Traction performance of a model 4WD tractor[1]

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Wang, Guang, Kushwaha, R. L. and Zoerb, G. C. 1989. **Traction performance of a model 4WD tractor**. Can. Agric.Eng. **31**: 125–129. A model tractor, based upon approximately 1/4 length scale of the John Deere 8640 four-wheel drive tractor, was designed and fabricated for traction studies in a soil bin. The tractor was powered by a 2.25 kW electric motor and was capable of either two-wheel-drive or four-wheel-drive modes. Various components were instrumented to measure individual axle torque, axle speed, and drawbar pull. Data were collected with a HP2240A data logger connected to a HP1000 mainframe computer. Tests were conducted in front-wheel-drive, rear-wheel-drive and four-wheel-drive modes to investigate the traction characteristics with different drive modes. Test results showed the four-wheel-drive mode produced a drawbar pull about three times of that produced by the rear- or front-wheel-drive mode. The rear-wheel-drive mode was found more favorable than the front-wheel-drive mode. The motion resistance of the four-wheel mode was greater than that of the front- or rear-wheel-drive mode. A theoretical analysis and model tractor tests were conducted to find the optimum traction ratio. The results showed the optimum traction ratio ranged from 0.3 to 0.4.

INTRODUCTION

Transfer of engine power to drawbar power in the case of agricultural tractors and off-road wheeled vehicles is dependent upon a number of interrelated parameters. Tire characteristics, soil condition, type of loading, as well as static and dynamic weight distribution are some of the parameters which affect tractor performance. Methods of studying tractive performance include theoretical or mathematical analysis, scale model testing under controlled conditions and field testing of full-sized tractors. The mathematical analysis and actual field testing represent two opposites within the realm of traction mechanics. A scale model, however, fits between these two limits. Traction studies using a model tractor have several advantages — it is easier to instrument a model tractor than a full-sized tractor; tests can be conducted at any time of the year; and it is easier to change loading conditions and soil conditions.

Murillo-Soto and Smith (1977, 1978) reported weight transfer and traction efficiency of 4WD tractors using a model tractor based on a John Deere 7020 tractor. They tested the effect of drive axle speed ratio, drawbar hitch height and static weight distribution on the weight transfer and tractive efficiency. Effects of tire size, wheel slip and soil conditions on the tractive performance of a single wheel have been investigated (Freitag (1966), Turnage (1972), Wismer and Luth (1973), Dwyer et al. (1975), Gee-Clough et al. (1978), McKyes (1985) and many others. Equations have been developed relating the tractive performance ratios (traction ratio and motion resistance ratio), wheel slip, soil cone index, tire size and wheel load. These relationships have been applied for prediction of tractive efficiency.

The objective of this study was to investigate the traction characteristics of 4WD tractors under two- and four-wheel drive modes with a model tractor as well as 4WD mode under different tractor ballasts. An analysis was conducted to find the optimum traction ratio, which could be used to assist farmers in the selection of tractor ballasts.

TEST EQUIPMENT AND PROCEDURE

The model tractor was designed and fabricated to 1/4-length scale of the John Deere 8640 tractor (Close and Fahlman 1986; Zyla 1987). The wheelbase was 795 mm and tire size was 584-216 mm (23-8.5 in.). The tractor was powered by a 2.25-kW electric motor and was capable of either two-wheel or four-wheel drive modes with power delivered to the drive axles by chains. Figure 1 shows the model tractor operating in the soil bin. The drive axle torque was measured for each wheel by measuring the tension in the driving chain. The axle speed was measured with a magnetic pickup sensor. Figure 2 illustrates the chain drive train and locations of the torque and speed transducers. A detailed diagram showing the torque and speed sensors is given in Fig. 3. As shown, beam A is bonded with strain gauges, two on each side. The tension in the chain is transferred to beam A, causing a bending moment in the beam. The strain measured by the strain gauges is proportional to the chain tension. The tractor axle speed was sensed from the idler sprocket by a magnetic pickup. The model tractor had a total weight of 2852 N, with the total front wheel load being 1676 N and the total rear wheel load 1176 N. The drawbar hitch height was 236 mm above the ground.

Tests were conducted with four-wheel-drive (4WD), front-wheel-drive (FWD) and rear-wheel-drive (RWD) modes. To achieve the two-wheel-drive (2WD) mode, either the front or axle chains were removed from the drive train. During the tests, the model tractor was connected to the transport carriage (Fig. 1) via a strain gauge load cell for draft measurement. Various slip values were obtained by setting the tractor motor speed at levels to produce a ground speed greater than the carriage speed. The data were collected by a HP2240A data logger, which was connected to a HP1000 main frame computer.

