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Field compaction capacity of agricultural tyres

P. Prikner[1,*], M. Kotek[1], P. Jindra[1] and R. Pražan[2]

[1]Czech University of Life Science Prague, Faculty of Engineering, Department of Vehicles and Ground Transport, Kamýcká 129, CZ16521 Prague, Czech Republic
[2]Research Institute of Agricultural Engineering, Drnovská 507, CZ161 01 Prague, Czech Republic
[*]Correspondence: prikner@tf.czu.cz

Abstract. The rating of soil compaction potential of agricultural tyres, in term Field Compaction Capacity (FCC index), is presented in the paper. Principal task of tyre FCC is used to predict a compaction risk of tyre under arbitrary combinations with inflation pressure and tyre load. FCC improves the originally used Compaction Capacity of tyre (tyre CC-rating) that expresses a compaction potential of single nominal tyre's contact footprint area for every catalogues load limits i.e. speed level under 10 km h^{-1} and relevant inflation pressures exclusively. Primarily, FCC evaluation of tyre includes a calculation of standardized tyre footprint contact area. Adequate combinations of load limits and inflation pressure are used in a range of nominal tyre manufacture's dimensions ('catalogue size') according to ETRTO standards. The contact area size strictly depends on coefficient of tyre stiffness and sidewall deflection; both of them are a function of inflation pressure. Compaction effect of standardized contact area size is converted using compaction function in given contact pressure range. Databank of soil compaction functions for original CC evaluation is unchanged. The soil dry density limit in FCC conception corresponds with tyre CC approach since adequate (individual) mean contact pressure can be converted into compaction function i.e. the application of the same conversion rule for combination: actual versus standardized contact area size; actual versus nominal load, both for corresponding inflation pressure level. Critical soil dry density values for every soil type are set according to pedologic standards. FCC index offers a realistic prediction of the compaction level for any soil type under individual combination of tyre size, load and inflation pressure in depths 20, 30, 40 and 50 cm below a ground surface. It must be considered as the advantageous indicator of ecological tyre operations on cultivated crop-producing land.

Key words: field compaction capacity, agricultural tyres, contact pressure, contact area.

INTRODUCTION

Enormous field traffic produces compaction of soil profile up to the depth 50 cm minimally. Soil deformation reduces soil regimes, biodiversity and plant growth (Gutu et al., 2015). It´s primarily a matter of agricultural traction tyres of vehicles or machinery even if they are loaded and inflated according to regulations because data refer to operation on firm surface. Håkansson in 1990 proposed to use the degree of compactness as a standardized parameter of soil profile damage. The scientific and practical approach of Håkansson & Petelkau (1994) has particularly appreciates for the definition of general limits to axle loads. The sophisticated approach of compaction modelling was reported by Bailey et al. (1996).

Nowadays, advanced research (e.g. in Sweden, Netherlands, Denmark, USA) is aiming at elucidation of links between stress field and compaction of the ground, e.g. Arvidsson & Håkansson (2014), van den Akker & Hoogland (2011), Xia (2011), Keller & Lamandé (2014), Schjønning et al. (2015), however, their conclusions confirm inaccuracies in outputs prediction when crucial parameters are compared with reality (Keller & Lamandé, 2014).

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 tyre load using mean contact pressure in standardized tyre's footprint area. This has been the cornerstone of the CC rating approach which uses laboratory compaction experiments under strictly controlled conditions (Grečenko & Prikner, 2014).

The presented tyre soil compaction potential evaluation, based on the principal study of this subject published in (Grečenko, 1996; Grečenko & Prikner, 2014; Grečenko, 2016), includes the development and application of empirical prediction of individual tyre's contact area size using catalogue's data only. Thus required mean contact pressure in a given contact area is converted into pattern of compaction function conversion. The final product of the presented approach is marked as a FCC index.

