

# **The Effect of Tyres and a Rubber Track at High Axle Loads on Soil**

## **Compaction, Part 1: Single Axle Studies**

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One option for ground drive systems with large harvesting equipment is to use rubber belted tracks; however, little is known about the performance of these relative to appropriately sized pneumatic tyres. We aimed to study the effect of self propelled wheels and a track with high axle loads (9-24t) on soil compaction. This was assessed by embedding talcum powder lines as tracer into the soil during preparation to measure soil displacement and soil density changes. Additionally, soil dry bulk density and penetrometer resistance were measured. The track with loads of both 10.5 and 12 t compacts the soil less than wheels at 10.5 t load in both weak uniform and stratified soil. Towed implement wheels with 4.5 t load caused similar soil displacement to the track with a load of 12 t. Inflation pressure had a significant influence on soil parameters and a larger overall diameter is more beneficial than a wider tyre. The study emphasises the importance of contact pressure and its distribution with respect to soil density changes. Total axle loads are less important than how these are distributed on the ground.

### **1. Introduction**

This paper is the first in a series of three; it describes an investigation into the effect of different drive systems on soil compaction in a controlled laboratory environment. The second paper deals with the effect of machine configurations on soil compaction and explains track behaviour. The final paper extends and develops prediction models to estimate the

1 increase in soil density from both tyres and rubber tracks and relates these to the experimental  
2 results in the earlier two papers.

3  
4 Cereal farmers are under significant pressure due to a reduction in product related  
5 subsidies and a low world market price for cereals. Farmers must either grow in size and raise  
6 productivity or cease operation. In order to gain income with a given amount of produce,  
7 productivity has to increase.

8  
9 Productivity can either be enhanced by more efficient machinery using more sophisticated  
10 technology or as a result of economies of scale. The current tendency is clearly towards larger  
11 machinery (Kutzbach, 2000), but larger machinery tends to imply heavier machinery and the  
12 threat of soil compaction increases. Raper (2005) has reported that there were no laboratory  
13 investigations published concerning axle loads significantly higher than 10 t and the  
14 comparison of wheels and tracks was limited to in - field investigations.

15  
16 The aim of this study was to conduct a fundamental study in a controlled laboratory  
17 environment into the relative effects of a track and self propelled wheels with axle loads of 9-  
18 24 t on soil physical parameters. The effect of soil compaction was assessed by measuring soil  
19 displacement, changes to soil density and cone penetrometer resistance. The same type of tyre  
20 and track as used for the study is shown in *Fig. 1* in a field situation.

## 21 22 **2. Literature Review**

23  
24 In general, tracks are better than wheels at limiting soil compaction (Erbach, 1994).  
25 However, according to Culshaw (1986) and Erbach (1994) they can have detrimental effects  
26 upon soil for several reasons: a) although the calculated mean contact pressure is smaller than

1 for a wheel, it is applied for longer; b) the idler wheel configuration and track belts with  
2 inadequate tension may result in a non uniform pressure distribution, and c) vibrations from  
3 the engine and other machine parts are more readily transmitted into the soil on tracks  
4 because of the reduced suspension effect.

5 .

6 Investigations showing the advantage of steel tracks were published by Reaves and Cooper  
7 (1960), Soane (1973), Taylor and Burt (1975), Janzen *et al.* (1985), Erbach *et al.* (1988),  
8 Erbach *et al.* (1991), and Kinney *et al.* (1992). For a 40 t steel tracked excavator changes in  
9 pre-compression stress in the topsoil could only be detected in very wet conditions with no  
10 detectable change in the subsoil conditions irrespective of moisture status (Berli *et al.*, 2003).  
11 Steel bogie tracks on a trailer are beneficial compared to wheels according to Bygden *et al.*  
12 (2004). However, no differences between a steel tracked and a rubber tyred tractor could be  
13 detected by Burger *et al.* (1983) and Burger *et al.* (1985). These authors conclude that  
14 machine related factors other than contact pressure had an influence on the results.

15

16 The less rigid belt of rubber tracks, whilst an advantage for highway travel, is a  
17 disadvantage compared with traditional steel track belts on soft surfaces due to the problem of  
18 an uneven weight distribution below the rubber belt due to the idler configurations and belt  
19 tension effects referred to earlier by Brown *et al.* (1992). Their results showed that rubber  
20 tracks performed in an intermediate manner between those of wheels and steel tracks and  
21 were not significantly different from either.

22

23 Campbell *et al.* (1988) found a greater cone penetrometer resistance after using a wheeled  
24 tractor even though the rubber - tracked machine had a 24% greater total mass. Comparisons  
25 between a wheeled and a rubber tracked tractor by Pagliai *et al.* (2003) showed less soil  
26 density change and penetrometer resistance increase in the top 100 mm for the wheeled

1 tractor, less for the tracked vehicle between 100 – 200 mm depth and no difference between  
2 either at a depth of 200 – 400 mm. This was supported by the results of Servadio *et al.* (2001)  
3 and Brown *et al.* (1992). Servadio *et al.* (2001) found lower penetrometer resistance in the top  
4 200 mm and a greater resistance between 200 – 400 mm depth for a wheeled tractor in  
5 comparison to a rubber tracked tractor. Brown *et al.* (1992) found more compaction in the top  
6 125 mm for wheeled tractors, but below 125 mm differences were minimal between wheeled  
7 and tracked tractors.

8  
9 Blunden *et al.* (1994) could not detect significant penetrometer resistance differences at  
10 500 mm depth between a wheeled and a rubber belted tractor. Between 400 and 500 mm the  
11 wheeled tractor produced 0.03 MPa less penetrometer resistance. These results are interesting  
12 as the wheeled tractor weighed 18 t and the tracked one 15 t with a mean contact pressure  
13 below the tracked one which was 25% lower. From this work it is not evident why the  
14 differences in penetrometer resistance were small but this could be due to unequal pressure  
15 distribution below the track as reported by Weissbach, (2003), Keller *et al.* (2002) and Tijink,  
16 (1994).

17  
18 All the above results cannot be generalized but they show the importance of designing the  
19 track frame carrying the rubber belts and transferring the weight whereas the frame is less  
20 crucial for steel tracks. A summary of papers reporting advantages (Bashford *et al.*, 1988 and  
21 Rusanov, 1991) or disadvantages (Blunden *et al.*, 1994) of tracks on soil compaction is given  
22 by Alakukku *et al.* (2003).

### 25 3. Methods

26

1 The rubber track, harvester tyres and implement tyres used in this study are specified in  
2 Table 1. The track was loaded to both 10.5 t and 12 t enabling the comparison of the tyre and  
3 the track under the same overall load and under the same working conditions. The additional  
4 weight of the track system for a given combine harvester is 1.5 t per track unit. Three  
5 different harvester tyre sizes were selected at the recommended inflation pressure for a 10.5 t  
6 load. The medium section width tyre was chosen to be operated at half the recommended  
7 inflation pressure to investigate the effect of a lower inflation pressure. The four implement  
8 tyres were laden to 4.5 t and inflated to the recommended inflation pressures. These  
9 implement tyres are typical rear tyres of a combine harvester and will be used to mimic whole  
10 machines in the second paper of this series.

11  
12 The study was conducted in the 20 m long, 1 m deep, and 1.8 m wide soil bin laboratory at  
13 Cranfield University, Silsoe. The laboratory has been described in detail by Alexandrou and  
14 Earl (1998). The soil used was a sandy loam (Cotterham series) with 17% clay, 17% sand and  
15 66% sand and water content was maintained at 10% dry base during the studies. Both a  
16 uniform and a stratified soil condition were prepared. The uniform soil condition with a dry  
17 bulk density of  $1.4 \text{ g/cm}^3$  was chosen to imitate soil conditions with a low bearing capacity  
18 and to enhance the differences between the single treatments. Under these conditions the  
19 benefit of tracks would be expected to be greatest. The initial penetrometer resistance is  
20 shown in *Fig. 2* for both the uniform and stratified soil conditions. The stratified soil  
21 condition replicated a real in-field situation with a subsoil, a dense 'plough layer' and a soft  
22 working depth, with dry bulk densities of  $1.5 \text{ g/cm}^3$ ,  $1.6 \text{ g/cm}^3$ , and  $1.4 \text{ g/cm}^3$ , respectively.  
23 The 900mm/10.5t/1.9bar tyre was compared to the T12t type to simulate field loading  
24 conditions on the stratified soil.

25 In addition to the initial values for the stratified soil conditions in the soil bin, *Fig. 2* also  
26 includes the penetrometer resistance of a real field condition with a 'plough layer'. The close

1 agreement of the field and soil bin conditions show that it was possible to replicate these field  
2 strength conditions in the soil bin. The working depth from 0 – 200 mm shows the least  
3 resistance, followed by the compacted ‘plough layer’ between 200 – 300 mm, below which,  
4 in the subsoil from 300 – 700 mm, the depth penetrometer resistance reduces. The only  
5 difference between field and soil bin conditions is that the plough layer was situated 30 – 40  
6 mm deeper in the field.

7

### 8 3.1. *Track and tyre test apparatus*

9

10 To test the harvester tyres and the track, a test apparatus was designed and built in  
11 accordance with the requirements of the study and the soil bin (Godwin *et al.*, 2006). The  
12 apparatus, shown in *Fig. 3* with a track unit before a run (left hand side) and a 900 mm  
13 section width tyre after a run (right hand side), allowed the application of 0 to 14 t on to a self  
14 propelled wheel or track mounted on a standard Claas Lexion axle using a hydraulic cylinder.  
15 The test apparatus was self propelled in a similar manner to the single wheel tester built by  
16 Billington (1973). However, the load was applied indirectly on to the wheel/track which  
17 simplified the handling of the rig because the loading weights supplying the counterforce of  
18 the cylinder were spread over the frame of the test rig and remained in place during the  
19 change of drive systems.

20

21 Wheel or track loads could easily be adjusted as the applied load was a function of the  
22 pressure in the hydraulic cylinder for which the pressure was set using a pressure maintaining  
23 valve. The hydraulic cylinder was also used for lowering the wheel and track onto the surface  
24 of the soil and raising it up again. All the forces, except the vertical component, and the  
25 torques developing from both the weight application to and the movement of the wheel and  
26 track were removed by the use of linear bearings to prevent weight transfer from the axle. The

1 axle was a standard Claas – Lexion combine axle which included the 300 kW hydraulic motor  
2 and gear box with the differential locked. The hydraulic power to drive the self propelled  
3 wheels and the track using the hydraulic motor on the axle was supplied from a PM1000  
4 hydraulic pump which was able to supply 60 kW. This, in turn, was driven by a Perkins 6354  
5 88 kW combustion engine.

