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THE EFFECTS OF REDUCED INFLATION PRESSURE ON SOIL–TIRE INTERFACE STRESSES AND SOIL STRENGTH

R. L. RAPER,* A. C. BAILEY,* E. C. BURT,* T. R. WAY* and
P. LIBERATI†

Summary—Inflation pressures as low as 41 kPa have been recommended by agricultural tire manufacturers for minimizing an oscillatory vibration problem, commonly called "power hop". Other benefits of these lower inflation pressures might include decreased soil–tire interface pressures, increased tire performance, and decreased soil compaction. Measurements of soil–tire interface stresses were made at four positions on the lugs and at three positions between lugs on an 18.4-R38 R-1 radial tractor tire operated at four combinations of dynamic load and inflation pressure. These measurements showed that as inflation pressure increased, the soil–tire interface stresses near the center of the tire increased, while the stresses near the edge of the tire did not change. The increased stresses near the center of the tire were also transferred to the soil as a compaction increase sensed with the cone penetrometer. "Correctly" inflated tires (i.e. lower inflation pressures) also improved net traction and tractive efficiency.

INTRODUCTION

Problems sometimes lead to previously unforeseen benefits. This was the case with power hop [1]. This problem plagued many farmers using large four-wheel drive tractors and caused dangerous behavior of their tractors. In the cooperative effort between the agricultural equipment industry and the agricultural tire industry to find a solution, a "new" tire operational variable was re-discovered which could help increase the competitiveness of all of American agriculture. Ths "new" variable is inflation pressure.

Initially, farmers having problems with power hop were told that they could minimize its occurrence by adjusting draft, tillage depth, or ground speed. Some farmers even reverted to buying their new four-wheel tractors with bias-ply tires and foregoing the inherent advantages of radial tires [2]. The tractor and tire manufacturers responded by presenting an alternative solution to the power hop problem [3–5]. They recommended that farmers pay proper attention to proper sizing of tires for loads, ballasting, and maintaining proper inflation pressure. Along with these recommendations came new load–inflation-pressure tables allowing agricultural tires to be inflated to as low as 41 kPa, much lower than previous tables allowed.

Decreasing the inflation pressure of the tire has other positive benefits besides minimizing power hop. An inherent advantage of radial tires over bias-ply tires is their larger contact area. This allows radial-ply tires to convert more axle power to drawbar power, i.e. increasing the tractive efficiency [6]. Radial tires when properly

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*USDA-ARS National Soil Dynamics Laboratory, Auburn, AL 36831, U.S.A.
†Institute of Farm Machinery and Agricultural Mechanization, University of Bologna, Bologna, Italy.

inflated, however, tend to have a large bulge similar to radial automobile tires. Many farmers, unaware of the implications, overinflated their tires to minimize this bulge. The increased inflation pressure caused smaller areas of the tire to be in contact with the soil and diminished the advantages of radials.

Inflation pressure has long been recognized as an important variable in the optimization of tire performance [7]. Other research has also shown the positive benefits of reduced inflation pressure [8–10]. It is not certain, however, how a reduction in inflation pressure causes an increase in traction. Is the positive traction effect due to the increased length of the footprint alone, or does the effectiveness of the lugs change? The research described in this paper was aimed toward improving the understanding of the interaction of tire inflation pressure, the soil–tire interface stresses, and the resulting soil deformation.

Objectives

1. To determine the effect of inflation pressure on soil–tire interface stresses.
2. To determine the effect of inflation pressure on soil–tire contact angle.
3. To determine the effect of inflation pressure on cone index in the tire tracks.
4. To determine the effect of inflation pressure on net traction and tractive efficiency.

METHODS AND MATERIALS

An experiment was conducted in the soil bins at the USDA-ARS National Soil Dynamics Laboratory (NSDL) during the fall of 1992 to investigate the effect of new lower inflation pressure values established by the agricultural tire industry. An indoor soil bin was used for this experiment because of the capability of controlling moisture content over a relatively long period of time. The soil used was a Norfolk sandy loam (*Typic Paleudults*) under two different conditions (Table 1). The first soil condition included a hard pan which was created at a depth of approximately 41 cm by using a 30 cm wide rigid wheel to pack directly behind a moldboard plow which was laterally displacing soil. This process was incrementally repeated until the entire soil bin width was covered. The soil was then bladed and leveled. The second soil condition was a uniformly loose condition that involved tilling with a rototiller to a constant 60 cm depth.

