (3)$$

$$\sigma = \frac{v_{th} - v}{v_{th}} = 1 - \frac{v}{\omega \times r_{\mathrm{dyn}}} \qquad (4)$$

where:
M_T – input torque
r_{dyn} – relevant dynamic tire radius
v_{th} – speed without slip
v – actual speed of the tire

For obtaining the basic information, as well as for the validation of the traction prediction equations, field measurements are unavoidable of traction and rolling resistance of agricultural tires under different traction conditions. Different single wheel testing devices have been developed for these measurements (Steinkampf 1974; McAllistar 1979; Armbruster & Kutzbach 1989; Du Plessis 1989; Upadhyaya *et al.* 1993; Smulevich *et al.* 1994).

Upadhyaya *et al.* (1989) conducted extensive field tests using a single wheel tire tester and found that the traction test results always fitted the equations of the following type for the net traction ratio with good correlations.

$$\chi = a(1 - e^{-c \times \sigma}) \qquad (5)$$

where:
κ – net tractrion ratio
σ – slip

He used different semi-empirical methods and linear regressions to determine the empirical coefficients *a* and *c* with the measured parameters, like the maximum shear stress and characteristics of the contact patch.

For the description of describe the traction behaviour of tires, the tractive force F_x and the rolling resistance force F_R are often based on the tire load F_z. The net traction ratio κ and the rolling resistance ratio ρ are calculated as shown in Eqs (6) and (7).

$$\kappa = \frac{F_X}{F_z} \quad (6)$$

$$\rho = \frac{F_R}{F_z} \quad (7)$$

The third important value for the tractive behaviour, especially for the tractive efficiency, is the slip σ (Eq. (4)). The dependence of the rolling resistance ratio ρ and the net traction ratio κ on the slip can be described by Steinkampf's empirical Eqs (8) and (9), which are defined by 3 and 2 coefficients (Steinkampf & Jahns 1986).

$$\kappa = a - b \times e^{c \times \sigma} \quad (8)$$

$$\rho = a + b \times \sigma \quad (9)$$

The coefficients *a*, *b* and *c* describe the tire behaviour. This approach is used as the base of the presented equation for traction, because Eqs (8) and (9) fit the measurements very well and a large number of measurements providing a good description of the tire and soil parameters are available.

MATERIAL AND METHODS

New proposal for the function of net traction ratio

For the description of the dependence of the rolling resistance ratio and net traction ratio on the slip, Eqs (10) and (11) provide good results. They are based on Steinkampf's Eqs (8) and (9), the κ-equation being extended by the term $- d_1 \times \sigma$ (Scheiber 2006; Schreiber & Kutzbach 2007). With this linear component, a local maximum can be displayed, which is important as the measurements show a maximum of the net traction ratio at less than 100% slip. The recpective curves are shown in Figure 1.

$$\kappa = a_1 - b_1 \times e^{-c_1 \times \sigma} - d_1 \times \sigma \quad (10)$$

$$\rho = a_2 + b_2 \times \sigma \quad (11)$$

To predict these curves, coefficients a_1 to d_1, a_2 and b_2 must be calculated using the tire and soil parameters. While a_2 and b_2 in Eq. (11) are concrete values (a_2 is the rolling resistance ratio at zero-slip ρ(0), b_2 is the gradient of the rolling resistance ratio ρ'), coefficients a_1 to d_1 in Eq. (10) are not that demonstrative. The same equation can be defined by different 4 coefficients, as shown by Schreiber & Kutzbach (2007). These characteristic values are the x- and y-coordinates of the local maximum ($\sigma_{\kappa max}$ and κ_{max}), the y-axis-intercept ρ_e (external rolling resistance) and the gradient of κ at zero slip (κ'(0)). They were chosen to define exactly the same curve (Figure 1) as the 4 coefficients a_1 to d_1. The mathematical way to calculate these coefficients from the characteristic values is shown in the next chapter. The values $\sigma_{\kappa max}$, κ_{max}, κ'(0) and ρ(0) give clear information about the tire behaviour, like how large is the net traction ratio in the maximum, at which slip this maximum occurs, or how fast the slip increases with increasing tractive forces.