6  
7 Additionally, a fifth wheel could be mounted to the frame to measure the true speed during  
8 an investigation using a digital encoder. The speed of the tyre/track was measured via a  
9 second digital encoder mounted to the axle. The investigations were carried out at a speed of  
10 0.8 m/s and a slip of 0.14 for the tyres and 0.05 for the track.

11  
12 The implement tyres were placed in a test rig towed by the soil processor of the soil bin.  
13 The tyre was mounted on a continuous axle supporting the frame which accommodated up to  
14 14 t of additional load.

### 15 16 3.2. *Soil displacement measurement*

17  
18 A novel “non - invasive” procedure inspired by a technique of Trein (1995) was used to  
19 determine soil displacement (strain) and effective density change. This was achieved by  
20 placing talcum powder lines into the soil during preparation of the 20 m long, 1.7 m wide and  
21 0.7 m deep soil bin and measuring the change in their relative position following each passage  
22 of a tyre or track. Three sets of talcum powder lines were placed along the length of the soil  
23 bin. The position of the talcum powder lines was located from the digitized output of two  
24 drawstring transducers connected to a pin drawn to each talcum line appearing in the profile  
25 as a point, when the length of each draw string was recorded. From the length of each  
26 drawstring and the distance between the drawstring transducers, the vertical and horizontal

1 coordinates of each point were calculated. *Figure 4* shows the two points on either side of the  
2 soil bin in the areas undisturbed by the tyre/track which were taken as both depth and lateral  
3 position reference points. The initial positions of the other (central) talcum powder points  
4 were located at equal spacing along these lines from knowledge of their initial relative  
5 positions. Compared to the approach taken by Trein (1995) visualization had been enhanced  
6 as the talcum powder was much easier and hence faster to locate than the dye used earlier  
7 while maintaining accuracy.

8  
9 The mechanical accuracy of the measurements was assessed by printing an imaginary cut  
10 through the soil bin profile with a large CAD plotter and measuring the position of the points  
11 with the drawstring transducers. Hence the true position of every single point was known and  
12 then compared to its measured position. This comparison showed that the individual position  
13 of a single point could be measured to an accuracy of  $\pm 2$  mm, and the depth of a layer could  
14 be measured to within  $\pm 0.5$  mm with repeated measurements. Having gained the initial and  
15 the final positions of the talcum powder points, it was possible to draw a vector diagram of  
16 the soil movement from the initial coordinate to the final. Such a vector diagram is shown in  
17 *Fig. 5* for the 800mm/10.5t/2.5bar tyre.

18  
19 The vectors in *Fig. 5* exhibit near vertical soil displacement with little sideways movement  
20 which is independent of section width. Hence, it was concluded that the effect of the wall  
21 friction affecting the soil displacement was of little significance.

22  
23 To compare the different treatments in one diagram the length of the central four vectors  
24 was averaged for each depth. This average vector length representing the soil displacement of  
25 the central 300 mm for the rut is plotted against depth in *Fig. 6* for the 800mm/10.5t/2.5bar  
26 tyre. Vectors with greater displacement, as shown by the solid line, show a greater change in



1 soil density and a smaller displacement as shown by the broken line indicate smaller changes  
2 in soil density. *Figure 6* shows soil displacement as a function of depth, which can be  
3 described by the following equation fitted to the top 500 mm (with  $d(z)$  being positive with  
4 depth):

$$d(z) = d_0 - s \times z \quad (1)$$

7 where:  $d$  is the soil displacement in mm at a given depth  $z$ ;  $d_0$  is the displacement at the  
8 surface in mm;  $s$  is the change in vector length per unit of depth in mm/mm; and  $z$  is the depth  
9 in mm.

10  
11 When Eqn (1) is differentiated with respect to depth, the displacement change, *i.e.* the  
12 average increase in soil density is derived:

$$d'(z) = -s \quad (2)$$

15 Thus  $|s|$  is a direct measure of the relative increase in soil density caused by vertical soil  
16 movement and will be used to compare the treatments. As stated earlier, the maximum error  
17 in measuring the depth of a layer was +/- 0.5 mm which would result in 1% error of  $|s|$  in  
18 the worst case, *i.e.* all points line up in such a way that the top has a larger displacement of +  
19 0.5 mm than in reality and the bottom has 0.5 mm less than in reality. This is unlikely due to  
20 the large amount of measurements and handling errors do not exist with the drawstring  
21 method.

22

23

24 3.3. *Cone penetrometer resistance*

25

1 Cone penetrometer resistance was determined by measuring the force necessary to push a  
2 125 mm<sup>2</sup>, 30° cone into the soil. The data were automatically digitally recorded in 10 mm  
3 depth increments and plotted as penetrometer resistance with respect to depth. Cone  
4 penetrometer resistance was measured across the soil bin in ten places (1- 10) at 120 mm  
5 spacing for both the initial control and the three replicated positions of the wheel/track  
6 passage. This resulted in diagrams such as *Fig. 7*. The increase in measured penetrometer  
7 resistance at 700 mm depth was due to the penetrometer sensing the bottom of the soil bin.  
8 Consequently, the last five readings were always disregarded for statistical analysis. As *Fig. 7*  
9 indicates the central four readings were similar and thus averaged.

10

#### 11 3.4. *Dry bulk density*

12

13 Dry bulk density (DBD) and moisture content were measured at depths of 0, 250, and 500  
14 mm, with three replicates before and after each run, at the centre of the track mark in the soil  
15 bin by sampling using a cylindrical ring (60 mm diameter and 51.5 mm deep).

16

#### 17 3.5. *Statistical analysis*

18

19 Before the statistical analyses were conducted, the normal distribution of the data was  
20 always verified. All parameters were analyzed using generalized linear models to determine  
21 whether there were significant differences between the initial values and the treatment values,  
22 between single treatments, and for interactions over the depth of measurement collections at  
23 the 95% - level. Variances within the process of taking measurements were accounted for by  
24 identifying appropriate covariance parameters on the level of measurement and replication.  
25 As measurements were taken in the same soil bin several times per run, they have to be  
26 treated as repeated unpaired measurements (Piepho *et al.*, 2004). Normal probabilities were

1 used for multiple comparisons because the standard errors of the different treatments were  
2 similar in magnitude and differences are implied by analyzing the data as suggested by Nelder  
3 (1985).

4

### 5 3.6. *Repeatability of soil bin preparations*

6

7 Due to the time consuming preparation and data collection procedure, each treatment was  
8 usually only carried out once and repeated measurements taken which was taken into account  
9 in the statistical analysis. To show repeatability of the results in the soil bin, one treatment  
10 was carried out twice. As *Fig. 8* shows, results were repeatable if the soil bin was prepared to  
11 the same initial conditions and the same treatment was applied.

12

## 13 4. **Results**

### 14 4.1. *Uniform soil conditions*

#### 15 4.1.1. *Soil displacement*

16

17 In weak uniform soil conditions vertical soil displacement and strain were significantly  
18 smaller for the track compared to the wheels at both normal and half inflation pressures as  
19 shown in *Fig. 9*. This figure shows that there was an expected gradual increase in the slope of  
20 the line with depth which corresponded to a reduction in the density increase with depth.  
21 However, if the data for depths of 500 mm and less were considered, this effectively gave rise  
22 to a near constant slope and thus a uniform change in soil density. Applying this criterion  
23 showed that all treatments were statistically significantly different at the 95% - probability  
24 level except for the two track loads and the 800mm/10.5t/2.5bar tyre from the  
25 680mm/10.5t/2.2bar tyre.

26

1 The nearly identical soil displacement caused by these two tyres shown in *Fig. 9* was  
2 unexpected as the larger section width was expected to cause less soil displacement than the  
3 680mm/10.5t/2.2bar. However, the larger diameter of the 680mm/10.5t/2.2bar tyre (1.94 m  
4 diameter) gave rise to a larger contact patch than the 800mm/10.5t/2.5bar tyre (1.82 m)  
5 diameter (an area of 0.69 m<sup>2</sup> compared to 0.62 m<sup>2</sup>) and hence to the lower contact pressure.  
6 The 900mm/10.5t/1.9bar tyre due to its width and inflation pressure produced the least soil  
7 displacement at the recommended inflation pressure. The effect of reducing inflation pressure  
8 from 2.5 bar to 1.25 bar for the 800mm/10.5t tyre produced a significant decrease in soil  
9 displacement.

10

11 *Figure 9* also shows that the displacement of the soil caused by the tracks was  
12 approximately 60 mm at the soil surface and decreased to zero mm displacement at 500 mm  
13 depth. The track at a 12 t load caused 8% more displacement than the track at a 10.5 t load,  
14 but the difference was not statistically significant.

15

16 From Eqn (2) the tyres at a normal inflation pressure increased soil density by 18%, the  
17 tyre at half inflation pressure by 12% and the track by 13%. The data for the increase in  
18 density of individual treatments including the correlation coefficient for the regression lines is  
19 shown in Table 2. The higher increase in soil density caused by the tracks was due to their  
20 soil displacement being reduced to zero at 500 mm depth whereas all tyres showed a residual  
21 soil displacement between 8 – 14 mm.

22

23 *Figure 10* shows the soil displacement for the range of implement tyres tested. Larger  
24 contact areas and lower inflation pressure reduced soil displacement. Statistically all  
25 combinations were similar to each other with the exception of the 500-70mm/4.5t/2.3bar tyre.  
26 The similarity of the 500-85mm/4.5t/1.4bar and 600mm/4.5t/1.4bar, with contact areas of

1 0.41 and 0.39 m<sup>2</sup>, respectively, is similar to the case of the 680mm/10.5t/2.2bar and the  
2 800mm/10.5t/2.5bar. Again the higher section width of the tyre combined with an identical  
3 inflation pressure created identical soil displacement as the wider tyre. Despite the potential  
4 difference in carcass stiffness of cross ply vs. radial tyres, the two tyres produced near  
5 identical footprints although with different geometries. The 700mm/4.5t/1.0bar tyre was not  
6 able to utilize its large section width and low inflation pressure to create a significantly  
7 smaller soil displacement although having the largest contact area of 0.47 m<sup>2</sup>.