MATERIALS AND METHODS

Definitions and calculation of the tyre footprint area

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

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

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

In presented FCC conception, the prediction of individual tyre footprint area S_{Tx} (cm^2) uses tyre catalogue's parameters for any tyre load and inflation pressure combination. Generally, tyre catalogues include the nominal loads W_N (kg) for adequate inflation pressure p_i (kPa or bar) and speeds (km h^{-1}). The nominal tyre's footprint area for any line of nominal catalogue's combination load and inflation pressure W_N/p_i will be denoted S_{TN}.

Basic calculation of actual tyre footprint area includes comparison between tyre nominal sidewall stiffness C_N (kN cm^{-1}) and relevant tyre deflection f (cm). The static radius r_s assessment, tyre manufactures apply the combination of nominal tyre load and inflation pressure 160 kPa for speed limit 30 km h^{-1} (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^{-1}); however, nominal tyre 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 tyre nominal sidewall stiffness for required speed level 30 km h^{-1} will be:

$$c_{N(30)} = \frac{W_{N(30)}g}{f_{N(30)}}, \quad (2)$$

where: $c_{N(30)}$ – tyre sidewall stiffness (kN cm^{-1}); g – gravity constant (m s^{-2}); $f_{N(30)}$ – nominal deflection for speed 30 km h^{-1}.

The nominal tyre deflection $f_{N(30)}$ is product of catalogue's values for speed 30 km h^{-1}. There is advantageous to compare nominal deflection $f_{N(30)}$ with maximum tyre deflection $f_{x(10)}$ (refers to speed 10 km h^{-1}):

$$f_{x(10)} = \frac{\Delta W g}{c_{N(30)}}, \quad (3)$$

where: $f_{x(10)}$ – tyre deflection for speed 10 km h^{-1} (cm).
ΔW (kg) presents a difference of load limits under constant inflation pressure:

$$\Delta W = W_{N(10)} - W_{N\,(30)}, \quad (4)$$

where: $W_{N(10)/(30)}$ – nominal load (kg) for speed 10 and 30 km h^{-1}, respectively.
Thus appropriate static radius $r_{sx(10)}$related to the deflection $f_{x(10)}$ will be:

$$r_{sx(10)} = r_s - f_{x(10)}, \quad (5)$$

where: $f_{x(10)}$ – catalogue's tyre static load radius (cm).

Using of the Eq. 5, the coefficient of tyre deformation ε_d (-) as parameter of tyre footprint area change for catalogue's combinations W and p_i reads:

$$\varepsilon_d = 1 - \frac{r_{sx(10)}}{r_s}, \quad (6)$$

where: $r_{sx(10)}$ – tyre static load radius for speed 10 km h^{-1} (cm), (see Eq. 5).

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

$$a_n = a_1 + (n-1)d$$
$$a_{Tx} = (n-1)\varepsilon_d, \quad (7)$$

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

The tyre CC/FCC evaluation, catalogue's combinations W_N and p_i for speed level 10 km h^{-1} can describe a static tyre's load compaction effect sufficiently. Thus contact area S_{TN} (cm^2) for nominal catalogue's load and corresponding inflation pressure combination based on modification S_T (cm^2) (see Eq. 1) has a form:

$$S_{TN} = 0.94(1 - a_{Tx})S_T, \quad (8)$$

where: parameter 0.94 (–) represents a standard ratio of real width of tyre thread pattern to catalogue's tyre section b_t, (i.e. 94% reduction of b_t), this proved latest experiments; S_T – nominal tyre contact area adopted from CC-rating, (cm^2).

Grečenko (1996) published the prediction of individual tyre's footprint area A_0 using of correction factor α_A (ratio of actual to nominal contact area):

$$\alpha_A = \alpha_W^n = \left(\frac{W}{W_N}\right)^n, \qquad (9)$$

where: α_W^n – ratio of actual to nominal tyre load, (kg); n – correction factor; W – actual load (kg); W_N – nominal load (kg).

