The design factors of tyres and tracks that affect traction, compaction, and flotation are discussed. The past work of the USDA in traction research is summarized and some new work is discussed. The effects of track shoe design, spacing of track rollers, and track performance in submerged sand are discussed. The polygon effect of track drive sprockets that results in vertical and horizontal speed variations is shown.

The effects of lug spacing, lug angle, tyre width, tyre diameter, radial ply construction and tyre load on pneumatic tyre performance are discussed. The traction and compaction of a wide, low-pressure tyre, dual tyres, and a single tyre are compared. Four-wheel, or all-wheel, drive is shown to be advantageous for traction performance.

Forces in the soil under tyres and tracks are compared. The results of recent work with a steel track, a pneumatic track, and a pneumatic tyre are presented. Some possible advantages of a pneumatic track are discussed.

INTRODUCTION

Agricultural efficiency, when measured in output per farm worker, has increased rapidly in the past 30 years. One reason for this has been the use of more machinery that was carefully designed to do a specific job. Unfortunately, it is still quite common for engineers almost to ignore the design of the traction element for a machine which, in all other respects, they have designed carefully. The designer usually selects either pneumatic tyres or steel tracks from a readily available inventory. It is a sad but not uncommon sight to see a large, expensive harvesting machine sitting idle and useless — not because of any failure in its harvesting elements, but because of the inability of its traction element to support and propel it through the field.

Selection and design of the traction element as an integral part of any machine has been discussed by Taylor and will not be repeated here. An extensive review of literature will not be included but prior work at the National Tillage Machinery Laboratory will be summarised. The design factors which affect traction in tyres and tracks will be discussed, as well as the general areas of flotation and compaction. Finally, some recent research on a pneumatic track, a steel track, and a tyre will be presented.

The objective of this report is to present some guidelines, based on past research, that should be helpful to machine designers, and to attempt to create more interest in the design of the traction elements by presenting some new research findings.

PREVIOUS RESEARCH

Several important concepts concerning traction research may be better understood by studying Fig. 1. First, the weight carried by a traction device so
Directly affects the pull generated that the pull-weight ratio is used as a performance factor. The vertical scale in Fig. 1 shows this pull-weight ratio, which is commonly called coefficient of traction, or dynamic traction ratio. Second, the difference in soil types or other surfaces on which a traction device is operated has a much greater effect upon the amount of pull generated than any design factor of the traction device. Fig. 1 shows the pull-weight ratio for sand, the Decatur clay soil, and concrete. Finally, there are several ways of affecting traction performance by design of the traction device. Radial ply construction, shown in Fig. 1, has more effect on traction performance generally than most other factors known to research workers.

![Diagram showing dynamic traction ratio vs travel reduction for different surface types and tire ply constructions.](NTML Photo no. P-10,225 g)

This discussion of Fig. 1 should help to put the factors involved in traction into proper perspective. The effects of the design factors which will be discussed in this paper are rather insignificant when compared with the effects of weight carried or soil type, but, because of the magnitude of the world-wide traction problem, any small increase in traction performance is extremely valuable.

Tracks are generally used for low-speed, high-pull jobs. They provide good flotation and minimum soil compaction because their contact area with the ground is greater than that for tyres. Tracked vehicles generally utilise more of their weight to produce drawbar pull.

In a study of track shoe design, Kuether et al found little difference in the 5 designs tested, except for a semigrouser shoe that was significantly lower in performance. A grouser was definitely needed, but the width and depth was not very important in their test conditions.

A track shoe dynamometer was designed by Reed that measured the horizontal and vertical forces on a single shoe throughout each revolution of
the track. This work showed that the polygon effect of the track drive sprocket caused as much as 1.5 cm chordal rise and fall of the track chain and speed variations up to 3.6% of the maximum speed. The number and spacing of the track rollers were varied. Spacings closer than 1.7 times the pitch length of the track chain did not affect the horizontal or vertical forces exerted on the track shoe.

Reidy et al. measured the coefficient of traction in submerged sand. They were able to obtain a coefficient of traction of 0.35 in these underwater tests by using a narrow track having its centre of gravity forward of centre. Slow speeds and an open track were beneficial, particularly in conditions where a weak layer of soil covered a stronger subsoil.