8  
9 The track at 12 t load in this context caused similar soil displacement to the three lower  
10 pressure implement tyres at 4.5 t; although the track carried 2.67 times the load. Additionally  
11 the tyres caused a residual soil displacement of 3 – 7 mm at 500 mm depth. The average  
12 increase in soil density caused by the implement tires was similar to the 800mm/10.5t/1.25bar  
13 tyre, both increasing soil density by 12%. Thus approximately half the load on a smaller tyre  
14 increased density by a similar amount to the total load at half the recommended inflation  
15 pressure. The individual increases in soil density are listed in Table 2.

16

#### 17 4.1.2. Penetrometer resistance

18

19 The average of the central four penetrometer resistance readings over depth is shown in  
20 *Fig. 11*, including both the undisturbed initial readings as a mean over all experiments and the  
21 LSD with 5% error probability. This demonstrates that tracks caused a higher penetrometer  
22 resistance than tyres at depths close to the surface where the increase in strength can be more  
23 easily alleviated. All the tyres had higher penetrometer resistance in the subsoil (below 250 –  
24 300 mm) than the tracks.

25

1 The grouping of the tyre configurations (680mm/10.5t/2.2bar and 800mm/10.5t/2.5bar  
2 against the 900mm/10.5t/1.9bar and 800mm/10.5t/1.25bar) indicates a relationship between  
3 inflation pressure and penetrometer resistance as the tyres with lower inflation pressures  
4 created less penetrometer resistance. Again, all comparisons were significantly different with  
5 the exception of the 680mm/10.5t/2.2bar from the 800mm/10.5t/2.5bar and the two track  
6 loads from each other.

7  
8 From *Fig. 11* it can be seen that the shape and the values of the penetration resistance  
9 curves for the track at both loads of 12 t and 10.5 t were not significantly different, except at  
10 depths between 100 and 200 mm. Below 350 to 400 mm depth the penetration resistance  
11 approached that of the initial condition for T10.5t and the difference between the final and  
12 initial conditions was only significant for the T12t. The LSD shown in *Fig. 11* did not vary  
13 with depth as the depth factor was accounted for as covariance parameter.

14  
15 The tracks exhibited a major change in penetrometer resistance close to the surface. For the  
16 wheels, the peak penetrometer resistance was smaller near the surface, with the penetrometer  
17 resistance in deeper layers being significantly higher than for tracks. Thus the advantage of  
18 tracks was that while there was a greater increase in penetrometer resistance this was close to  
19 the surface, where it could be alleviated with shallower tillage operations. The origin and  
20 implications of the peak in penetrometer resistance for the tracks will be discussed in detail in  
21 Part II, Multi-Axle Machine Studies.

22  
23 Penetrometer resistance for the implement tyres is shown in *Fig. 12* and the values were  
24 not significantly different at the 5% level. The penetration resistance of these tyres were all  
25 significantly smaller than those of larger harvester tyres.

26

1 4.1.3. *Dry bulk density*

2

3 The final measured dry bulk density (DBD) for both tyres and tracks was significantly  
4 higher than initial DBD over all depths. The differences were in the range of 0.11 – 0.15  
5 g/cm<sup>3</sup> and the least significant difference at the 95 % level was 0.046 g/cm<sup>3</sup>. The data  
6 including the least significant difference bars is shown in *Fig. 13*. The difference between the  
7 tyre and track was just significant, whereas the statistical analysis of individual tyres and  
8 tracks showed no significant differences. The implement tyres show the same soil density as  
9 the track. In addition the final DBD was estimated from the initial DBD and the slope of the  
10 soil displacement lines and did not show significant differences except for the tyre.

11

12 From these results the conclusion could be drawn that the soil displacement analysis was  
13 more sensitive in determining differences between the single treatments, but the overall trends  
14 followed a similar pattern.

15

16 Campell (1994) discussed the difficulty in assessing soil compaction using dry bulk  
17 density. The soil displacement data had a finer resolution than the dry bulk density. The  
18 measured increase in DBD for the tyres was on average 11% and for both the tracks and the  
19 implement tyres it was 8%.

20

21

22

23 4.2. *Stratified soil conditions*

24 4.2.1. *Soil displacement*

25

1        *Figure 14* compares the soil displacement in the stratified soil conditions with a simulated  
2 'plough layer' at a depth between 200 – 300 mm. This figure shows that due to the stronger  
3 soil conditions of the stratified soil, the displacement was reduced to 20 % rut depth and  
4 hence soil displacement of that in uniform soil conditions which was included as reference.

5  
6        The displacement by the track was less than by the tyre over the entire depth and was  
7 reduced to zero at 300 mm. The 900mm/10.5t/1.9bar, however, pushed the 'plough layer'  
8 with a small increase in density down into the weaker subsoil. Soil displacement for the tyre  
9 approached zero at a depth between 500 – 600 mm.

10

#### 11 4.2.2. Penetrometer resistance

12

13        After the pass of the 900mm/10.5t/1.9bar tyre the penetrometer resistance increased  
14 significantly as shown in *Fig. 15 (a)* which exhibits that the tyre increased penetrometer  
15 resistance over the whole profile except for the 'plough layer'. The shape of the penetrometer  
16 resistance curve for the tyre was similar for the stratified and uniform soil. The final  
17 penetrometer resistance below 130 mm was constant at 2 MPa excluding the 'plough layer'.  
18 The plough layer did not become stronger, but its thickness was increased by about 20 mm.  
19 *Figure 14* confirms this as it shows that the 'plough layer' was pushed down into the weaker  
20 subsoil increasing the thickness of the 'plough layer'.

21

22        The initial and final penetrometer resistance for the track in stratified soil conditions is  
23 shown in *Fig. 15 (b)*. As with the tyre, the final curve was similar to that in uniform soil  
24 conditions with a pronounced peak close to the soil surface followed by a reduction in  
25 penetrometer resistance. The penetrometer resistance for the final condition merged with that



1 for the initial condition above the plough layer. No soil compaction occurred below the  
2 'plough layer'.

3  
4 The benefit for soil physical conditions after the pass of the rubber track compared to  
5 wheel/tyre systems was clearly shown in uniform and stratified soil conditions. The most  
6 significant effect of the study was to record how close to the surface the maximum  
7 penetrometer resistance can be kept using tracks compared to tyres and that with a 'plough  
8 layer' below 200 mm there was no change in penetrometer resistance and hence apparent soil  
9 strength.

10

## 11 **5. Discussion**

12

13 The results of this work have shown that soil displacement measurements are a sensitive  
14 method to determine differences between treatments. The penetrometer resistance could not  
15 detect any differences for the implement tyres, but measuring soil displacement differences  
16 could be detected. Stranks (2006) found similar results during an investigation with pea  
17 harvester tyres loaded to 4.5 t.

18

19 The rubber track used in this study weighed 1.5 t more, but caused a significantly smaller  
20 increase in soil displacement and penetration resistance than wheels in controlled laboratory  
21 conditions. Therefore the overall finding is that rubber belted tracks have significant benefits  
22 over the currently available tyre choices, corroborating the work of Erbach (1994). However,  
23 it is in contrast to the results by Brown *et al.* (1992) where rubber tracked vehicles were  
24 intermediate to steel tracked and wheeled vehicles but not significantly different from either.  
25 The reason for this may be due to improved frame and belt tension for this track system  
26 compared with those used by Brown *et al.* (1992) and the controlled conditions. The

1 significantly reduced penetrometer resistance in the subsoil was not detected by Blunden *et al.*  
2 (1994), Pagliai *et al.* (2003) and Brown *et al.* (1992) when using rubber tracks. Servadio *et al.*  
3 (2001) only found a lower penetrometer resistance below a rubber belted tractor in the range  
4 of 200 to 400 mm depth than for a wheeled tractor. The large natural variation in field data  
5 might be a possible reason for this. Research could not be found indicating the reduced  
6 penetrometer resistance down to 650 – 700 mm.

7  
8 These results confirm the results from Bekker (1956) and Hakanson (1988) who state that  
9 tyres with a smaller section width can reduce soil compaction when the contact area is  
10 maintained or increased with a longer contact patch resulting from a larger wheel diameter.  
11 The track can achieve this whilst confined to a much smaller vertical envelope.

12  
13 Tracked vehicles equipped with such a belt and frame system as those used in this  
14 investigation may be the answer to the requirement of highly efficient farm machinery  
15 simultaneously protecting the soil as postulated by Hamza and Anderson (2005). Taking the  
16 reduced soil compaction in deeper soil areas into account and ignoring the higher soil  
17 compaction close to the surface, where it can easily be alleviated, tracks may be the answer to  
18 maintain high yields in agricultural systems relying on heavy farm machinery in order to  
19 maintain or increase productivity.

20  
21 With stratified soil conditions the ‘plough layer’ was able to protect the subsoil for the  
22 tracked treatment. Brandhuber *et al.* (2006) were able to show in field measurements the  
23 benefit of tracked sugar beet harvesters. Our results of the 900mm/10.5t/1.9bar on the same  
24 soil conditions agree with the findings from Arvidsson *et al.* (2001), Trautner & Arvidsson  
25 (2003) and Yavuzcan *et al.* (2004) who detected increases in soil density to 0.3-0.4 m for  
26 wheeled sugar beet harvesters in field measurements. The subsoil conditions in the soil bin

1 were insufficiently strong to resist the load without density change as found in field by  
2 Dickson (1994) on a previously compacted soil after passes with a combine harvester.

3

4 The benefit of constant tramlines for all field work shown by Chamen *et al.* (1994) will  
5 work very well with the track especially as it creates a high penetration resistance close to the  
6 surface which can act as a pathway.

7

8 The results of this investigation add to the evidence to support the conclusions for the tyre  
9 data given in Alakukku *et al.* (2003) and Keller and Arvidsson (2004) and contradiction to the  
10 establishment of an axle load limitation as suggested in Ericsson *et al.* (1974), Carpenter *et al.*  
11 (1985) and van der Ploeg *et al.* (2006).

12

## 13 **6. Conclusions**

14

15 (1) The change in soil physical properties commonly referred to as soil compaction is not a  
16 function which only is influenced by load; it is also influenced by the spreading of the  
17 load over a large contact area. With the same load this study found a range of responses  
18 for different under carriage systems, whereby some caused significantly less soil  
19 compaction than others.

20 (2) The major benefits of 'Terra Trac' drive systems over conventional tyre systems were:

21 (a) a reduction in the surface rut depth and the sub-surface soil displacement of  
22 approximately 40% compared to that of a tyre system with substantial reductions in  
23 the increase in soil bulk density (*i.e.* a 13% rather than a 18% increase).

