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Improvement in tyre soil compaction rating for global agricultural systems

Master Thesis

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Authorship Declaration

Hereby I declare that this thesis titled "*Improvement in tyre soil compaction rating for global agricultural systems*" was written by me and all the sources have been quoted and acknowledged by means of complete references.

I agree that this thesis will be stored in the Library of Czech University of Life Sciences Prague and will be used for studying purposes.

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Abstract

The topic of this diploma thesis explains a model of tyre FCC (Field Compation Capacity) – rating as an indicator of detrimental soil compaction effect and its commercial possibilities of use. The field compaction capacity rating of tyres (further FCC rating) is a numerical index expressing the compaction risk of loaded tyres for any combination of tyre load and inflation pressure, respectively. The FCC rating can substitute the original tyre CC-rating conception published by Grečenko and Prikner (2014). The thesis includes an evaluation of tyre footprint measurements applied in the improvement of original equation for the nominal tyre contact area size calculation when compaction effect of arbitrary tyre for any combinations of tyre load and inflation pressure is estimated. Experiments were performed using two tyres Mitas RD-03 650/65 R 38 and Continental STV 650/85 R 38. A linoleum plate was used in footprint area measurement under load combination and inflation pressures. The original of footprint was photographed; picture processed in Corel Draw X4 and using scale constant converted into output of footprint area size. For the both tyre's compaction models (CC and FCC ratings) a loaded tyre footprint area is represented by a substituting pressure plate and adequate mean contact pressure. Using original databank of compaction function (Grečenko and Prikner, 2014), the average soil compaction is compared with critical soil compacting state in the range of soil profile depths from 20 to 50 cm under loaded tyres.

Keywords:

soil compaction, tyre contact area, contact pressure, agricultural tyres, compaction capacity of tyre

Abstrakt

Diplomová práce zahrnuje vyhodnocení pneumatik modelem *FCC* (Field Compation Capacity) - jako indikátorem škodlivého efektu zhutnění půdy a možnost jeho komerčního využití. Kompakční potenciál pneumatik pro pole (dále jen FCC rating) je číselný index vyjadřující riziko utužení půdy pneumatikami pro libovolnou kombinaci zatížení pneumatiky a libovolný vztyčný tlak. Hodnocení *FCC* může nahradit původní koncepci CC-ratingu pneumatik, kterou publikovali Grečenko a Prikner v roce 2014. Téma diplomové práce zahrnuje vyhodnocení měření rozměrů obtisků pneumatik použitých pro zdokonalení původní rovnice pro výpočet velikosti kontaktních ploch pneumatik, ve kterém se stanovuje efekt kompakce libovolných pneumatik pro jakékoliv kombinace zatížení a huštění pneumatiky. Pro provedení pokusů byly použity dva typy pneumatik: Mitas RD-03 650/65 R 38 a Continental STV 650/85 R 38. Pro měření otisku pneumatiky při různých kombinacích zatížení a tlaku huštění byla použita linoleová deska. Obtisky byly vyfotografovány; obrázky zpracovány v Corel Draw X4 a pomocí měřítka převedeny konstantou na výstupní velikost plochy obtisku. Pro oba modely kompakce (CC a FCC rating) jsou reprezentovány zatížené plochy pneumatik tlakovou deskou a odpovídajícím kontaktním tlakem. Použitím původní databanky kompakce (Grečenko a Prikner, 2014) se průměrné zhutnění půdy porovnává s kritickým stavem zhutnění půdy v rozmezí hloubky půdního profilu od 20 do 50 cm pod zatíženými pneumatikami.

Klíčová slova:

zhutnění půdy, kontaktní plocha, kontaktní tlak, zemědělské pneumatiky, kapacita zhutnění

Contents

List of Tables and Figures

List of Tables:

List of Figures:

List of Abbreviations and definitions

α_A	correction factor
α_W^n	ratio of actual to nominal tyre load, (kg)
A_0	individual tyre's footprint area
α	half apex angle of the cone
AR	aspect ratio of tyre section
b_t	tyre section (cm)
C	referring to pressure plate C
CC rating	tyre Compaction Capacity rating
C_N	nominal tyre sidewall stiffness (kN cm^{-1})
CP	compaction profile
d_t	outer diameter (cm)
d_t	tyre outer diameter (cm)
d_r	rim diameter (inch)
FCC index	numerical value of FCC rating
FCC	Field Compaction Capacity of tyre
$f_{N(30)}$	nominal deflection for speed 30 km.h^{-1}.
g	gravity constant (m s^{-2})
h_t	tyre section height (cm)
k'	ratio of the actual length l_0 to the virtual length
LCC rating	tyre Low Compaction Capacity rating
l_0	actual scale length
l_x	real footprint scale on photo
n'	parameter of tyre sidewall deformation
n	number of observations
n_x	coefficient deformation
n_{x1}	0.7 experimental coefficient for Diploma Thesis
n_{x2}	0.67 coefficient based on Grečenko, 1995
PR	penetration resistance (MPa)
p_i	inflation pressure (kPa)

q_s	highest contact pressure amid contact surfaces (kPa)
r	hypothetical mean radius of the circular area (cm)
ρ_d	critical limit of soil dry density ($kg.m^{-3}$)
ρ_{ds}	soil dry density ($kg.m^{-3}$)
ρ_{dl}	critical value of soil dry density
r_s	static load radius (cm)
S_c	real footprint area (cm^2)
$S_c^{'}$	converted footprint area size (cm^2)
S_h	hypothetical rectangular area (cm^2)
S_o	the size of the contact area (m^2)
S_T	contact area for nominal load (cm^2)
S_{TP}	predicted contact area for nominal load (cm^2)
S_{TM}	published contact area for nominal load of tyre manufacture`s (cm^2)
S_{TNi}	individual nominal contact area (cm^2)
S_{T0}	contact area for actual load (cm^2)
S_{TPi}	predicted individual contact area (cm^2)
S_{Tx}	prediction of tyre's contact area (cm^2)
σ_z	vertical component of stress (kPa)
W	actual load (kg)
W_{Ni}	individual nominal load (kg).
z	depth (cm)

1 Introduction

Soil compaction is one of the most important factors responsible for the soil physical degradation (Pagliai et al., 2003). Soil compaction may decrease soil porosity and change pore shape and pore size distribution (Pagliai et al., 2003), decrease aeration (Czyz et al., 2001), decrease water infiltration and increase preferential flow (Kulli et al., 2003), and increase surface runoff with consequent soil erosion (Horn et al., 1995). The environmental degradation resulting from subsoil compaction is likely to include loss of quality of the aeration, surface waters, ground waters and soil resources generally (Söhne and van Ouwerkerk, 1995, Filipovic et al, 2011). Subsoil compaction may persist for a very long time and is thus a threat to the long-term productivity of the soil (Etana and Håkansson, 1994, Håkansson and Reeder, 1994 and Söhne and van Ouwerkerk, 1994). Methods for the control of traffic-induced soil compaction are therefore needed (Horn et al., 2000).

Soil compaction is a worldwide environmental problem of increasing importance occurring in arable and grassland as well as in forest soils. It is caused by the use of heavy machinery (Söhne and van Ouwerkerk, 1994; Horn et al., 2000), but also by livestock trampling (Murphy et al., 1995; Chan and Barchia, 2007) and human leisure activities (Pizl and Schlaghamersky, 2007; Kissling et al., 2009; Beylich et al., 2010). Due to population growth there are increasing demands on agriculture and its intensification. Large and very efficient agricultural machinery is being used, which causes harmful damage to soil profile. Mechanisation forms the basis of modern agriculture in developed countries, however it is spreading even to developing countries.

Compaction caused by wheels of heavy agricultural machinery has negative effect on physical properties on soil profile. The usage of agricultural machinery is connected to undesirable compaction, which goes to the depths of about 40 cm but up to 100 cm. Limit values of contact pressure are between 100 and 160 kPa, depending on soil type, and if the values are crossed, negative influence of tyre is expected (Keller et al., 2007).

Manufacture's agricultural tyre data books state permissible load limits as related to a tyres inflation pressure. Proper combinations of tyre load limits and inflation pressures may be derived from long – time terrain experiments. The stress/strain behaviour of soils under loads classical soil mechanics theory modified by Fröhlich (1934) and Söhne (1958) is the primary basis for quantification of the subsoil. The study of terrain mechanics close a number of fundamental outside factors influence the resulting stress strain behaviour of soils under tyre and/or track loading (Söhne & Van Ouwerkerk, 1994). Improvements on the class of problems related to classic soil physics extended to the application in terrain mechanics (Way et al. 1997) are used to design new models supporting agriculture machinery applications (Keller et al. 2007). Grečenko & Prikner (2014) presented theories on the relationships between soil compaction under tyres without touching the stresses in the ground. The Compaction capacity of tyres (the tyre CC-rating) is apparently the only existing direct assessment of soil compaction risk, which means that it evaluates directly the compaction of a central soil column under the tyre contact area. This rating reflects tyre design parameters, inflation pressure and loading.

One way to minimise harmful soil compaction is to use limit values for tyre loads determined according to the standardised tyre CC-rating methodology. The tyre CC-rating (Compaction Capacity of tyre), based on the tyre catalogue data, it is directly possible to determine the load limits of any tyre for a given combination of its load and inflation pressure. It indicates the extent of the soil profile compaction to a depth of 50 cm at a humidity limit where the soil is the most vulnerable to changes in bulk density. The volume overrun of the soil mass over its critical value is represented by the CC value. Another option of CC-rating is to assess the current combination of inflation pressure and load directly under operating conditions. The Field Compaction Capacity (*FCC*) allows you to immediately determine the inflation pressure level to optimally reduce the contact pressure for a given tyre load with reference to the current *FCC* Compaction Index.

The aim of diploma thesis is describe generally soil compaction effect and the possibilities of its measurement. The second part of this thesis explains the soil properties influencing soil compaction and descripte of compaction of agricultural soil and its negative impacts of agricultural machinery. The practical part deals with the comparison of the measured and calculated contact area using 2 different coefficients compared to the catalogue values from the manufacturers. Results obtained from standardized laboratory tests should indicate the effect of the inflation pressure and the tyre load on the formation of contact area and the contact pressure. The last chapters describe the measurement results and recommendations for further development.

2 Literature review

2.1 Soil characteristic

Soil is the top layer, biologically alive part of the earth crust. It has been created due to effects of so called soil-creative factors and is serving very important production and ecological purposes. Soil has to be protected because of its irreplaceable functions in agriculture and thus we need to take measure in preventing of decreasing of area and degradation of agricultural land. Further the decrease of soil fertility has to be stopped and eliminated degradation which resolves in lower outcome productivity. Main factors of degradation are water-logging, compaction, erosion and contamination (pollution) (Lhotský, 2000).

The scientific field of terramechanics is elaborating on interactions between vehicles and the soil and it also includes the problematics how to eliminate the harmful soil compaction. The main goal of heavy machines used in agriculture is to increase the efficiency by reducing the negative impact on soils. (Wong, 2010).

2.1.1 Soil Structure

The aspects of soil compaction are of a big importance, especially when soils are being used as building materials in infrastructures such as highway embankments, bridge abutments and dams. Samples which have been compacted on the wet side are considerably different than the engineering parameters of clay soils compacted on the dry side of optimum (Lambe, 1958a, b; Mitchell, 1993).

Soil compaction is causing destruction of soil structure and leads to densification of soil matter. In a grassy soil the effects of vital organic life and highly dense grass rooting systems are causing the positive effect of the soil structure being well developed opposite to soils which haven't been tilled for a long time (Pagliai et al., 2003, Wong, 2010).

Well structured soil matter is having a positive effect in the wet seasons where during rainfall the soil can absorb significant amount of water and the soil doesn't wash away. That's why the tillage and mechanical loosening by rooting systems or soil animals such as earthworms in general increases absorption capacity. The mechanical properties of soils tilled with plow pan are however a bit different that the ones done naturally. A sudden rainfall on a dry tilled soil creates a seal that becomes a crust when it dries. The crust is then significantly decreasing the infiltration capacity of the soil. That's why only tillage doesn't help to improve the soil structure. Also organic matter has to be put into soil like that the biological activity is simulated and the soil structure can be improved. (Holtz and Kovacs, 1981; Duiker, 2004, Mitchell, 1956; Seed and Chan, 1959).

2.1.2 Soil Moisture Contents

One of the most important aspects of soil compaction is the capacity of water absorption. (Vaz and Hopmans, 2001). That's why monitoring of this is so critical to avoid soil compaction.

Most compaction studies are performed at moisture contents near field capacity (approximately 24 hours after soaking rain) to simulate worst-case scenarios (Kanali et al., 1996, Horn et al., 2000).

Dry soil can withstand high axle loads and high contact pressures without significant effects. If farmers could stay away from their fields when soils are too wet, soil compaction would not be likely to become a problem. However the problem is, that factors such as optimum planting or harvest time often dictate that a farmer will be on the field at a time not optimal for soil moisture conditions for traffic (Chamen, 2003).

The soil compaction is much more likely to have damaging affects on wet soils. That's why driving of heavy machinery on wet soil causes rutting, slipping and increased deep soil compaction. In contrary the dry soil cannot be compressed to such a great density as moist soils (Ferrero et al., 2005).

For testing the plastic limit, or the optimum water content for compaction the Proctor density test is being used. That's why at moisture contents above the "plastic limit" soil compaction decreases because all pores are filled with water that cannot be compressed. (Duiker, 2004; Håkansson and Lipiec, 2000; Silva, et al, 1997)

Water is one of the most important components of the soil. Its content is dependent on meteorological and pedological conditions. Bulk moisture is the share of the water volume of the total volume of soil, relative humidity is expressed as a proportion of the water volume.The total porosity of the soil and moisture by weight as the ratio of weight of water and the weight of dry soil. Soil moisture affects primarily porosity, soil structure and content of humid substances. In terms of compatibility measurement results are primarily dependent on the water content in soil, organic matter content and particle size distribution. Fine-grained soils have a higher susceptibility to compaction density in dependence on the water content in the soil. According Chancellor (1976) and Ljugarse (1977), the water content is the most important factor affecting the size of the compaction caused by machinery travels (Way, 2000).

Trafficking very wet soil (especially with high loads and tyre pressures) causes a “hydraulic ram” effect. The topsoil is compressed very quickly to saturation. Because water cannot be compressed, surface stresses are now directly transferred to the subsoil. Therefore, driving on very wet soil is very likely to cause subsoil compaction. Plowing with one wheel in the furrow also directly compacts subsoil (Duiker, 2004).

