APPLICATION OF TIRE RATING WITH AIM TO IMPLEMENT THE MATTER ON AGRICULTURAL TIRES

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Abstract

The soil compaction rating of agricultural tires, in term Soil Compaction Effect of tires (SCE index), is presented in the paper. Principal task of tire SCE is used to predict a compaction risk of tire under arbitrary combinations with inflation pressure and tire load. SCE improves the originally used Compaction Capacity of tire (tire CC-rating). Primarily, SCE evaluation of tire includes a calculation of standardized tire footprint contact area for adequate combinations of load limits and inflation pressure used in a range of nominal tire manufacture's dimensions according to ETRTO standards. Compaction effect of standardized contact area size is converted using compaction function in given contact pressure range. The SCE conception corresponds with tire CC-rating approach since adequate mean contact pressure can be converted into compaction function, i.e. the application of the same conversion rule for combination of actual versus standardized parameters for corresponding inflation pressure level. SCE index offers a realistic prediction of the compaction level for any soil type under individual combination of tire size, load and inflation pressure in depth range 20 - 50 cm below a ground surface. It must be considered as the advantageous indicator of ecological tire operations on cultivated crop producing land.

Keywords: SCE index, agricultural tires, contact pressure, contact area

1. Introduction

Nowadays, professionals in the industry and farming still miss comparative technical data indicating the potential of agricultural vehicles and machinery to inflict compaction damage upon the cultivated soil. It´s primarily a matter of agricultural tires even if they are loaded and inflated according to regulations because data refer to operation on firm surface. The general trend is to restrict the excessive soil compaction by loaded wheels of farm power and machinery. Håkansson and Petelkau (1994) advanced the fusion of science and praxis conception proposing general limits to axle loads. The sophisticated soil compaction modelling was reported by Bailey et al. (1996). Some of the numerous research and technical reports up to date have been aiming at elucidation of links between stress behavior and soil compaction state (e.g. Wulfson and Upadhaya (1991), Trautner et al. (2003), van den Akker (2004), Keller et al. (2007). Almost all of these conclusions confirm inaccuracies in outputs prediction when crucial parameters are compared with reality (Keller and Lamandé, 2010).

The carried out research in the Czech Republic is to avoid the complicated stress – strain theory and to relate soil compaction directly to the acting tire load using mean contact pressure in standardized tire's footprint area. This has been the cornerstone of the CC-rating approach which uses laboratory compaction experiments under strictly controlled conditions (Grečenko and Prikner, 2014).

The presented tire soil compaction potential evaluation, based on the principal studies published by Grečenko (1996) and Grečenko and Prikner (2014), includes the application of empirical prediction of individual tire contact area size using catalogue data only. Thus required mean contact pressure in a given contact area is converted into compaction function pattern. The final product of the presented approach is marked as a Soil Compaction Effect (SCE index).

2. Materials and methods

2.1 Definitions and calculation of the tire footprint area

For purposes of tire Compaction Capacity evaluation described by (Grečenko and Prikner, 2014), the tire footprint area has been represented by a virtual round pressure plate of the same area to compare the suitability of different tire sizes for field operation with realistic assessment of ground compaction. Using SGP equation (Surface-Grečenko-Prikner), nominal tire contact area S_T (cm^2) can be calculated with good precision using the tire dimensions published in manufacturers' technical catalogues, which mostly comply with official manuals (e.g. ETRTO, 2008). The SGP equation has conventional form:

$$S_T = cb_t\sqrt{d_t^2 - 4r_s^2} = \\ = (0.927 + 0.761AR - 1.215AR^2)b_t\sqrt{d_t^2 - 4r_s^2} \quad 1$$

, where: c − scaling factor depends on AR (aspect ratio of tire section), $AR = (d_t - d_r)/2b_t$ (-); b_t − tire section; d_t − tire outer diameter; r_s − static loaded radius.

In presented SCE conception, the prediction of individual tire footprint area S_{Tx} (cm^2) uses tire catalogue's parameters for any tire load and inflation pressure combination. The SCE index supersedes offered FCC rating (Field Compaction Capacity) aimed on individual tire inflation pressure modification requirements under any tire load (Prikner, et al. 2017). Actually, latest experiments have revised the scaling factor $c = f(AR, p_i)$ for modern traction tires, thus complemented SGP equation reads a form:

$$S_T = c_c b_t\sqrt{d_t^2 - 4r_s^2} \\ = (2.233 + 3.22AR - 1.51AR^2)b_t\sqrt{d_t^2 - 4r_s^2} \quad 2$$

Generally, tire catalogues include the nominal loads W_N for adequate inflation pressure p_i and speeds (km/h). The nominal tire footprint area for any line of nominal catalogues' combination load and inflation pressure W_N / p_i will be denoted S_{TN}.