24 (b) a smaller increase in penetrometer resistance in the subsoil layers, albeit with a greater  
25 increase in penetrometer resistance in the surface layers which can be more easily and  
26 more cheaply removed with subsequent shallower tillage operations.

- 1 (3) The effect on soil displacement and penetrometer resistance from a ‘Terra Trac’ loaded to  
2 12 t, whilst higher, is not significantly greater compared to 10.5 t load.
- 3 (4) Track loads of 10.5 t and 12 t caused similar soil displacement as smaller tyres with 4.5 t  
4 of load.
- 5 (5) Reducing the inflation pressure from 2.5 bar to 1.25 bar for the 800 mm section width tyre  
6 significantly reduced the penetrometer resistance, surface rut depth, and sub surface soil  
7 displacement. This effect reduced the increase in dry bulk density from 18% to 12%.
- 8 (6) Soil compaction in a stratified soil (to simulate a dense layer situated 200/300 mm deep as  
9 in field conditions) in the laboratory stopped at the ‘plough layer’ for the ‘Terra Trac’  
10 whereas the tyre pushed the hard pan into the weaker subsoil below.
- 11 (7) The results from the layered soil conditions show the benefit in managing hard pans  
12 effectively in the intended traffic lanes as they can protect the underlying soil from  
13 compaction.

14

## 15 **Acknowledgement**

16

17 The authors want to thank Claas – Company, Harsewinkel, Germany, for its support and  
18 Gordon Spoor for useful suggestions concerning the work. Thanks must go to Prof. Kutzbach  
19 from the University of Hohenheim for enabling Dirk Ansorge to participate in the Double  
20 Degree Program under which these parts of the study were conducted. The help in analyzing  
21 the data statistically from Prof. Piepho from the University of Hohenheim was very valuable.

22

23

## 24 **References**

25

- 1 **Alakukku L; Weisskopf P; Chamen W C T; Tijink F G J; van den Linden J P; Pires S;**  
2 **Sommer C and Spoor, G** (2003). Prevention strategies for field traffic – induced subsoil  
3 compaction: a review. Part 1. Machine / Soil interactions. Soil and Tillage Research  
4 **73**(1-2), 145-160
- 5 **Alexandrou A and Earl R** (1998). The relationship among pre-compaction stress, volumetric  
6 water content and initial dry bulk density of soil. Journal of Agricultural Engineering  
7 Research **71**(1), 75-80
- 8 **Arvidsson J; Trautner A; van den Akker J J H and Schjonning P** (2001). Subsoil  
9 compaction caused by heavy sugarbeet harvesters in southern Sweden II. Soil  
10 displacement during wheeling and model computations of compaction. Soil and Tillage  
11 Research **60**(1-2), 79-89
- 12 **Bashford L L; Jones A J and Mielke L N** (1988). Comparison of bulk density beneath a belt  
13 track and a tyre. Applied Engineering in Agriculture **4**(1): 122- 125
- 14 **Bekker M G** (1956). Theory of Land Locomotion. University of Michigan Press, Ann Arbor  
15 Michigan, USA.
- 16 **Berli M; Kirby J M; Springman S M and Schulin R** (2003). Modeling compaction of  
17 agricultural subsoils by tracked heavy construction machinery under various moisture  
18 conditions in Switzerland. Soil and Tillage Research **73**(1-2), 57-66
- 19 **Billington W P** (1973). The N.I.A.E. MKII Single Wheel Tester. Journal of Agricultural  
20 Engineering Research **18**(1), 67-70
- 21 **Blunden B G; McBride R A; Daniel H and Blackwell P S** 1994. Compaction on an earthy  
22 sand by rubber tracked and tyred vehicles. Australian Journal of Soil Research **32**(6),  
23 1095-1108
- 24 **Brandhuber R; Geischeder R and Demmel M** (2006) Effects of heavy agricultural  
25 machines for sugar beet harvesting on subsoil physical properties. Proceedings  
26 International Soil and Tillage Research Organisation, Kiel, Germany

- 1 **Brown H J; Cruse R M; Erbach D C and Melvin S W** (1992). Tractive device effects on  
2 soil physical properties. *Soil and Tillage Research* **22**(1-2), 41-53
- 3 **Burger J A; Perumpral J V; Kreh R E; Torbert J L and Minaei S** (1983). The effect of  
4 track and rubber – tyred vehicles on soil compaction. ASAE Paper No. 83-1621
- 5 **Burger J A; Perumpral J V; Kreh R E; Torbert J L and Minaei S** (1985). Impact of  
6 tracked and rubber – tyred tractors on a forest soil. *Transactions of the American Society*  
7 *of Agricultural Engineers* **28**(2), 369-373
- 8 **Bygden G; Eliasson L and Wasterlund I** (2004). Rut depth, soil compaction and rolling  
9 resistance when using bogie tracks. *Journal of Terramechanics* **40**(3), 179-180
- 10 **Campbell D J** (1994). Determination and use of dry bulk density in relation to soil  
11 compaction. In: *Soil Compaction in Crop Production. Developments in Agricultural*  
12 *Engineering* 11 (Soane B D; van Ouwerkerk C eds), pp 113 – 139, Elsevier, Amsterdam
- 13 **Campbell D J; Dickson J W and Owen G M** (1988). Soil compaction, drawbar pull and  
14 stability measurements for Hytracker all terrain vehicle. Dep. Note 14, Scottish Center  
15 for Agricultural Engineering, Penicuik
- 16 **Carpenter T G; Fausey N R and Reeder R C** (1985). Theoretical effect of wheel loads on  
17 subsoil stresses. *Soil and Tillage Research* **6**(2), 179-192
- 18 **Chamen W T C; Dowler D; Leede P R and Longstaff D J** (1994). Design, operation and  
19 performance of a gantry system: experience in arable cropping . *Journal of Agricultural*  
20 *Engineering Research* **59**(1), 45-60
- 21 **Culshaw D** (1986). Rubber tracks for agriculture. Div. Note DN 1345, Natl. Inst. Agric.  
22 Engng., Silsoe. UK
- 23 **Dickson J W** (1994). Compaction by a combine harvester operating on moist loose soil. *Soil*  
24 *and Tillage Research* **29**(2-3), 145-150
- 25 **Eriksson J; Hakansson I and Danfors B** (1974). Effects of soil compaction on soil structure  
26 and crop yields. *Swedish Institute of Agr. Eng. Bull.* 504

- 1 **Erbach D C; Melvin S W and Cruse R M** (1988). Effects of tractor tracks during secondary  
2 tillage on corn production. ASAE Paper No. 88-1614
- 3 **Erbach D C; Melvin S W and Cruse R M** (1991). Low ground pressure equipment fleets  
4 for crop production. ASAE Paper No. 91-1517
- 5 **Erbach D C** (1994). Benefits of tracked vehicles in crop production. In: Developments in  
6 Agricultural Engineering 11. Soil Compaction in Crop Production (Soane B D; van  
7 Ouwerkerk C eds), pp501-520, Elsevier, Amsterdam
- 8 **Godwin R J; Brighton J L; Blackburn K; Richards T E; Ansorge D and Wheeler P N**  
9 (2006). Off-road dynamics research at Cranfield University at Silsoe. Proceedings  
10 ASABE Annual International Meeting, Portland, Oregon.
- 11 **Hakansson I; Voorhees W B and Riley H** (1988). Vehicle and wheel factors influencing  
12 soil compaction and crop response in different traffic regimes. Soil and Tillage Research  
13 **11**(3-4), 239-282
- 14 **Hamza M A and Anderson W K** (2005). Review – Soil Compaction in Cropping Systems.  
15 A review of the nature, causes, and possible solutions. Soil and Tillage Research **82**(2),  
16 121-145
- 17 **Janzen D C; Hefner R E and Erbach D C** (1985). Soil and corn response to track and wheel  
18 compaction. Proceedings International Conference on Soil Dynamics, National Soil  
19 Dynamics Laboratory, Auburn, AL, USA
- 20 **Keller T and Arvidsson J** (2004). Technical solutions to reduce the risk of subsoil  
21 compaction: effects of dual wheels, tandem wheels and tyre inflation pressure on stress  
22 propagation in soil. Soil and Tillage Research **79**(2), 191-205
- 23 **Keller T; Trautner A and Arvidsson J** (2002). Stress distribution and soil displacement  
24 under a rubber tracked and a wheeled tractor during ploughing, both on land and within  
25 furrows. Soil and Tillage Research **68**(1), 39-47

- 1 **Kinney G R; Erbach D C and Bern C J** (1992). Soil strain under three tractor  
2 configurations. Transactions of the American Society of Agricultural Engineers **35** (4),  
3 1135-1139
- 4 **Kutzbach H D** (2000). Trends in Power and Machinery. Journal of Agricultural Engineering  
5 Research **76**(3), 237-247
- 6 **Nelder J A** (1985). Discussion of Dr. Chatfield's paper. Journal of the Royal Statistical  
7 Society. Series A, **148** (3), 238
- 8 **Pagliai M; Marsili A; Servadio P; Vignozzi N and Pellegrini S** (2003). Changes in some  
9 physical properties of a clay soil in central Italy following the passage of rubber tracked  
10 and wheeled tractors of medium power. Soil and Tillage Research **73**(1-2), 119-129
- 11 **Piepho H P; Buechse A and Richter C** (2004). A mixed modeling approach for randomized  
12 experiments with repeated measures. Journal of Agronomy and Crop Science **190**(4),  
13 230-247
- 14 **Raper R L** (2005). Agricultural traffic impacts on soil. Journal of Terramechanics **42**(3-4),  
15 259-280
- 16 **Reaves C A and Cooper A W** (1960). Stress distribution in soils under tractor loads.  
17 Agricultural Engineering **41**(1): 20-21, 31
- 18 **Rusanov V A** (1991). Effects of wheel and track traffic on the soil and crop growth and yield.  
19 Soil and Tillage Research **19**(2-3), 131-143
- 20 **Soane B D** (1973). Techniques for measuring changes in the packing state and cone  
21 resistance of soil after the passage of wheels and tracks. Journal of Soil Science **24**(3),  
22 311-323
- 23 **Servadio P; Marsili A; Pagliai M; Pellegrini S and Vignozzi N** (2001). Effects on some  
24 clay soil qualities following the passage of rubber – tracked and wheeled tractors in  
25 central Italy. Soil and Tillage Research **61**(3-4), 143-155