The original value of correction factor $n = 2/3$ was recommended by Grečenko (1996). Latest experiments confirmed that the n value corresponds with AR and ε_d, respectively. Thus coefficient n based on tyre type and size reaches the range 0.6–0.78.

Prediction of tyre's contact area S_{Tx} (cm^2) under any load and inflation pressure combinations, the Eq. 8 requires modification using correction factor α_A (Eq. 9):

$$S_{Tx} = \alpha_A S_{TN} = \left(\frac{W}{W_N}\right)^n S_{TN} \qquad (10)$$

Definitions and calculation of the tyre FCC

The tyre FCC index is a dimensionless number that compares the state of soil compaction under a loaded tyre 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 (CC-rating) (Grečenko & Prikner, 2014):

$$CC \Rightarrow FCC = 1{,}000\,[(\rho_{ds} / \rho_{dl}) - 1] = 1{,}000[(\rho_{ds}/1{,}420) - 1] \qquad (11)$$

The dry density ρ_{ds} (kg m^{-3}) 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:

$$\rho_{ds} = \tfrac{1}{4}\,(\rho_{d20} + \rho_{d30} + \rho_{d40} + \rho_{d50}), \qquad (12)$$

where: ρ_{dl} – critical value of soil dry density (clay loam = 1,420 kg m^{-3}) limiting the growth of field crops on loamy soils (Lhotský, 2000).

The CC rating (Grečenko & Prikner, 2014) proposed the computation of just the nominal tyre contact area S_T (cm^2) for the same load and inflation pressure combination 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 tyre's 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.

Experiments

Tyre 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 p_{im} = 400 kPa, (PTG Co., Germany). Five pairs of tyre lugs of tyre thread pattern were painted with ink. The real tyre footprints S'_{T0} (cm^2) were exclusively of multiple imprint type when wheel required partial turn corresponded to lug width 5 cm approximately.

Subsequently, they were photographed together with the standard scale of 10 cm. The tyre footprint areas S_{T0} (cm^2) 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 tyre deformation characteristic statement for nominal combinations p_i and W_N, respectively.

Figure 1. Testing of traction tyre Mitas 650/65R38 (RD-03) and laboratory equipment.

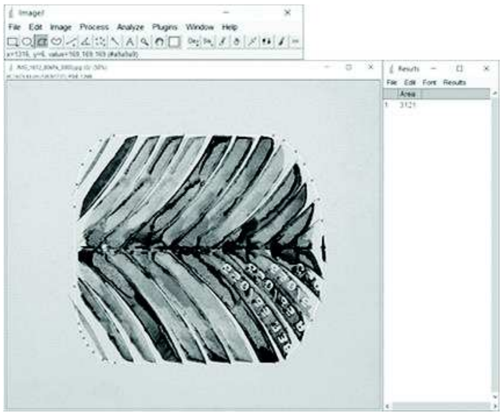

Figure 2. Print screen of ImageJ outputs for tyre multiple footprint area Mitas 650/65R38; (load 3,000 kg, inflation pressure 80 kPa).

Statistical evaluation

Software Statistica Cz 12 (StatSoft, Inc.) was used to evaluate the prediction accuracy of tyre's footprint area. The using Eq. 10, correctness of footprint area estimation was revised with the dimensions of tyre 650/65R38 selected from tyre manufactures. This yields the root mean square error (RMSE) between published and predicted footprint area. The RMSE is given as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(|S_{TP} - S_{TM}|)^2}, \tag{13}$$

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

$$bias = \frac{1}{n}\sum_{i=1}^{n}(|S_{TP} - S_{TM}|)\ , \tag{14}$$

where: n – number of observations; S_{TP} – predicted contact area (cm^2); S_{TM} – contact area published in tyre's data book (cm^2).