Calculation of tire footprint area includes comparison between tire nominal sidewall stiffness C_N (kN/cm) and relevant tire deflection f (cm). The static radius r_s size, tire manufactures apply the combination of nominal tire load and inflation pressure 160 kPa for speed limit 30 km/h (ETRTO, 2008). Corresponding load limit W_N for a given inflation pressure can be specified with the use of the given static radius r_s (speed 30 km/h); however, nominal tire load deflection f_N (cm) is an average value over the catalogue range of inflation pressure since the static radius r_s does not remain strictly constant. The tire nominal sidewall stiffness for required speed level 30 km/h will be:

$$c_N = \frac{W_N \,.\, g}{f_N} \quad 3$$

, where: C_N – nominal tire sidewall stiffness; g − gravity constant; f_N – nominal deflection for speed 30 km/h.

The nominal tire deflection f_N is product of catalogue values for speed 30 km/h. There is advantageous to compare nominal deflection f_N with a maximum of tire deflection f_M (refers to speed 10 km/h):

$$f_M = \frac{\Delta W \,.\, g}{c_N} \quad 4$$

, where ΔW (kg) presents a difference of load limits under constant inflation pressure:

$$\Delta W = W_{N\,(10)} - W_{N\,(30)} \quad 5$$

, where: $W_{N\,(10)\,/\,(30)}$ – nominal loads for speed 10 and 30 km/h, respectively.

Thus appropriate static radius $r_{s(10)}$ related to the deflection f_M will be:

$$r_{s\,(10)} = r_s - f_M \quad 6$$

, where: r_s – catalogues' tire static loaded radius.

Using of the Eq. 6, the coefficient of tire deformation ε_d as parameter of tire footprint area change for catalogues' combinations W and p_i reads:

$$\varepsilon_d = 1 - \frac{r_{s\,(10)}}{r_s} \quad 7$$

, where: $r_{s\,(10)}$ – tire static loaded radius for speed 10 km/h; (see Eq. 6).

Modification of arithmetic progression model a_n, product a_{tx} can reliably describe uniformly decreasing (linear trend) of tire footprint area size:

$$a_n = a_1 + (n-1)d_a \quad 8a$$

$$a_{tx} = (n-1)\varepsilon_d \quad 8b$$

, where: $a_1 = 0;\ n \geq 1;\ n \in N$; ($a_1$ – arithmetic progression; n – n^{th} term of the sequence $a_n \Rightarrow a_{tx}$; $d_a \Rightarrow \varepsilon_d$ – the common difference of successive members; N – counting number).

The tire CC/SCE evaluation, catalogues' combinations W_N and p_i for speed level 10 km/h can describe a static tire load compaction effect sufficiently. Thus contact area S_{TN} for nominal catalogues' load and corresponding inflation pressure combination based on modification S_T (see Eq. 2) has a form:

$$S_{TN} = 0.92(1 - a_{tx})S_T \quad 9$$

, where: parameter 0.92 (–) represents a standard ratio of real width of tire thread pattern to catalogues' tire section b_t, (i.e. 92% reduction of b_t), this proved latest experiments; S_T - nominal tire contact area adopted from CC-rating.

Grečenko (1995) published the prediction of individual tire's footprint area A_0 using of correction factor α_A (ratio of actual to nominal contact area):

$$\alpha_A = \alpha_W^n = \left(\frac{W}{W_N}\right)^n \quad 10$$

, where: α_W^n – ratio of actual to nominal tire load; n - correction factor; W - actual load; W_N - nominal load.

The original value of correction factor $n = 2/3$ was recommended by Grečenko (1995). Latest experiments confirmed that the n value corresponds with AR and ε_d, respectively.

Progress in modification of correction factor $n \Rightarrow n_c$ relates to the aspect ratios AR (AR'') of tire as follows:

$$n_c = \frac{AR''}{AR} = \frac{h_t''/b_t''}{h_t/b_t} \quad 11$$

, where AR'' depends on corrected tire thread pattern (real) width b_t'', (see Eq. 9):

$$b_t'' = 0.92 b_t \quad 12$$

When tire is loaded, section height $h = r_s - d_r / 2$ can be reduced using static loaded radius $r_{s\,(10)}$ for speed 10 km/h:

$$h_t'' = r_{s(10)} - d_r/2 \qquad 13$$

Thus coefficient n_c based on tire type and size reaches the range 0.6 − 0.87. Prediction of individual tire contact area S_{Tx} (cm^2) under any load and inflation pressure combinations, the Eq. 9 requires modification using correction factor α_A (Eq. 9):

$$S_{Tx} = \alpha_A S_{TN} \Rightarrow \left(\frac{W}{W_N}\right)^{n_c} S_{TN} \qquad 14$$