- 1 **Taylor J H and Burt E C** (1975). Track and tyre performance in agriculture. Transactions of  
2 the American Society of Agricultural Engineers **18**(1), 3-6
- 3 **Tijink F G J** (1994). Quantification of vehicle running gear. In: Developments in  
4 Agricultural Engineering 11. Soil Compaction in Crop Production (Soane B D; van  
5 Ouwerkerk C eds), pp 391-415, Elsevier, Amsterdam
- 6 **Trautner A and Arvidsson J** (2003). Subsoil compaction caused by machinery traffic on a  
7 Swedish Eutric Cambiosol at different soil water contents. Soil and Tillage Research  
8 **73**(1-2), 107-118
- 9 **Trein C R** (1995). The mechanics of soil compaction under wheels. PhD-Thesis in  
10 Agricultural Engineering. Cranfield University, Silsoe College, UK.
- 11 **Van der Ploeg R; Ehlers W and Horn R** (2006). Schwerlast auf dem Acker[Heavy load on  
12 the field.] Spektrum der Wissenschaft, August 2006: 80-88
- 13 **Weissbach M** (2003). Landtechnische Untersuchungen zur Wirkung bodenschonender  
14 Fahrwerke an Schleppern und Arbeitsmaschinen mit verschiedenen Radlasten  
15 [Agricultural engineering research with of soil protecting drive systems from tractors and  
16 self propelled agricultural machinery.] Habilitationsschrift, University of Kiel. Logos  
17 Verlag, Berlin
- 18 **Yavuzcan G H; Matthies D and Auernhammer H** (2005). Vulnerability of Bavarian silty  
19 loam soil to compaction under heavy wheel traffic: impacts of tillage method and soil  
20 water content. Soil and Tillage Research **84**(2), 200-215

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**Table 1**

**Tyre and Track Specifications**

<i>Undercarriage System</i>	<i>Load (t)</i>	<i>Inflation Pressure (bar)</i>	<i>Abbreviation Section Width/Load/Inflation Pressure</i>
680/85 R32	10.5	2.2	680mm/10.5t/2.2bar
800/65 R32	10.5	2.5	800mm/10.5t/2.5bar
900/65 R32	10.5	1.9	900mm/10.5t/1.9bar
800/65 R32	10.5	1.25	800mm/10.5t/1.25bar
Claas Terra Trac	10.5	0.75 <sup>(1)</sup>	T10.5t
Claas Terra Trac	12	0.86 <sup>(1)</sup>	T12t
500/70 R24	4.5	2.3	500-70mm/4.5t/2.3bar
500/85 R24	4.5	1.4	500-85mm/4.5t/1.4bar
600/55 – 26.5	4.5	1.4	600mm/4.5t/1.4bar
710/45 – 26.5	4.5	1.0	700mm/4.5t/1.0bar

(1) mean pressure assuming a contact patch of 1.4 m<sup>2</sup>

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**Table 2**  
**Average Increase in Soil Density for Tyre and Track Specifications**

<i>Undercarriage System (Section Width/Load/Inflation Pressure)</i>	<i>Average Increase in Soil Density (%)</i>	<i>Regression Coefficient of regression line</i>	<i>Least Significant Difference</i>
680mm/10.5t/2.2bar	17.7	0.989	0.1
800mm/10.5t/2.5bar	17.6	0.999	0.1
900mm/10.5t/1.9bar	17.3	0.994	0.1
800mm/10.5t/1.25bar	11.6	0.997	0.1
T10.5t	12.4	0.952	1.5
T12t	13.4	0.968	1.5
500-70mm/4.5t/2.3bar	14.3	0.989	0.8
500-85mm/4.5t/1.4bar	11.1	0.968	0.8
600mm/4.5t/1.4bar	11.0	0.985	0.8
700mm/4.5t/1.0bar	10.6	0.995	0.8



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2 *Fig. 1. During harvest a track and a tire identical to the ones used in the study*

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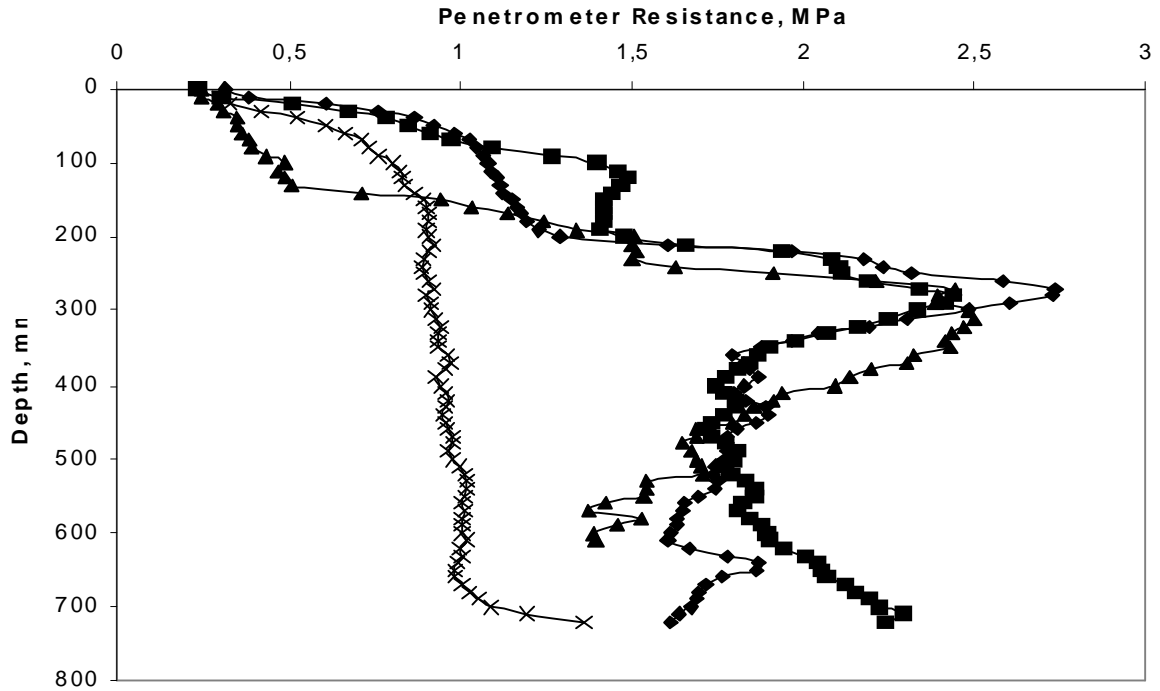
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2 *Fig. 2. Initial penetrometer resistance profiles in the soil bin of uniform and stratified soil*

3 *conditions and including a field condition: ×, uniform; ■, ◆, stratified one and two;*

4 *▲, field condition*

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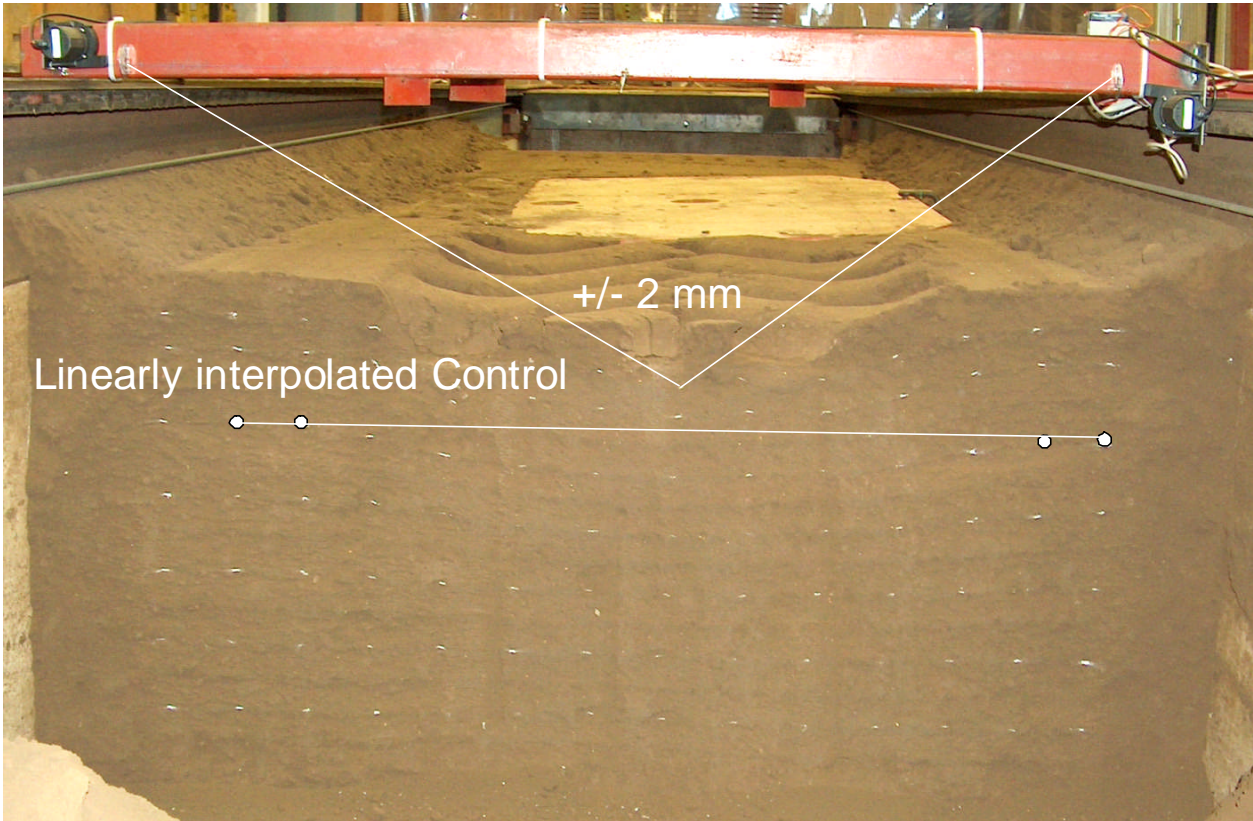
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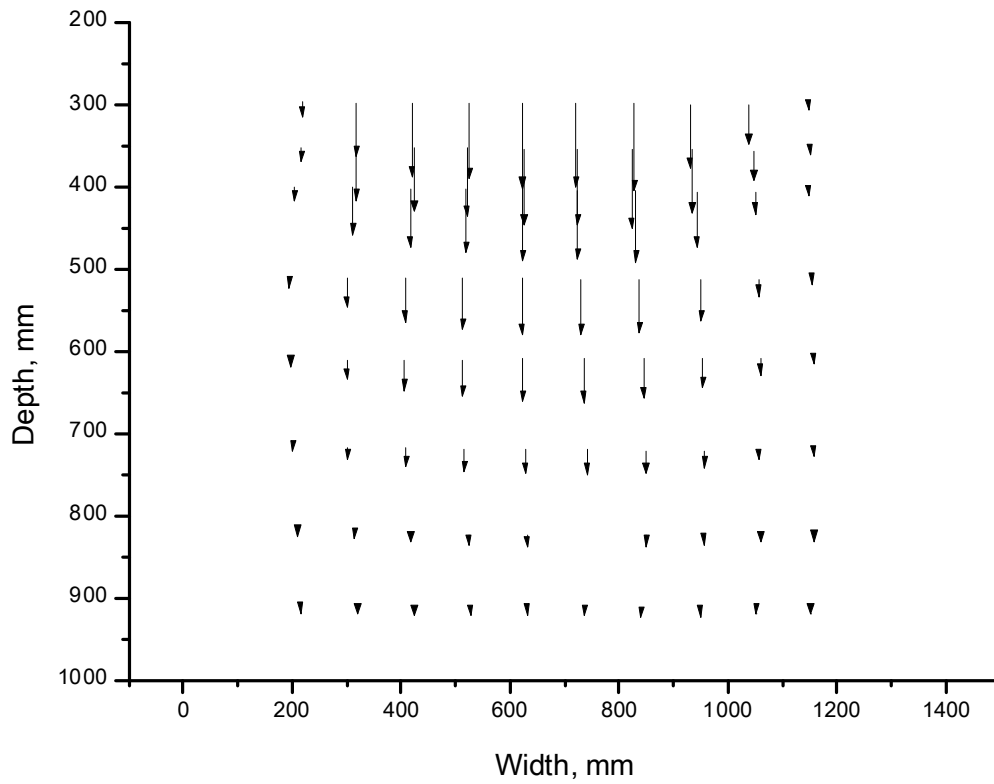