RESULTS AND DISCUSSION

Table 1. presents tyre parameters of tested tyre's size 650/65 R 38. It appears that these formulae can be branded as fully satisfactory but the given values by the tyre manufactures must also be taken into account. The use of Eq. 10, Fig. 3 demonstrates the accuracy in prediction of footprint areas S_{TP} (cm^2) for tyre's size 650/65 R 38 of chosen manufactures. Evaluation confirms the theory of suitability to apply the stiffness tyre sidewall into calculation of tyre footprint area as a main factor affecting progressive change of footprint area size.

Table 1. Catalogue's 650/65 R 38 tyre size from selected manufactures; ETRTO (2008): p_i = 160 kPa, speed 30 km h^{-1}

650/65 R 38	b_t	d_t	r_s	W_k	S_{TM}*
Firestone	640	1,850	828	4,745	3,096
GoodYear	653	1,839	823	4,415	2,905
Michelin	646	1,819	801	4,740	3,000
Mitas	622	1,840	810	4,745	2,400[†]
Trelleborg	645	1,810	815	4,745	3,050

Note: [†]unexpected low value in Mitas data book; real footprint area $S'_{T0} \Leftrightarrow S_{TM}$ = 3,100 cm^2; * manufacture's data.

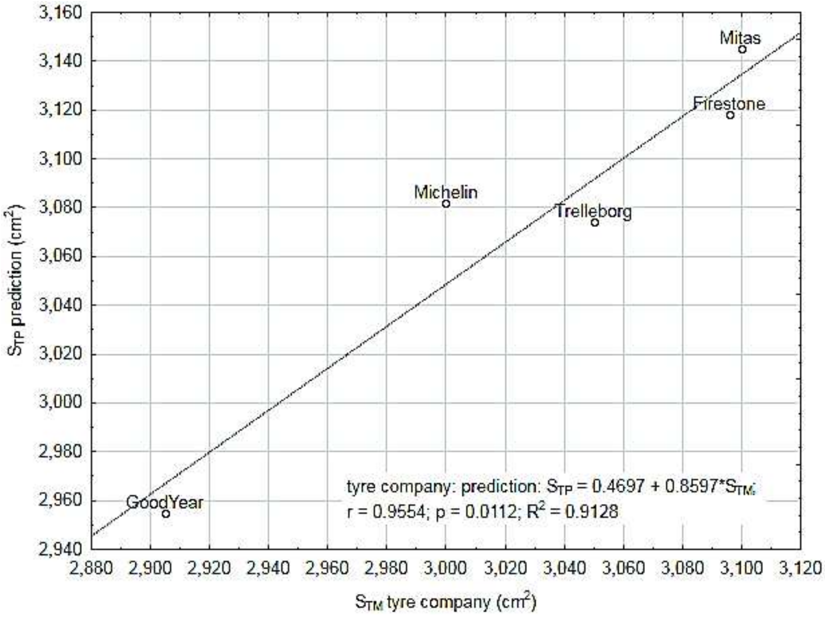

Figure 3. Contact area S_T predicted using the Eq. 10; R^2 – modified coefficient of determination; $RMSE$ = 49.62 cm^2 and $bias$ = 44.60 cm^2; (Statistica Cz 12, original copy).

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

$$q = (1.06 - 0.06\lambda)q_s, \quad (15)$$

where parameter λ (–) as a ratio of width b (cm) and length l (cm) of contact area gives accuracy to the Eq. 15:

$$\lambda = l/b \quad (16)$$

The advantageous substitution of original footprint shapes by circular area for the radial type of traction tyres 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. Fig. 4, A, B shows comparison of the size for different shapes of multiple tyre footprints.

Generally, the standardized footprint area on a hard ground disposes lower size then published one for a soft soil. In the terrain, tyre contact area can be achieved by an increase up to 80% if the thread pattern is fully pressed (e.g. Schwanghart, 1995; Keller, 2005).

