Evaluation of soil-tire interaction on a soil bin

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Abstract: A single wheel tester with the attention to the size of soil bin has been designed and fabricated to study soil tire interactions, in controlled soil environment. The main parts of a single wheel tester include chassis, reduction gear unit, three-phase AC electric motor, hydraulic cylinder, tank, pump and valve, load cell and tires. The experiment was designed with two levels of tire axle loads (15 and 25 kN) and two inflation pressures (70 and 150 kPa). The tire (18.4/15-30) was run at a constant forward speed of 0.3 m s^{-1}, 13% slip and 12% moisture content(d.b.) on clay loam soil. A statistical comparison was made for the cone index values measured in the undisturbed soil, at the center of the track, and at the edge of the track. A significant difference in cone index was found for all treatments. Inflation pressure at the center and load at the edge of tire track has significant effect on cone index and dry bulk density.

Keywords: cone index, inflation pressure, load; dry bulk density, soil bin

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1 Introduction

Soil compaction mainly depends on the compression applied on the ground surface by agricultural machines. Hence, ground pressure at the soil-machine interface can be measured as a good indicator of the potential compaction on agricultural soils (Abou-Zeid et al., 2004). Soil compaction increases soil strength and bulk density, decreases size, total porosity and continuity of the pores and limits nutrient comprehension, gas exchange, water infiltration and root development resulting in decreased produce, increased power requirement for tillage and erosion (De Souza Dias Junior, 2003). One measure of soil compaction usually used is cone index. Cone index is calculated with a soil cone penetrometer which is described by ASAE Standard S313.3 and ASAE Standard EP542. Greater cone index values are usually observed in trafficked areas (Raper, 2005).

A valid mathematical model for the soil-traction communication process allows researchers to examine many problems related to tractor performance under a wide range of conditions with the goal to improve efficiency tractor operational parameters, to improve tractor design, and to improve the tractor/implement match. Comparative significance of these agents affecting field performance of a tractor can be attained without expensive field-testing. These models can also aid tractor operators to improve the efficiency in their tractors arrangement to match the operating conditions (Tiwari et al., 2010).

Tractor tire aspect ratio effects on soil bulk density and cone index were studied (Way et al., 2009). They used a statistical comparison by SAS statistical program to analyze cone index and dry bulk density. They found that bulk density and cone index in soil just above a hardpan were significantly less beneath the edge than beneath the centerline of the tire tread, so for the tires and conditions they used, soil just above a hardpan was compacted less beneath the edge of a tire than beneath the tire centerline.

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Soil-tire interface cone index for 16.9R38 tractor drive tire on a loose sandy loam in field was measured (Mohsenimanesh and Ward, 2007). They used a statistical comparison by MSTATC statistical program for analysis among the cone index values measured in the undisturbed soil, at the center of the track, and at the edge of the track. Cone index was less for undisturbed soil than for trafficked soil at the center and the edge of the tire track. At the center of the tire track, only inflation pressure caused significant differences in cone index and near the edge, load caused significant differences in cone index. Soil-tire interface cone index for rubber track compared to wheel/tire on sandy loam were measured (Ansorg and Godwin, 2007). The comparison cone index for wheel/tire showed that the plough layer did not become stronger, but its thickness was increased and in rubber track after the pass the penetrometer resistance for the final condition merged with that for the initial condition above the plough layer and no compaction occurred below the plough layer.

2 Materials and methods

The main parts of single wheel tester include chassis, reduction gear unit, three-phase AC electric motor, hydraulic cylinder, tank, pump and valve, load cell, torque transducer and tires. For designing the chassis of single wheel tester, AISI 1018 steel profiles were used (Figure 1). The dimensions of the chassis were 3,100 mm in length, 1,900 mm in width and 2,230 mm in height.

Figure1 Single wheel tester in AERI Institute

The tests was conducted at Agricultural Engineering Research Institute (AERI) with the assistant of the Biosystem Engineering Faculty, Tehran University, Karaj, Iran, to investigate the effect of tire-soil interface on volumetric change of compacted soil under different inflation pressures and loads. The tire used for the experiment was a Barez 18.4/15-30 bias type agricultural tractor tire, which was mounted on the Single wheel tester that was designed and manufactured in the AERI with the assistant of Biosystem Engineering Faculty, Tehran University (Figure 1).