2.2 *Definitions and calculation of the tire SCE index*

The tire SCE index is a dimensionless number that compares the state of soil compaction under a loaded tire with the critical compaction of standardized clay loam soil type (identical conception as CC-rating). It is computed from the same formula pattern as the former Compaction Capacity (tire CC-rating) (Grečenko and Prikner, 2014):

$$\begin{aligned} CC \Rightarrow SCE &= 1000\,[(\rho_{ds} / \rho_{dl}) - 1] \\ &= 1000[(\rho_{ds}/1420) - 1] \end{aligned} \qquad 15$$

The soil dry density ρ_{ds} is the average value of the function $\rho_d = f(z)$ after loading in the depth range z = 20 to 50 cm, approximately computed from four dry density readings ρ_{dx} at the depths 20, 30, 40 and 50 cm below the field surface:

$$\rho_{ds} = \tfrac{1}{4}\,(\rho_{d20} + \rho_{d30} + \rho_{d40} + \rho_{d50}) \qquad 16$$

, where: ρ_{dl} – critical value of soil dry density (clay loam = 1420 kg/m^3) limiting the growth of field crops on loamy soils (Lhotský, 2000).

The CC rating (Grečenko and Prikner, 2014) proposed the computation of just the nominal tire contact area S_T for the nominal load and inflation pressure combinations range that might guarantee simple readings of soil density expected within the stated mean contact pressure range.

This access was found out as impractical for the commercial or operating employment because under a given tires' load state referring to inflation pressure according to present experimental evidence, the corresponding mean contact pressure behaviour in contact area describes precisely soil profile damage after external load.

2.3 *Experiments*

Tire footprint areas were measured with the improved precision on a laboratory stand including hydraulic actuation attachment and electronic scales up to 65 kN, (Fig. 1). The imprints were made on 1.2 m^2 white chipboard plate placed and fixed on the weight platform 1.5 m^2. The inflation pressure was controlled by the AirBooster with nominal inflation pressure capacity p_{iN} = 400 kPa, (PTG Co., Germany). Five pairs of tire lugs of tire thread pattern were painted with ink. The real tire footprints S'_{T0} were exclusively of multiple imprint type when wheel required partial turn corresponded to lug width 5 cm approximately.

Fig. 1. *Testing of traction tire Mitas 650/65 R 38 (RD-03) and laboratory equipment.*

Subsequently, they were photographed together with the standard scale of 10 cm. The tire footprint areas S_{T0} were determined using ImageJ software from the saved pictures (Fig. 2). The pictures were transformed by the internal software scale set up on 10 cm as the length of the standard that corresponds with reality. Accuracy of any footprints evaluation guaranteed a reliability of tire deformation characteristic statement for nominal combinations p_i and W_N, respectively.

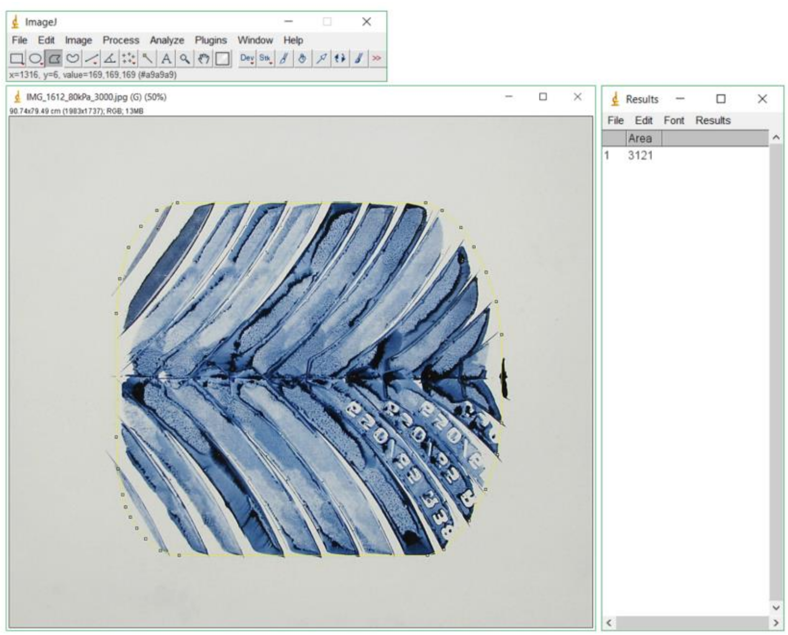

Fig. 2. *Print screen of ImageJ outputs for tire multiple footprint area Mitas 650/65 R 38; (tire load 3000 kg, inflation pressure 80 kPa).*

2.4 Statistical evaluation

Software Statistica Cz 12 (StatSoft, Inc.) was used to evaluate the prediction accuracy of tires' footprint area. The using Eq. 14, correctness of footprint area estimation was revised with the dimensions of tire 650/65R38 selected from tire manufactures. This yields the root mean square error (*RMSE*) between published and predicted footprint area. The *RMSE* is given as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(|S_{TP} - S_{TM}|)^2} \qquad 17$$

, evaluation includes the fit to the measured data by means of the bias in to form:

$$bias = \frac{1}{n}\sum_{i=1}^{n}(|S_{TP} - S_{TM}|) \qquad 18$$

, where: n - number of observations; S_{TP} - predicted contact area; S_{TM} - contact area published in manufactures' tire data book.