Table 1. Soil initial conditions (Norfolk sandy loam soil—sand 72%, silt 17%, clay 11%)

Depth (m)	Bulk density (Mg/m^3)	Moisture content (%db)	Cone index (MPa)
Hard pan			
0.01–0.05	1.18	6.4	0.17
0.36–0.40	1.32	7.1	0.72
0.42–0.46	1.89	7.8	6.03
Uniformly loose			
0.01–0.05	1.24	7.6	0.14
0.32–0.36	1.19	7.7	0.94
0.40–0.44	1.19	7.6	1.10

A Goodyear* 18.4-R38 Dyna Torque Radial (2 star) R-1 agricultural tractor tire was used to perform the inflation pressure tests. This tire was instrumented with seven soil–tire interface transducers both on the lug of the tire and in the undertread area (Fig. 1). Commercially available Sensotec pressure transducers were used for this application with the transducers on the lug having twice the capacity of those used for the undertread area. These transducers had physical dimensions of 1.1 cm width × 1.6 cm length × 0.2 cm thickness. The tire was mounted on the Research Traction Vehicle which has provisions for operating and controlling a single tire for use in the soil bins [11, 12].

The high sampling frequency used for the soil–tire interface transducers resulted in large amounts of data. The interface data was collected at approximately every 2° of rotational angle. Peak values of soil–tire interface stress were used for analysis because this value was assumed to have a direct influence on the resulting soil compaction.

Four different combinations of inflation pressure and dynamic load were chosen for the experiment with the choices providing for a 2 × 2 factorial experimental design. The notation used to indentify the treatments consists of two sets of numbers. The first set of numbers is the dynamic load and the second set of numbers is the inflation pressure. The treatments used included the following: 13.1–41, 25.3–124, 13.1–124 and 25.3–41. The 13.1–41 and 25.3–124 load tests were taken from the load–inflation tables supplied by the tire industry. The 13.1–124 load test consisted of using the same dynamic load as used for the 13.1–41 load test, but increasing the inflation pressure to that used for the 25.3–124 load test. The 13.1–124 load test is very similar to conditions commonly found on most improperly inflated farm tractors in use today.

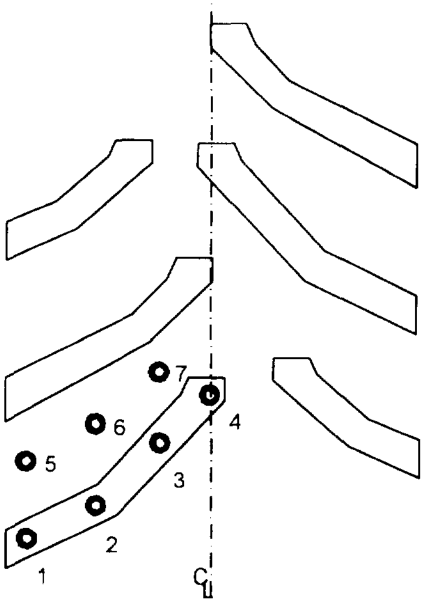

Fig. 1. Locations of the soil–tire interface transducers on the 18.4-R38 radial tire.

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*The use of tradenames or company names does not imply endorsement by USDA-ARS.

The 25.3–41 load test consisted of using the same dynamic load as used for the 25.3–124 load test, but decreasing the inflation pressure to that used for the 13.1–41 load test. Four replications of each test were run at a constant forward velocity of 0.15 m/s and a constant average slip of 10%.

At the conclusion of the experiment, several measurements were taken to determine the resulting soil condition. These included penetrometer measurements taken with the NSDL penetrometer car in undisturbed soil areas, in the center of the tire in the lug print area, and at the edge of the tire in the lug print area. Bulk density and moisture content measurements were also taken in the tire tracks and in undisturbed areas between tire tracks.

Stress-state transducers were also placed in the soil beneath the tire in several locations to determine the effect of changes in inflation pressure and dynamic load on soil stresses. The results from this part of this experiment as well as the bulk density results from the tire tracks are presented by Bailey *et al.* [13] for two soil types and two soil conditions.*

RESULTS AND DISCUSSION

Changes in inflation pressure caused the peak soil–tire interface pressures to behave differently on dissimilar parts of the lug (Figs 2 and 3). As the inflation pressure was decreased, the peak soil–tire interface stresses also decreased near the center of the tire, particularly noticeable in the hard pan soil condition. Decreases were also noted near the outside edge of the tire in most cases, but their statistical