The experiment was designed with two levels of static load (15 and 25 kN), and two levels of inflation pressure (70 and 150 kPa) (Table 1), and guided at a constant forward speed of 0.3 m s^{-1}, 13% slip on clay loam soil. The average values of moisture content the soil (0 to 300 mm) was 12% (d.b.). The single wheel tester was conducted in the 16 m long, 1.3 m deep and 1.7 m wide soil bin at the AERI, Karaj, Iran. Axle loads, cone index and dry bulk density were measured by using a load cell (CLP-3B) of tire under different loads, penetrometer (Eijkel Kamp) and cylindrical ring (50mm diameter and 51 mm deep) respectively (Figure 2).

Table 1 Load and inflation pressure combination

Treatment	Load/kN	Inflation pressure/kPa
15 - 70	15	70[a]
15 - 150	15	150[a]
25 - 70	25	70[b]
25 - 150	25	150[c]

Note: The tire was correctly inflated when used as a single tire for a maximum speed of 32 km h^{-1}.

[a] This combination of load and inflation pressure is not recommended by the tire manufacturer.

[b] Tire was underinflated in this treatment.

[c] This combination of load and inflation pressure is recommended by the tire manufacturer.

a. Load cell (CLP-3B) b. Penetrometer (Eijkel Kamp)

Figure 2 Measuring instruments

Cone index is measured with a soil cone penetrometer which is defined by ASAE Standard S313.3 and ASAE Standard EP542. Cone penetrometer resistance was determined by measuring the force necessary to push a 100 mm^2, 30° cone into the soil. Cone penetrometer measurements were taken in an undisturbed soil area, in the center, and at the edge of the tire in the lug print area (Figure 3).

Figure 3 Lug print area after pass single wheel test

3 Results and discussion

The SAS 9.1 statistical program was used for analysis data, and a randomized complete block (RCB) experimental design was chosen with four replications. Variance analyses for cone index and dry bulk density were done for each working condition. Duncan test was used for multiple comparisons of mean values of cone index and dry bulk density.

3.1 Cone index

Cone index was used as an indicator of enlarged soil strength increased by the tractor tire. Cone index was less for undisturbed soil than for trafficked soil at the center and the edge of the tire track for all treatments (Figure 4). Cone index was lower for undisturbed soil than trafficked soil at the center and edge of the tire track for all treatments are similar with the result of McDonald et al. (1996)'s research. Table 2 shows the analysis of variance (ANOVA) for cone index in the center and the edge of the tire track. As can be seen, variance analyses showed that the load has statistically significant effect on center and edge of tire track (P<0.01), but inflation pressure caused statistically significant difference just for the edge of tire track (P<0.05). On the other hand, load × inflation pressure interactions for cone index in center of tire track was statistically significant while it has not statistically significant effect on cone index in the edge of tire track.

Table 2 Analysis of variance (ANOVA) of cone index

Source	Sum of squares		df	Mean Square		F	
	Center	Edge	Center	Center	Edge	Center	Edge
Load	0.058	0.178	1	0.058	0.178	20.970^{**}	93.083^{**}
Inflation pressure	0.002	0.012	1	0.002	0.012	$0.674^{n.s}$	6.306^{*}
Load×inflation pressure	0.148	0.01	1	0.148	0.01	53.796^{**}	$5.048^{n.s}$
Error	0.022	0.015	8	0.003	0.002	-	-

Note: **= statistically significant (P < 0.01); *= statistically significant (P < 0.05); ns = not significant.