In pneumatic tyre work, several factors that affect traction performance have been identified. Taylor et al. have presented evidence that increasing the diameter of the tyre gives an increase in pull and coefficient of traction when tyre width, dynamic weight, and inflation pressure are held constant.

The effect of tyre width on traction performance is not consistent. Tyre width has frequently been increased to carry a greater load without changing the height of a vehicle.

The effect of lug spacing, angle, height, and shape on pneumatic tyre performance is much discussed. Taylor could find no significant effect of lug angle on traction performance. He stated that there might well be an effect of lug angle on wear rate of tyres on hard-surfaced roads. Taylor found no significant effect of lug spacing on traction performance within the range of spacings tested. Radial ply construction does not increase maximum traction but does improve traction performance in the normal operating range below 30% travel reduction. Vanden Berg et al. showed that traction improved by an average of 15% when tyres of radial ply construction were used.

The question of tyres versus tracks is not an easy one to answer. The operating conditions should determine the designer's choice of a traction device. When the soil-vehicle system fails to perform properly, it is usually because of a weakness in the soil rather than any structural failure of the traction device.

Reaves et al. have measured ground pressures under tyres and tracks. Their results show that vertical soil stresses under tyres are generally twice as great as those under tracks at any depth for the same load (Fig. 2).

Four-wheel drive was shown by Reed et al. to have better traction performance than has 2-wheel drive. The 4-wheel drive has a higher coefficient of traction and higher tractive efficiency, primarily because of lower rolling resistance for the second wheel in each track. Chang et al. using steel rice paddy wheels, found that the wheel's total power consumption was minimum at zero pull. This indicates an advantage for powering all wheels.

McLeod et al. compared 3 traction units consisting of a single tyre, dual tyres, and a Terra-tire* in a clay soil and in a sandy loam. At the same static load, traction performance was best for the Terra-Tire and poorest for the single tyre. Soil compaction was least for the Terra-Tire and greatest for the single tyre. The dual tyres were between the other two units in both traction performance and compaction.

As machines have grown heavier, the load has been spread over more soil area by using larger tyres, dualing tyres, using Terra-Tires, or switching
to tracks. In many cases designers have been quite proud of their accomplishment when they were able to double the weight of a machine, yet keep the ground contact pressure from changing by doubling the area of contact. This practice has maintained mobility in most cases but often at the expense of damage to the soil condition which affects its crop growing ability.

There are 2 important effects upon the soil resulting from increased total loads and increased area of contact. In many cases the ground contact pressure is already sufficient to retard root growth. If the width of a tyre or track is increased for a larger machine in order to maintain a constant ground contact pressure, then more soil is compacted to a growth-retarding level. This could, theoretically, be avoided by increasing the length of the contact area rather than the width — a solution that might be possible with a track, but not, ordinarily, with a tyre.

A second aspect of our common practice of continuously increasing machine size seems to be little understood. We have laboured under the false assumption that if we want to reduce compaction in the soil all we have to do is reduce the unit load applied to the soil and the pressure in the soil will be reduced proportionally. This is true only for the surface pressure, not for pressures in the soil. Many years ago, Froehlich showed that pressure in the soil below the surface was a function not only of the unit pressure, but also of the total load applied to the soil surface. Froehlich’s formula should be used more often today. It would help us to understand some of the soil physical problems occurring on fields traversed by heavy machinery.

**MATERIALS AND METHODS**

The unique facilities of the National Tillage Machinery Laboratory,
ARS, USDA, Auburn, Alabama, were used to conduct the research reported here. Three traction devices were compared in 2 soil bins. Each soil was tested twice, and the resulting moisture-density levels are shown in Table 1.