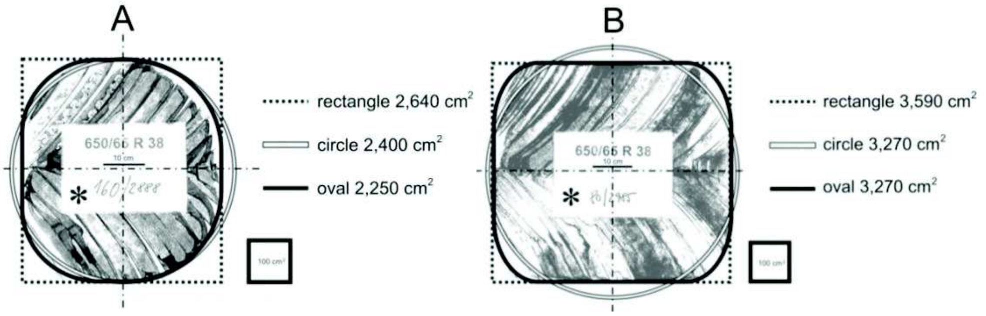

Figure 4. Part (A) multiple tyre footprint (MITAS 650/65 R 38 RD-03) allows to compare contours and differences between regular shapes; Part (B) shows the effect of 50% underinflation (160 → 80 kPa) for similar tyre load; 1,000 cm^2 presents positive 30% contact area increasing (hard surface).

Field compaction capacity (FFC) index expresses a soil compaction risk of tyres for any load capacity listed in catalogue's inflation pressure groups. Similarly, as CC rating, when tyre's mean contact pressure is lower than 70 kPa, both starting S_{Tx} (cm^2) are identical, FCC values are considered as a 'soil friendly'. Fig. 5 shows and proves the difference between FCC 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 tyre's contact maximal area S_T (cm^2) across the inflation pressure range. The FCC insists on precise contact area S_{Tx} calculation under a given load which produced contact pressure (Eq. 15). This transformation prefers a cubic polynomial; however the quadratic type is sufficient as well.

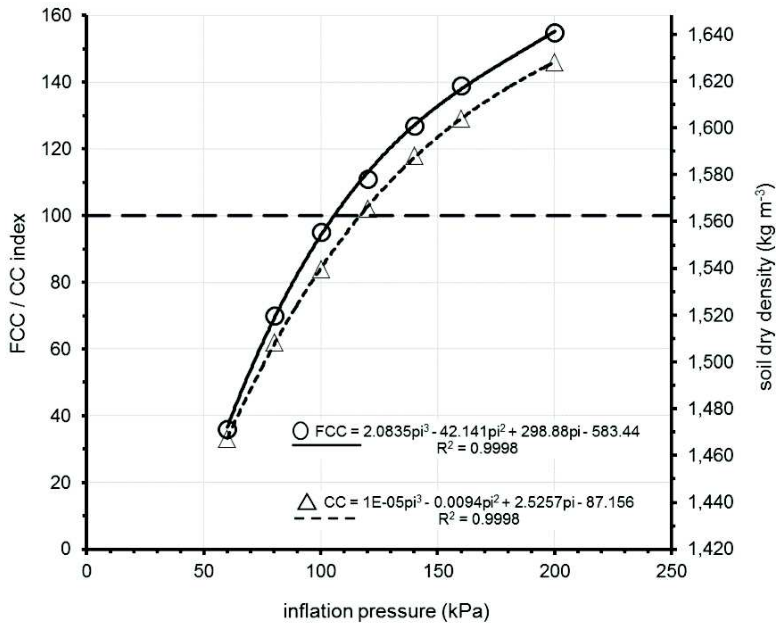

Figure 5. Comparison of FCC and CC quantification for nominal catalogue's load range in dependence on inflation pressure for speed 10 km h^{-1}; (Mitas 650/65 R 38 RD-03); compaction index limit reports to the extreme range of clay-loam soil dry density.

The tyre FCC approach is heading to supplement of the data books of tyre manufacturers for specific agricultural vehicles; alternatively, FCC can be used as a tyre load calculator in soil-friendly traffic propagation. Examples of application of FCC and CC indices are shown in Table 2 (Cross−ply tractor tyres), Table 3 (Radial front tractor tyres) and Table 4 (Radial rear tractor tyres).