Soil moisture indicates amount of water in the soil. There are two types:

1. The mass humidity - ratio of water and the weight of dried sample
2. Moisture volume – ratio of water volume and total volume of soil sample

Soil moisture is primarily influenced by porosity, texture and content of hummus. With increasing moisture content, soil aeration decreases. (Jandák et al., 2007).

Soil moisture content is related to retention curve. Retention curve is a chart of dependence of the suction pressure or pressure altitude soil on bulk moisture. Describes the soil‘s water retention capacity at different humidity and is known as a moisture retention curve or with a logarithmic axis of potential as the pF-curve. The difference between the waveform at humidification and soil drainage is called hysteresis (Yang, 2015).

2.1.3 Soil Density

The soil density is directly determined by the soil compaction. Soil compaction can be defined as modifying the soil structure and soil pore system geometry on the bulk soil and profile scale (Wiermann et al., 1999; Werner and Werner, 2001), as well as on the soil aggregate scale (Larink et al., 2001). Generally, soil compaction affects soil physical properties by increasing soil bulk density and by changing the size distribution as well as the tortuosity and connectivity of soil pores (Richard et al., 2001; Pagliai et al., 2003, 2004; Schaffer et al., 2008a, b).

The most significant form of soil degradation is excessive soil compaction, which can harmfully influence soil chemical, biological, and physical processes. Gupta and Allmaras (1987) have stressed out the need to characterise and quantify the effect of compaction on soil structure. In this respect, measurements of soil structure such as bulk density and pore size distribution characterise soil compaction at the macroscopic scale (Gupta et al. 1989). Koolen (1987) and Gupta et al. (1989) also lay emphasis on that bulk density being an important factor which influences not only macroscopic but also microscopic soil properties (e. g., large pores, hydraulic conductivity, penetration resistance) both very significant in land utilisation. For tillage studies, macroporosity provides a useful index of soil compaction effects on pore geometry, especially for medium-textured soils (Douglas 1986; Carter 1988).

There has been research conduceted examining the critical limits of soil bulk density, considering ecological properties, such as porosity and hydraulic conductivity, or crop growth and yield. Nevertheless, optimal and critical limits of soil bulk density for crop growth depend upon soil texture, mineralogy, particle shape, and organic matter, which affect structure and thus, water, air and mechanical resistance of the soil. Each crop and cultivar reacts differently to soil compaction depending upon their rooting system (Guimaraes et al., 2002). Soil porosity and hydraulic conductivity are ecological properties due to their narrow relation with the environment, particularly with gas exchange with the atmosphere (Horn et al., 1995).

The knowledge of the critical values would help decisions about soil management and, consequently, improvements in soil quality for crop growth and yield. However not all increase in bulk density has to necessarily to worsen crop growth. Into some extend the density can be beneficial for storing water and that also increases the capacity of the soil to support when agricultural vehicles traffic.

To calculate the acceptable limits for bulk density there is research done and is referred to as degree of compactness. Degree of compactness is an estimate of relating field bulk density to reference bulk density. Pidgeon and Soane (1977), Carter (1990) and Silva et al. (1994) used the maximum bulk density from the Proctor test at a given amount of impacting energy. The Proctor test which is mostly used for disturbed soil material, usually results in greater values of reference bulk density, and this difference depends on type and load or energy level, ranging from 7 to 17 % in Swedish soils (Håkansson, 1990) and from 10 to 18 % in South African soils (Smith et al., 1997a,b).

Density is measured in kg.m^{-3} of soil material weight and total volume. Unlike particle densities, which provide only solid particles, bulk density includes pores. To express the density used standardised sampling rollers 100 cm3 (ASAE, 2006). This method is widely used and advantage is that the soil sample can be accurately identified. Since the 90s, the interest in the possibility of the use of techniques using gamma radiation. Modes of transmission gamma rays have precise measurements of spatial resolution. With a single narrow probe carrying the source, the sensor can be retained on the surface (ASAE, 2006; Carter, 1990; Czyz, 2004; Duiker, 2004).

2.1.4 Soil porosity

Soil porosity is the total percentage of pores or space in the soil, which is not filled by solid matter. It allows a flow of air and water in the soil and ensures metabolic reaction between microorganisms and plant roots. The pores are of different shapes and sizes and are variously connected. The porosity of agricultural land lies between 40-50 % and it can be significantly affected by processing of the soil. Soil porosity values allow to objectively indicate aeratedness and compactness of the soil. Methods of determining the porosity are based either on the total pore volume and the total soil volume in a natural storing. (Nimmo, 2004; Pokorný et al., 2007).

Porosity is dependent on both depth and on effective stress. Porosity does not always decrease with depth; however, it increases when the increase of the effective stress with depth is smaller than the effective stress in the normal compaction condition (Brewer,1976; Fitz Patrick, 1993;)

The total pore volume and porosity can be calculated from the bulk density of the soil. Porosity is dimensionless parameter and depends only on the particle density. The size of the air pores is significantly influenced by the change in pore size distribution during compaction. Air porosity is dependent on the water content in the soil and is called a standard value of suction of soil water. Changes in the total porosity and pore size distribution is attributable to a static load published by e.g. Sommer et al. (2014).

The porosity of soil decreases due to the increase in bulk density. Primarily affected by soil compaction are macropores which are crucial for water circulation in soil.

Research has shown that for healthy root system creation of plants an porosity of at least 10 percent is necessary to enable a proper growth. It is important to know that tilled compacted soils are more vulnerable to be recompacted.

As the pore characteristics influence several functions in soils, their characteristics measurements are becoming more and more used to characterise soil structure. One important function of soil is water transmission, which directly affects plant productivity and thus the environment. Infiltration of water increases water storage for plants and groundwater recharge and reduces erosion. The rate of infiltration is controlled by the pore size distribution and the continuity of pores or pathways (Kutílek, 2004). The role of macropores in rapid infiltration under ponded conditions (preferential flow) was stressed in numerous papers (Ehlers, 1975; Lin et al., 1996; Arvidsson, 1997; Gue´rif et al., 2001). Lin et al. (1996) reported that 10 % of macro-pores (>0.5 mm) and meso-pores (0.06–0.5 mm) contributed about 89 % of the total water flux. As shown by Ehlers (1975), the maximum infiltrability of conducting channels in untilled soil was more than 1 mm/min, although the volume of these channels amounted to only 0.2 vol.%.

Table 1: Critical soil parameters (soil compaction state limit), (Lhotský, 2000).

	C	*Cl*	*L*	*SL*	*LS*	*S*
$\rho_{d\ crit.}$	> 1350	> 1400	> 1450	> 1550	> 1600	> 1700
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).

2.1.5 Penetration Resistance

Crop production is influenced by the direct soil management which is defined by the compaction caused by heavy vehicles. (Soane and Ouwerkerk, 1995 and Lipiec and Hatano, 2003). The more intense usage of agricultural machinery is a significant reason of caused soil compaction and decline of soil structure (Horn at al., 2000), surface crust resistance (Gallardot-Carrera et al., 2007) and root growth (Gliński and Lipiec, 1990 and Busscher and Bauer, 2003). This property can be quite easily measured and therefore penetration resistance is widely used to evaluate the effects of changes in soil pore and aggregate structure (Perfect et al., 1990 and Dexter et al., 2007). The penetration resistance was the essential variable in developing pedotransfer functions to water estimates at different pore water pressures (Pachepsky et al., 1998) and also in predicting the soil thermal conductivity (Usowicz et al., 2006).

For the measuring purpose of soil water contents the penometers are being used. With their newly developed features such as probes for soil water content, soil electrical conductivity, thermal conductivity or near-infra red reflectance. Those combined deliver measurements within the same location and thereby reduce soil disturbance and enhance applicability of the penetrometry.

This measurements on the spatial distribution of the penetration resistance is helpful in identifying zones with soil compaction problems and development of management options that minimise or even eliminate crop production risks and the harmful impact of traffic on the environment. Geostatistical techniques, together with classical statistics, constitute an important tool in determining spatial effects of soil management practices (Wendroth et al., 1992, Koszinski et al., 1995, Maiorana et al., 2001 and Özgöz et al., 2007). The spatial pattern of the penetration resistance variability can be used to determine minimum number of penetrations and sampling positions for accurate evaluation of the effectiveness of agricultural practices and mechanical impedance for root growth (Sirjacobs et al., 2002; Ferrero et al., 2005).

For the measurements of penetration resistance a soil cone penetrometer measuring device is being used which enables rapid measurement of penetration. According to international standards (ASAE, 2006), there are two standards specified soil penetrometer; taper angle 30° and the 3.23 cm^2 surface of the base of the cone for light soils and 1.29 cm^2 for heavy soil. Several measurements techniques have been compared by Voorhees et al. (1978) in the study of five compaction resulting from different levels of the transport wheel.

It was found out that the bulk density increased by 20 % and the differences were not significant due to the operation to a depth of 150 mm, whereas the corresponding increase in penetration resistance was 400 % after one year were significant differences caused by the operation to a depth of 600 mm. Anderson et al. (2003) developed a new electronic mobile penetrometer, which may be associated with programming the calculator and on-site measurements to provide statistical mean and standard deviation values.

If roots encounter significant resistance then the root penetration becomes limited. Research shows that root growth is decreasing linearly with the resistance from 100 psi to 300 psi where the root growth completely stops. Comparing bulk density and penetration resistance on which indicator is more informative then the penetration resistance wins. That's because with this indicator the results can be interpreted regardless of soil structure and texture.

2.1.6 Water Infiltration

The soils capacity to absorb water is determined by several factors. One of those is soil porosity and other amount of organic matter. Both play an important role in biological productivity and hydrology in agriculture. The water infiltration is influenced by the pore size, shape. Soil have different characteristics in terms of storage and discharge of water, the movement and distribution of gases and ease of penetration of growing roots. (van den Bygaart and Kay, 2002). The pore size is negatively influenced by soil compaction which reduces the size and shape and consistency of soil particles, thereby reduces permeability and spread of liquids and gases in the soil.

There are measurement methods to quantify both the air and water permeability. The ways of measuring air permeability are much more advanced, because the flow is rapidly equalised and the air is easier to transport and to control than water. Air permeability is a determination of gas exchange, where the degree of compaction of the size is dependent on the depth (Kuncoro et al., 2014).

The functions negatively influenced by the soil compaction are water infiltration, hydraulic conductivity, air permeability (Horn et al., 1995; Richard et al., 2001) and aeration. (Czyz et al., 2001; Czyz, 2004) Those are especially decreased, leading to an increased potential for surface water runoff, soil erosion and unfavourable effects on plant growth (Soane and van Ouwerkerk, 1994; Horn et al., 2000).

Soil compaction causes shrinking of macropores which causes lower infiltration of water into soil. The movements and flows of water in the water saturated soils are described as hydraulic conductivity. On the other hand unsaturated hydraulic conductivity is the movement and flow of water in soils that are not saturated. The soil compaction can increase unsaturated hydraulic conductivity, which is important for water to move to the roots (Usowicz et al., 2006).

There has been several experiments initiated on grassland. The results have been focused on the macropore volume of compacted soil and it proved that on a compacted soil the macropores volume has been half that of uncompacted soil. The water and air infiltration rate was dramatically reduced (Richard et al., 2001).

During rains the effects of raindrops on the compacted soil surface can be observed. Especially in fields with created wheel tracks including the stagnating water which cannot infiltrate. This form of compaction caused by agricultural vehicles wheels is the one most likely to suffer under runoff and erosion. (Horn et al., 2000)

2.1.7 Soil fertility

Soil fertility is capability of the soil to grant to the plants necessary conditions for development, such as supplies of nutritions, water and air. Soil fertility is defined by a group of biological, chemical and physical properties. Natural fertility is defined by genetical development and evolution and makes possible to have a crop yield without additional human interaction. In opposite an effective fertility is determined by the human interactions and is usually higher than the natural one (Wong, 2010).

2.1.8 Nutrient Uptake

The nutrition uptake is influenced by soil compaction. One of the important nutrition parameters is the amount of nitrogen contained in the soil and it is affected by the compaction in a number of ways:

- low drainage of the soil causes dentrification losses and decreases organic nitrogen mineralization
- increasing loss of nitrate
- loss of organic nitrogen and possible increase of nitrogen fertiliser

- nitrate and ammonium are absorbed slower by the roots in wet compacted soils but faster in dry ones;

In areas with humid climates the soil compaction primarily increases denitrification and reduces nitrogen mineralization. The phosphorus uptake is also strongly influenced by the compaction because phosphorus is very permanent in soil. To make a sufficient phosphorus uptake possible large root systems are necessary. Due to extensive compaction root growth gets reduced and phosphorus uptake is limited in compacted soil. (Brussaard and Faassen, 1994; Duiker, 2004, Werner and Werner, 2001)

2.2 Compaction state of agricultural soil

In soil mechanics, compaction is defined as the densification of soils by the expulsion of air through the application of mechanical energy (Holtz and Kovacs, 1981).

Soil compaction can be defined as the soil volume reduction due to external influencers. This causes reduction of soil productivity and makes the environmental quality worse. When a soil is compacted, the void ratio and porosity are decreased and, conversely, the bulk density is increased. If the shape of a soil volume changes, then we talk about shear deformation (Karafiath and Nowatzki, 1978).

Compaction is a process during which the compression of the soil produces crust on the top of surface and consequently degrades physical properties of the soil. Compaction adversely affects the production capacity of the soil, because compacted soil contains less water and the air, water and soil temperature regime is disturbed. Soil compaction is caused by wheels or tracks of heavy modern agriculture machinery or heavy layers of snow and ice. Agricultural soils are threatened by compaction to 45 % (Lhotský, 2000).

The cause for soil compaction pressures is the effect of riding gears of farm machinery and other agriculture equipments to the ground. Soils more sensitive to compaction are damp or wet soil and tillage soils. These soils lose its inherent strength and hence the ability to withstand compressive forces of agriculture machines. Parameters used for determining the degree of compaction of soil are density, bulk density, porosity and minimum air capacity (Brady, 1974; Raper, 2005).

Some properties of soils have permanent characteristics and significantly do not change while driving with heavy machinery or on dry, wet or compacted and aerated soil. Here belong the properties: size and form of the particles, mineral composition, consistency limits and density. Based on these features the type of soils are being distinguished.

In order to estimate the soil behaviour, the interim soil characteristics are being used, which determine mutability on the surface while taking into consideration conditions of the environment and load. These are physical properties such as Volume weight after drying, porosity, soil's penetration resistance, moisture, compactness, plasticity, cohesion and others. (Karafiath, 1978; Lhotský, 2000).