**TABLE 1.** Soil moisture-density levels for traction tests in May 1973.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Date of tests</th>
<th>23 May 1973</th>
<th></th>
<th>25 May 1973</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soil depth (cm)</td>
<td>Moisture (%)</td>
<td>Bulk density (gm/cc)</td>
<td>Moisture (%)</td>
<td>Bulk density (gm/cc)</td>
</tr>
<tr>
<td>Norfolk sandy loam</td>
<td>0-6</td>
<td>9.98</td>
<td>1.28</td>
<td>8.37</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>6-12</td>
<td>9.53</td>
<td>1.68</td>
<td>8.47</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>12-18</td>
<td>8.09</td>
<td>1.61</td>
<td>8.41</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>18-24</td>
<td>7.57</td>
<td>1.42</td>
<td>8.20</td>
<td>1.42</td>
</tr>
<tr>
<td>Decatur clay</td>
<td>0-6</td>
<td>14.67</td>
<td>1.09</td>
<td>15.04</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>6-12</td>
<td>15.59</td>
<td>1.49</td>
<td>15.15</td>
<td>1.49</td>
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<tr>
<td></td>
<td>12-18</td>
<td>15.94</td>
<td>1.34</td>
<td>15.16</td>
<td>1.36</td>
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<tr>
<td></td>
<td>18-24</td>
<td>15.07</td>
<td>1.24</td>
<td>15.06</td>
<td>1.23</td>
</tr>
</tbody>
</table>

The first of the 3 traction devices was the Bonmartini pneumatic track, an experimental pneumatic track of Italian origin. This was designed to carry a maximum vertical load of approximately 600 kg. It was constructed much like a tyre with a belt of nylon on the inside—acting something like a conventional tyre bead. The device was deformed by mounting it on a track frame as shown in Fig. 3. The ground contact surface was approximately (16 x 140) 2 240 cm².

The second device was a conventional steel track made by an American manufacturer. The ground contact surface was approximately (25 x 152) 3 800 cm².

The third device was a 12.4/11 — 28, 4-ply tyre with an R-1 tread. The ground contact surface for the tyre was approximately (32 x 70) 2 240 cm².

The inflation pressure for both the pneumatic track and the tyre was 1.0 kg/cm². Two vertical loads were used: a 550 kg load for all 3 devices and in addition, a 1 000 kg load on the tyre and the steel track.

The track test car and the tyre test car of the National Tillage Machinery Laboratory were used for making the measurements. Drawbar pull, torque, linear velocity, angular velocity, and weight were continuously measured throughout the tests, and travel reduction was calculated simultaneously by an analog computer. Each of these variables was recorded on an oscillograph and on magnetic tape. Drawbar pull versus travel reduction curves were plotted during the tests as a general check on the test procedures. The tests were replicated 5 or 6 times. The data reduction from the magnetic tape consisted of computing and plotting the dynamic traction ratio versus travel reduction curves and the tractive efficiency versus travel reduction curves. (Terminology used in discussing these tests is defined in ASAE R296.1.)
RESULTS AND DISCUSSION

The combination of 2 loads in 2 soils having 2 moisture-density levels gives 8 unit conditions in the testing sequence. Since 2 performance factors were used (dynamic traction ratio and tractive efficiency), a total of 16 sets of curves is available for discussion. To conserve space, 4 sets of curves were selected as typical of the test results. These performance curves are for both Norfolk sandy loam and Decatur clay at the 550 kg load. The moisture-density levels for the tests reported here are shown under the test date of 25 May 1973, in Table 1. Both dynamic traction ratio and tractive efficiency curves are shown for the test conditions described above.

Fig. 4 (a) shows the dynamic traction ratio for Norfolk sandy loam, and Fig 4(b) shows the same for Decatur clay. When the actual performance curve is shown, little explanation or discussion in necessary. For those not familiar with traction tests, steel tracks are normally operated at less than 10% travel reduction; whereas, pneumatic tyres are usually operated below 25% travel reduction. Nebraska tests have 7% and 15% travel reduction set as maximum limits for steel tracks and pneumatic tyres, respectively, under their test conditions.

Figs. 4(a) and 4(b) show typical results for dynamic traction ratio. Notice the shape of the curves: The steel track reached its maximum performance below 10% travel reduction. The performance curve for the tyre never really peaked, but continued to rise at a decreasing rate with travel reduction. The pneumatic track curve fell in between. This was also generally true for the higher load and second soil condition which is not shown or discussed in this report.