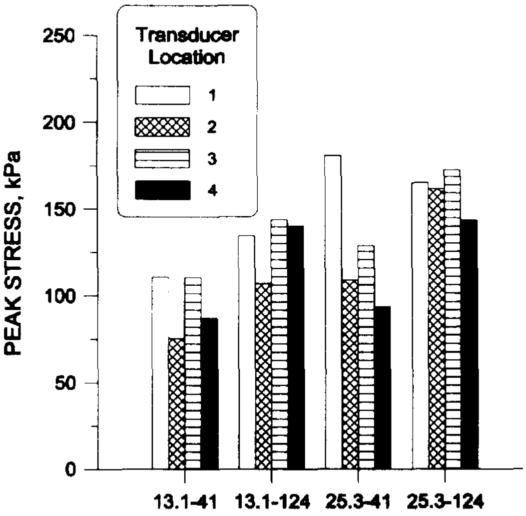

Fig. 2. Peak soil–tire interface stresses for the hard pan soil condition.

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*Soil–tire interface data were obtained on two soil types, a Norfolk sandy loam soil and a Decatur clay loam soil, but statistically significant results were only found in the Norfolk soil. An interaction between large aggregate size and small transducer size caused excessive variability in the data from the Decatur soil. The standard error in the Norfolk soil rarely exceeded 10%, while in the Decatur soil this value was closer to 25%.

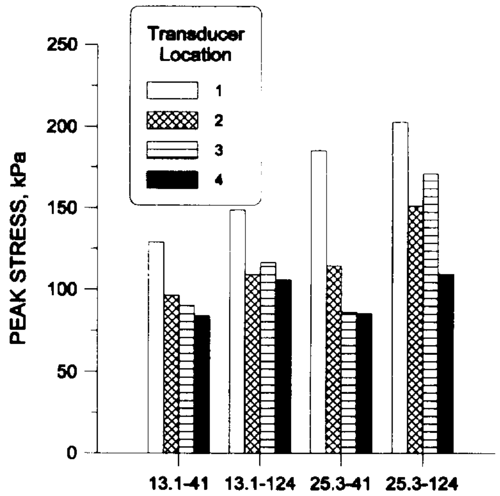

Fig. 3. Peak soil–tire interface stresses for the uniformly loose soil condition.

significance was less because of increased variability. The sidewall stiffness became a factor near the outside edge and inflation pressure effects were not as easily seen.

Table 2 shows the F-test probability levels [14] associated with the factors in both soil conditions for the Norfolk sandy loam soil. This table was compiled from the significance levels found when the peak soil–tire interface stresses were statistically compared. This table gives the probability of obtaining an F-value larger than a calculated critical F-value given that the two means are equal. Small values (< 0.10) indicate that the treatments were statistically significant. For example, the value of 0.782 for inflation pressure for transducer 1 in the hard pan indicates that there is no reason to reject the null hypothesis that all inflation pressure treatments at this location are equal.

In the lug near the edge of the tire (transducers 1 and 2), dynamic load was the predominant statistically significant factor (Table 2). In the lug near the center of the tire (transducers 3 and 4), inflation pressure was the predominant statistically significant factor. In the undertread area, inflation pressure was not very important

Table 2. F-test probability levels for soil–tire interface transducers for both soil conditions

	Interface transducers in lug (from edge to center of tire)				Interface transducers in undertread (from edge to center)		
	1	2	3	4	5	6	7
Hard pan							
Inflation pressure	0.782	0.098^{a}	0.013^{b}	0.021^{b}	0.180	0.872	0.844
Dynamic load	0.004^{c}	0.085^{a}	0.097^{a}	0.708	0.014^{b}	0.028^{b}	0.174
Interaction	0.168	0.649	0.684	0.890	0.260	0.988	0.827
Loose							
Inflation pressure	0.372	0.045^{b}	0.004^{c}	0.006^{c}	0.274	0.084^{a}	0.868
Dynamic load	0.021^{b}	0.020^{b}	0.036^{b}	0.692	0.089^{a}	0.003^{c}	0.019^{b}
Interaction	0.952	0.289	0.020^{b}	0.864	0.708	0.272	0.598

The superscript letters denote levels of statistical significance. ^{a}Denotes significance at the 0.1 level; ^{b}denotes significance at the 0.05 level; ^{c}denotes significance at the 0.01 level.

while dynamic load was, particularly at transducer 6. The interaction of inflation pressure and dynamic load was mostly unimportant and was only significant at one transducer location.