3 Results and discussion

Table 1 presents tire parameters of tested tire's size 650/65 R 38. It appears that these formulae can be branded as fully satisfactory but the given values by the tire manufactures must also be taken into account. The use of Eq. 14, Table 1 demonstrates the accuracy in prediction of footprint areas S_{TP} for tire size 650/65 R 38 of chosen manufactures. Evaluation confirms the theory of suitability to apply the stiffness tire sidewall into calculation of tire footprint area as a main factor affecting progressive change of footprint area size. Relative Error (*RE*) range (3.01 – 3.37 %) confirms very good accuracy in prediction of tire footprint area, when tire manufacture tolerates 12% difference, generally; (Mitas tires product manager advice).

Table 1. Catalogues' 650/65 R 38 tire size from selected manufactures; ETRTO (2008): p_i = 160 kPa, speed 30 km/h.

650/65 R 38	b_t [cm]	d_t [cm]	r_s [cm]	W_N [kg]	S_{TM}* [cm^2]	S_{TP} [cm^2]	*RE* [%]
Firestone	635	1850	815	4645	3096	**2985**	3.37
GoodYear	653	1839	823	4415	2905	**3031**	3.01
Michelin	646	1819	801	4740	2999	**3098**	3.09
Mitas	622	1840	810	4745	2700	**2745**	3.02
Trelleborg	645	1814	815	4707	2999	**2921**	3.10

* Tire manufacture data book; R^2 = 0.54; p = 0.1283; *RMSE* = 96.03 cm^2, *bias* = 91.80 cm^2.

Theory of Soil Compaction Effect (SCE index) is based on effect of contact pressure in circular contact area. Identical conception as CC rating approach (Grečenko and Prikner, 2014) applies modification of mean contact pressure q_s (kPa) into contact pressure q (kPa) in term:

$$q = (1.06 - 0.06\lambda)q_s \qquad 19$$

, where parameter λ as a ratio of width b and length l of tire contact area gives accuracy to the Eq. 19:

$$\lambda = l/b. \qquad 20$$

The advantageous substitution of original footprint shapes by circular area for the radial type of traction tires is evident. Cross–ply type produces more oval or ellipse area shape; however, identical circular size produces similar outputs in term of mean contact pressure production. Figure 4 shows comparison of the size for different shapes of multiple tire footprints.

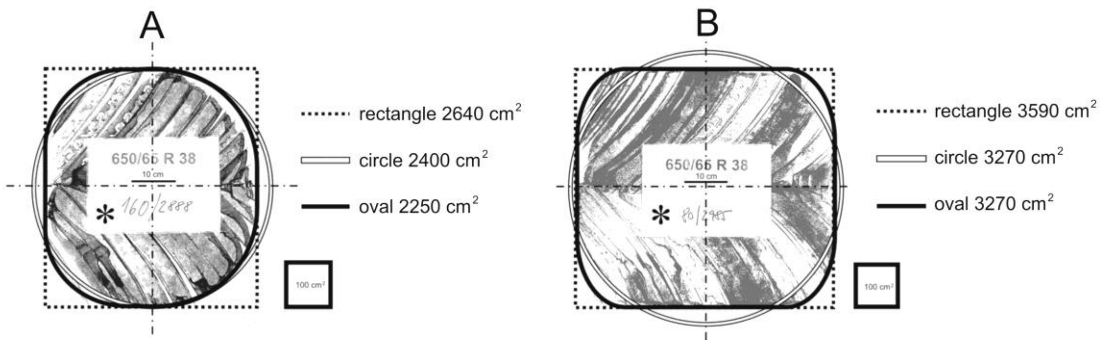

Fig. 4. *Part (A) multiple tire footprint (MITAS 650/65 R 38 RD-03) allows to compare contours and differences between regular shapes; Part (B) shows the effect of 50% underinflation state (160 → 80kPa) for similar tire load; 1000 cm² presents positive 30% contact area increasing (hard surface).*

Generally, the standardized footprint area on a hard ground disposes lower size then published one for a soft soil. In the terrain, tire contact area can be achieved by an increase 85%, if the thread pattern is fully pressed in to the soft surface (e.g. Schwanghart, 1991).