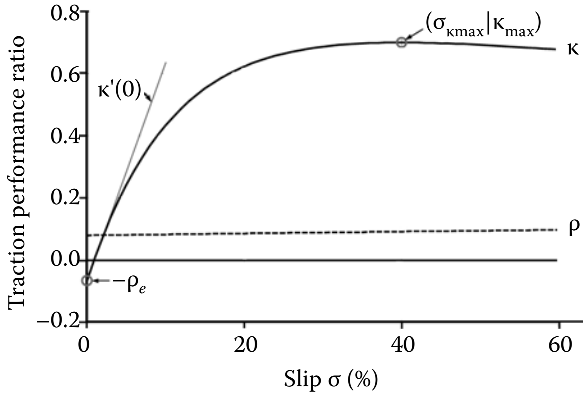

Figure 1. Net traction ratio and rolling resistance ratio over slip

Converting the coefficients

After the coefficients σ_{pull}, κ_{max}, ρ_e and κ'(0) have been calculated (Eqs (20)–(26)), the curves for the tire behaviour are already defined. To calculate the values for different slip and displaying them as in Figure 1, they have to be converted into coefficients a_1 to d_1 in Eq. (10). As shown by Schreiber & Kutzbach (2007), this can be done in 4 steps:

(1) The absolute gradient κ'(0) has to be converted into the standardized gradient κ_{sta}'(0), which means in relation to the local maximum of the curve.

$$\kappa'_{sta}(0) = \kappa'(0) \frac{\sigma_{\kappa max}}{\kappa_{max} + \rho_e} \quad (12)$$

(2) The backup-parameter p has to be solved numerically by equation (13).

$$\kappa'_{sta}(0) = \frac{(p-1) \times \ln(p)}{1 + p \times (\ln(p) - 1)} \quad (13)$$

The inverse function cannot be calculated explicitly, however, satisfactory values can be calculated also by the approximated inverse function.

$$p \approx e^{\frac{\ln(\kappa'sta(0)) - 0.683}{-0.194}} \quad (14)$$

(3) The next step is to calculate b_1 and c_1 using Eqs (15) and (16).

$$b_1 = \frac{\kappa_{max} + \rho_e}{1 - p(1 - \ln(p))} \quad (15)$$

$$c_1 = -\frac{\ln(p)}{\sigma_{\kappa\,max}} \quad (16)$$

(4) Calculate a_1 and d_1 using Eqs (17) and (18).

$$d_1 = p \times b_1 \times c_1 \quad (17)$$

$$a_1 = b_1 - \rho_e \quad (18)$$

With these equations, parameters a_1 to d_1 can be determined and used in Eq. (10) to calculate the curves for the net traction ratio.

Determination of the coefficient

To estimate these new, characteristic parameters for different tire- and soil-conditions, the first step was to calculate them for 850 curves measured (Schreiber & Kutzbach 2006). Steinkampf & Jahns (1986) observed the following tire-characteristics in his tests: tire labelling, inflation pressure, lug height, running direction, tire load, driving velocity, and the dynamic rolling radius. As the soil parameters, the soil type, tillage conditions (not tilled, cultivated, ploughed, ...), soil surface, and natural cover (Stubble, grass land, ...), preceding crop, moisture content and pore volume specify the traction tests. This provides a large database to fit the empirical functions and calculate the specific parameters from Figure 1. For an improved practical use, the model function input parameters were chosen differing from the database parameters. They are displayed in Table 1, all the parameters having relative values between 0 and 1 (0–100%).

RESULTS

Soil and tire parameters to calculate the coefficients

To figure out the influence of the soil and tire parameters on the specific coefficients, their correlation is investigated by Steinkampf's measurements. As an example, the maximum net traction ratio is displayed as a function of the clay content (Figure 2). The vertical alignment of the points results from the soil classes, in which the tests of the database were divided. In this case, all 850 values are used without looking for *ceteris paribus* conditions, which becomes obvious in the diffusion of the values for one clay content. However, the large number of values compensates this effect and the trend can be evaluated by the gradient of the linear fitting.

Another possibility to evaluate the relations is to use only tests with *ceteris paribus* conditions, and if there are more than 10 available, the values can be fitted linearly, as for example the inflation pressure and the maximum net traction ratio κ_{max} in Figure 3.