In both Figs. 4(a) and 4(b) the pneumatic track performance exceeded that for the steel track, but this occurred at a value of travel reduction above the normal operating range for a steel track. No one really knows what the
FIGURE 4. Dynamic traction ratio for the pneumatic track (BNF), the steel track (STEEL) and the pneumatic tyre (TIRE). (NTML Photo nos. P-10,233m and P-10,233a.)
operating travel reduction range should be for a pneumatic track.

Figs. 5(a) and 5(b) show the tractive efficiency for the same soil conditions and loads as in Fig. 4. There was little difference in tractive efficiency between the steel track and the pneumatic track. The tractive efficiency of the tyre was considerably lower in the Norfolk sandy loam, but much closer to that of the tracks in the Decatur clay. It should be remembered that the tyre and pneumatic track had equal ground contact area, but the steel track had approximately 66% more contact area.

These tests show the general superiority of tracks over tyres as traction devices. The reader is referred to Taylor for an explanation of the fact that many more wheeled vehicles are used than tracked vehicles. It is sufficient here to mention that traction devices serve also as steering systems and suspension systems, and that maintenance costs and travel on hard-surfaced roads are important factors.

The pneumatic track used in these tests was an experimental model. The tests showed that it compared favourably with the steel track in both dynamic traction ratio and tractive efficiency.

The pneumatic track could possibly equal the steel track as a traction device, while overcoming most of the objections to the steel track. It could operate on hard-surfaced roads, travel at higher speeds, and provide greater operator comfort through pneumatic springing as a suspension system. It could combine some of the best features of both the pneumatic tyre and the steel track. Of course, it is still a track system and, therefore, more complex than a wheel system. The problems of designing and manufacturing a pneumatic track for long life at an economically acceptable price are beyond the scope and training of the author.

CONCLUSIONS

The most influential factors affecting the traction performance for tyres or tracks are the load carried by the traction device and the soil condition upon which it is operated.

The influence of several design factors for pneumatic tyres is somewhat predictable.

Larger machines having larger areas of soil contact compact a higher percentage of the crop growing area.

Pressures in the soil beneath the surface are not a function of surface unit pressure alone, but are also dependent upon the total load applied to the soil surface.

The pneumatic track has a traction performance almost equal to the steel track.

Even though design and manufacturing problems for a pneumatic track may be formidable, the possibilities of its high-speed operation in the field and on hard-surfaced roads combined with its general traction performance and improved suspension system seem to justify further research.

REFERENCES


2. Froehlich, O. K. (1934). Druckverteilung in baugrunde (Pressure distributions in the
FIGURE 5. Tractive efficiency for the pneumatic track (BNF), the steel track (STEEL) and the pneumatic tyre (TIRE). (NTML Photo Nos. P-10,233f and P-10,233h).
soil). Wien.


* Trade names are used in this publication solely to provide specific information. Mention of a trade name does not constitute a guarantee or warranty of the product by the United States Department of Agriculture or an endorsement by the Department over other products not mentioned.

TRACCION, COMPACTACION Y FLOTACION EN LOS SUELOS LIVIANOS

James H. Taylor

RESUMEN

Los factores en el diseño de gomas y carriles que afectan la tracción, compactación y flotación son examinados en este trabajo. Los estudios anteriormente hechos por el Departamento de Agricultura de los Estados Unidos sobre investigaciones en tracción son resumidos y varios nuevos trabajos son realizados.

En este trabajo se estudia el efecto que se produce al entrar la cadena a la estrella y como la misma se desempeña al pasar por ella resultando en variaciones de velocidad horizontal y vertical.

En este trabajo también son analizados los efectos que en el rendimiento de una goma tiene la separación y ángulo de las agarraderas, ancho y diámetro de la goma y construcción radial de las lonas. Son comparadas la tracción y compactación de la zona ancha y de baja presión, de gomas sencillas y de gomas dobles. La ventaja de tractores con tracción en las cuatro ruedas sobre tractores con tracción en dos ruedas, es analizada. El efecto de las gomas y del carril en el terreno son comparados. Los resultados de trabajos recientes en carriles de acero, en gomas y en carriles neumáticos son expuestos. Algunas posibles ventajas de carriles neumáticos son discutidas.