*Fig. 3. Single Wheel/Track test apparatus with a track (left hand side) and a tyre (right hand side)*



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*Fig. 4. Vertical cut through soil with points of talcum powder and the drawstring transducers in the initial condition*



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2 *Fig. 5. Vector diagram of soil movement after the pass of an 800mm/10.5t/2.5bar tyre*

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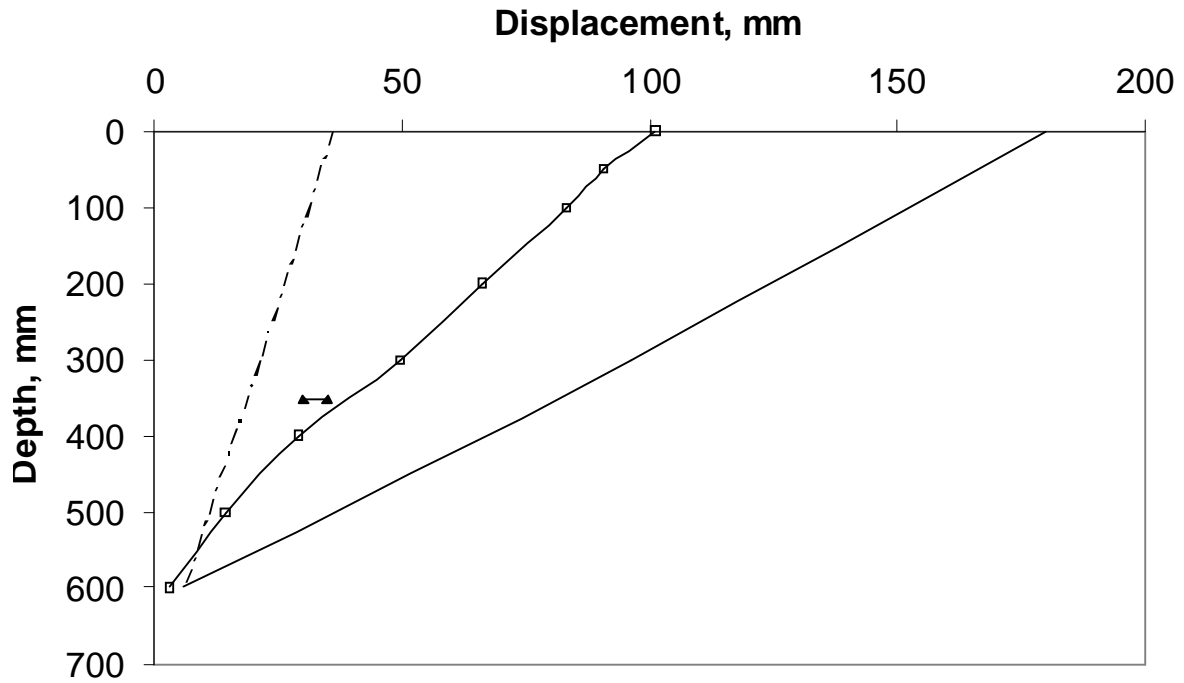
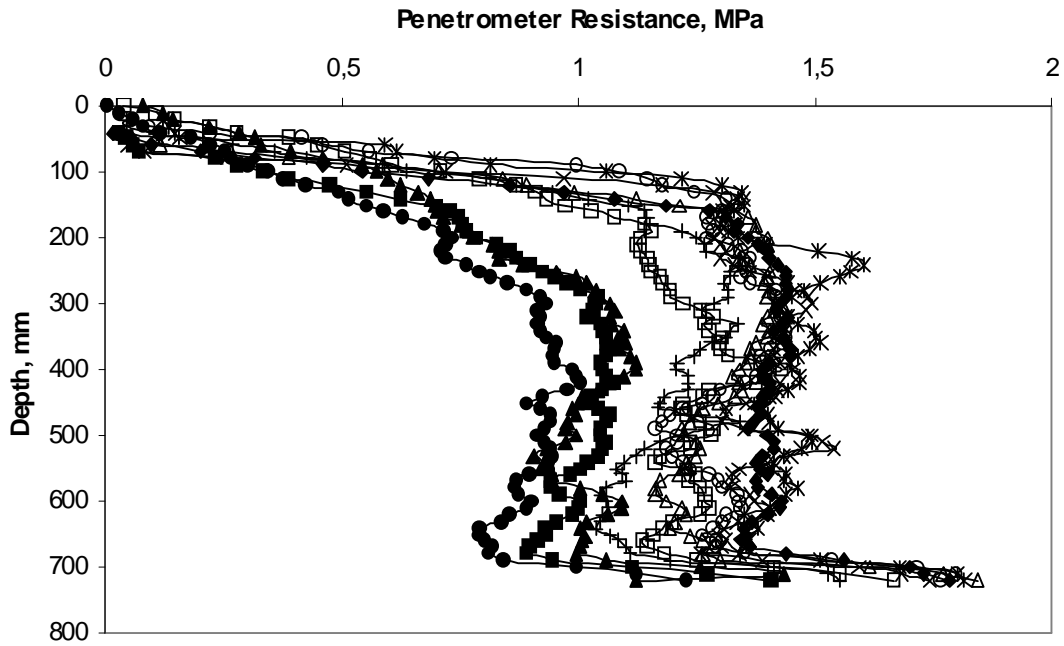


Fig. 6. Soil displacement vs. depth after a pass of an 800mm/10.5t/2.5bar: □, 800mm/10.5t/2.5bar; - - ,5% increase; - ,30% increase; and ▲ ,LSD

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3 *Fig. 7. Penetrometer resistance across the soil bin for the 900mm/10.5t/1.9bar tyre with ten*  
4 *readings: •, 1; ■, 2; +, 3; Δ, 4; ×, 5; ◆, 6; \*, 7; ○, 8; □, 9; and ▲, 10*

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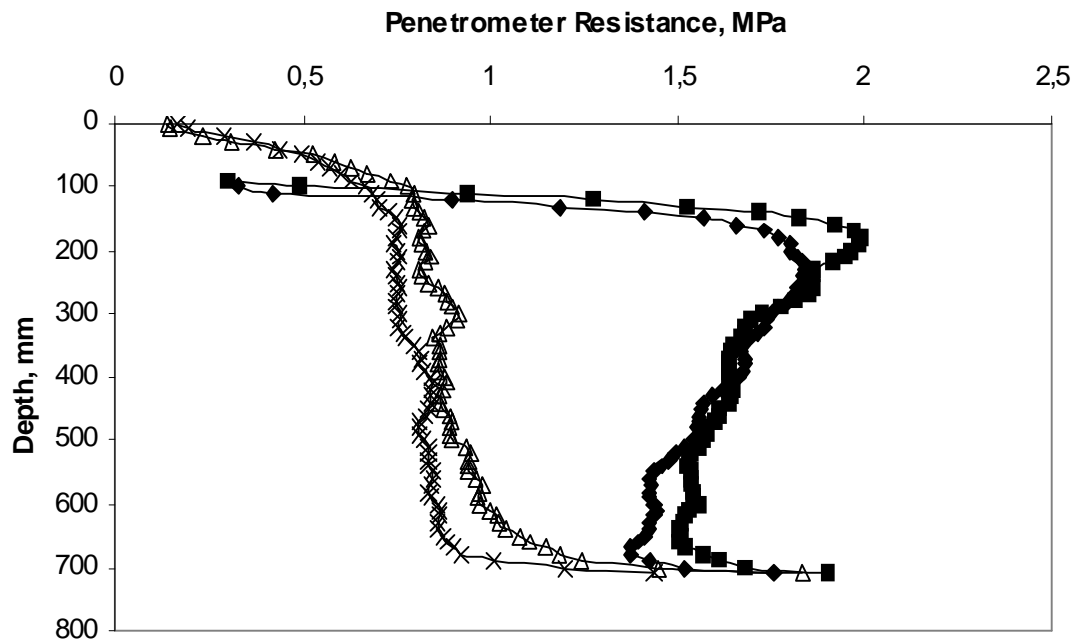