As shown, the linear approximation gives a good result, the gradient is calculated for these 32 values, but for different *ceteris paribus* conditions this gradient can differ. To compensate this effect, many

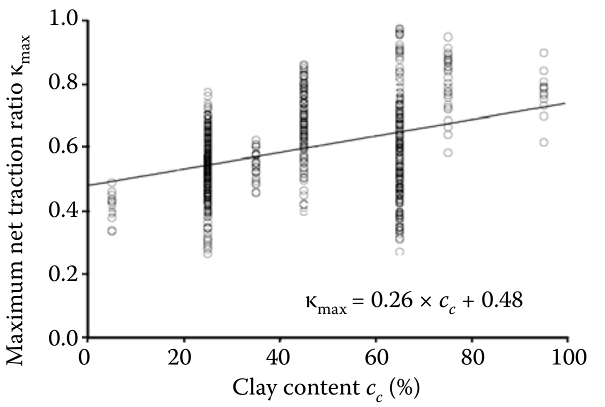

Figure 2. Maximum net traction ratio over clay content for 850 measured curves

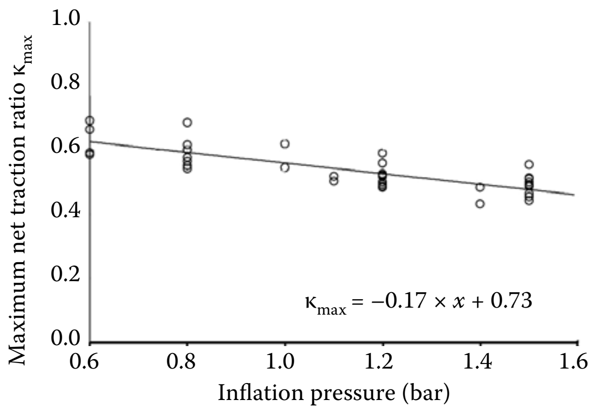

Figure 3. Maximum net traction ratio and inflation pressure for 32 measured curves

correlations have to be calculated for one parameter and the mean value of all these correlations can be chosen to characterise the dependency. To consider the correlations in the modelling equations, the gradients cannot be used directly, because the resulting range of values can scatter too much or too little. Thus, the minimum and the maximum values were chosen for each coefficient and the trend values were used to calculate the influence of the tire and soil conditions in relation.

For further simplification, the three tire parameters are combined into one new parameter, which is calculated as follows:

$$k_{tire} = \frac{k_{radius} + k_{width} + 1 - k_{pressure}}{3} \qquad (19)$$

This new parameter k_{tire} is a benchmark for the size of the contact patch, which increases with the increasing radius, width, and decreasing inflation pressure. Even if this is only an inexact value, which does not consider any soil conditions, the correlations between the tire behaviour and the modelling functions can be shown. This one tire parameter adequately represents the influence on the tractive behaviour compared to 5 soil parameters, because changes in soil conditions influence the tractive performance much more than the changes in the tire dimensions (Upadhyaya *et al.* 1989).

All parameters have an interdependent influence on the tire behaviour, but for almost all of them the trend remains the same. For example, parameters k_{tire} and $k_{strength}$ are strongly interdependent, but a larger contact patch is always good for a higher net traction ratio. The factor of the influence changes, but contrary behaviour is not reasonable. However, there exists one exception. The trend for the rolling resistance ratio is influenced contrarily by the parameters k_{tire} for loose and hard soil surfaces. It can be shown that for loose soil, a large contact patch is advantageous because of less sinkage and

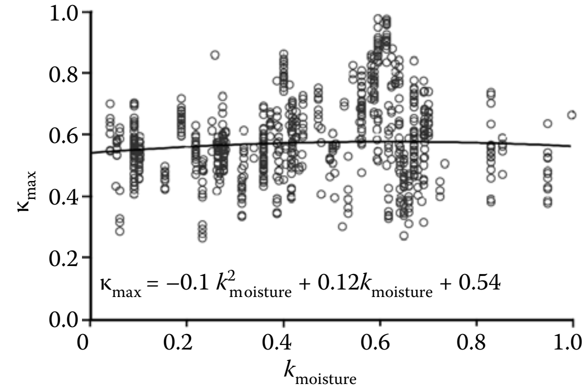

Figure 4. Maximum net traction ratio and inflation pressure for 32 measured curves

soil deformation. For a hard and dry stubble field, a smaller contact patch is of advantage, as the rolling resistance results mainly from the tire deformation and the friction in the contact patch. Thus, parameter k_{tire} influences the value of the rolling resistance ratio positively on hard soil and negatively on loose soil. This effect appears accounted linear in Eq. (20). More interdependences between the parameters are not considered in this model because they cannot be expected and could not be shown by the analysis of Steinkampf's data.

