# EFFECT OF PNEUMATIC TIRE PRESSURE AND DEFORMATION PARAMETERS ON DECREASING SOIL COMPACTION

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**Abstract.** Soil resources are limited and irregularly distributed around the Earth, that is why soil degradation, and, especially, soil compaction, is one of the top priority topics, which the world organizations are paying more and more attention to. Soil compaction causes are mostly related with using heavy agricultural machinery. In turn, for agricultural machines, the most important factors are the mass and dimensions of the contact area for wheels. The length and tire width are responsible for the contact surface. In modern agricultural technology the length parameter can be adjusted by changing the tire pressure. In terms of minimizing compaction, the greater the pressure, the larger the contact surface, therefore, the tractor mass is better distributed. However, the structural parameter is also important, which satisfies the condition of no folding of tire. If this parameter is satisfied, we can get reliable working of the tire throughout the entire period of operation. Experimental research was carried out on the field conditions in the centre of Lithuania, near Kaunas. For determination of soil compaction, a heavy tractor was used with approximately 30 t mass and automatic tire pressure changing technology. Using the previously proposed model for describing the tire using the properties of Cassinian ovals, it was possible to find that for the found angle 48° the optimal tire pressure should be 1.2 bar at a moisture content of 13.14%, a soil temperature of 18 ºC and a soil electrical conductivity of 123.75 mS·m$^{-1}$. This will help minimize compaction and satisfy the no folding condition for pneumatic tires.

**Keywords:** soil, compaction, tire pressure, wheel, heavy tractor, Cassinian curves.

## Introduction

The soil resources of our planet are strictly limited and unevenly distributed over its area. This means that their rational use is the task of all, without exception, inhabitants of the planet. Also, according to the UN (United Nation) data [1], by 2050 the population will increase to more than 9 billion people, which makes the problem of preserving and preventing soil degradation of any kind become the strategic task.

The soils also serve as a platform for raising food for animals and grazing. As reported [2]: 192 million km$^2$ global land area are soils. Only 93 million km$^2$ are biologically productive, where 33% of them are forests, 32% – pastures and only 11% – cropland [2]. For Europe, this number is almost 1.5 million km$^2$, which is 20% of the entire area of Europe and 13.8% of the area of all soils on the Earth [3]. As a result of assessment by [4], we can conclude that the soil compaction is the most predominant degradation type: over 62 million ha or 11% of the total area and 21.7% of all degradation. Frequent use of heavy machinery could be the main culprit of this negative phenomenon [5].

Compaction can lead to yield losses [6; 7], some examples shown in Figure 1, and to additional fuel consumption [7], which, in turn, increases greenhouse gas emissions into the atmosphere [8; 9], requires more fertilization and introduction of other agricultural chemicals that can get into the ground waters [5; 8]. Compaction can cause soil erosion [8; 10], physical, chemical and biological degradation, sometimes even destruction of the landscape [8] and flooding [5; 7]. Rarely studies indicate hundreds of millions damage in the countries scale, although it is very difficult to assess all negative effects in full, quantitatively and qualitatively [5].

Among the factors associated with the highest risk of compaction we can single out: a significant increase in the mass of tractors and harvesters during the XX-XXI centuries [5; 12]; uncontrolled traffic of agricultural machines [12], which is well solved with the introduction of precision farming [13]; high tire pressure during agricultural operations, as a result of which the area of contact with the soil is reduced, which, in turn, leads to greater pressure on the same area, which is often the cause of compaction. Whenever possible, it is recommended to use equipment with rubber tracks [11; 14-16], twin wheels [11; 18], and lower tire pressures [18-20]. Pneumatic radial tires, according to [21], can reduce the risk of soil compaction, too, but the tread pattern is also important [22]. When choosing tires, there is a need to study well the possibility of changing the inflation pressure, and only reduce the pressure in the field and within the allowed design boundaries. Otherwise, tires may become damaged and unusable earlier than expected.