Soil compaction, which is subsequently causing increased resistance when cultivating fields, is caused by several factors. The primary reason for soil compaction is the weight of soil itself and low content of soil organic matter. Secondly, the soil compaction is caused by agricultural activities on the affected soil. Such as vehicle movement in order to transport goods. Tertiary reason is wrong (uneducated) way of using fertilisers, unsuitable calcium usage, and insufficient usage of natural fertilisers.

Soil densification is a cumulative process within which the negative pressures to the soils are added. The change of soil properties in term of soil density variation can be revertible when contact pressure limit is 100 kPa maximally; in case of higher pressures there are other factors which play the role. Influence of contact pressure 150 kPa can affect soil profile depth up to 0.4 m (Lhotský, 2000).

2.2.1 Assessment of soil compaction

The direct evaluation methods of the soil compaction are based on samples extraction into Kopecky cylinders and subsequent laboratory examinations:

- weighting of samples while being in the original state
- drying of the samples in an oven with 105° degrees for at least 24 hours
- determination of basic soil characteristics: e.g. soil density, soil moisture content, porosity, plasticity index; (Pokorný et al, 2007).;

2.2.2 Negative impacts of agricultural machinery on soil profile

High weigh of modern agricultural machinery causes deformation of the soil profile and changes of fundamental properties of soil generally. Extreme load of agriculture vehicles cause soil volume decreases and reduction of air space, water and mineral content. (Busscher and Bauer, 2003).

Studies have shown that the density increase takes several years and the reduction of it by plowing freezing and defreezing might not be efficient (Voorhees, 1979). Main negative influences on agricultural machinery on soils are:

- axle load
- repeated field crossing
- creating compressed line
- depth of the track;

The legislation of the European Union limits the maximum axel load per vehicle which varies between 10 and 32 tons depending on the amount of axels and load on the steering axel must not be higher than 20 %. (EAGRI, 2015).

The tracks in a soil have a characteristic of the highest soil density. Usually they have a higher volume density than other soil in its surroundings. Unwanted densitification may be caused by some lighter agricultural machinery. In depths up to 15 cm the values which have been measured were 1400 – 1600 kg.m^{-3} for locations which have been exposed to machinery and 1100 až 1400 kg.m^{-3} in locations where no heavy machinery damages have been caused. (Voorhees, 1984).

A track created by the tyres is the first signal of soil profile deformation. Increase in axel load is gradually increasing the value contact pressure while increasing the depth of the tyre track. In case of the usage of smaller front tyres and equal axel load, the tyre trail depth is increased, causing higher damaged to the soil under the front axel (Raper, 1995; Way, 1997).

2.2.3 Soil stress

Soil stress can be used as indicator of the negative effects of axle load on soil profile (Arvidsson et al, 2002; Arvidsson, 1997; Olsen, 1994). In the vehicles application, the calculation of the nominal stress $\sigma_1 = \sigma_z$ (vertical) due to extreme contact pressure

q_s has a crucial importance. The other two soil stresses are in the horizontal axis σ_x and σ_y are lower, hence σ_z represents the most important value for compaction (Grečenko and Prikner, 2014).

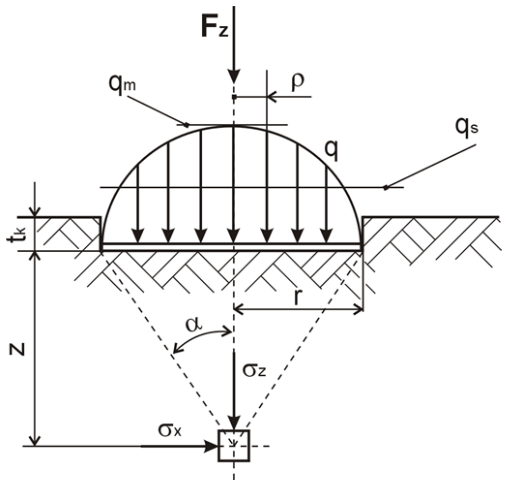

Figure 1: Diagram to calculate the stress under the axis of the circular plate with a load *Fz*, q indicates contact pressure between the plate and ground (Grečenko and Prikner, 2014).

Practical formulas for soil stress σ_z can be calculated by converting the contact area of the tyre to area of a circle of the same size.

$$r = \sqrt{\frac{S_o}{\pi}} \tag{1}$$

$$\alpha = arctg\,\frac{r}{z} = arctg\,\left(\frac{1}{z}\sqrt{\frac{S_o}{\pi}}\right) \tag{2}$$

where: r - hypothetical mean radius of the circular area

S_o- the size of the contact area

z - depth under load;

Formulas for the calculation:

$$\sigma_z = q_s (1 - cos^{\nu} \alpha) \quad (3)$$

where:

σ_z - vertical stress

q_s - the highest contact pressure amid contact surfaces

ν - the concentration factor depending on the state of soil

α - angle expressing the effect of soil stress in corresponding soil depth (°);

2.2.4 Contact pressure

Tyre contact pressure describes the pressure that is created by a tyre on the soil surface. If we achieve reducing the contact pressures the topsoil compaction is decreased. In hypothetical ideal situation of having completely flexible tyres, surface contact pressure equals the tyre pressure itself. In praxis most farm tyres surface contact pressure is circa one to two psi higher than tyre pressure itself due to stiffness in the tyre (Arvidsson, 2002).

Assessment of the contact pressure, there is the need to consider the load per wheel and divide it by the contact area - the area that the tyre touches the soil. This result will give you the mean contact pressure. The research shows that by decreasing the contact pressure it will affect positively the topsoil compaction but not subsoil compaction (Raper et al, 1995).

To increase the effectiveness and production outcomes the weight of agricultural machinery has been increasing during recent decades (Håkansson and Danfors, 1981) and it is expected to increase further. It goes hand in hand with the significant changes in European agriculture towards fewer and larger farms that show a greater need for larger and more efficient machines (Kutzbach, 2000).

This trend of involving larger vehicles increases the risk of subsoil compaction (Chamen et al., 2003) and that's why it is needed to come up with technical solutions that help reducing the compaction risk at high total loads. It is crucial for the agricultural engineers to work on the improvement and development of better wheel or track systems which can be used with higher total machine mass (Kutzbach, 2000). According to van den Akker et al. (2003), the future research ad development in subsoil compaction in Europe should include implementing of technical methods to reduce subsoil compaction, such as:

- reducing tyre inflation pressure
- ploughing on-land
- different wheel arrangements
- tracks instead of wheels
- automated low-weight machinery;

The weight of machines and vehicles and their effect on soil properties is often described by axle load (e.g. Håkansson, 1985, Alakukku, 1996, Lal and Ahmadi, 2000 and Radford et al., 2001), which is believed to be the basic cause of subsoil compaction (Taylor and Gill, 1984). Hence, limiting axle loads has been proposed as a strategy to avoid subsoil compaction (Kanali et al., 1996, Horn et al., 2000). Håkansson and Danfors (1981) recommended a limit of 6000 kg on a single axle. For tandem axle units, it has been recommended 8000 - 10000 kg. Botta et al. (2002) studied the effect of single and dual wheels on compaction and concluded that subsoil compaction due to traffic is directly related to axle load and independent of ground pressure, even for a dual tyre configuration or different sized tyres.

Nevertheless, van den Akker (1992) modelled stress distribution under wheels and discovered that stress in the subsoil is much lower for dual and tandem wheel configurations compared with single wheels. Olsen (1994) concluded that in order to divide the total load between axles or wheels, the axles or wheels should be spaced apart to avoid any interaction between them. According to Alakukku et al. (2003) recommendations should be established for wheel load–ground contact pressure combinations.

The contact pressure created by the agricultural machines can be reduced by increasing the ground contact area like by:

- using tracks instead of tyres
- using more tyres
- reducing tyre inflation pressure;

Tracked tractors usually have a greater contact area than wheeled tractors with equivalent power ratings (Brown et al., 1992). Keller et al. (2002) found that using tracks instead of wheels may reduce the risk of subsoil compaction if the tractor is well- balanced, i.e. when using proper adjustment of tillage tool to tractor. Several studies have shown that tyre inflation pressure affects the soil stress in the upper soil layers (Raper et al., 1995, Arvidsson et al., 2002 and Botta et al., 2002).

The size of the contact pressure to the road surface or the soil depends on the load per axle and the vertical force acting on the wheel. When driving on an uneven road surface, the tilt of the vehicle, transverse and longitudinal inclination of the road, the load movement in the back etc. can change the size of the force. The most important factors influencing or changing contact pressure are:

- speed
- damping weight fluctuations of axles
- design of suspension system;

Besides the vertical forces transmitted to the ground also horizontal forces occur, and these are created by the transmission of traction or braking force on the road surface in the direction of vehicle movement. These forces can work vertically to the direction of movement of the vehicle while driving in a curve. Their size depends primarily on the coefficient of sliding friction, vehicles construction and driving mode/style. (Celjak, 2013).

The general equation for calculating the mean value of the contact pressure q_s as a ratio of normal reactions, respectively of the total load F_z, working on the wheel and tyre imprint area S_o has form:

$$q_S = \frac{F_Z}{S_O} \tag{4}$$

The size of the contact pressure depends on the axle load and load, and is affected by all the factors that affect the size of normal reaction and surface fingerprint. The highest contact pressure qmax, is on a hard surface about 20 % higher. On a soft surface it is 50 to 100 % higher compared to the mean value of the contact pressure (Grečenko, 1995).

Contact pressure reduction can be achieved by appropriate choice of the tyre inflation pressure. Usage of low pressures positively affects the unwanted soil compression. Low pressure tyres are wider, which increases the contact area with the soil and decreases the pressure on soil. Usage of low pressure is suitable when working on agricultural lands. Negative impacts of the low tyre pressure are increased fuel consumption, increase of rolling resistance and degradation of tyre tread pattern on regular roads (Busscher and Bauer, 2003).

2.2.5 Contact area of the tyre

The effects of the tyre pressure on the soil are determined by the form and area size of the tyre imprint. The higher and more compact the tyre imprint is, the lower is the mean pressure value. Contact pressure means the pressure caused by the tyre upright to the soil and being effective in the tyre contact area. The contact area represents the total area of the tyre tread pattern and the area between the single spurs/arrows, which are buried into the soil and are participating in the forces transmissions. Contact area represents the touching area of the spurs/arrows on a hard pad (Grečenko and Prikner, 2014).

The imprint area S_o is characterised as even area, which occur on the pads with low load capacity. Compactness of the tyre pattern is determined by the ratio of contact area and the imprint, which on a hard soil reaches 30-60 %. Contact area S_d is part of the imprint area and is determined by the tyre tread peaks contact points with the pad.

2.2.6 Fundamental parameters for the tyre contact area calculation

The size of the contact area depends mainly on tyre deformation features and the soil characteristics and hence it is difficult to determine them accurately. Soil deformation depends on physical and chemical soil parameters and is mainly influenced by the inflation pressure and the effective load. With certain critical inflation pressure the tyre behaves like a solid structure, but in lower inflation pressures the tyre deforms and thus influences the size of the imprint area.

Models for the contact area calculation can be empiric, semi-empiric or theoretical depending on the used method. Theoretical models, which reflect the reality the most, are considering 2 basic possibilities: tyre on a firm and hard surface and a tyre on a soft surface. First of the models elaborates on the tyre on a firm and hard surface.

The tyres width is determined by the deflection and direct tyre diameter. This leads to creation of a small variance, because it becomes problematic which diagonal diameter value to use. This theoretical model of a tyre on a hard soil was developed by Ziani and Biarex (1990).

Second theoretical model describing interaction of loaded tyre on soft soil published Schwanghart in 1990.

Empirical models are based on theory, where the tyre contact area is considerd as a dependent variable and soil and tyre parameters as independent variables. Generally, used tyre parameters are: inflation pressure, tyre diameter, width of the tyre or its stiffness. Soil parameters are mainly penetration resistance, moisture or elasticity. Form and size of the contact area depends on the tyre construction, used inflation pressure and tyre load and also soil characteristics. On a hard surface have narrow tyres with high diameter and high inflation pressure an elliptical form of contact area. If the tyre's width increases, its form will become more rounded.

2.2.7 Soil stress

The soil under the wheels of agricultural machinery can sometimes be exposed to even higher pressures than the one allowed on the main roads. The operation of heavy machinery on fields can decrease the amount of pores filled with air and thus influences a huge variety of physical features of the soil. This has a direct impact on processes such as infiltration, flow of soil water and water conservation. Besides that the increase of soil density may lead to obstructions in roots growth. In depths higher than 0.4 m the soil density may remain for several decades or can be permanent, and hence the increase of soil density is a severe thread to the longterm crop productivity. In consequence of this it is necessary to understand how to decrease the soil density when using agricultural machinery. This problem was being solved by various different approaches (Trautner, 2003).

Iterative measurements showed that the elasticity theory and these soil tension anticipations are not satisfactory. The softer the soil, the more the concentration factor increases. Theoretical models take into consideration when the interaction between load and normal soil stress is compares only. Concentration factor ν specifies behaviour of normal stress under load for typical soil moisture conditions. In 1953 the concentration factor has been assigned values 4, 5, 6 in order to distinguish between dry, relatively dry and moist soil. The assumption taken at that time was that the more plastic soil the more the tension will be concentrated around the load axis and hence spread to a higher depths. (Söhne, 1958).

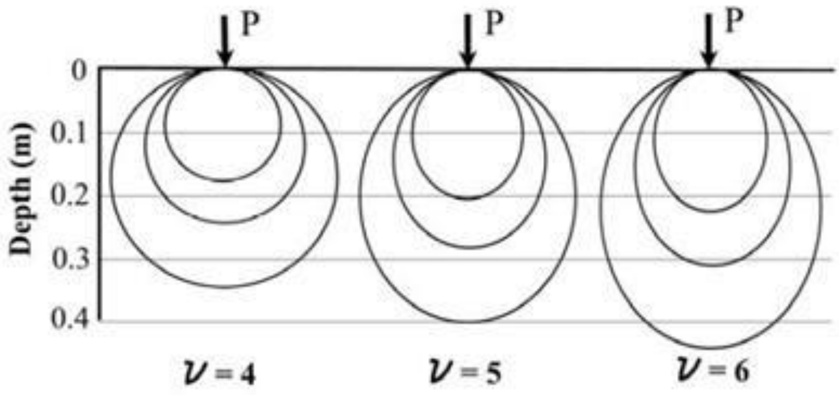

Figure 2: Stress bulbs in soils for different concentration factors under load. (Söhne, 1958).