Tire soil compaction effect (SCE index) expresses a soil compaction risk of tires for any load capacity listed in catalogues' inflation pressure groups. Similarly, as CC rating, when tire's mean contact pressure is lower than 70 kPa, both starting S_{Tx} are identical, SCE values are considered as a 'soil friendly'. Figure 5 shows and proves the difference between SCE and CC indexes. Contact pressure in both conceptions has distinct purpose. In the CC rating as the standardized factor, contact pressure q supports evaluation simplicity with the use of the tires' contact maximal area S_T across the inflation pressure range. The SCE insists on precise contact area S_{Tx} calculation under a given load which produced contact pressure (Eq. 19). This transformation prefers a cubic polynomial.

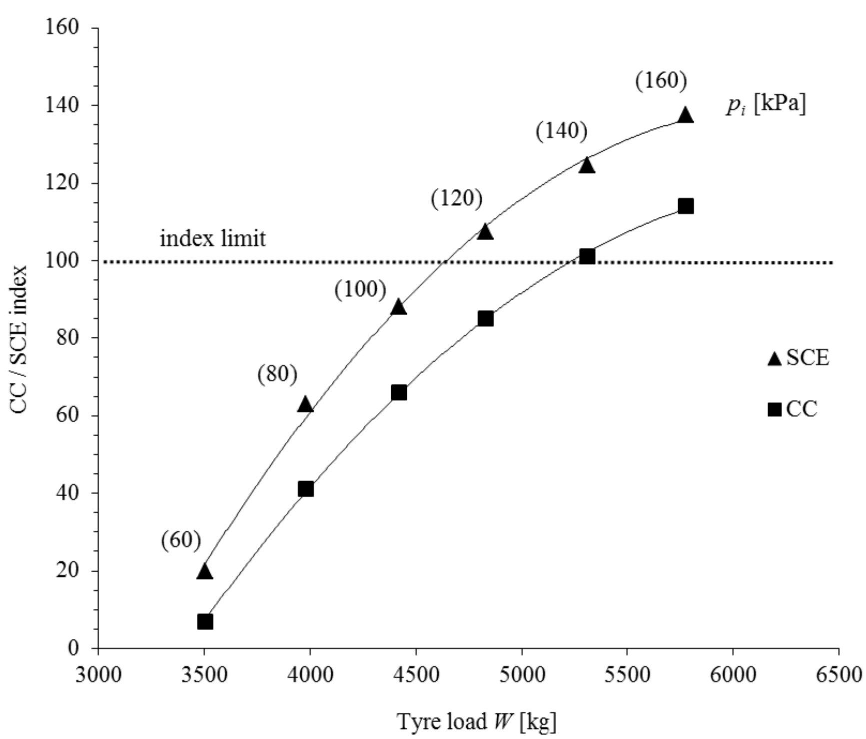

Fig. 5. *Comparison of SCE and CC quantification for nominal catalogues' load range in dependence on inflation pressure for speed 10 km/h; (Mitas 650/65 R 38 RD-03); compaction index limit reports to the extreme range of clay-loam soil dry density.*

The tire SCE approach is heading to supplement of the data books of tire manufacturers for specific agricultural vehicles; alternatively, SCE can be used as a tire load calculator in soil-friendly traffic propagation. Examples of application of SCE and CC indices are shown in Table 2 (*SVT* front tractor tires) and Table 3 (*SVT* rear tractor tires). Tire inflation pressure levels 160 and 120 kPa correspond to recommended road and field traffic, respectively.

Table 2. SCE index of selected front Super Volume Tires in comparison with original CC rating limits (speed 10 km/h) for standard inflation pressure 160 and reduction 120 kPa; *W* – load, W_N – nominal load.

SVT	600/70 R 30 152 D (155 A8)				620/75 R 30 163 B (163 A8)		
p_i [kPa]	160 – 120			p_i [kPa]	160 – 120		
W [kg]	S_t [cm^2]	q_s [kPa]	SCE	LC (kg)	S_t [cm^2]	q_s [kPa]	SCE
1500	1440 – 1635	102 –90	70 – 46	1500	1495 – 1690	98 – 87	59 – 37
2000	1718 – 1965	114 – 100	89 – 66	2000	1775 – 2020	111 – 97	77 – 57
2500	1970 – 2270	125 – 108	102 – 80	2500	2025 – 2320	121 – 106	87 – 71
3000	2200 – 2560	134 – 115	113 – 91	3000	2255 – 2605	131 – 113	93 – 80
3500	2420 – 2840	142 – 121	119 – 98	3500	2470 – 2880	139 – 119	96 – 86
$\frac{160\text{ kPa}}{120\text{ kPa}}$ W_N [kg]	S_t [cm^2]	q_s [kPa]	CC	$\frac{160\text{ kPa}}{120\text{ kPa}}$ W_N [kg]	S_t [cm^2]	q_s [kPa]	CC
4970	3530	137	109	5355	3760	139	114
4580		127	102	4780		124	103

Table 3. SCE index of selected rear Super Volume Tires in comparison with original CC rating limits (speed 10 km/h) for standard inflation pressure 160 and reduction 120 kPa; *W* – load, W_N – nominal load.