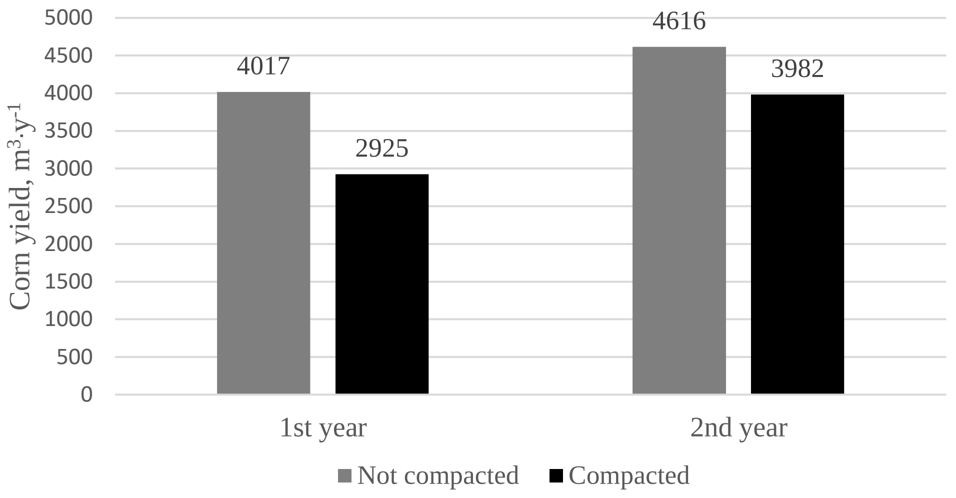


Fig. 1. **Corn yield loss due soil compaction (adopted from [6])**

The purpose of this study is practical examining and verification of the theoretical research data, which are designed to control and minimize the risks of soil compaction by keeping the theoretical parameter – angle $\alpha$.

## Materials and methods

Due to the fact that wheeled vehicles are still more common in agriculture, although vehicles with rubber tracks are gaining popularity, and it is possible to change wheels to tracks for almost any modern tractor, the task is to minimize soil degradation due to the motion of these wheeled vehicles, in particular compaction is very acute. It has been known for a long time that compaction can be minimized by adjusting the inflation pressure of the tires, when all other machine parameters being equal. In this case, decrease in the pressure increases the contact surface of the tire with the soil, and naturally less vertical stress from the machine is applied on this spot. However, if the tire inflation pressure is reduced too much, it can cause permanent tire deformation. To control the required (optimal) level of inflation pressure in the tire and prevent its deformation, a graphical-analytical model was developed based on the properties of Cassinian oval [24]. The operational shape of the tire can be modelled as Cassinian oval (Figure 2) with different parameters (1):

$$(x^2 + y^2)^2 - 2c^2(x^2 - y^2) = a^4 - c^4. \quad (1)$$

For various (parameter of Cassini ovals, which determines the shape of the curves) parameter values it is possible to observe different tire shape changing (deformation). After mathematical transformations within the framework of the graphic-analytical analysis of the tire shapes, the parameter $\alpha$ was found, while maintaining it by keeping the corresponding pressure in the tire, it will be possible to minimize the risk and degree of soil compaction and not unnecessarily deform the tire. This $\alpha$ is an angle, as you can see in Figure 3, that is formed by rays that start at the edges of the contact surface and pass through the centre of the wheel.

To test this theoretical thesis, near Kaunas (55'188119; 23'9198501), tests were carried out with various tire pressures. A tractor used for the tests was CLAAS XERION 5000 (530 hp) with tires TRELLEBORG 900/60 R32 TM. 1000 High Power.

The total weight of the tractor with balancers is 23230 kg. The front axle load 9476.5 kg, rear axle load 7753.5 kg. During the experiment the average moisture content was 13.14%, soil temperature 18 ºC and the soil electrical conductivity was 123.75 mS·m$^{-1}$. Of course, if the moisture increases, the risk of compaction increases, too, because the soil becomes easier to deform, and also, the wetter the soil, it will become more viscous and allow for the wheel slip, which will increase the load apply time. The internal pressure in the tires of the front and rear wheels was adjusted using the pressure change system of the tractor itself and was monitored using a pressure gauge. The tire pressure was varied from 0.6 bar to 1.8 bar in 0.2 bar increments. With a change in the pressure, the length of the contact surface and the controlled angle $\alpha$ were measured, respectively. In this way, 7 measurements and 3 repetitions were carried out. The tire width – 90 cm. The $\alpha$ angle was measured with a goniometer. A summary of the experimental data is presented in Table 1.

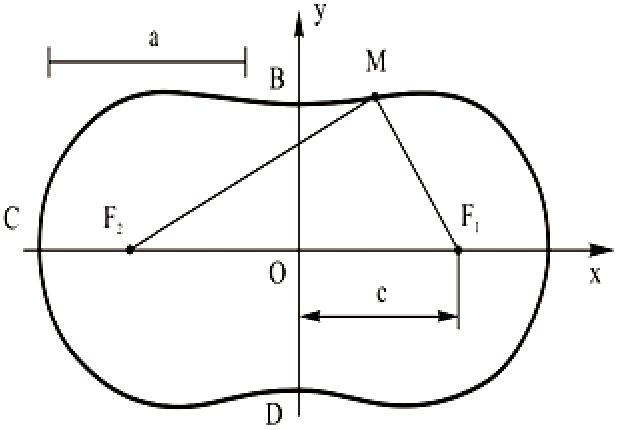


Fig. 2. **Cassinian oval [24]:**
a – product of distances from which up to two foci equal to $a^2 = (MF_2)^2 \times (MF_2)^2$;
$c$ – distance from origin to foci ($F_1F_2 = 2c$);
$F_1$, $F_2$ – foci points; $M$ – random point on Cassinian curve