Source: Söhne, W., 1958. Fundamentals of pressure distribution and soil compaction under tractor ty res. Agri- cultural engineering.

2.3 Research in detrimental soil compaction field

In initial studies of compaction (Sohne, 1976) were used several types of devices for transmission of gamma radiation of different construction. This leads to minor damage to the soil profile, high data output and a higher degree of spatial resolution in comparison with many other methods used. Device pursuant Geige-Müller detector is simple and stable, and scintillation detectors offer a much higher degree of spatial resolution, but are expensive and require special attention with regard to thermal stabilisation. In the long term it may be the initial state of the soil is subjected to a certain tension. The maximum density achieved in the Proctor test can be used to assess the relative compaction state of compaction and the comments field soil (Soanne and Owerkerk, 1995).

Håkansson (1990) defines the reference condition of the soil as a reference bulk density achieved by using a standardised large test sample of moist soil (diameter 350 mm, depth 120 mm) axial load pressure of 200 kPa. The reference state is used to evaluate the degree of compaction Keller. Sophisticated estimation of soil stresses under a tractor tyre at various loads and inflation pressures was described Bailey, Rapert, Way, Burt, Johnson in 1996. Keller et al, 2007 used estimation of soil stresses to evaluate compaction level for typical soil types.

Distinct research started Grečenko in 1995 and finally published in 2003. The tyre compacting effect as the tyre CN (compaction number) represented first approach for a standardised soil conditions without complicated estimation of soil stresses. Sophisticated progress based on previous research in standardised soil conditions was published by Grečenko and Prikner in 2009; the final of this approach in term of tyre compaction capacity (the tyre CC-rating) has been published in 2014.

Tyre – ground interaction has two principal aspects, namely the traction and the soil compaction, which became a weighty research subject since the tyre became a standard. Both these aspects underwent a steady development (Håkansson, 1990, van den Akker, 2004, Keller, 2007). Particularly, the compaction can be expected to receive a deserved attention because of necessity to keep food production and comply with ecological trends (Håkansson and Reeder 1994). The existing methods of evaluating soil compaction are mostly indirect, through intermediary of stresses (e.g. pressure bulbs, favoured in tyre catalogues) (Keller, 2005).

Several authors who were also dealing with the topic of soil compaction. Here I want to summarise the outcomes of the research conducted by several scientists.

In 1994 Håkansson, Reed examined the subsoil compaction by vehicles with high axle load and the soil and crop response to this effect. They are discussing methods which can protect subsoil deterioration and are describing exact negative impacts of the compaction.

They are working with 3 main status quos:

1. Wet soils are more likely to be in the depths more compacted. The traffic on moist and wet soils generally causes deep subsoil compaction.
2. Their observation showed that axle loads of 10 t and more causes compaction which typically penetrates to the depth of 50 cm
3. Subsoil compaction in depth greater than 40 cm is practically permanent and cannot be reverted by plowing.

They are working with the statement that nowadays the agricultural vehicles are carrying higher loads ant thus compaction to greater depths has been observed; there have been cases reported where the compaction was up to a depth of 1 m. The complete improvement of so deep soil compactions by mechanical loosening is virtually impossible and if so, then extremely expensive. The main result of their research is that the soil compaction has a direct impact on the crop yields and the greater and deeper compaction the higher reduction in crop yields it causes. Hence they are elaborating on the necessity for introducing guidelines for limitations of weight limits with the aim to protect the soil and limit the compaction. The proposed guidelines should be introduced preferably in an international effort.

R.L. Raper in the paper "Agricultural traffic impacts on soil" from 2005 describes soil disturbances caused by heavy vehicles and the negative outcomes to the ecosystem. He is working with 2 asumptions:

1. There are several types and combinations how to configure tyres and tracks and these setups vary in the ability to generate tractive force.
2. Different tractive forces have different impact on soil disturbance.

Raper discusses the impact of agricultural vehicles on fields and gives recommendations how to minimise the impacts of the traffic. He is giving practical recommendations such as reducing axle load, reducing trackting elements, increasing soil drying before using traffic, using of conversion tillage systems which minimises traffic, using controlled traffic system and not random routes on the field. His outcomes can be summarised that the soil compaction cannot be completely eliminated but can be significantly reduced and controlled by implementing specific counter measures and following meaningful guidelines.

Håkansson, Voorhees and Riley in 1988 wrote paper on "Vehicle and wheel factors influencing soil compaction and crop response in different traffic regime"

They examine effects of stress distribution under running gears and divide effects of soil compaction into several categories:

- direct damage to growth plants
- effects of compactness of plough layer
- residual effects after re-loosening
- effects of subsoil compaction;

They illustrate traffic intensity and wheel track distribution in different cropping systems. Also they discuss possibilities of reducing heavy traffic and evaluate the soil compactness in different parts of the world by giving examples of economic analyses.

Keller and Arvidsson in 2004 described technical solutions how to reduce the risk of subsoil compaction by using dual wheels, tandem wheels and tyre inflation. In their very practical paper they describe 3 experiments of measuring vertical soil stress and 4 significant results:

1. Stress on the soil in different depths is function of stress on the surface and the contact area. These are functions of wheel load, wheel arrangement, tyre inflation, contact stress distribution and soil condition.
2. Soil stress and compaction are not functions of axle load neither of total vehicle load.
3. Reducing wheel load by using dual or tandem wheels allows tyre inflation to be reduced and hence the risk of soil compaction decreased.
4. Stress of the tyre to the soil declines from the centre to the edge of the contact area.

Group of scientists including Soaen, Blakcwell, Dickson published in 1980 a paper on compaction by agricultural vehicles. They are working with the status quo that the factors influencing compaction are soil and wheel parameters. In their paper they review the parameters and methodology how to measure the compaction. Especially they stress out:

- the need for standardisation in soil testing procedures
- the standardisation in results presentation
- the necessity of soil characterisation consistent with application of suitable theories;

They work with the “critical state soil mechanics theory” and describe the important role of soil compactibility influencers: soil strength, water status, organic matter.

In 1995 Söhne, Ouwerkerk published “Implications of soil compaction in crop production for the quality of the environment”. They examine the influence of soil compaction to changes in soil properties which affect the amount of fertilisers used and energy consumed in crop production. They examine soil compaction as an important soil degradation process and describe the long term effects of the soil compaction to the environment such as:

- emission of greenhouse gases
- runoff of water and pollution into surface waters
- nitrate and pesticides into ground water;

2.4 Compaction capacity of agricultural tyres

The tyre CC-rating (*CC* stands for soil *Compaction Capacity*) has been developed to quantify the soil compaction risk due to tyre load at various inflation pressures. It is being used when deciding about the most efficient and ecological tyre outfit for off-road vehicles (Grečenko and Prikner, 2014).

The tyre-CC rating is the soil compaction effect of a wheel applied on a laboratory pressure plate. This technique introduce an important benefit for soil compaction with combination of soil external loading, without dealing with soil stresses (Grečenko and Prikner, 2014; Söhne, 1958; Söhne and Ouwerkerk, 1994).

The reduction of the detrimental soil compaction by loaded wheels of power and transport equipment is becoming a general trend. Compaction Capacity (*CC*) the tyre CC-rating was initially introduced as compaction number (C_N) rating. (Grečenko, 2003) The Compaction Capacity rating indetnify soil dry density along a vertical column 20– 50 cm deep in the ground. Approach of Compaction Capacity is that it converts directly laboratory compaction measurements on soil compaction profiles without touching the stresses in the ground. The laboratory soil compaction is done with round pressure plate and the tyre contact area is simulated by a virtual plate loaded by the same mean contact pressure. (Grečenko and Prikner, 2014)

The tyre CC-rating is a numerical index expressing the risk of soil compaction by loaded wheels with tyres and reflecting tyre dimensions, load and inflation pressure. The compaction is defined by soil dry density. The tyre-CC rating is based on processed laboratory measurements of soil compaction by pressure plates and thus avoids dealing with complicated stress field in the ground. The compaction profile under an evaluated tyre is computed using a databank of compaction functions measured under round flat pressure plates in a laboratory testing bin filled with Suchdol loam. A tyre itself is represented by a substituting plate of the same footprint area and mean contact pressure. The tyre footprint area on firm ground can be established either by measurement on a stand or using a convenient formula as it will be the case in this paper. The tyre CC- rating compares the average soil compaction by evaluated tyre in the depths between 20 and 50 cm under the ground surface with critical soil compaction after Lhotský (Lhotský, 2000).

The tyre CC-rating is apparently the only existing direct assessment of soil compaction risk, which means that it evaluates directly the compaction of a central soil column under the tyre contact area (Grečenko, 1995). This rating reflects tyre design parameters, inflation pressure and loading. The tyre CC-rating can with advantage be applied to complete vehicles or machines; the product with lower total rating can in general be more expensive, however, may raise the production and economy of operation. The tyre CC-rating has the character of trademark meaning that it relates to a defined soil type, soil status and evaluation procedure (Grečenko, 2003).

Details on the the tyre CC-rating theory and experimental background have been published (Grečenko and Prikner 2014). The paper presents original equation including new scaling factor for calculation of a tyre contact area and demonstrates the practical use of this approach by comparing the tyre CC-rating of typical groups of agricultural tyres.

2.4.1 Tyre CC rating

One way of minimising harmful compaction of the soil profile is to use the tyre load limits set by standardised methodology the tyre CC-rating, (Grečenko and Prikner, 2014). The tyre CC-rating / Compaction Capacity is a progressive trend for modern agriculture, based on tyres catalogue data and it allowsto determine the load limits any tyres for a given combination of load and inflation pressure. Indicates the degree of compaction of the soil profile to a depth of 50 cm at the limit humidity when the soil is the most susceptible to changes in bulk density. The volumetric excess of soil weight above its critical value represents the value of *CC*. A standardised method was developed for the clay-loam the soil representing a general soil type possessing ideal granulometric composition for the monitoring of soil compaction. The basic index value 100 may represent a limit value of density clay loam of soil 1,420 kg.m^{-3}, ensuring optimum conditions for the growth of the root system. Assessment extent of compaction index *CC* is as follows: *CC* 0-100, tyre does not damage the soil profile; *CC* 101-150 already constitutes a harmful combination of nominal inflation pressure and tyreload, pointing to exceed the limit of density. *CC* 151-200 the extreme range-limit value and if the tyre reached values within this range, it would not be suitable for use in specific operating conditions. *CC* index higher than 200 is not recommended at all, and is described as fatal. The described method of evaluating compact potential of tyres should primarily help producers of agricultural equipment in the selection of appropriate tyres for a particular machine by nominal technical. Other option of tyre CC-rating tyres evaluation is compare actual tyre pressure and load combination directly in field conditions. Part of Field Compaction Capacity allows to immediately determine the level of inflation pressure for specific load with result of actual index of *FCC*.

3 Aims of the Thesis

Aims of the thesis were:

1. To analyse in detail and specify characteristics of wheels of agricultural machinery and their influence on detrimental compaction of soil profile.
2. To evaluate specific contact area of selected agricultural tyres as a function of load and inflation pressure from multiple tyre footprints.
3. To compaction potential database complementarity for new types and sizes of agricultural tyres in dependence on the nominal values of inflation pressure and load obtained from laboratory modelling experiments of soil compaction for specified soil moisture conditions.
4. To compare obtained and given results using the tyre CC-rating evaluation procedure (Compaction Capacity) published in the Journal of Terramechanics (Grečenko and Prikner, 2009).

Hypotheses of the thesis were:

1. Tyre deformation coefficient 0.67 will be recommended for front traction tyre and deformation coefficient 0.7 will be recommended for rear traction tyre types; (proposed for precise tyre footprint assessment).
2. Difference between catalogue value and predicted value of contact areas will be up to 10 %.
3. Original tyre CC-rating based on nominal tyre contact area will have lower values than modification of *CC* based on the actual area (*FCC*).

4 Material and Methods

The structure of the thesis was composed according to the Methodical Manual for the MSc Theses Writing of the Faculty of Tropical AgriSciences (FTAa), Czech University of Life Sciences (CULS) Prague. References were cited according to the Citation Rules of the FTA, CULS Prague (FTAb).

4.1 Literature review

The literature review was written from the analysis of scientific articles - especially from the scientific database Science Direct and Web of Science.

Articles were searched by following keywords: soil compaction, tyre contact area, tyre contact pressure, agricultural machinery, soil profile, tillage, agricultural technology.

4.2 Data collection

The plan was to evaluate 2 tyres (see Table 2) for different sizes and applications (radial, super volume type).

The first measurement started on April 15, 2013 in the experimental grounds of the Czech University of Life Sciences Prague under the supervision of Ing. Patrik Prikner, Ph.D. First tyre was measured for one week as well as the second. Measurement of second tyre began one year later - in the last week in March, 2014. There were tested 2 tyres in total 52 imprints.

Table 2: Data of testing tyres.

No.	Manufacturer	Type	Size	b_t	d_t	r_s	W*	p_i*	S_{TM}*
1	Mitas	RD-03	650/65 R 38	620	1830	810	4775	160	2950
2	Continental	SVT	650/85 R 38	720	2070	920	6965	160	4078

Legend: b_t - tyre section (cm); d_t - tyre outer diameter (cm); r_s - static loaded radius (cm); W - tyre load (kg); p_i - inflation pressure (kPa); S_{TM} - nominal tyre contact area (manufacture`s data).
* Tyre parameters for a 30 km.h^{-1} (ETRTO, 2008).

Tyres selected from Continental, Mitas and Michelin tyre manufacture´s data were used for calculation of contact area S_{TC} and calculation S_{T1} and S_{T2} based on Eq. (19). Table 3 shows technical parameters of selected agricultural tyres.

Table 3: Selected tyres and their contact area for combination of inflation pressure and load for 30 km.h^{-1} (ETRTO, 2008).

No.	Manufacturer	Tyre size	p_i	W	S_T
1	Continental	12.4 R 28	160	1550	1041
2	Continental	16.9 R 30	160	2460	1799
3	Continental	14.9 R 34	160	2430	1521
4	Continental	18.4 R 34	160	3000	2033
5	Continental	13.6 R 38	160	1930	1206
6	Continental	18.4 R 38	160	3210	2297
7	Continental	20.8 R 38	160	4125	2860
8	Continental	540/65 R 24	160	2 875	1850
9	Mitas	540/65 R 28	160	3050	2 100
10	Mitas	600/65 R 28	160	3 625	2 540
11	Mitas	540/65 R 30	160	3 135	2 240
12	Mitas	600/70 R 30	160	4 085	3 000
13	Continental	620/75 R 30	160	4120	2720
14	Michelin	540/65 R 34	160	3 335	2 180
15	Continental	650/65 R 34	160	4120	2 930
16	Mitas	650/75 R 38	160	5 605	2 720
17	Mitas	650/85 R 38	160	6 270	3 960
18	Mitas	800/70 R 38	160	7 360	4 400
19	Continental	900/60 R 38	160	7 245	4 500
20	Mitas	710/70 R 42	160	6 440	3 600

Legend: p_i - inflation pressure (kPa)*;* W - tyre load (kg)*;* S_{TM} - nominal tyre contact area (manufacture`s data).