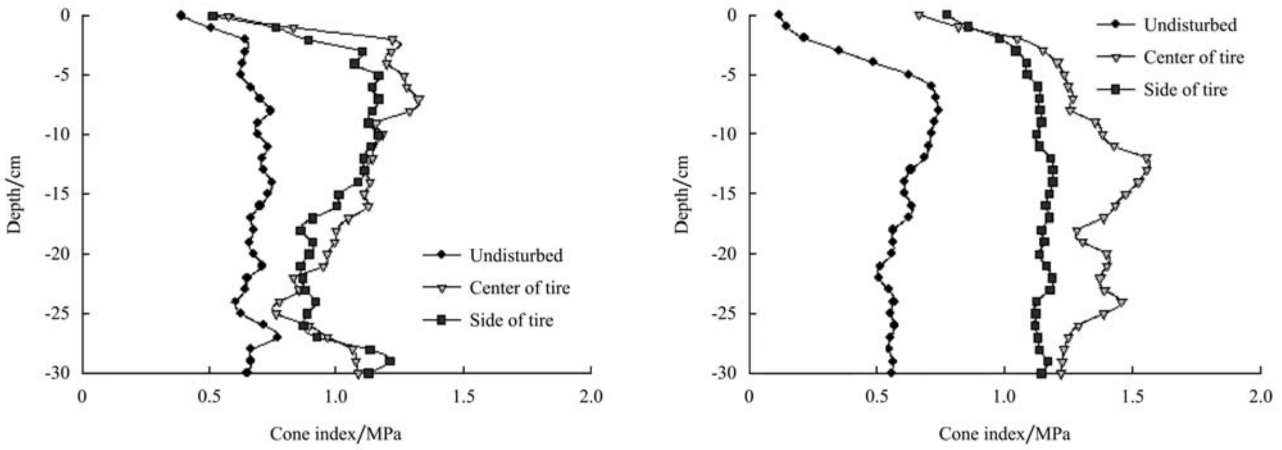
In Table 3, results of Duncan statistical method test with significance level 0.01 are shown. Inflation pressure caused significant differences in cone index for the center of the tire track (Table 3). But in 15-70 and 15-150 treatments inflation pressure has a statistically effect on cone index at the edge of the tire track. When lower inflation pressures were used, cone index decreased in the center and the edge of the tire track (Raper et al.1995). In the edge of tire track, load caused significant differences with significance level of 0.01 in cone index (Table 3), as is shown in Figure 4. This is in agreement with the work of Mohsenimanesh and Ward (2007). In edge of tire track, only load caused significant differences in cone index under two different conditions (Raper et al. 1995).

Table 3 Duncan multiple range test with significance level 0.01 for cone index

Treatment	Center	Edge
15-70	1.306^{c}	1.006^{b}
15-150	1.060^{b}	0.886^{c}
25-70	1.223^{c}	1.193^{a}
25-150	1.420^{a}	1.180^{a}

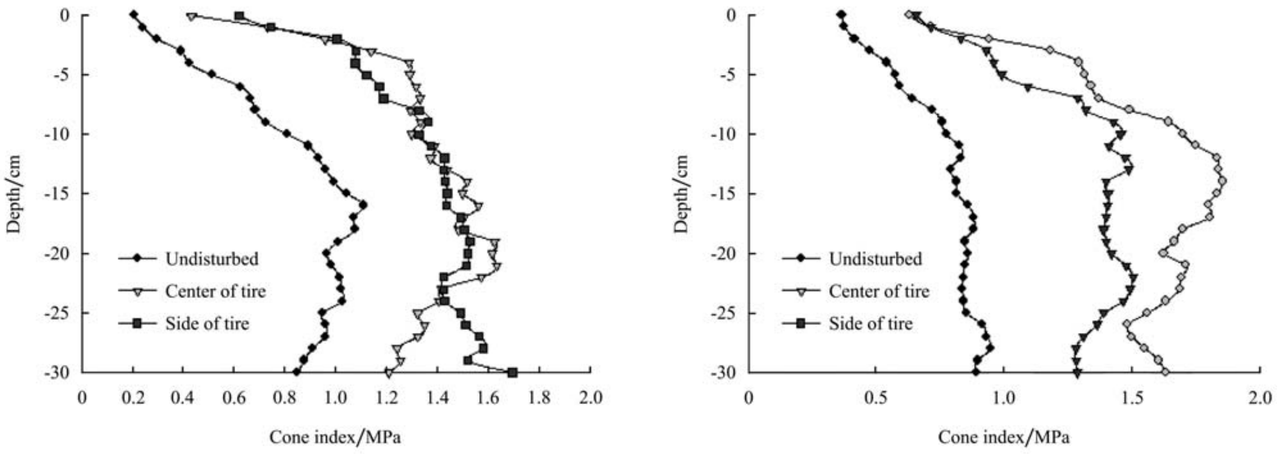
On the one hand, according to the equation, by increasing of F or decreasing of A, the pressure on the soil surface increased. Hence, it increases the soil cone index. On the other hand, increase in inflation pressure of tire reduced curvature radius of the tire at contact area with the soil surface in the center of the tire and therefore it would more severely increase soil cone index of soil. In Figure 4, the comparison between the vertical loads and forces are shown. As it can be seen, the vertical load increases cone index of soil in the center and the edge of the tire track.