It is a fact that, for the net traction ratio, a moisture content between 15% and 20% is the optimum, for higher and lower moisture contents the maximum value is lower. Steinkampf's measurements, shown in Figure 4, support this observation.

Therefore, parameter $k_{moisture}$ is considered quadratic and not linear, as shown in Eq. (20). The disadvantage is that the influence of this parameter is rather too low, but if it was considered linear, the optimum occurred for extremely wet conditions, which is even more unrealistic as a too low influence. The remaining parameters shown in Table 1 are considered linear, and that keeps the equations simple.

Table 1. New input parameters for the traction equations with their minimum- and maximum-conditions

	Value of the parameter			Model function's input parameters
Natural cover (roots)	tilled	stubble field	grassland	k_{cover}
Upper soil strength	very loose soil		compacted soil	$k_{strenth; A}$
Lower soil strength	very loose soil		compacted soil	$k_{strenth; B}$
Clay content	pure sand		pure clay	k_{clay}
Soil moisture content	dry (5% moisture)		wet (30% moisture)	$k_{moisture}$
Tire radius	50 cm (small tire)		90 cm (big tire)	k_{radius}
Tire width	25 cm		80 cm	k_{width}
Inflation pressure	0.5 bar		2 bar	$k_{pressure}$

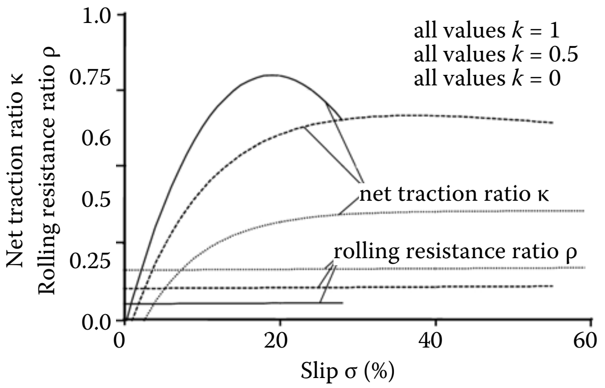

Figure 5. Simulated curves for extreme *k*-values

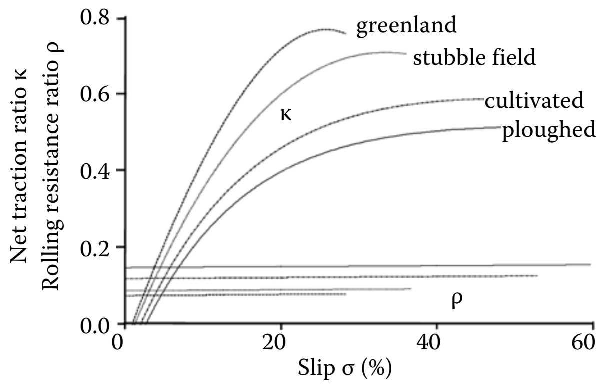

Figure 6. Four simulated curves for different tire-soil-behaviour

For a further optimisation of the model, more tests have to be performed and, if there are more interdependences or nonlinear relations, they could be considered in the prediction equations.

The interpretation of the new database is not yet finished, and the analysis of further measurements is needed to optimise this model for the traction prediction, but even now the results are good and display a realistic tire behaviour. If no significant relation could be found between the input parameters and the characteristic coefficients, these are not included in the equation for that value.

Proposed equation for traction

The resulting prediction equations comprising the influence of soil and tire parameters are as follows:

$$\kappa_{max} = 0.31 + 0.13k_{cover} + 0.11k_{strenth;A} + 0.09k_{strenth;B} + 10.07k_{clay} + 0.09\,(-4k_{moisture}^{2} + 4k_{moisture}) + 0.13\,k_{tire} \quad (20)$$

$$\sigma_{\kappa max} = \frac{55 - 18k_{cover} - 12k_{strenth;A} - 8k_{strenth;B} - 6k_{clay} + 8k_{moisture}}{100} \quad (21)$$

$$\kappa'(0) = 5 + 2.8k_{cover} + 1.3k_{strenth;A} \quad (22)$$

The internal rolling resistance ratio ρ_i increases with bigger tires and lower inflation pressure.