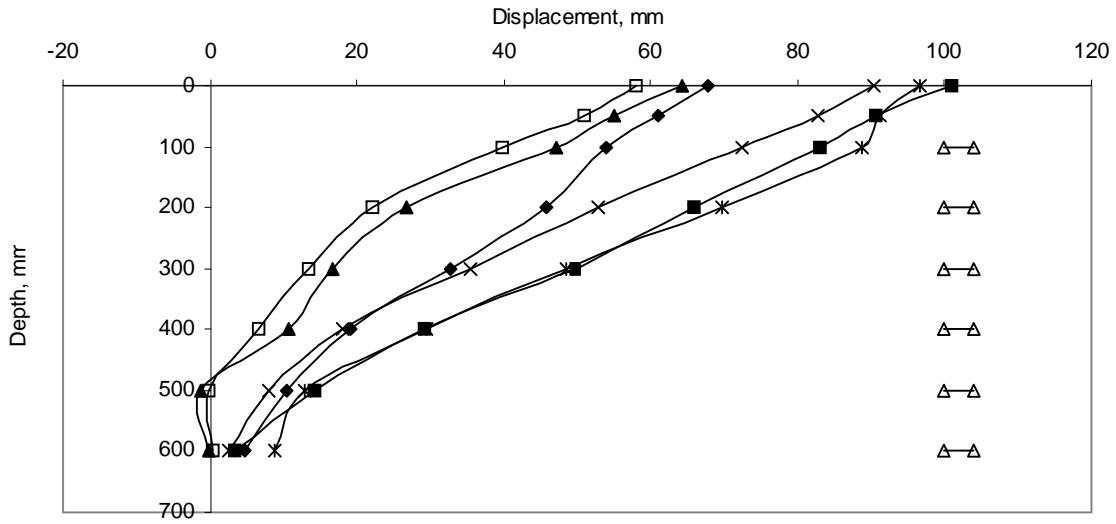
Fig. 8. Repeated treatments with near identical initials and results: ♦, 680mm/10.5t/2.2bar

Test 1; ■, 680mm/10.5t/2.2bar Test 1; ▲, Initial Test 1; and ×, Initial Test 2

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5 *Fig. 9. Vertical soil displacement caused by harvester tyres at recommended and reduced*  
 6 *inflation pressure and tracks: \*, 680mm/10.5t/2.2bar; ■, 800mm/10.5t/2.5bar;*  
 7 *×, 900mm/10.5t/1.9bar; ◆, 800mm/10.5t/1.25bar; □, T10.5t; ▲, T12t; and Δ,*  
 8 *least significant difference at 95% confidence level at given depth*

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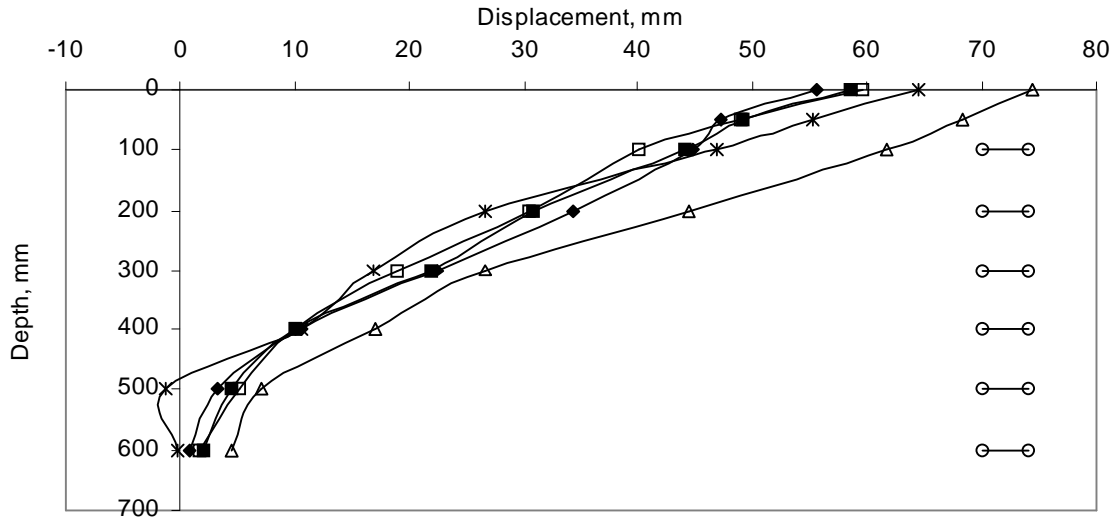
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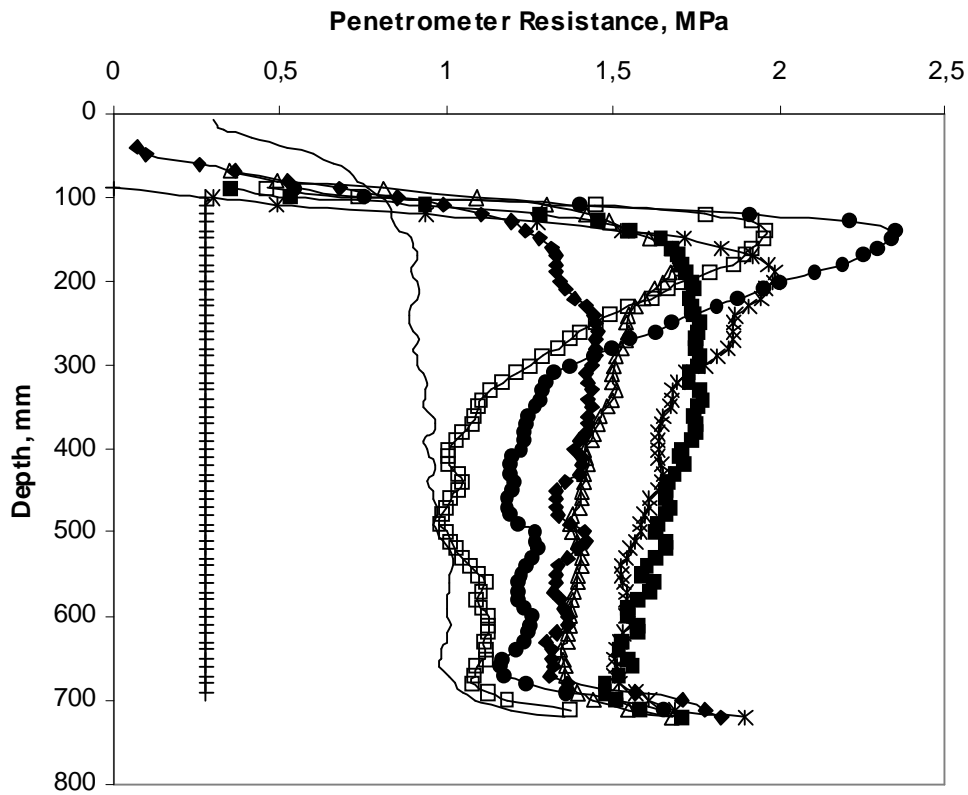
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Fig. 10. Soil displacement vs. depth for the implement tyres including a track: ◆, 700mm/4.5t/1.0bar; ■, 600mm/4.5t/1.4bar; □, 500-85mm/4.5t/1.4bar; Δ, 500-70mm/4.5t/2.3bar; \*, T12t; and ○, least significant difference at 95% confidence level

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4 *Fig. 11. Penetration resistance vs. depth initial and after the pass of the front tyres and the*  
5 *track: - , initial; \*, 680mm/10.5t/2.2bar; ■, 800mm/10.5t/2.5bar; ◆,*  
6 *900mm/10.5t/1.9bar; Δ, 800mm/10.5t/1.25bar; □, T10.5t; •, T12t; and +, least*  
7 *significant difference at 95% confidence level*

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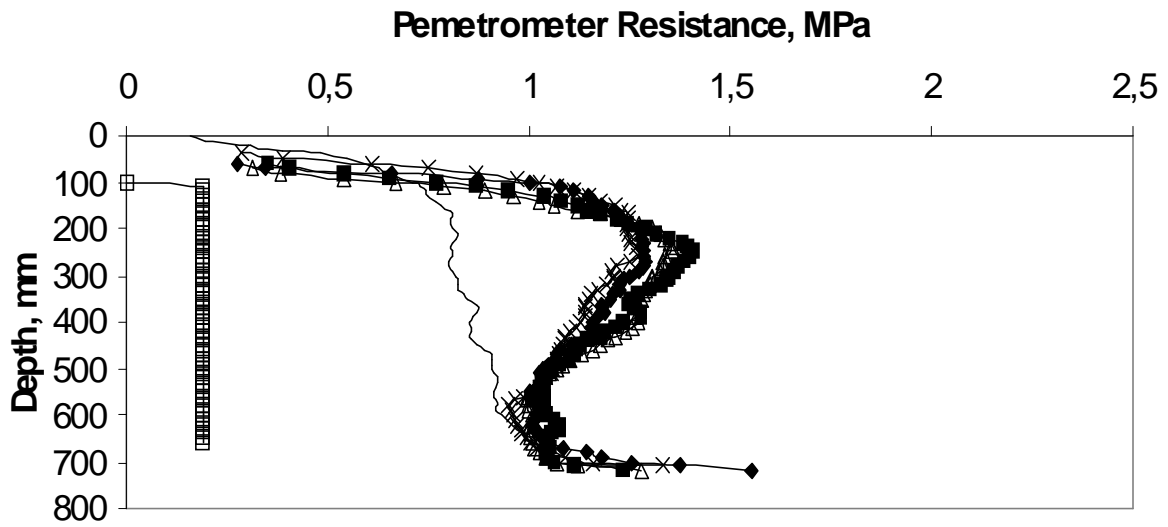


Fig. 12. Penetrometer resistance for the implement tyres: -, initial; ♦, 700mm/4.5t/1.0bar; ■, 600mm/4.5t/1.4bar; \*, 500-85mm/4.5t/1.4bar; Δ, 500-70mm/4.5t/2.3bar; and □, least significant difference at 95% confidence level