SVT	800/70 R 38 171 D (178 A8)				900/60 R 38 172 D (175 A8)		
p_i [kPa]	160 – 120			p_i [kPa]	160 – 120		
W [kg]	S_t [cm^2]	q_s [kPa]	SCE	W [kg]	S_t [cm^2]	q_s [kPa]	SCE
2500	2260 – 2700	109 – 91	115 – 90	2500	2285 – 2640	107 – 93	105 – 78
3000	2540 – 3020	116 – 98	123 – 100	3000	2590 – 3080	114 – 96	113 – 89
3500	2800 – 3325	123 – 103	129 – 108	3500	2880 – 3340	119 – 103	118 – 98
4000	3050 – 3600	129 – 108	134 – 115	4000	3153 – 3670	124 – 107	121 – 104
4500	3280 – 3900	135 – 113	138 – 120	4500	3450 – 4000	129 – 111	123 – 109
$\frac{160\text{ kPa}}{120\text{ kPa}}$ W_N [kg]	S_t [cm^2]	q_s [kPa]	CC	$\frac{160\text{ kPa}}{120\text{ kPa}}$ W_N [kg]	S_t [cm^2]	q_s [kPa]	CC
8960	6585	133	144	8820	7030	123	136
7965		118	133	7460		104	114

Grečenko in 2016 published the addition to the previous (Grečenko and Prikner, 2014) to specify the eCC index (equivalent Compaction Capacity) for critical parameters of various soil types (Table 4). The eCC index describes the tire soil compaction capacity for arbitrary soil in the same way as the CC index for standard soil.

Table 4. Critical soil parameters (soil compaction state limit); (Lhotský, 2000).

	C	*Cl*	*L*	*SL*	*LS*	*S*
$\rho_{d\ crit.}$	> 1,350	> 1,400	> 1,450	> 1,550	> 1,600	> 1,700
Porosity (% vol.)	< 48	< 47	< 45	< 42	< 40	< 38
PR	2.8–3.2	3.3–3.7	3.8–4.2	4.5–5.0	5.5	> 6.0

Legend: *C* – clay; *Cl* – clay loam; *L* – loam; *SL* – sandy loam; *LS* – loamy sand; *S* – sand; $\rho_{d\ crit}$ – critical limit of soil dry density; *PR* – penetration resistance.

Original CC or the latest SCE modification (see Eq. 15), compares ratio of soil compaction state to critical dry bulk density for clay-loam soil type (1420 kg/m^3) exclusively. The eSCE index using previous formula can be defined:

$$eCC \Rightarrow eSCE = [(CC + 1000)\rho_{dl} / \rho_d - 1000] \quad 21$$

The rear traction tire 650/65 R 38 is used routinely for agricultural tractors in the engine power range 180 – 210 hp and totally mass up to 11000 kg. Applying eSCE to different soil types, the Fig. 6 demonstrates evaluation of tire equivalent soil compaction effects for Mitas tire 650/65 R 38 (RD-03) for objective tire load standard 3000 kg.

When the value of eSCE = 100 is considered as an upper limit of permissible soil compaction state, the clay soil admits combination of tire load 3000 kg and inflation pressure 60 kPa. The index limit for clay loam soil type allows applying of the tire load 3000 kg at inflation pressures limit 140 kPa. The loam soil type enables to use tire load 3000 kg in presented inflation pressure range certainly. The outputs of tire compaction capacity indexes (CC, SCE, eCC, eSCE) confirm a high soil resistance to critical compaction state in the whole range of inflation pressures for sandy soil types demonstrably. The eSCE of tire is presented for standard hard ground conditions exclusively; however, eSCE can be reached about 30 units less when tire thread pattern lugs are fully pressed into the soil surface (see Fig. 7).