$$\rho_i = 0.015 + 0.01 \times k_{tire} \quad (23)$$

The rolling resistance ratio is calculated by:

$$\rho(\sigma=0) = 0.18 - 0.02\,k_{cover} - 0.06k_{strenth;A} - 0.05\,k_{strenth;B} - (k_{strenth;A} + k_{streth;B} - 1) \times 0.03\,k_{tire} \quad (24)$$

The gradient of this rolling resistance ratio can be approximated linearly with the slip. The values differ in a small range for all measurements and the influence of this value is not that important for the tire behaviour. This, it is considered as a constant value.

$$\rho_{gradient} = 0.013 \quad (25)$$

The external rolling resistance ratio ρ_e is the main part of the total rolling resistance ratio.

$$\rho_e = \rho - \rho_i \quad (26)$$

Examples for net traction ratio and rolling resistance ratio

One advantage of this model is, that even for extreme assumptions concerning the k-values, like all *k*-values = 1 or all *k*-values = 0, the results are not unrealistic. The curves show an extreme behaviour, however, a net traction ratio higher than 1 or comparable absurd results are avoided by this model, Figure 5.

To figure out the quality of these equations, these were used for defined tire and soil conditions to calculate the net traction ratio and rolling resistance ratio. As an example, four different soil/ field – conditions are used to show the results of the model. The results are shown in Figure 6.

Table 2 shows the respective values. In the first third, the tire and soil parameters are shown. They can be easily assumed for any soil condition.

It is obvious that, on a cultivated field, there is no biological cover and the upper soil is very loose. In the second part of the table the new, characteristic coefficients are shown, calculated by Eqs (20) to (26). They already show the best traction conditions on the grass land, as they can be compared easily and allow an interpretation of the tire behaviour. In the last part of the table, the parameters derived from Eqs (10) and (11) are shown, as calculated by Eqs (12)

Table 2. Examples for 4 different soil conditions (used tire: 540/65R30)

		Stubble field	Grass land	Ploughed	Cultivated
Tire and soil parameters	k_{cover}	0.5	0.9	0.0	0.0
	$k_{strenth; A}$	0.6	0.7	0.0	0.25
	$k_{strenth; B}$	0.8	0.8	0.1	0.6
	k_{clay}	0.5	0.5	0.5	0.5
	$k_{moisture}$	0.5	0.6	0.5	0.5
	k_{tire}	0.6	0.6	0.6	0.6
Characteristic κ- and ρ-coefficients	κ_{max}	0.7073	0.7667	0.5133	0.5858
	$\sigma_{\kappa max}$	0.3340	0.2580	0.5520	0.4820
	$\kappa'(0)$	5.1092	5.2293	5.0000	5.0000
	ρ_i	0.0203	0.0203	0.0203	0.0203
	ρ_e	0.0641	0.0517	0.1243	0.0963
	$\rho(0)$	0.0844	0.0720	0.1446	0.1166
	ρ'	0.0130	0.0130	0.0130	0.0130
Coefficients of equations (11) and (12)	a_1	6.775504	0.904692	0.575806	0.757757
	b_1	6.839570	0.956358	0.700072	0.854023
	c_1	1.712710	–3.658403	7.304972	6.194184
	d_1	6.611145	–8.991432	0.090685	0.267193
	a_2	0.0844	0.0720	0.1446	0.1166
	b_2	0.0130	0.0130	0.0130	0.0130

to (18). These values are unsuitable for interpretation but needed to display the curves.

The curves do not fit all values measured, which is hardly possible, but the results are realistic for further calculations and they describe standard tire behaviour for special conditions. For example a high net traction ratio at low slip values on grass land. This can be explained by the grass cover, which holds the tire and a high net traction results. After the grass cover is sheared off at slip values between 20% and 30%, the net traction decreases. Another point is a high rolling resistance ratio for cultivated and ploughed soils. All these model curves agree well with the tire behaviour in the field.

CONCLUSIONS

The results of the proposed equations are good, even if they have to be further optimised. This can happen by analysing more different traction tests and calibrating the numeric values of the equations. If the tests show more interdependent or nonlinear behaviour, the equations can be extended to take this into account.

The proposed empirical equations give a good opportunity to estimate the tire behaviour for any kind of agricultural tires used on farmland. The main advantage compared to other models is that the results can be calculated by some equations without the need of complex models. The input parameters are easy to measure or to estimate for standard soils, which is essential for further vehicle modelling, and the results are realistic and representative for the tractive behaviour in the field.