For statistical analysis there were used selected tyres from scientific paper Tyre rating based on soil compaction capacity (Grečenko and Prikner, 2014), see table 4.

Table 4: Selected tyres from scientific paper Tyre rating on soil compaction capacity (Grečenko and Prikner, 2014).

Tyre size	b_t	d_t	r_s
540/65 R 28	537	1398	624
540/75 R 28	550	1500	663
540/65 R 30	551	1465	655
600/70 R 30	625	1595	700
620/75 R 30	611	1602	704
650/65 R 34	645	1719	769
650/75 R 34	775	1815	805
650/75 R 38	667	1944	872
650/85 R 38	720	2070	920
800/70 R 38	765	2052	911
710/70 R 42	731	2070	935
710/75 R 42	710	2157	959

Legend: b_t - tyre section (cm); d_t - tyre outer diameter (cm); r_s - static loaded radius (cm).

4.3 Laboratory testing of tyre footprint area

Laboratory tyre footprint attachment was used for tyre testing. The imprints were made on linoleum 1.2 x 1.2 m fixed on weigh plate. Footprint areas were measured for maximal tyre load and next unloading 25, 50 and 75 % respectively; range of tyre pressure from 60 to 200 kPa).

4.3.1 Equipments

Laboratory tyre footprint attachment, linoleum, printing ink, paint roller, camera, tripod, tyres, soap water, sponge, bucket, paper with measure of 10 cm length and size of tyre (serial number), meter, GlobalMacros (shape.gms) for Corel X4, Statistica Cz 12, StatSoft, Inc., 2013.

Figure 3: Laboratory equipment includes soil compactor and tyre footprint attachment; (source: author).

The laboratory tyre footprint attachment with load control and electronic weight scale for loads up to 69 kN is shown in Figure 3. This attachment enabled, in addition to direct contact area measurement helped to developing of a new equation for calculating the contact area with improved precision, which is essential for reliable evaluation of the *CC* index. Three tractor tyres considered for traction operations were tested (Table 2), and quantities were evaluated: b_t, d_t, r_s, W, p_i, S_T, q_s (mean contact pressure).

4.3.2 Workflow of measuring

1. Linoleum was fixed on weigh plate.
2. Stamp ink was applied on tyre tread pattern by paint roller.
3. Setting of inflation pressure to a desired level.
4. Wheel load calibration.
5. The tyre moving from top to plate with linoleum several times under same load pressure and different wheel position.
6. Camera on a tripod 1.5 m taking pictures of imprint tyre tread and paper with serial number and the standard length of 10 cm
7. Verification of tyre footprint by meter.

8. Washing and drying linoleum.
9. Measured values and photographs stored for subsequent calculations.

Figure 4: Tyre footprint example of tested tyre 650/65R38 on the linoleum; (source: author).

The footprints were made on linoleum fixed to the pressing plate, tyre was moving from top. Example of tyre imprint is showed in Figure 4. Tyre tread was coloured with stamp ink. For better shape of imprint was repeating imprinting several times with some intermediate wheel rotation.

The tyre contact area can be reliably obtained using a multiple tyre footprint technique. Each time the tyre is started, the tyre is rotated by an angle corresponding to the tyre tread width. With this method, it is easy to compare the different tyre types and sizes, even in a very sophisticated way, from the point of view of undesirable effects on the soil in the form of compaction.

After every measuring the imprints were photographed together with a serial number and the standard length of 10 cm. Sizes of imprints were measure by meter and after that analysed in application Corel Draw X4. The circuit was determined with a shape vector from the enlarged picture. The real circuit was calculated with the scale 10 and the length.

4.4 Data processing

4.4.1 Contact area evaluation

The area was determined using an original pattern in Corel Draw X4 from the scan photography (Figure 5), the readings were multiplied by the square of the scale which was 10 and the length of the standard was as it appeared in the picture.

Assumption:

- the actual scale length l_0 = 10 cm on the real footprint corresponds to a scale of l_x cm on photo
- the conversion is performed (the ratio of the relative ratio of the measurements, 10 cm / l_x)
- calculate the ratio of k' the actual length l_0 to the virtual length l_x

$$k' = l_0/l_x \tag{5}$$

- for the calculation of the real area S_T, the area S_c is converted (index C = Corel; T = tyre)
- necessary conversion of unit areas detected by S_c' as the area size under the curve from m^2 to cm^2;

(From macro add-in for Corel = shape.gms)

Then apply:

$$S_C = (S'_C.1000) \tag{6}$$

The final calculation of the actual S_T area from the S_c photo area using Corel Draw X4 will be:

$$S_T = (k')^2 \, .S_C(cm^2) \tag{7}$$

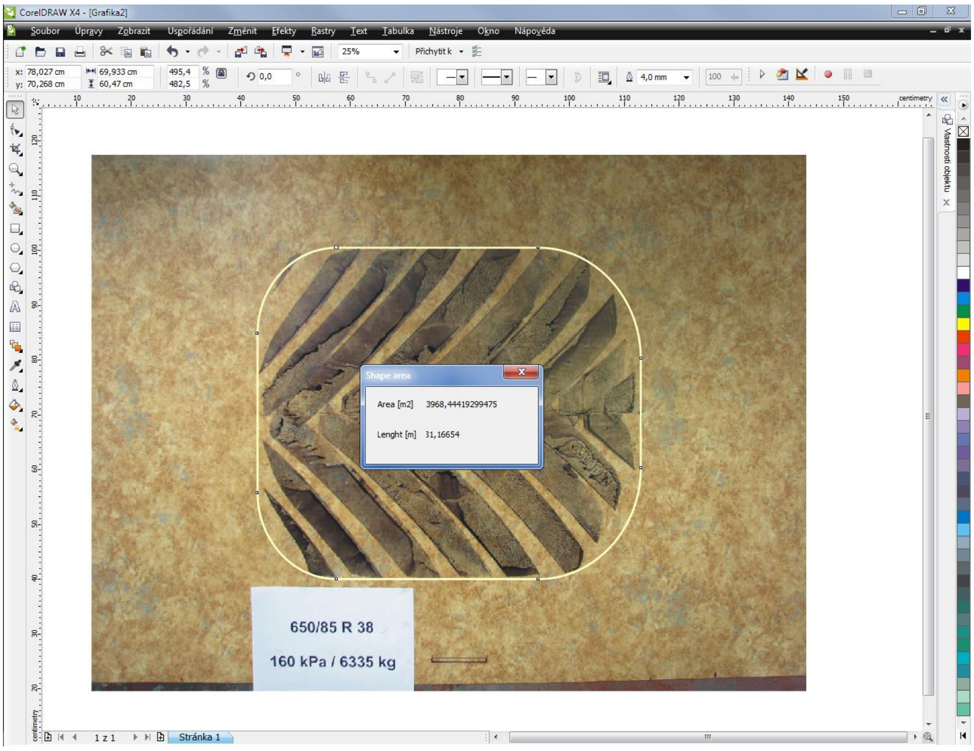

Figure 5: Example of determination area in Corel X4 with GlobalMacros (shape.gms); (source: author).

Tyre footprint evaluation and declaration of results verity are declared in Figure 7. Part (a) as multiple tyre footprint (650/65 R 38 MITAS RD-03) allows to compare contact area contours and differences between regular shapes.

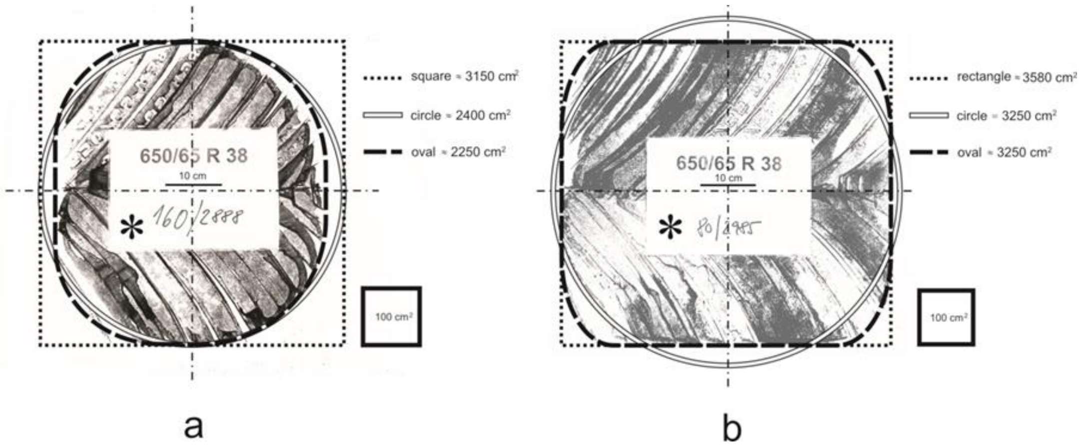

Figure 6: Multiple tyre footprint comparison and differences between regular shapes; (source: author).

Part (a) as multiple tyre footprint (650/65 R 38 MITAS RD-03) allows to compare contact area contours and differences between regular shapes. Part (b) shows the effect of 50 % under inflation (160 → 80 kPa) for similar tyre load (2888 → 2995 kg), where about 1000 cm^2 presents positive of 30 % contact area increase; (*) all combinations were adjusted for 50 % of nominal load for corresponding inflation pressure, thus difference 97 kg is negligible; (Prikner, unpublished results).

4.5 Tyre contact area

Tyre nominal contact (footprint) area on firm ground, when tyre loading matches the inflation pressure, can be calculated with good precision using the principle tyre dimensions from manufacturer's technical catalogues, which mostly comply with official manuals such as (ETRTO, 2008).

Some tyre dimensions, which are explained in the ISTVS Standards (1977), are:

d_t – outer diameter

b_t – tyre section width

r_s – static loaded radius;

associated dimensions and parameters:

d_r – rim diameter

h_t – tyre section height ...$h_t = (d_t - d_r)/2$ (8)

AR – aspect ratio of tyre section...$AR = h_t/b_t$ (9)

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:

$$S_T = cb_t\sqrt{d_t^2 - 4r_s^2} = (0.927 + 0.761AR - 1.215AR^2)b_t\sqrt{d_t^2 - 4r_s^2} \quad (10)$$

where:

c – scaling factor depends on AR (aspect ratio of tyre section),

$AR = (d_t - d_r)/2b_t$

b_t – tyre section

d_t – tyre outer diameter

r_s – static loaded radius;

In presented *FCC* conception, the prediction of individual tyre footprint area S_{Tx} uses tyre catalogues parameters for any tyre load and inflation pressure combination. Generally, tyre catalogues include the nominal loads W_N 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 catalogues 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). Coressponding 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:

$$c_{N(30)} = \frac{W_{N(30)}g}{f_{N(30)}} \tag{11}$$

where:

$C_{N(30)}$ – tyre sidewall stiffness

g – gravity constant

$f_{N(30)}$ – nominal deflection for speed 30 km.h^{-1};

The nominal tyre deflection $f_{N(30)}$ is product of catalogues values for speed 30km.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}):

$$f_{x(10)} = \frac{\Delta W g}{c_{N(30)}} \tag{12}$$

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:

$$\Delta W = W_{N(10)} - W_{N\,(30)} \tag{13}$$

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:

$$r_{sx(10)} = r_s - f_{x(10)} \tag{14}$$

where: r_s – catalogues tyre static load radius.

Using of the Eq. 14, the coefficient of tyre deformation ε_d (-) as parameter of tyre footprint area change for catalogues combinations W and p_i reads:

$$\varepsilon_d = 1 - \frac{r_{sx\,(10)}}{r_s} \tag{15}$$

where: $r_{sx(10)}$ – tyre static load radius for speed 10 km.h^{-1} (cm), (see Eq. 14).

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

$$a_n = a_1 + (n-1)d \tag{16a}$$

$$a_{Tx} = (n-1)\varepsilon_d \tag{16b}$$

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, individual catalogues combinations W_{Ni} and p_i for speed level 10 km.h^{-1} can describe a static tyre's load compaction effect sufficiently. Thus contact area S_{TNi} for individual nominal catalogues load and corresponding inflation pressure combination based on modification S_T (see Eq. 10) has a form:

$$S_{TNi} = 0.94(1 - a_{Tx})S_T \tag{17}$$

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

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

$$\alpha_A = \alpha_W^{n'} = \left(\frac{W}{W_{Ni}}\right)^{n'} \tag{18}$$

where:

$\alpha_W^{n'}$ – ratio of actual to nominal tyre load

n' – correction factor

W – actual load

W_{Ni} – individual 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. Prediction of individual tyre contact area S_{TPi} under any load and inflation pressure combinations, the Eq. 17 requires modification using correction factor α_A (Eq. 18):

$$S_{TPi} = \alpha_A S_{TNi} = \left(\frac{W}{W_{Ni}}\right)^{n'} S_{TN} \tag{19}$$

4.6 Compaction Capacity of tyre (The tyre CC-rating)

The tyre CC-rating is a dimensionless index, which compares the state of soil compaction under a loaded tyre with the critical compaction of particular soil (Grečenko & Prikner, 2014):

$$CC = 1000\left[\left(\frac{\rho_{ds}}{\rho_{dl}}\right) - 1\right] \tag{20}$$

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

$$\rho_{ds} = {}^{1}\!/_{4}\,(\rho_{d20} + \rho_{d30} + \rho_{d40} + \rho_{d50}) \tag{21}$$

and ρ_{dl} (kg.m^{-3}) is the critical value of dry density limiting the growth of field crops on loamy soils (Lhotský, 2000).

4.7 Definitions and prediction 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 standardised clay loam soil type (identical conception as tyre CC-rating). It is computed from the same formula pattern as the former Compaction Capacity (the tyre CC-rating) (Grečenko & Prikner, 2014):

$$CC \Rightarrow FCC = 1000\ [(\rho_{ds} / \rho_{dl}) - 1] = 1000[(\rho_{ds}/1420) - 1] \tag{22}$$

Soil 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:

$$\rho_{ds} = \tfrac{1}{4}\,(\rho_{d20} + \rho_{d30} + \rho_{d40} + \rho_{d50}) \tag{23}$$

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 & Prikner, 2014) proposed the computation of just the nominal tyre contact area S_T 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.