As can be seen in Figure 4 in all conditions (four treatments) the cone index is smoothly increased from the surface of soil to 50 mm depth. Although the behavior of cone index is increasing at the depth of 50-150 mm, the rate of its increase is greater than the value of that in 0-5 mm. In last section of the graph (150-300 mm) the cone index is approximately constant. This is in agreement with the work of Mohsenimanesh and Ward (2007) that found this result for cone index graph. It is important to notice that the research which was conducted by Mohsenimanesh and Ward (2007) were in field condition but the cone index of soil in the soil bin has been investigated and evaluated in this study. Hence, in the graph of cone index, they found the value of cone index after 250 mm had been increased. This may be due to the fact that the soil structure after 250 mm in the real condition (field) is harder and it is known as subsoil.



a. 15 kN load and 70 kPa inflation is not recommended by the tire manufacturer

b. 15 kN load, overinflated pressure 150 kPa



c. 25 kN load, underinflated inflation pressure of 70 kPa

d. 25 kN load, correct inflation pressure of 150 kPa

Figure 4 Cone index as measured in the Barez 18.4/15-30 bias type agricultural tractor tire

3.2 Dry bulk density

Dry bulk density was lower in undisturbed soil than trafficked soil at both the center and the edge of the tire track for all treatments (Figure 5). Table 4 shows the analysis of variance (ANOVA) for dry bulk density in the center and the edge of the tire track. Variance analyses showed that the load has a statistically significant effect on dry bulk density at the center and the edge of tire track ($P<0.01$), but inflation pressure caused statistically significant difference just for center of tire track ($P<0.01$). On the other hand, load × inflation pressure interaction for dry bulk density in the edge of tire track was statistically significant and for the center of tire track was not significant.

Table 4 Analysis of variance (ANOVA) of Dry bulk density

Source	Sum of squares		df	Mean Square		F	
	Center	Edge	Center	Center	Edge	Center	Edge
Load	0.016	0.046	1	0.016	0.046	21.255^{**}	$1.080E3^{**}$
Inflation pressure	0.062	0.000	1	0.062	0.000	81.773^{**}	$4.931^{n.s}$
Load×inflation pressure	0.003	0.004	1	0.003	0.004	$4.328^{n.s}$	104.339^{**}
Error	0.006	0.000	8	0.001	4.22E-5	-	-

Note: ** = statistically significant ($P < 0.01$); ns = not significant.

The final measured dry bulk density for tire was significantly higher than initial dry bulk density in all treatments (Figure 5). The differences were in the range of 1.168 – 1.615 g cm^{-3}.

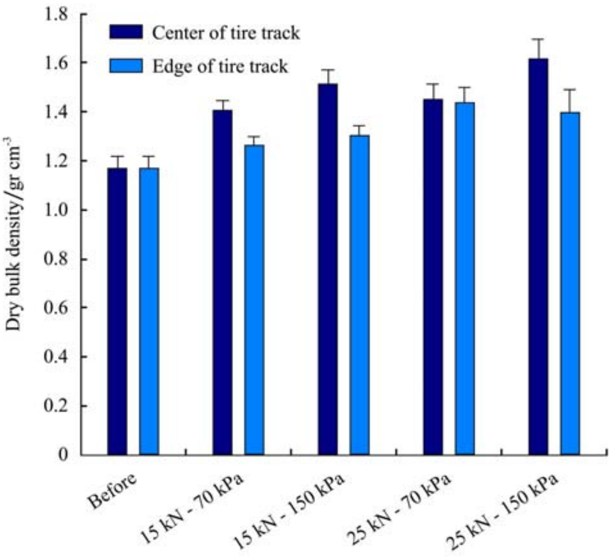


Figure 5 Dry Bulk Density in center and edge of the tire for all treatment

In Table 5 results are based on Duncan statistical method with significance level of 0.01. Inflation pressure caused significant differences in dry bulk density for the center of the tire track (Table 5), in addition, it affect at the edge of the track. Near the edge, load caused significant differences with significant level of 0.01 in dry bulk density, which is similar with the result of cone index.

Table 5 Duncan multiple range test with significance level 0.01 for Dry Bulk Density

Treatment	Center	Edge
15-70	1.393^{c}	1.268^{c}
15-150	1.504^{b}	1.314^{b}
25-70	1.434^{bc}	1.420^{a}
25-150	1.611^{a}	1.403^{a}

4 Conclusions

We can reach the following conclusions:

1) It is found that the cone index and dry bulk density are useful parameters to investigate soil compaction.

2) At the center of the tire track, it is inflation pressure that caused significant difference in cone index and dry bulk density on clay loam soil while at the edge of the tire track it is load. Hence, it can be stated that inflation pressure is more effective in cone index and dry bulk density at the center of the tire track while major effect of vertical load is in cone index and dry bulk density at the edge of the tire track compacted.

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