References

Armbruster K., Kutzbach H.D. (1989): Development of a single wheel tester for measurements on driven angled wheels. In: Proc. 4th European Conf. ISTVS, Bd. 1, Wageningen, 8–14.

Bekker M.G. (1956): Theory of Land Locomotion. The Mechanics of Vehicle Mobility. Ann Arbor. The University of Michigan Press.

Bekker M.G. (1960): Off-the-road Locomotion. Research and Developments in Terramechanics. Ann Arbor. The University of Michigan Press.

Du Plessis H.L.M. (1989): The combined lateral and longitudinal forces on a 18.4-35/15-35 tractor tyre. In: Proc. 11th Int. Congr. Agricultural Engineering, Bd. 3, Dublin, 1755–1761.

McAllistar M. (1979): A rig for measuring the forces on a towed wheel. Journal of Agricultural Engineering Research, **24**: 259–265.

Schreiber M. (2006): Kraftstoffverbrauch beim Einsatz von Ackerschleppern im besonderen Hinblick auf CO_2-Emissionen. [Ph.D. Thesis.] Universität Hohenheim, Shaker Verlag.

Schreiber M., Kutzbach H.D. (2006): A traction prediction model for agricultural tyres. In: 10th European Conf. ISTVS, October 3–6, 2006, Budapest.

Schreiber M., Kutzbach H.D. (2007): Comparison of different zero-slip definitions and a proposal to standardize tire traction performance. Journal of Terramechanics, **44**: 75–79.

Smulevich I., Ronai D., Wolf D. (1994): A new field single wheel tester. In: Proc. 12th Int. Congr. AgEng. August 29 – September 1, 1994, 510–511, Paper 94-D-034.

Steinkampf H. (1974). Ermittlung von Reifenkennlinien und Gerätezugleistungen für Ackerschlepper. [Ph.D. Thesis.] TU Braunschweig, Landbauforschung Völkenrode, Sonderheft 27.

Steinkampf H., Jahns G. (1986): Betriebseigenschaften von Ackerschlepperreifen bei unterschiedlichen Einsatzbedingungen. Numerische Beschreibung der Betriebseigenschaften von Ackerschlepperreifen. Landbauforschung Völkenrode, Sonderheft 80.

Upadhyaya S.K., Wulfsohn D. (1990): Review of traction prediction equations. In: Int. Winter Meeting of the ASAE. Chicago.

Upadhyaya S.K., Wulfsohn D., Jubbal G. (1989): Traction prediction equations for radial ply tyres. Journal of Terramechanics, **26**: 149–175.

Upadhyaya S.K., Wulfson D., Mehlschau J. (1993): An instrumented device to obtain traction related parameters. Journal of Terramechanics, **30**: 1–20.

Wismer R.D., Luth H.J. (1973): Off-road traction prediction for wheeled vehicles. Journal of Terramechanics, **10**: 49–61.

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Abstrakt

Schreiber M., Kutzbach H.D. (2008): **Vliv půdy a pneumatik na pohon.** Res. Agr. Eng., **54**: 43–49.

Tahová síla, prokluz a valivý odpor jsou hlavními kriterii pohonu terénních vozidel. Kromě motoru je tahová síla ovlivněna vlastnostmi půdy a pneumatik. Tyto vlastnosti musí být popsány omezeným počtem parametrů, které se dají jednoduše určit. K analýze 850 trakčních křivek byly užity empirické rovnice, které byly naměřeny a publikovány Steinkampfem. Výsledkem analýzy bylo určení několika důležitých parametrů, tří parametrů charakterizujících pneumatiku (poloměr, šířka, tlak nahuštění) a pět půdních parametrů (půdní povrch, pevnost horní části půdy, pevnost spodní části půdy, obsah jílu, půdní vlhkost). Tyto parametry s relativními hodnotami mezi 0 a 100 % jsou užity k určení rovnic pro předpověď pohonu. Hlavními kroky k dosažení tohoto cíle jsou: rozšíření rovnice prokluzu o lineární člen prokluzu, a popis této rovnice 4 významnými charakteristickými koeficienty: souřadnicemi x a y u κ-maxima ($\sigma_{\kappa max}$, κ_{max}), úseku na ose y ρ_e, a gradientu κ při nulovém prokluzu (κ'(0)).

Klíčová slova: pneumatika; pohon; prokluz

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