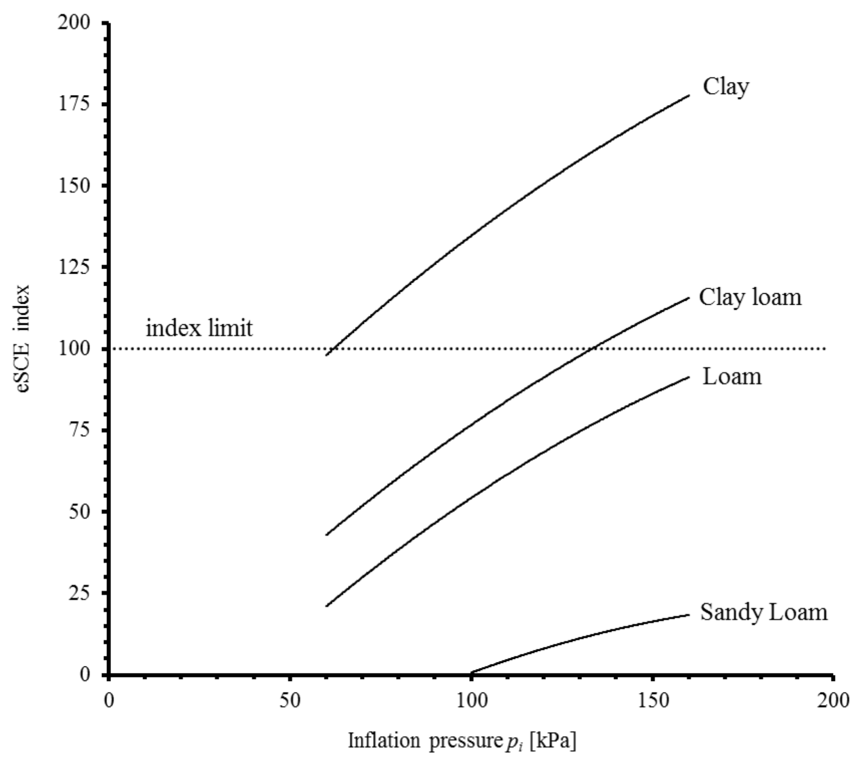

Fig. 6. *Trends of the eSCE in selected soil types for optimal tire load 3000 kg in dependence on inflation pressure; (Mitas 650/65 R 38 RD-03); eSCE index limit reports to the extreme range of soil dry density, referring to Clay loam standard.*

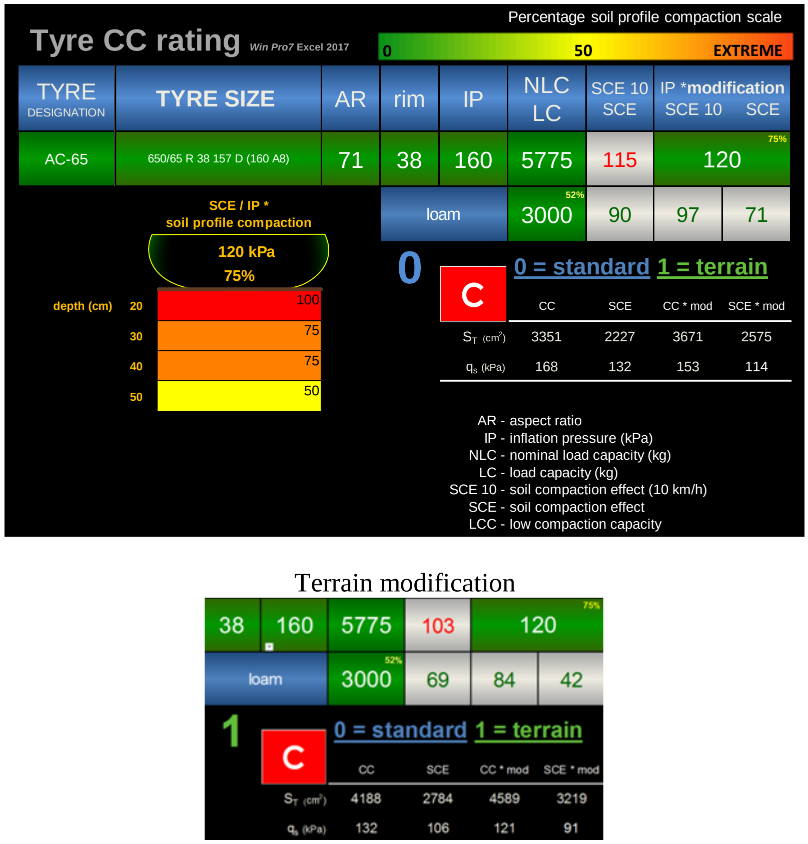

Fig. 7. Tire index SCE 10(eSCE) for nominal catalogue load at 10 km/h (160 kPa), combination of tire load 3000 kg and inflation pressure modification(120 kPa); the appendix shows terrain modification ("1"); (Mitas 650/65 R 38 RD-03); adjusted Loam soil type as a standard.