When inflation pressure was decreased, the soil–tire interface pressures near the center of the tire also decreased. However, the soil–tire interface pressures near the edge of the tire did not increase significantly when inflation pressure decreased. In fact, when inflation pressure decreased, the length of tire contacting the soil increased. By monitoring the angle of the soil–tire interface stresses on the tire, the contact angle or the entire sweep of the transducer in contact with the soil was determined. This examination shows that the contact angle for the edge transducer (No. 1 from Fig. 1) increased by 17% in the Norfolk sandy loam soil when inflation pressure was lowered from 124 to 41 kPa for the 13.1 kN load (Fig. 4). At each transducer location, the effect of dynamic load and inflation pressure was significant on soil contact angle.

To minimize soil compaction, the load should be equally distributed over the largest possible area. It therefore seems reasonable that the effect of decreasing inflation pressure would decrease soil compaction because of the more uniform contact pressures, and the larger contact angle. Cone index was used as an indicator of increased soil strength caused by the tractor tire. Differences are easily seen from the undisturbed condition to that caused by the tractor tire down to the hardpan layer (Fig. 5). Clear differences are also seen between the edge of the tire and the center of the tire for this treatment (25.3–124) and this soil condition (hard pan). A statistical comparison was made between the cone index measured in the center of the tire track and the cone index measured at the edge of the tire track. Cone index readings occurring at an arbitary depth of 0.3 m were found to differ significantly from the edge to the center of the tire for both the hardpan and uniformly loose soil conditions.

Within each soil condition, differences were also noted because of the dynamic load and inflation pressure effects (Fig. 6). These differences were also checked at the arbitrary depth of 0.3 m to determine if the load treatments caused the cone index to

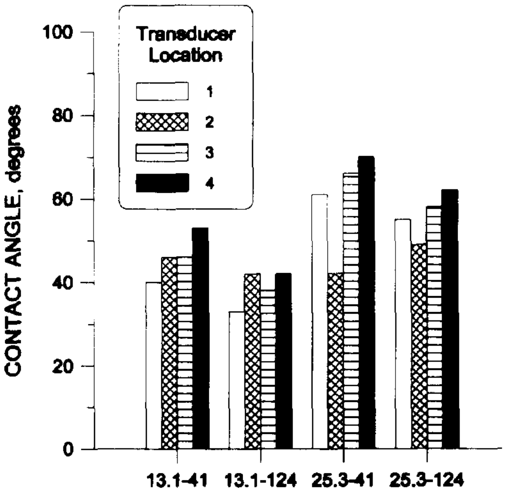

Fig. 4. Contact angle for the 18.4-R38 soil–tire interface transducers.

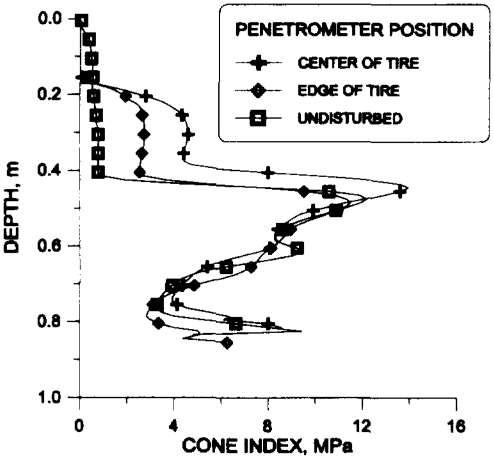

Fig. 5. Cone index as measured in the track of an 18.4–R38 tire operating at the 25.3–124 treatment for the hard pan soil condition.

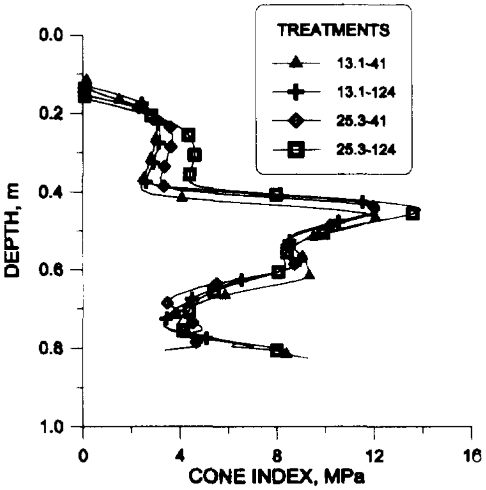

Fig. 6. Cone index as measured at the center of the track of an 18.4-R38 tire operating in the hard pan soil condition.

differ. At the center of the tire, both inflation pressure and dynamic load caused significant differences in cone index to be found for both soil conditions. Near the edge, however, only dynamic load caused significant differences in cone index for both soil conditions. Inflation pressure did have an effect at the edge in the uniformly loose soil condition, but to a much lesser extent than dynamic load. The predominance of dynamic load at the edge correlates very well with the results discussed earlier from the soil–tire interface transducers. It seems that lower soil–tire interface stresses near the center of the tire caused by decreased inflation pressure result in lower soil compaction beneath the center of the tire. Near the edge of the tire, the cone index measurements differ primarily because of dynamic load, as with soil–tire interface stresses.