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

$$q = (1.06 - 0.06\lambda)q_s \tag{24}$$

where parameter λ (–) as a ratio of width b (cm) and length l (cm) of contact area gives accuracy to the Eq. 24:

$$\lambda = l/b \tag{25}$$

4.8 Statistical analysis of contact area prediction

Data were organised into tables and statistically processed in the Microsoft Excel and the Statistica CZ 12 (StatSoft, Inc., 2013). Significance level $\alpha = 0.05$ was established for all calculations. All calculated numerical values were rounded off to two decimal places. All results were expressed as mean ± standard deviation.

Because the data had the normal distribution, parametric tests were used (Kolmogorov-Smirnov test, $p > 0.05$). For analyses, frequency tables and paired two-sample t-test were used

For evaluation of the predicted accuracy of tyre's footprint area was used the Eq. 14, correctness of footprint area estimation was revised with the dimensions of tyre 650/65 R 38 selected from tyre manufactures. This yields the root mean square error (*RMSE*) between published and predicted footprint area. The *RMSE* is given as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(|S_{TP} - S_{TM}|)^2} \qquad (26)$$

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

$$bias = \frac{1}{n}\sum_{i=1}^{n}(|S_{TP} - S_{TM}|) \qquad (27)$$

where:

n – number of observations

S_{TP} – predicted contact area

S_{TM} – contact area published in tyre's data book

5 Results

Primarily, tyre contact area verification tests were performed with two agricultural traction tyre Mitas 650/65 R 38 RD-03 and Continental 650/85 R 38 SVT (*Super Volume Tyre*). The trend of tyre contact area decreasing, Figures 7 and 8 present behaviours in nominal combination levels of tyre load for speeds 10 and 30 km.h^{-1}, respectively. This is evidently, the inflation pressure as main parameter strictly affects tyre stiffness C_N, and thus outputs in linear function form are obtained.

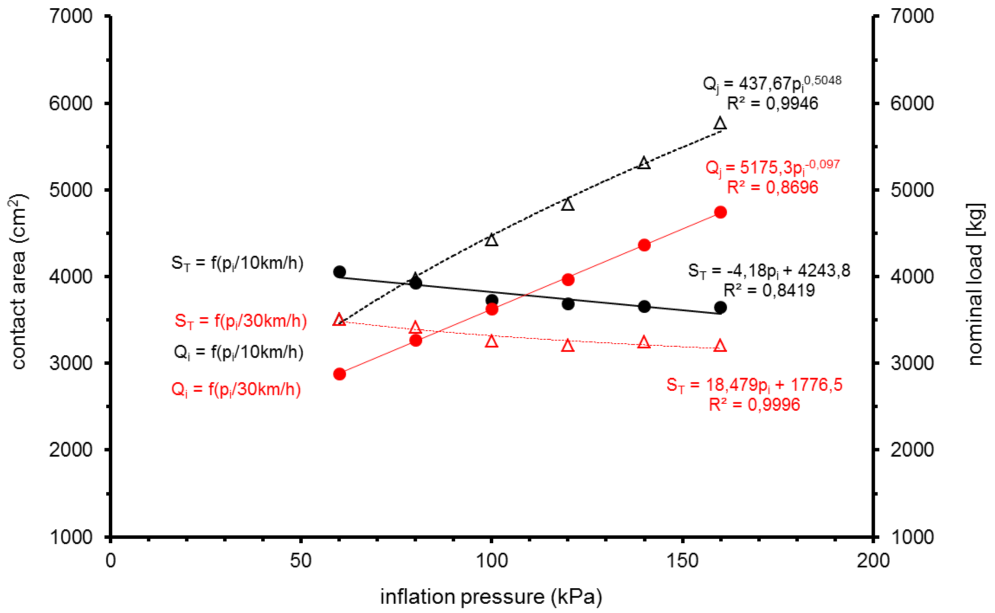

Figure 7: Comparison of tyre contact areas for speed 10km.h^{-1} and 30km.h^{-1} in nominal load and inflation pressure range; tyre 650/65 R 38 RD-03.

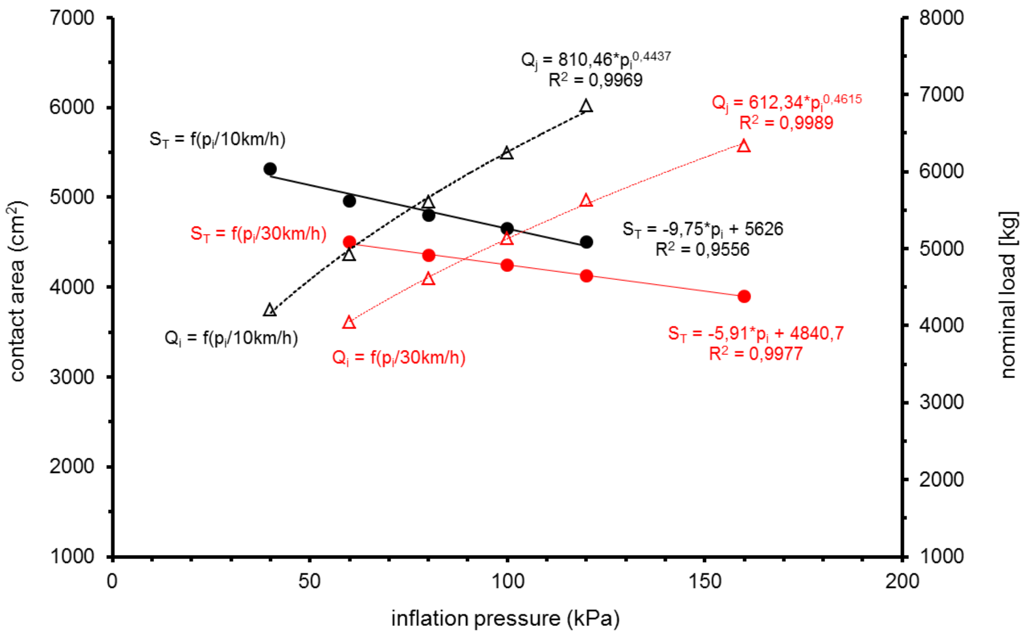

Figure 8: Comparison of contact areas for speed 10km.h^{-1} and 30km.h^{-1} in nominal load and inflation pressure range; tyre 650/85 R 38 SVT.

Note: experimental part for Continental SVT tyre 650/85 R 38 was possible only for maximal load of 7000 kg because of construction limit.

Nominal catalogues tyre load W_N was decreased in 25 % tyre load interval for all tyre inflation pressure levels in tyre 650/65 R 38 tests. Table 5 shows results confirming that the contact area decreases linearly in dependence on the change of tyre inflation pressure. Tyre Continental 650/85 R 38 SVT was tested in two speed levels 10 and 30 km.h^{-1}. Tyre contact area was measured for accuracy evaluation of contact area calculation only. Average difference 4.5 % corresponds with tyre's manufacture recommendation of acceptable difference upto 10 %, (personal correspondence with Mitas tyres product manager).

Table 5: Measured values of contact area for 10 km.h^{-1}; coefficient 0.67 in (Eq.19), Mitas 650/65 R 38.

650/65R38	p_i	60	80	100	120	140	160	200
ΔW	W	3505	3980	4420	4830	5310	5775	6190
	S_T	4100	3945	3911	3810	3740	3670	3429
-25 %	W	2630	2985	3315	3623	3983	4331	4613
	S_T	3433	3270	3325	3170	3130	3100	2893
-50 %	W	1753	1990	2210	2415	2655	2888	3095
	S_T	2518	2500	2455	2325	2360	2350	2115
-75 %	W	1000	995	1105	1208	1328	1444	1548
	S_T	1400	1300	1270	1240	1270	1290	1190

Legend: pi - inflation pressure (kPa); W - tyre load (kg); W_x – specific load (kg); S_T – tyre contact area (cm^2).

Table 6: Difference between measured and calculated contact area for speed 10 km.h^{-1} ΔS_T – cm^2; Continental 650/85 R 38 SVT.

p_i	40	60	80	100	120
ΔS_T	90	80	100	110	120
W	4210	4930	5610	6250	6855

Legend: p_i - inflation pressure (kPa); W - tyre load (kg); ΔS_T – tyre contact area difference (cm^2).

Table 7: Difference between measured and calculated contact area for speed 30 km.h^{-1}; Continental 650/85 R 38 SVT.

p_i	60	80	100	120	160
ΔS_T	150	140	130	130	150
W	4050	4610	5135	5630	6335

Legend: p_i - inflation pressure (kPa); W - tyre load (kg); ΔS_T – tyre contact area difference (cm^2).

The tables 8 and 9 presents technical data of tested tyre sizes 650/65 R 38 and 650/85R38 of selected tyre's manufactures. The use of Eq. 19, Figures 9 and 10 declarates accuracy of footprint areas S_{TP} prediction for tyre's size 650/65 R 38 in comparison with published tyre contact area S_{TM} (manufacture databook). In general, product S_{TPi} (see Eq. 19) which includes tyre deformation parameter n = 2/3 (Grečenko, 1995) ⇒ n_1 = 0.67 can describe the tyre footprint area size reliably.

Table 8: Catalogues tyre size 650/65 R 38 from selected manufactures; p_i = 160 kPa, speed 30 km.h^{-1}, ETRTO (2008).

650/65 R 38	b_t	d_t	r_s	W_N	S_{TM}*
Firestone	640	1850	828	4745	3096
GoodYear	653	1839	823	4415	2905
Michelin	646	1819	801	4740	3000
Mitas	622	1840	810	4745	2400†
Trelleborg	645	1810	815	4745	3050

Legend: b_t - tyre section (cm); d_t - tyre outer diameter (cm); r_s - static loaded radius (cm); W_N - nominal load from tyre manufacture catalogue (kg); S_{TM} -contact area published in tyre's data book (cm^2).

Note: †unexpected low value in Mitas data book; real footprint area $S'_{T0} \Leftrightarrow S_{TM}$ = 3100 cm^2;
*manufacture's data.

Table 9: Catalogue 650/85 R 38 tyre size from selected manufactures; ETRTO (2008): p_i = 160 kPa, speed 30 km.h^{-1}.

650/85 R 38	b_t	d_t	r_s	W_N	S_{TM}
Firestone	701	2030	915	6280	3550
GoodYear	694	2060	909	5820	3400
Michelin	720	2050	911	5850	3600
Mitas	720	2070	920	6250	3960
Trelleborg	710	2071	910	6075	3570

Legend: b_t - tyre section (cm); d_t - tyre outer diameter (cm); r_s - static loaded radius (cm); W_N - nominal load from tyre manufacture catalogue (kg); S_{TM} -contact area published in tyre's data book (cm^2).

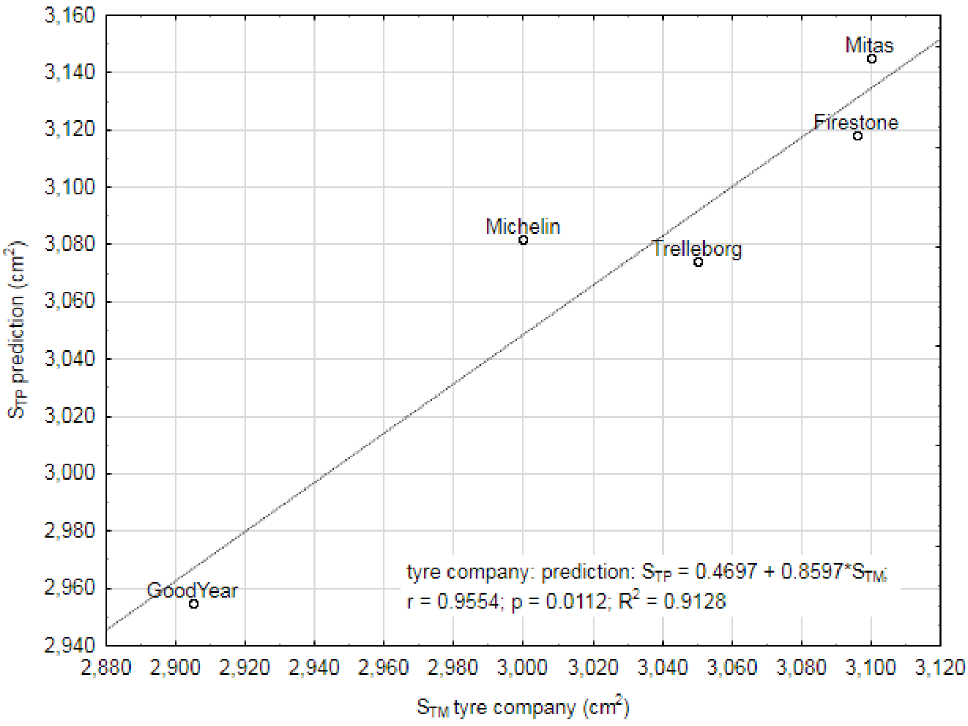

Figure 9: Contact area S_{TP} predicted using the Eq. 19; R^2 – modified coefficient of determination; *RMSE* = 49.62 cm^2 and *bias* = 44.60 cm^2; (Statistica Cz 12, original copy).

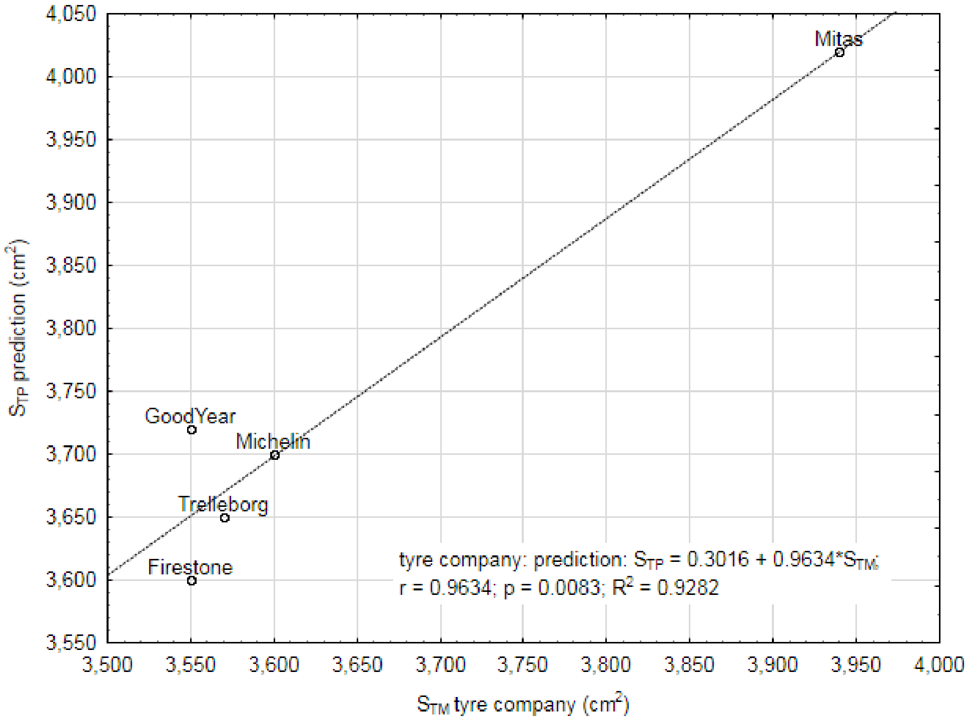

Figure 10: Contact area S_{TP} predicted using the Eq. 19; R^2 – modified coefficient of determination; *RMSE* = 104.12 cm^2 and *bias* = 96.00 cm^2; (Statistica Cz 12, original copy).