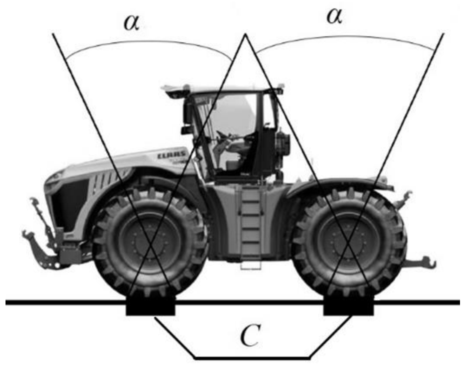


Fig. 3. **Options for controlling angle of pneumatic tire–soil contact area (adopted from [24]):** $C$ – tire-soil contact surface; $\alpha$ – angle formed by rays that start at the edges of the contact surface and pass through the centre of the wheel

Table 1

**Summary of the experimental data**

| **Tire pressure, Bar** | **S FW, cm** | **L FW, cm** | **S FW, cm** | **L RW, cm** | **S′ FW, cm²** | **S′ RW, cm²** | **p FW, kPa** | **p RW, kPa** | **$\alpha$ FW, º** | **$\alpha$ RW, º** |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.6 | 90 | 110 | 90 | 85 | 10230 | 7820 | 28.95 a | 34.98 ab | 82 | 59 |
| 0.8 | | 103 | | 81 | 9064 | 7371 | 32.68 b | 37.11 bc | 75 | 56 |
| 1.0 | | 100 | | 78 | 8900 | 8370 | 33.28 b | 32.68 a | 54 | 50 |
| 1.2 | | 90 | | 75 | 8010 | 6750 | 36.96 c | 40.52 cd | 51 | 47 |
| 1.4 | | 78 | | 67 | 7020 | 6030 | 42.19 d | 45.36 de | 48 | 44 |
| 1.6 | | 66 | | 60 | 5940 | 5400 | 49.86 e | 50.65 e | 45 | 38.5 |
| 1.8 | | 58 | | 45 | 5220 | 4050 | 56.74 f | 67.54 f | 38 | 31 |

Note. The meanings of the columns marked with the same letter (a, b, c, etc.) are not statistically significant differences, with a confidence level of 95%). For $p_{FW}$ – $HSD_{0.05} = 0.717$, $HSD_{0.01} = 0.916$; for $p_{RW}$ – $HSD_{0.05} = 7.607$,
$HSD_{0.01} = 9.713$.

$S_{FW}$ – front wheel width;
$S_{RW}$ – rear wheel width;
$L_{FW}$ – length of the contact surface for the front wheel;
$L_{RW}$ – length of the contact surface for the rear wheel;
$S'_{RW}$ – rear wheel contact area with soil;
$S'_{FW}$ – front wheel contact area with soil;
$p_{FW}$ – front wheel pressure on the soil in the contact area;
$p_{RW}$ – rear wheel pressure on the soil in the contact area;
$\alpha_{FW}$ – angle $\alpha$ for the front wheel at the given inflation pressure;
$\alpha_{RW}$ – angle $\alpha$ for the rear wheel at the given inflation pressure.

The estimated accuracy of the research result on average 5% (with a numeric accuracy value $p < 0.05$). The one-factor analysis of the data variance was used, using the Honest Significant Difference Method between the averages of the data evaluation ($HSD_{05}$) (probability level 95%).

A dispersion analysis was performed on the Tukey HSD test for mathematical statistics, evaluating the essential difference margin of $HSD_{05}$ at probability level of 95%, in order to make sure that the differences between the averages of the data were significant. In Table 1, the letters indicate substantial differences between the factors. Uniform letters show that there is no substantial difference.

After the evaluation of the accuracy of the experimental data, the calculated numerical values of the test accuracy revealed that the calculated data were very precise. The accuracy specified did not exceed 5% (with a numeric accuracy value of $p < 0.05$).

## Results and discussion

The most important results are graphically summarised in Figure 4. With a linear increase in pressure, the tire-soil contact area decreased, since the length of this area decreased, with a constant tire width – 90 cm, and the load on a smaller area became more linearly, but with insignificant fluctuations.