4 CONCLUSIONS

The paper describes prediction of the agricultural traction tire footprint area on a hard ground (area of the envelope to the contact patch) that can be applied more readily in agricultural engineering. The proposed approach enables to convert the content of tire catalogue data only. Such a conversion leads to the nominal footprint area which refers to any combination of inflation pressure and load listed in the catalogues. Progress in prediction includes the tire sidewall stiffness depending on tire static radius variability that guarantees to establish size of tire footprint area in the range of inflation pressure for any tire load. Thus tire CC index (rating) can be transformed into real compaction effect of tire marked as SCE 'Soil Compaction Effect' using polynomial function. The SCE, based on a given tire footprint on hard ground, can describe the actual tire compaction effect more precisely then linear interpolation of nominal load combinations applied in CC-rating approach. SCE modification into the eSCE refers to soil compaction risk for characteristic soil types. This is recommended for tire and machine manufactures to publish optimal tire inflation pressure levels or suggest advantageous combinations of type or size tires for field operations on moist soils.

Nomenclature

A_0	tire footprint area	[cm^2]
b	width of tire contact area	[cm]
b_t	tire section	[cm]
bias	systematic error	[cm^2]
c	scaling factor	[-]
c_c	corrected scaling factor	[-]
C_N	nominal tire sidewall stiffness	[kN/cm]
d_t	tire outer diameter	[cm]
d_r	rim diameter	[cm]
f	tire deflection	[cm]
f_N	nominal tire deflection	[cm]
f_M	maximum of tire deflection	[cm]
g	gravity constant	[m/s^2]
h_t	tire section height	[cm]
l	length of tire contact area	[cm]
n, n_c	correction factor	[-]
p_i	inflation pressure	[kPa]
PR	penetration resistance	[MPa]
q	contact pressure	[kPa]
q_s	mean contact pressure	[kPa]
r_s	static loaded radius	[cm]
RE	relative error	[%]
RMSE	root mean square error	[cm^2]
W	actual tire load	[kg]
W_N	nominal tire load	[kg]
S_T	tire contact area	[cm^2]
S_{TN}	nominal tire contact area	[cm^2]
S_{TP}	predicted tire contact area	[cm^2]
S_{TM}	manufacture tire contact area	[cm^2]
S_{Tx}	individual tire contact area	[cm^2]
S'_{T0}	real tire footprint area	[cm^2]
AR	tire aspect ratio	[-]
α_A	contact area correction factor	[-]
α_W	tire load correction factor	[-]
ε_d	coefficient of tire deformation	[-]
λ	tire dimension ratio	[-]
ρ_d	soil dry density	[kg/m^3]
ρ_{dl}	critical soil dry density	[kg/m^3]

References

Bailey, A.C., Raper, R.I., Way, T.R., Burt. E.C., Johnson, C.E. 1996. Soil stresses under a tractor tire at various loads and inflation pressures. Journal of Terramechanics, 33, 1–11.

ETRTO. Engineering design information. Brussels-Belgium: European tire and rim technical organization. 2008.

Grečenko, A. 1995. Tire footprint area on hard ground computed from catalogue values. Journal of Terramechanics, 32, 325–33.

Grečenko, A., Prikner, P. 2014. Tire rating based on soil compaction capacity. Journal of Terramechanics, 52, 77–92.

Grečenko, A. 2016. Tire compaction capacity rating on non-standard soil. Journal of Terramechanics, 66, 59–61.

Håkansson, I., Petelkau, H. 1994. Benefits of limited axle load. In: Soane, B.D. and Van Ouwerkerk, C. (Eds.), Soil Compaction in Crop Production. Developments in Agricultural Eng. 11, Elsevier, Amsterdam, The Netherlands, 479–99.

Keller, T., Défossez, P., Weisskopf, P., Arvidsson, J., Richard, G., 2007. SoilFlex: a model for prediction of soil stresses and soil compaction due to agricultural field traffic including a synthesis of analytical approaches. Soil Tillage Research, 93, 391–411.

Keller, T., Lamandé, D. 2010. Challenges in the development of analytical soil compaction models. Soil Tillage Research, 111, 54–64.

Lhotský, J. 2000. Soil compaction and measures against it [in Czech, abstract in English]. In: Study Inf. Plant Product, 7. Prague: Institute of Agric. and Food Ind. Informations.

Prikner, P., Kotek, M., Jindra, P., Pražan, R. 2017. Field compaction capacity of agricultural tyres. Agronomy Research, 15, 806-816.

Schwanghart, H. 1991. Measurement of contact area, contact pressure and compaction under tires on soft ground. Journal of Terramechanics, 28, 309–18.

Trautner, A., Arvidsson, J. 2003. Subsoil compaction caused by machinery traffic on a Swedish Eutric Cambisol at different soil water contents. Soil Tillage Research, 73, 107-18.

van den Akker, J.J.H. 2004. SOCOMO: a soil compaction model to calculate soil stresses and the subsoil carrying capacity. Soil Tillage Research, 79, 113–27.

Wulfsohn, D., Upadhyaya, S. 1991. Traction of low-pressure pneumatic tires in deformable terrain. SAE International, Technical Paper 911862.