Calculation of any nominal tyre contact area S_{TPx} based on Eq. 19 as modification of SGP equation (Prikner and Grečenko, 2014) includes tyre deformation parameter $n = 2/3$ (0.67) as a standard, the Table 10 presents also calculation accuracy when two values $n = n_1 = 0.67 \Rightarrow S_{TP1}$ and $n_2 = 0.7 \Rightarrow S_{TP2}$ are compared; manufacture's contact area S_{TM}.

Table 10: Selected tyre - catalogue value and values of contact areas calculated for hard ground.

No.	Manufacturer	Tyre size	p_i	W	S_{TM}	S_{TC1}	S_{TC2}
1	Continental	12.4 R 28	160	1550	1041	912	895
2	Continental	16.9 R 30	160	2460	1799	1829	1796
3	Continental	14.9 R 34	160	2430	1521	1534	1514
4	Continental	18.4 R 34	160	3000	2233	2250	2206
5	Continental	13.6 R 38	160	1930	1206	1237	1209
6	Continental	18.4 R 38	160	3210	2297	2220	2179
7	Continental	20.8 R 38	160	4125	2860	2865	2867
8	Continental	540/65 R 24	160	2875	1850	1857	1831
9	Mitas	540/65 R 28	160	3050	2100	2161	2132
10	Mitas	600/65 R 28	160	3625	2540	2504	2474
11	Mitas	540/65 R 30	160	3135	2240	2219	2193
12	Mitas	600/70 R 30	160	4085	3000	2943	2903
13	Continental	620/75 R 30	160	4120	2720	2742	2692
14	Michelin	540/65 R 34	160	3335	2180	2160	2130
15	Continental	650/65 R 34	160	4120	2930	3009	2969
16	Mitas	650/75 R 38	160	4505	2720	2715	2707
17	Mitas	650/85 R 38	160	6270	3550	3434	3470
18	Mitas	800/70 R 38	160	7360	4400	4411	4394
19	Continental	900/60 R 38	160	7245	4500	4472	4397
20	Mitas	710/70 R 42	160	6440	3600	3565	3611

Legend: p_i - inflation pressure (kPa); W - tyre load (kg); S_T – tyre contact area (cm^2); S_{TM} - nominal tyre contact area (manufacture`s data); S_{TP1} – calculated contact area with coefficient $n = 0.67$; S_{TP2} - calculated contact area with coefficient $n = 0.7$.

Significant differences were not found between catalogues values S_{TM} and S_{TP1} values (paired two-sample t-test: $p > 0.05$). As well, any significant differences were not found between catalogue values S_{TM} and S_{TP2} values (paired two-sample t-test: $p > 0.05$).

Figure 11 presents design of prediction *CC* and *FCC* in MS Excel (*Win Pro7* Excel 2010) for evaluation of tyre parameters and compaction level named as tyre CC-rating (Grečenko and Prikner, 2014). Values of S_T / S_{TP} and *CC* / *FCC* were calculated automatically after selecting tyre designation, tyre and rim size, respectively.

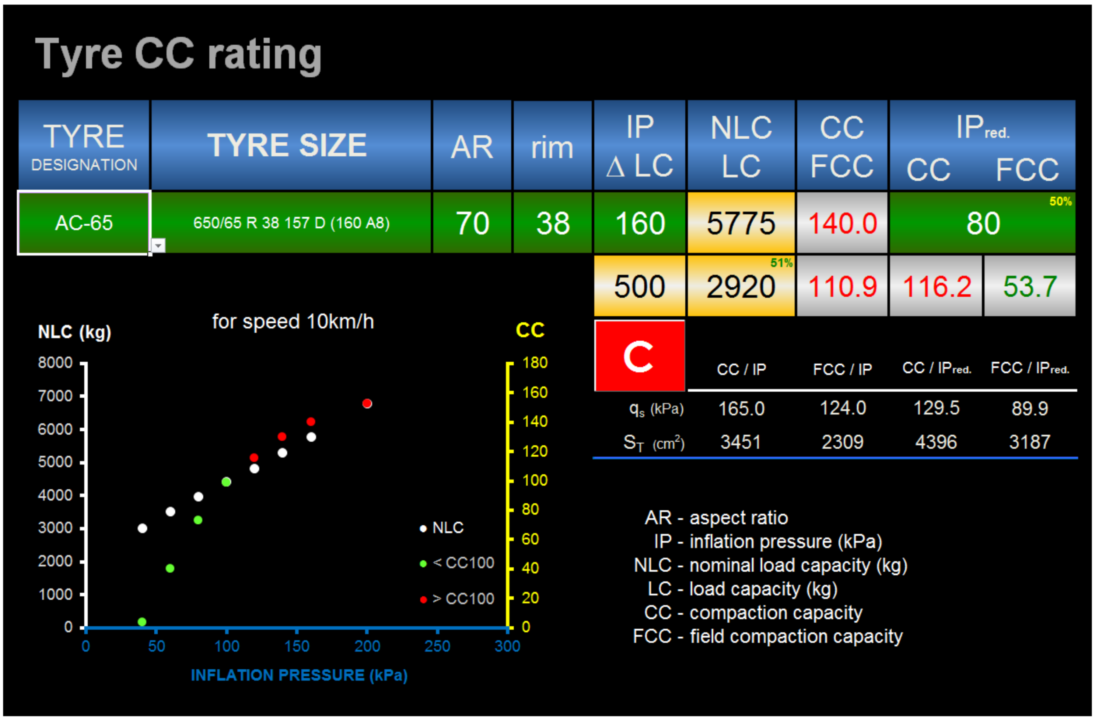

Figure 11: Design of CC-rating computer program, (demo version 2015); (source: author).

The original tyre CC-rating based on quantification by Grečenko and Prikner (2014), presented *FCC* includes modification of nominal contact area S_T. Nominal tyre contact area S_{TP} depends on actual combinations of W_N and p_i, respectively. Figure 12 shows and proves the difference between *FCC* and *CC* indexes. Contact pressure in both conceptions has distinct purpose. In the tyre CC-rating as the standardized factor, contact pressure q supports evaluation simplicity with the use of the tyre's contact maximal area S_T across the inflation pressure range. The *FCC* insists on precise contact area S_{Tx}

calculation under a given load which produced contact pressure (Eq. 19). This transformation prefers a cubic polynomial; however the quadratic type is sufficient as well.

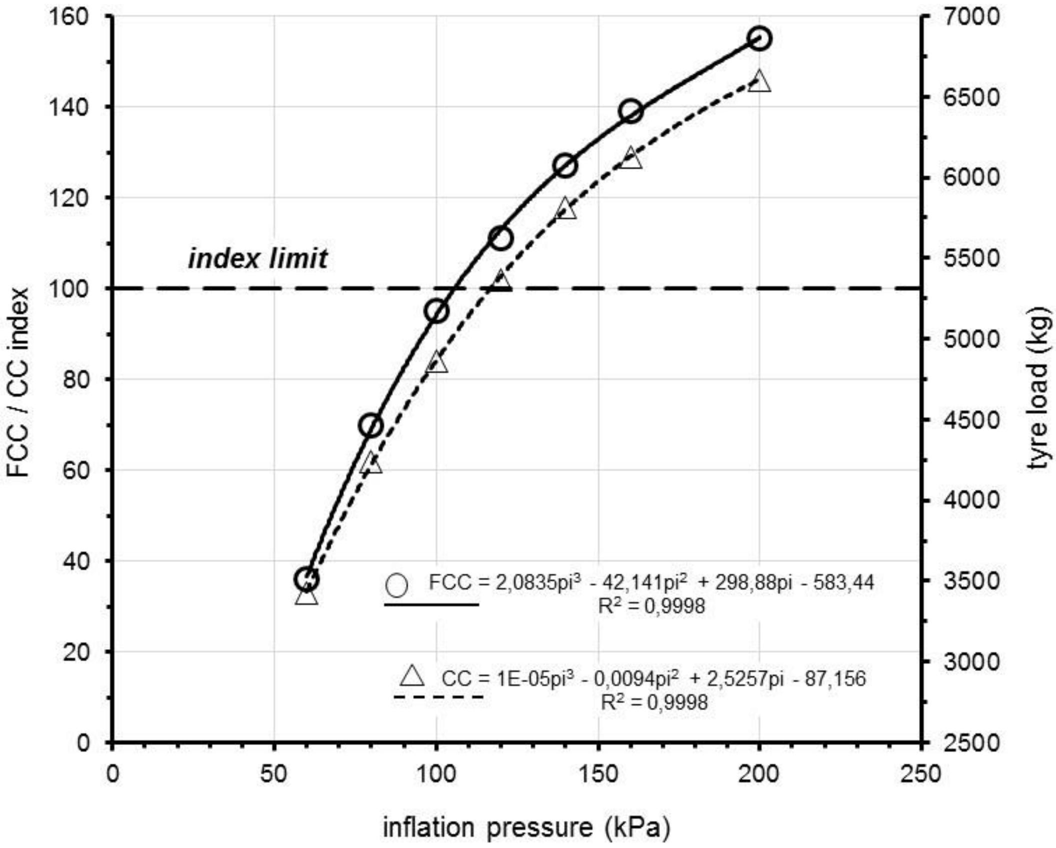

Figure 12. Comparison of FCC and CC quantification for nominal catalogues load range in dependence on inflation pressure for speed 10 km.h^{-1}; (Mitas 650/65 R 38 RD-03); compaction index limit reports to the extreme range of clay-loam soil dry density; (source: supervisor).

Tables 11 - 23 present evaluation of compaction potential *CC* and *FCC* of selected traction tyres for speed of 10 km.h^{-1}. The tyre *CC*/*FCC* evaluation, catalogues combinations W_N and p_i for speed level 10 km.h^{-1} can describe a static tyre's load compaction effect sufficiently.

Table 11: Obtained values of *CC* and calculated *FCC* for tyre 540/65 R 28.

p_i	60	80	100	120	140	160	200
NLC	2505	2815	3095	3340	3545	3710	3975
q	75	87	99	111	123	134	150
CC	0	14	31	47	60	74	×
FCC	8	35	55	74	88	98	107
S_T	3321	3205	3089	2973	2857	2741	2625

Table 12: Obtained values of *CC* and calculated *FCC* for tyre 540/75 R 28.

p_i	60	80	100	120	140	160	200
NLC	3000	3295	3575	3860	4140	4425	4940
q	91	100	112	124	138	152	175
CC	15	58	73	86	98	107	121
FCC	44	59	78	93	106	116	127
S_T	3259	3167	3074	2982	2890	2790	2706

Table 13: Obtained values of *CC* and calculated *FCC* for tyre 540/65 R 30.

p_i	60	80	100	120	140	160	200
NLC	2090	2655	2910	3165	3420	3680	4165
q	67	88	101	114	128	144	171
CC	0	16	33	49	63	76	98
FCC	11	36	59	78	94	106	119
S_T	3085	2973	2861	2750	2638	2526	2303

Table 14: Obtained values of *CC* and calculated *FCC* for tyre 600/70 R 30.

p_i	60	80	100	120	140	160	200
NLC	3295	3750	4180	4580	4805	4970	5325
q	82	97	112	127	138	149	166
CC	1	52	67	81	94	104	×
FCC	31	64	91	109	119	125	132
S_T	3973	3840	3708	3575	3443	3310	3178

Table 15: Obtained values of *CC* and calculated *FCC* for tyre 620/75 R 30.

p_i	60	80	100	120	140	160	200
NLC	3350	4205	4490	4780	5065	5355	5940
q	87	113	125	137	151	165	190
CC	57	97	107	116	122	128	137
FCC	43	92	107	118	127	134	142
S_T	3803	3684	3565	3446	3327	3209	2971

Table 16: Obtained values of *CC* and calculated *FCC* for tyre 710/65 R 30.

p_i	60	80	100	120	140	160	200
NLC	3260	4135	4535	4935	5335	5735	6490
q	63	83	94	106	120	134	159
CC	0	9	39	66	88	105	128
FCC	41	48	82	108	127	140	153
S_T	5142	4959	4770	4594	4412	4230	3865

Table 17: Obtained values of *CC* and calculated *FCC* for tyre 650/65 R 34.

p_i	60	80	100	120	140	160	200
NLC	3645	4095	4500	4860	5165	5425	6025
q	87	102	116	130	143	156	181
CC	29	58	78	95	106	114	128
FCC	47	77	100	116	126	133	142
S_T	4132	3993	3854	3715	3575	3436	3297

Table 18: Obtained values of *CC* and calculated *FCC* for tyre 650/75 R 34.

p_i	60	80	100	120	140	160	200
NLC	4510	4910	5310	5710	6110	6870	7165
q	74	84	94	106	119	132	153
CC	65	84	101	114	124	133	142
FCC	12	53	83	106	124	136	146
S_T	6040	5807	5573	5340	5107	4874	4407

Table 19: Obtained values of *CC* and calculated *FCC* for tyre 650/75 R 38.

p_i	60	80	100	120	140	160	200
NLC	4405	5015	5585	6125	6505	6825	7590
q	98.7	115.4	132.1	149	163	176	202
CC	30	87	104	117	126	134	145
FCC	77	107	126	138	145	150	156
S_T	4428	4310	4192	4074	3956	3838	3720

Table 20: Obtained values of *CC* and calculated *FCC* for tyre 650/85 R 38 SVT.

p_i	60	80	100	120	140	160	200
NLC	4930	5610	6250	6855	7315	7715	8500
q	97	113	129	145	159	172	194
CC	1	76	96	112	124	134	146
FCC	82	113	132	144	151	156	161
S_T	5051	4934	4816	4698	4581	4463	4346

Table 21: Obtained values of *CC* and calculated *FCC* for tyre 800/70 R 38.

p_i	60	80	100	120	140	160	200
NLC	5730	6525	7270	7965	8500	8960	9850
q	85	99	114	129	142	155	176
CC	23	100	118	131	141	148	156
FCC	64	106	131	146	154	159	165
S_T	6716	6522	6327	6133	5938	5744	5549

Table 22: Obtained values of *CC* and calculated *FCC* for tyre 710/70 R 42.

p_i	60	80	100	120	140	160	200
NLC	4970	5655	6305	6910	7400	7840	8540
q	93	109	126	143	159	174	197
CC	20	89	108	122	133	141	151
FCC	76	109	131	144	151	156	162
S_T	5292	5126	4960	4794	4628	4462	4296

Table 23: Obtained values of *CC* and calculated *FCC* for tyre 710/75 R 42.

p_i	60	80	100	120	140	160	200
NLC	4765	6025	6555	7090	7620	8150	9115
q	91	118	131	146	161	176	203
CC	49	108	123	134	142	149	156
FCC	69	122	136	146	153	158	165
S_T	5180	5060	4939	4819	4699	4578	4338

Original *CC* or *FCC* modification (see Eq. 22), compares ratio of soil compaction state to critical dry bulk density for clay-loam soil type (1420 $kg.m^{-3}$) exclusively. The *eFCC* index using previous formula can be defined:

$$eCC \Rightarrow eFCC = [(CC + 1000)\rho_{dl} / \rho_d - 1000] \qquad (28)$$

The evaluation of tyre *eFCC* index is demonstrated using five soil types in Figure 13. Considering the value of *eFCC* = 100 as an upper limit, the clay soil admits acceptable *eFCC* index when tyre load of about 3530 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.