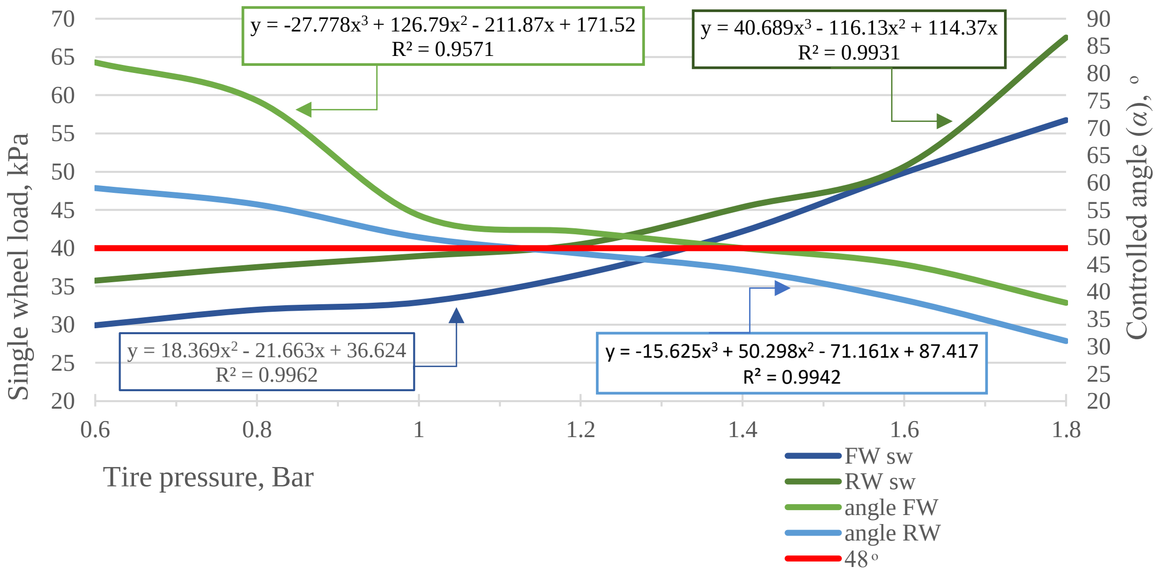


Fig. 4. **Single wheel load and control angle *α* relative to tire inflation pressure**

Theoretically optimal angle for minimising compaction and to satisfy no folding condition – $\alpha = 48^{\circ}$ (red line), FW sw – front single wheel load (dark blue line), RW sw – rear single wheel load (dark green line), angle FW – controlled angle on the front wheel (light green line), angle RW – controlled angle on the rear wheel (light blue line)

The observed angle $\alpha$ decreased in the value with increasing the tire inflation pressure, with small fluctuations, too. Close to the optimal value of this controlled angle $\alpha = 48^{\circ}$ (red line) was achieved with a tire pressure of 1.2 bar, at this time the load on the soil surface on the front wheel was almost 37 kPa, on the rear – 40.5 kPa. The minimum for the front wheel is 28.95 kPa at the pressure of 0.6 bar, the maximum at the pressure of 1.8 bar – 56.74 kPa. With similar tire pressures for the rear wheel, the maximum load was 67.54 kPa, the minimum was almost 35 kPa. From the recommendations of the developers and the operation of agricultural machinery it is known that the internal tire pressure at the level of 0.9 bar improves the traction characteristics of the machine and it is recommended for field work [26]. When the pressure rises to 1.2 bar, the traction power of the tractor decreases on average by 12%, but it is not clear whether the performance parameters of the tires are taken into account or not. In addition, in order to adequately supply 0.9 bar pressure, special low- and ultra-low-pressure tires are required, which requires a significant cost. In this regard, in some cases, it may be more rational to replace the wheels with a system of rubber tracks, which, in comparison with the wheels, have lower risks of compaction and now it is possible to replace wheels on any agricultural machinery with rubber tracks [11].

Among other things, since the parameter theoretically claims to be universal for all types and sizes of tires, additional long-term studies are needed while maintaining the given theoretical angle $\alpha$ = 48º for various additional conditions and different tire types and designs.

## Conclusions

1. The trend for the $\alpha$ value to change is inversely proportional to the change in the tire inflation pressure, and correlates well with the change in the pressure on the contact area.
2. While maintaining the theoretically optimal angle $\alpha$ = 48º, the pressure should be close to 1.2 bar. This will help minimize compaction risks, when working with tractors, and satisfy no folding condition (maintaining optimal working conditions for the tire).
3. Additional long-term research is required with control of maintaining the angle $\alpha$, using various tires (including with improved flexion and very flexible).

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