Table 2. FCC rating of selected Cross−ply tractor tyres in comparison with original CC rating limits (speed 10 km h^{-1}) for standard inflation pressure 140 and reduction 120 kPa; W – load, W_N – nominal load

tyre	16.9–34 (8 PR)			tyre	18.4–34 (8 PR)		
p_i (kPa)	140–120			p_i (kPa)	140–120		
W (kg)	S_T (cm^2)	q (kPa)	FCC	W (kg)	S_T (cm^2)	q (kPa)	FCC
875	1,059–1,185	81–72	6–0	1,200	1,255–1,407	94–84	29–14
1,250	1,153–1,302	106– 94	39–24	1,650	1,363–1,541	119–105	62–45
1,625	1,264–1,440	126–111	60–44	2,100	1,490–1,700	138–121	82–71
2,000	1,400–1,609	140–122	72–55	2,550	1,645–1,891	152–132	93–79
2,375	1,568–1,817	149–128	78–61	3,000	1,834–2,127	160–138	98–83
W_N (kg)	S_T (cm^2)	q (kPa)	CC	W_N (kg)	S_T (cm^2)	q (kPa)	CC
2,750	1,782	153	81	3,450	2,074	165	101
2,470	1,807	135	67	3,100	2,104	146	88

Table 3. FCC rating of selected front radial tractor tyres in comparison with original CC rating limits (speed 10 km h^{-1}) for standard inflation pressure 160 and reduction 120 kPa; W – load, W_N – nominal load

tyre	600/70R30 152 D (155 A8)			tyre	620/75R30 163 B (163 A8)		
p_i (kPa)	160–120			p_i (kPa)	160–120		
W (kg)	S_T (cm^2)	q (kPa)	FCC	W (kg)	S_T (cm^2)	q (kPa)	FCC
1,500	1,949–2,183	76–67	14–0	1,500	1,866–2,085	79–71	43–1
2,000	2,072–2,344	95–84	60–35	2,000	1,973–2,226	100–8	76–45
2,500	2,211–2,526	111–97	90–65	2,500	2,093–2,383	117–103	98–75
3,000	2,371–2,735	124–108	107–84	3,000	2,229–2,561	132–115	113–95
3,500	2,555–2,975	134–115	116–96	3,500	2,383–2,763	144–124	123–106
W_N (kg)	S_T (cm^2)	q (kPa)	CC	W_N (kg)	S_T (cm^2)	q (kPa)	CC
4,970	3,310	149	125	5,355	3,209	165	134
4,580	3,575	127	109	4,780	3,446	137	118

Table 4. FCC rating of selected rear radial tractor tyres in comparison with original CC rating limits (speed 10 km h^{-1}) for standard inflation pressure 160 and reduction 120 kPa; W – load, W_N – nominal load.

tyre	540/65 R 38 147 D (150 A8)			tyre	600/65R38 153 D (156 A8)		
p_i (kPa)	160–120			p_i (kPa)	160–120		
W (kg)	S_T (cm^2)	q_s (kPa)	FCC	W (kg)	S_T (cm^2)	q_s (kPa)	FCC
1,500	1,528–1,720	96–86	48–29	1,500	1,828–2,047	81–72	25–3
2,000	1,646–1.874	120–105	82–62	2,000	1,940–2,192	101–90	69–46
2,500	1,779–2,049	138–120	100–80	2,500	2,065–2,357	119–104	95–74
3,000	1,938–2,256	152– 131	111–91	3,000	2,208–2,544	133–116	110–91
3,500	2,124–2,499	161–137	115–98	3,500	2,373–2,758	145–125	117–102
W_N (kg)	S_T (cm^2)	q_s (kPa)	CC	W_N (kg)	S_T (cm^2)	q_s (kPa)	CC
4,305	2,523	168	119	5,110	3,120	162	130
3,640	2,709	132	95	4,275	3,364	125	103

Grečenko (2016) published the addition to the previous (Grečenko & Prikner, 2014) to specify the eCC index (equivalent Compaction Capacity) for critical parameters of various soil types (Table 5). The eCC index describes the tyre soil compaction capacity for arbitrary soil in the same way as the CC index for standard soil.