Mean net traction and tractive efficiency data for both soil conditions are presented

Table 3. Mean tractive performance data for the 18.4-R38 tire

Load treatment	Net traction (kN)	Tractive efficiency
13.1-41	5.4	0.674
13.1-124	3.9	0.584
25.3-41	11.6	0.687
25.3-124	8.3	0.620

in Table 3. Increased inflation pressure caused a decrease in both net traction and tractive efficiency. Increasing the inflation pressure from 41 to 124 kPa for the 13.1 kN dynamic load (13.1–41 vs 13.1–124) decreased the net traction by 28%. This result is important because tires on farm tractors are typically underloaded and are improperly inflated by excessive amounts. Significant gains in net traction and tractive efficiency can now be achieved by following load–inflation-pressure tables supplied by tire manufacturers and setting inflation pressures to the minimum amounts recommended.

CONCLUSIONS

Tire inflation pressure greatly affected the soil–tire interface stresses across the surface of the tire, particularly on the lug. Increased inflation pressure caused soil–tire interface stresses on the lug near the center of the tire to also increase.

The shape of the tire contacting the soil changed with inflation pressure. The contact angle between the soil and the tire was increased as inflation pressure decreased.

The effect of increased inflation pressure on soil strength was also sensed in the tire track with a cone penetrometer. An increase in cone index values found at a depth of 0.3 m near the center of the tire track correlated well with the increased soil–tire interface stresses when inflation pressure was increased.

Tractive performance data demonstrated the advantages of properly inflated tractor tires. Net traction and tractive efficiency were both increased when inflation pressure was correctly set according to the tire manufacturers specifications.

REFERENCES

1. J. C. Wiley, B. E. Romig, L. V. Anderson and F. M. Zoz, Optimizing dynamic stability and performance of tractors with radial tires. ASAE Paper 921586, American Society of Agricultural Engineers, St Joseph, MI (1992).
2. L. Reichenberger, Radial tires need "cheeks". *Farm J.* (Reprint) (February 1992).
3. John Deere, "New" radial tire inflation pressure recommendations. *Tractor Talk* (February 1992).
4. Goodyear, *Optimum Tractor Tire Performance Handbook*. The Goodyear Tire and Rubber Company (January 1992).
5. Firestone, Maximize tractive performance of radial rear tractor tires with proper inflation. Bridgestone/Firestone, Inc. (Febuary 1992).
6. P. J. Forrest, I. F. Reed and G. V. Constantakis, Tractive characteristics of radial-ply tires. *Trans. ASAE*, **5**(2), 108–115 (1962).
7. E. G. McKibben and J. B. Davidson, Transport wheels for agricultural machines III. Effect of inflation pressure on the rolling resistance of pneumatic implement tires. *Agricultural Engng*, **21**(1), 25–26 (1940).
8. E. C. Burt and A. C. Bailey, Load and inflation pressure effects on tires. *Trans. ASAE*, **25**(4), 881–884 (1982).

9. D. C. Erbach and K. K. Knoll, Inflation pressure effect on soil compaction. ASAE Paper 921582, American Society of Agricultural Engineers, St Joseph, MI (1992).
10. R. K. Wood and D. A. Mangione, Tractive benefits of properly adjusted inflation pressures: farmer experiences. ASAE Paper 921583, American Society of Agricultural Engineers, St Joseph, MI (1992).
11. E. C. Burt, C. A. Reaves, A. C. Bailey and W. D. Pickering, A machine for testing tractor tires in soil bins. *Trans. ASAE*, **23**(3), 546–547; 552 (1980).
12. P. W. L. Lyne, E. C. Burt and J. D. Jarrell, Computer control for the National Tillage Machinery Laboratory single-wheel tester. ASAE Paper No. 83-1555, ASAE, St Joseph, MI (1983).
13. A. C. Bailey, R. L. Raper, T. R. Way, E. C. Burt and C. E. Johnson, Soil stresses under tractor tires at various inflation pressures. *Proc. 11th Ann. Conf. of the ISTVS*, Incline Village, NV (1993).
14. SAS, *SAS/STAT User's Guide*, Version 6, 4th Edition. SAS Institute, Inc., Cary, NC (1990).