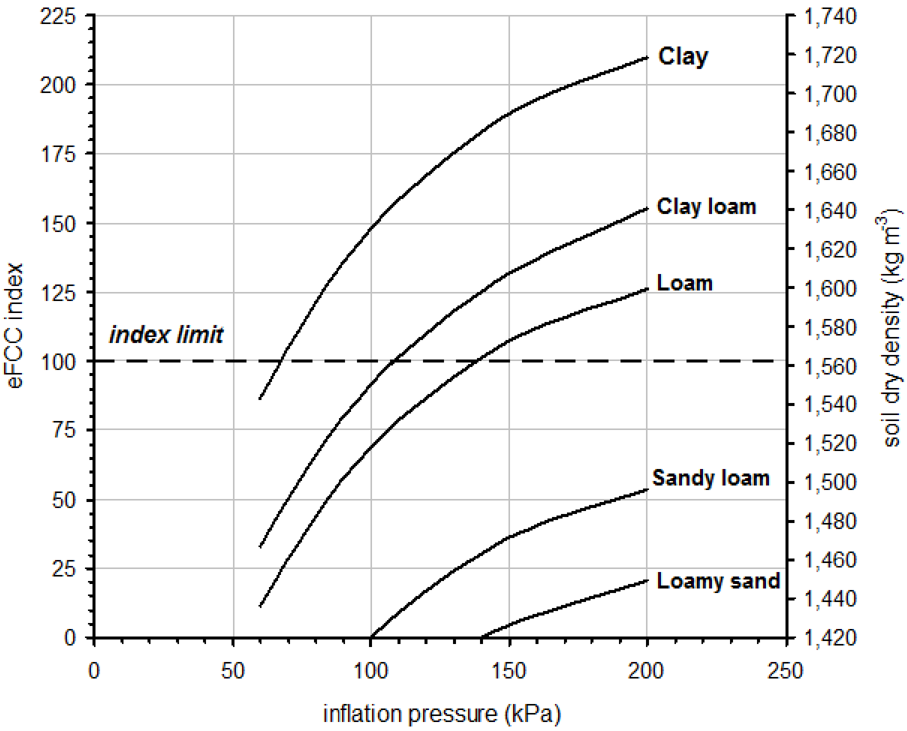

Figure 13 Trends of the *eFCC* for selected soil types; nominal catalogues load range in dependence on inflation pressure for speed 10 km.h^{-1}; (Mitas 650/65 R 38 RD-03); *eFCC* index limit reports to the extreme range of soil dry density, referring to clay loam standard; (source: sepervisor).

Original *CC* evaluation produced lower values than *FCC* due to different conception of contact area size prediction in 91.01 % of cases. Detailed result are available in Table 24.

Table 24: Difference between catalogues value *CC* and *FCC* values of contact areas measured.

	Number of cases	Frequency (%)
No	8	8.99
Yes	81	91.01

Number of cases when the difference between value of contact area in manufacures catalogues and values of calculated contact areas based on coefficient n = 0.67 and coefficient n = 0.7, were lower or higher than 10 % are in Table 25.

Table 25: Difference between catalogues value and values of predicted contact areas, tyre divided by the size of the rim.

Size of tyre	Coeficient	Difference	Number of cases	Frequency (%)
< R 34	0.67	> 10 %	1	8.33
		< 10 %	11	91.67
	0.7	> 10 %	1	8.33
		< 10 %	11	91.67
> R 36	0.67	> 10 %	0	0.00
		< 10 %	8	100.00
	0.7	> 10 %	0	0.00
		< 10 %	8	100.00

6 Discussion

The prediction of the tyre contact (footprint) area of a modern agricultural tyres using laboratory testing procedure on the hard surface was presented. The results are the base for specification of the standardized tyre contact area. Basic equations for the calculation were published earlier (Grečenko, 1995) and modified (Grečenko and Prikner, 2014) with respect to the calculation of the nominal contact area for determining the compaction potential of the tyre CC-rating. The compaction potential of the tyre allows developing a computer model (written as a macro in Visual Basic implemented in an Excel spreadsheet). The calculation is based on tyre dimensions data exclusively. With regard to the nominal deformation of the casing, it is possible to determine the nominal size of the contact area. Using verification, the magnitude of the deformation coefficient, the contact area size can be determined for any combination of inflation pressure and load in relation to specific tyre parameters such as rim size and profile number. This calculation is included in the test demo version of the tyre CC-rating model. In 1995, Grečenko recommends using the general rate 0.67 based on tests and available resources. This value reliably determines contact area values for greater load and lower inflation pressure values; however, the values are obtained for the mean size of the radial and diagonal tyres. The coefficient is not suitable for the calculation of the contact area for large traction tyres from the width of the casing 650 mm, free diameter 1800 mm and rim size from 38 ". This deficiency was partially corrected by determining the tyre deformation function as a function of the size of the tyre profile number (Grečenko and Prikner, 2014). According to the statistical evaluation is advantageous to use for large traction tyres type a value of deformation coefficient n′ = 0.70, which takes into account the change in the tyre stiffness in dependence on inflation pressure variability. Statistical evaluation of predicted contact area sizes where different values of deformation coefficient n′ = 0.67 (0.7) were used; conclusions confirm any significant differences in context to ΔS_T up to 10 %. 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 as declarates example of evaluated tyre 12.4 – 28 (n′ = 0.67 ⇒ 12.4 % and n′= 0.7 ⇒ 14 %).

In this respect, the tyre width and the relative deformation of the sidewall significantly affect the change of contact area shape under load. The oval shape of the contact area is obtained under high inflation pressure. Low inflation pressure causes a rectangular shape with a constant width of the imprint. The value of the deformation coefficient 0.7 is used to supplement the compaction capacity of the tyre, so that the *FCC* (Field Compaction Capacity) is a set value according to the actual inflation pressure values, respectively. The deformation and the load change in relation to the nominal catalogue value. Determination of the contact area is currently solved for field conditions (e.g., Keller, 2005 and 2007, Diserens, 2009), however the variability of soil conditions cannot provide standard conditions for determining the results. The values obtained so far can not be compared to each other.

This thesis quotes improving of original formula predicting the off-road tyre footprint area on hard ground (area of the envelope to the contact patch) using a new parameter *c* as a scaling factor characterising the tyre aspect ratio which can be applied more easily in engineering. Such conversion leads to the nominal footprint area which refers to any inflation pressure-load combination listed in the catalogue. The application of improved equation, following conclusions may be drawn from the preceding text: (Håkansson, 1990) the compaction risk grows with tyre size and load; (van den Akker, 2004) lower inflation pressure must be in link with lower tyre load to reduce soil compaction; (Keller, 2007) the total mass of heavy vehicles should be distributed among more than two axles with smaller tyres; (Håkansson and Reeder, 1994)) radial ply tyres loaded to their nominal capacity produce higher compaction potential than equivalent cross ply tyres because of their greater nominal load capacity; (Grečenko and Prikner, 2014) the tyre CC-rating provides simple and practical soil compaction risk assessment unattained so far by other known methods such as stress analysis.

The results and conclusions of previous studies of subsoil compaction are recorded and emphasise still the same problem, namely that the use of axles with heavy load in soils with high moisture content causes deep and lasting subsoil compaction (Akker, 2003).

Arrangement in agriculture engineering branch in relation to the compaction of the soil profile are still insufficient. A positive trend is that the politicians of the European Union recognise the soil as a vital and largely non-renewable resource. A negative trend is the fact that the load wheels and belts are still increasing, causing serious damage to the soil (the European Parliament, 2002).

The tyre CC-rating (Compaction Capacity = compaction potential of tyres) is a suggested for progressive agriculture system, which can be directly determined using tyre catalogues data and given combination of load and inflation pressure. The value of *CC* is a dimensionless number expressing exceeded soil bulk density above its critical value. A standardised method was developed for the clay-loam soil representing the standardized soil type with reference to its preferred percentage composition: 27 % clay, 48 % silt and 25 % sand. At 85 % moisture limit of plasticity (23 %) reaches the limit value of density of soil 1420 kg.m^{-3}, which defines a critical condition for plant growth.

Evaluation of tyre CC-rating of the tyre is based on specification of compaction functions using circular plates and compressing desired mean contact pressure in the soil half space with standardised methodology. Standardzed circular plates represent a contact area of the tyre (recalculation loaded areas), which can be replaced with a circular surface. When the average density provided for soil at depths of 20, 30, 40 and 50 cm standardised exceeds the limit of 10 %, value of the tyre rating is 100.

Prediction of the compaction potential of the tested tyre was performed using modified tyre CC-rating model (combination with *FCC*) that allows assessment of any combination of load and inflation pressures.

The range of tyre *CC* and *FCC* scale evaluation (0 - 100) assess a tyre as a soil friendly. When the tyre compaction index exceeds 100 this advices 10 % exceeding of the critical soil dry density limit in both *CC* and *FCC*, respectively.

Considering the value of *FCC* = 100 as an upper limit, the clay soil admits acceptable FCC index of tyre 650/65 R 38 when load of about 5200 kg at 100 kPa inflation pressure. The limit for clay loam soil type allows to nominal combinations of load and inflation pressures for 100 and 120 kPa, respectively. Tyre Continental 650/85 R 38 SVT produce *FCC* 82 for combination load 4930 kg and 60 kPa inflation pressure. Nominal catalogue combination 80 kPa inflation pressure and corresponding load 5610 kg produces *FCC* 113; however, this can be admined as a upper limit of combination under specific soil dry conditions. Grečenko in 2016 published appendix to previous

(Grečenko and Prikner, 2014), that describes modification of the tyre CC-rating for other soil types in term *eCC* rating as equivalent Compaction Capacity of tyre (see Eq. 28). The conception of *eCC* utilizes soil types limits for fundamental soil parameters published by Lhotský in 2000, (see Table 1 and Figure 13).

Presented calculation (prediction) of the contact areas of a modern agricultural traction tyre based on verification tests of the contact area. The 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.

Compaction in the topsoil can be avoided by reducing tyre pressure, using flotation tyres, doubles, radial tyres, or tracks, and by employing large-diameter tyres. Reducing the number of trips over the field and reducing the total area per acre actually traveled are recommended. Driving on soil that is wetter than the plastic limit should be avoided at all times.

7 Conclusion

Applycation of appropriate agricultural technologies can minimize negative effect on the soil and consequently reduce fertility. The correct choice of tyre is to reduce negative impact of agricultural machinery on soil profile and minimize soil compaction effect, particularly through the use of technology at 60 % of the land, with a minimum crossing system and Controlled Traffic Farming. In addition, reducing of axle load and the mass of vehicle, or using low-pressure radial tyres that reduce the compaction of tyres and increase the tensile strength, especially the application of recommended tyre inflation pressure and reduction of the tyre mean contact pressure by means of dual wheels conception.

Size of tyre contact area with the subsoil is required to calculate the mean contact pressure and compaction of the capacity of tyres. Evaluation of tyre contact area by measuring the area of the footprint on a hard surface is very laborious, but the area corresponds to the tyre's load under certain inflation. Determination of tyre footprint area, there is relationship based on catalogue parameters; however, in some cases have significant differences from the measured values (e.g. Grečenko, 1995).

The compaction risk increases with tyre load. Lower inflation pressure must be combined with lower loading to reduce soil compaction. The mass of heavy vehicles should be distributed among more than two axles with smaller tyres. Radial ply tyres loaded to their nominal capacity have higher tyre compaction capacity than equivalent cross ply tyres because of their greater nominal load capacity. The tyre CC/FCC-rating provides simple and practical soil compaction risk assessment, but does not reach so far by other known methods such as stress analysis. The tyre compaction capacity technique has capacity to evaluate the increased soil compaction risk for tyres operating in a furrow.

It follows from the findings above that the application of the modified method of calculating the interface area size to the original tyre CC-rating concept can achieve tighter tyre ratings compared to the original tyre CC-rating. According to my optinon, the inclusion of a FCC rating can be used as a part of the catalogue data for each combination of load and inflation pressures that would make it easier to select the appropriate tyre size for the machine in order to reduce the risk of soil compaction.

The FCC-rating (*eFCC* modification) can be suggested as a mobile smartphone application which integrated the calculation system into the on-board computer of modern agricultural machines. The application can be able to predict the optimal inflation pressure level for actual load under a given regions after GPS tracking before field travel without exceeding the nominal values of the load and pressure combinations listed in the tyre catalogue. In the future, extracted software can include the integration of geomap databases and rainfall frequency for soil moisture conditions monitoring. Conception of agricultural machines, this is possible to design software fully automated, which is able to control pressure in tyres. Using a modern approach, world farming can reduce soil compaction and increase yields of cultivated crops.

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