Table 5. 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 (kg m^{-3}); *PR* – penetration resistance (MPa).

Original CC or FCC modification (see Eq. 11), compares ratio of soil compaction state to critical dry bulk density for clay-loam soil type (1,420 kg m^{-3}) exclusively. The eFCC index using previous formula can be defined:

$$eCC \Rightarrow eFCC = [(CC + 1{,}000)\rho_{dl} / \rho_d - 1{,}000] \qquad (17)$$

The evaluation of tyre eFCC index is demonstrated using five soil types in Fig. 6. Considering the value of eFCC = 100 as an upper limit, the clay soil admits acceptable eFCC index when tyre load of about 3,530 kg at 60 kPa inflation pressure. The limit for clay loam and loam soil type allows to nominal combinations of load and inflation pressures for 100 and 140 kPa, respectively. The outputs of tyre compaction capacity indexes (CC, FCC, eCC, eFCC) confirm a high soil resistance to critical compaction state in the whole range of inflation pressures for sandy soil demonstrably.

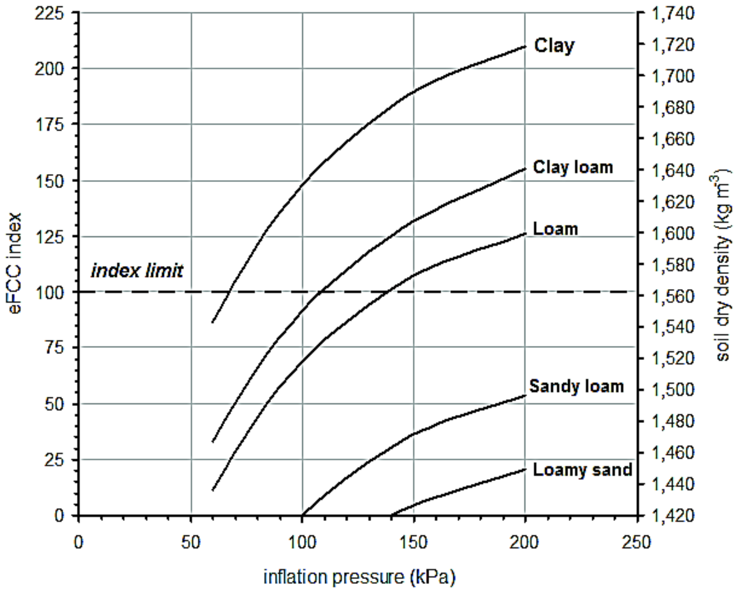

Figure 6. Trends of the eFCC for selected soil types; nominal catalogue's load range in dependence on inflation pressure for speed 10 km h^{-1}; (Mitas 650/65 R 38 RD-03); eFCC index limit reports to the extreme range of soil dry density, referring to clay loam standard.

CONCLUSIONS

The paper describes prediction of the off-road tyre's 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 tyre catalogue data only. Such a conversion leads to the nominal footprint area which refers to any combination of inflation pressure load listed in the catalogues. New prediction includes the tyre sidewall stiffness in dependence on tyre static radius change, which guarantees to establish size of tyre footprint area in the range of inflation pressure completely. Thus tyre CC index (rating) can be transformed into actual compaction capacity of tyre marked as FCC 'Field compaction capacity' using polynomial function. The FCC index, based on tyre footprint on hard ground, can describe the tyre's compaction effect more precisely. FCC modifications into the eFCC refers to soil compaction risk to characteristic soil types. This is recommended for tyre and machine manufactures to publish optimal tyre inflation pressure levels or suggest advantageous combinations of type or size tyres for field operations on moist soils.

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