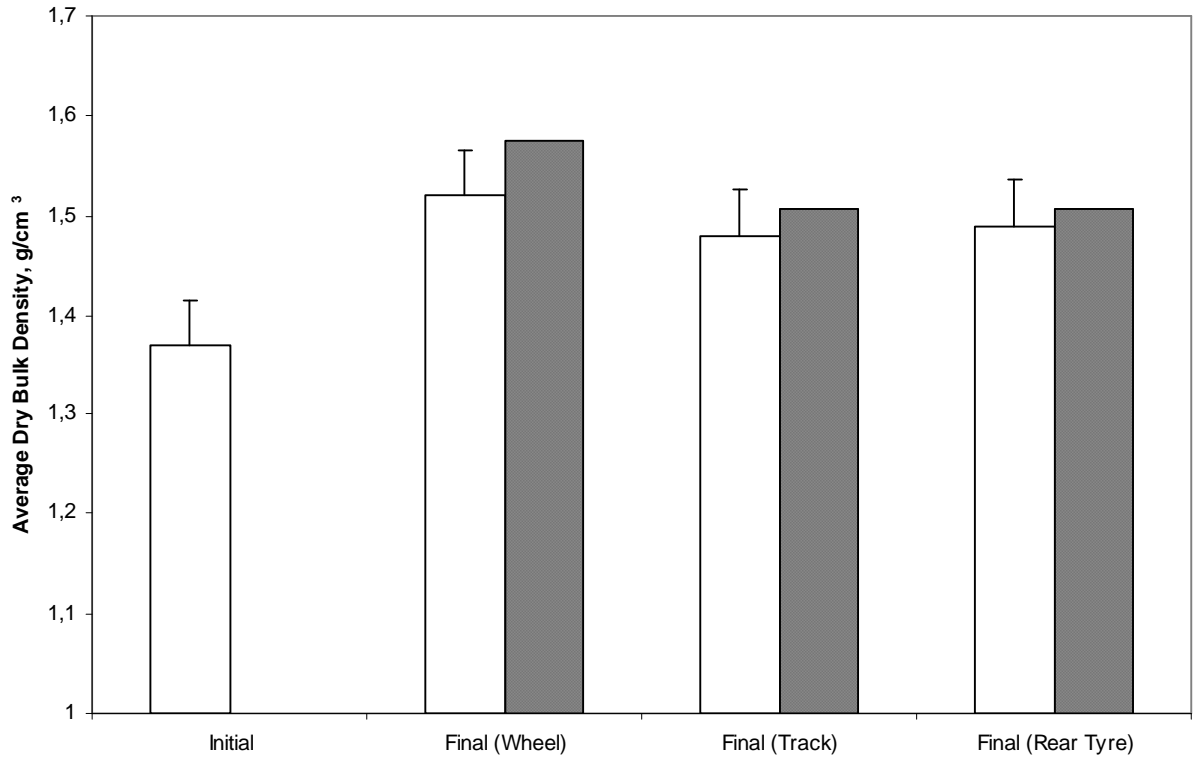


Fig. 13. Overall dry bulk density initially and finally measured (white bars) and calculated from soil displacement (shaded bars) for wheels and for tracks including least significant difference bar at 95%-probability

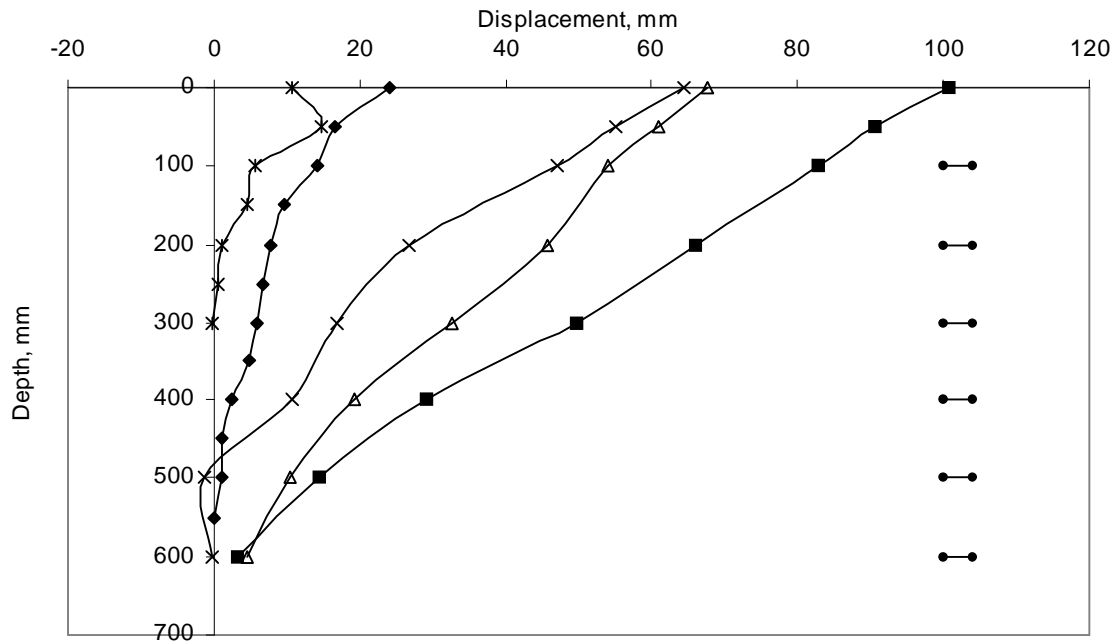


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6 *Fig. 14. Soil displacement over depth for stratified soil conditions and uniform conditions as*

7 *reference: \*, T12t stratified; ◆, 900mm/10.5t/1.9bar stratified; ×, T12t; Δ,*

8 *800mm/10.5t/1.25bar; ■, 800mm/10.5t/2.5bar; +, 900mm/10.5t/1.9bar; •, least*

9 *significant difference at 95% confidence level*

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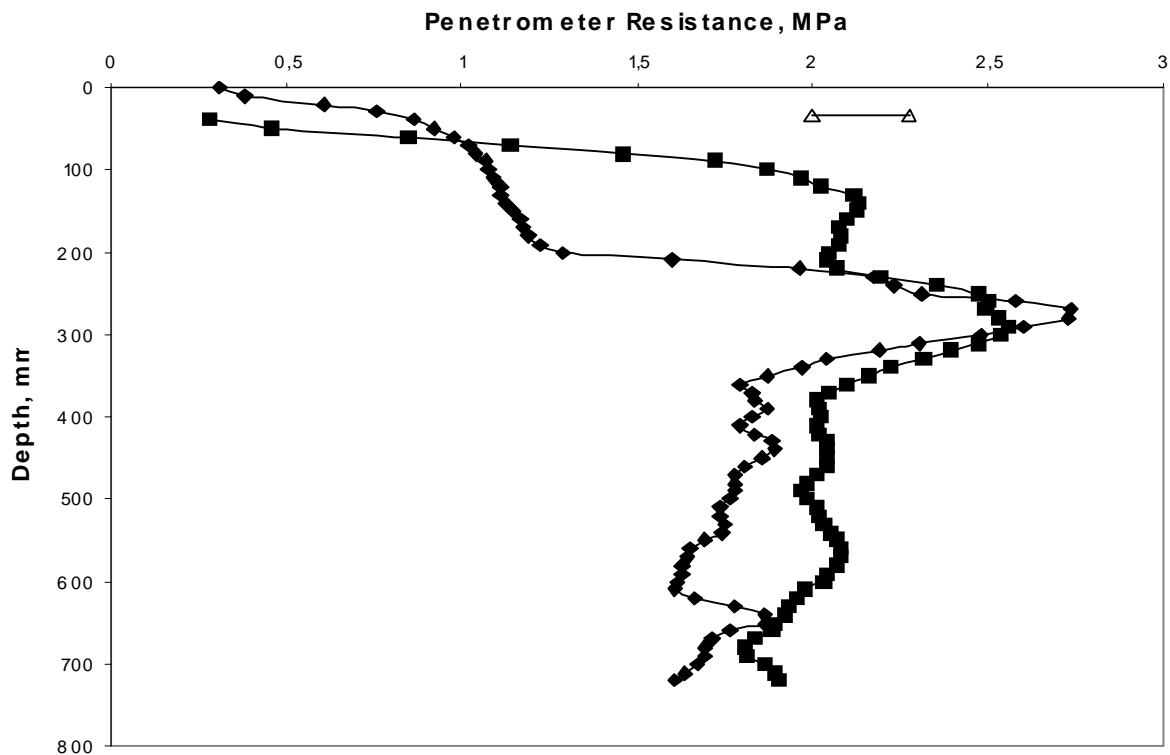
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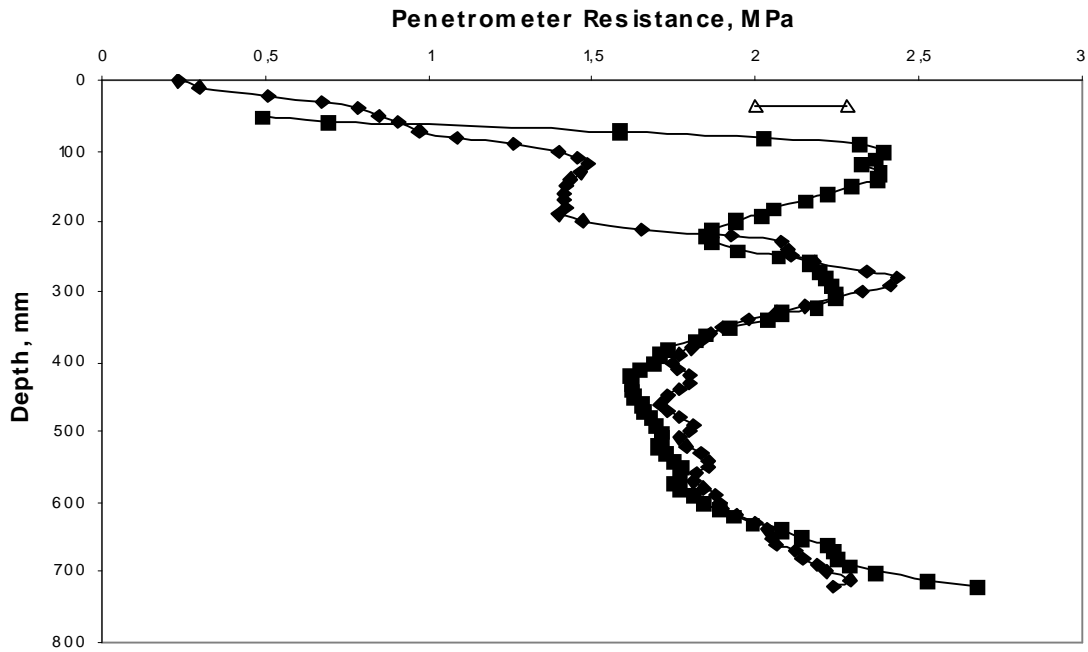
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Fig. 15 a. Stratified soil conditions for the 900mm/10.5t/1.9bar: initial, ◆, and final, ■, including a least significant difference, Δ, at 95% confidence level

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Fig. 15 b. Stratified soil conditions for the T12t: initial,  $\blacklozenge$ , and final,  $\blacksquare$ , including a least significant difference,  $\Delta$ , at 95% confidence level

# The effect of tyres and a rubber track at high axle loads on soil compaction, Part 1: Single axle-studies

Ansorge, Dirk

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D. Ansorge and R.J. Godwin, The effect of tyres and a rubber track at high axle loads on soil compaction, Part 1: Single axle-studies, Biosystems Engineering, Vol. 98, Iss 1, Sept 2007, pp. 115-126  
<http://hdl.handle.net/1826/1937>

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