RESULTS AND DISCUSSION

Comparison of different drive modes

Table I lists the soil conditions including soil cone index and soil moisture content. Soil cone index, determined from cone penetrometer tests (American Society of Agricultural Engineers 1986) was used as the measure of soil strength. This cone index was used instead of soil cohesion and friction angle because of its simplicity of measurement and popularity in traction analysis. The test soil was fine-grained Saskatchewan clay loam. A rotary cultivator was used to till the soil. The tilled soil was compacted by a heavy roller. Soil compaction levels were

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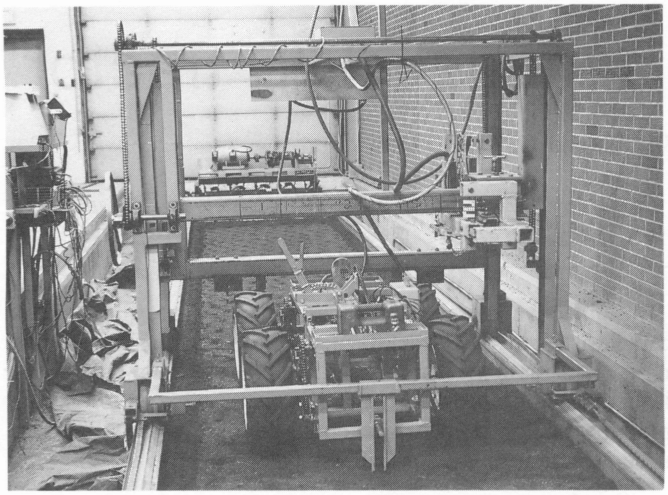

Figure 1. Electric-powered model tractor operating in a soil bin.

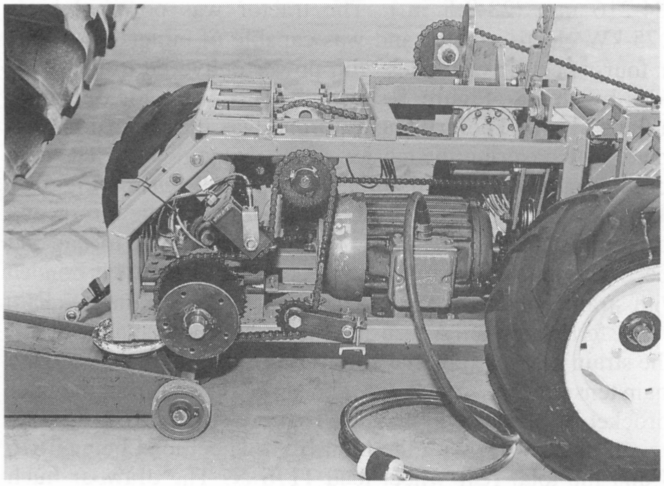

Figure 2. Picture showing the model tractor drive train.

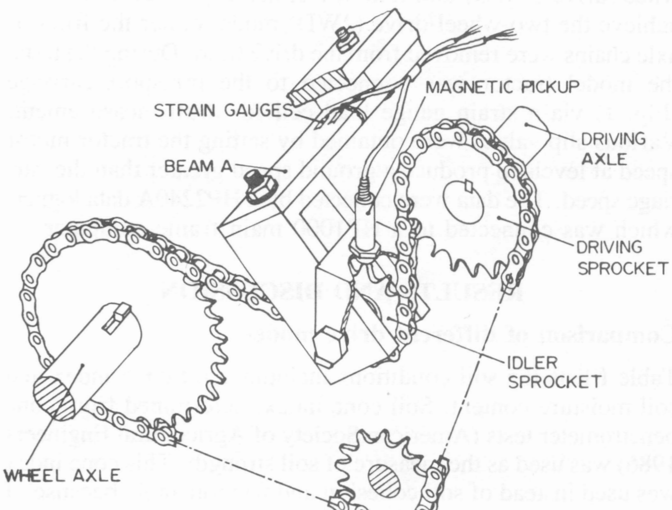

Figure 3. Diagram showing the torque measurement mechanism and the axle speed sensor.

Table I Soil conditions for the tests of three drive modes

Drive mode	Soil cone index (kPa) Before 1st pass†	Soil cone index (kPa) After 1st pass	Soil moisture content (%*db*)
4WD	231	628	14
FWD	224	751	13
RWD	217	736	12

†Soil was tilled 100 mm deep.

controlled by the number of passes of the roller on the soil. Tests were carried out to investigate the effect of different drive modes on the tractive performance of the tractor. The tractive performance of a tractor refers to drawbar pull, tractive efficiency and motion resistance. The calculations were made using the following definitions.

Tractive efficiency:

$$\eta = \frac{\text{output drawbar power}}{\text{input power to driving axle}} \quad (1)$$

Motion resistance ratio:

$$\rho = \frac{H-D}{W} \quad (2)$$

where:
ρ = motion resistance ratio,
H = gross traction,
D = horizontal drawbar pull, and
W = tractor weight.

Gross traction:

$$\text{H} = \frac{\text{axle torque}}{\text{rolling radius}} \quad (3)$$

The rolling radius equals the advance under no load per wheel revolution divided by 2π.

Drawbar pull and tractive efficiency

As shown in Fig. 4, the drawbar pull for the 4WD mode is about three times that for the FWD mode or the RWD mode. This situation was caused by the extra motion resistance from the towed wheels, which were drive wheels for 4WD mode. The drawbar pull for the FWD mode was nearly equal to that for the RWD mode, although the dynamic load on the front wheels was about 1.2 times that on the rear wheels. The reason the RWD mode produced more pull was that the rear wheel travelled on the soil compacted by the front wheels. The compacted soil increased the traction ability of the rear wheels.

The tractive efficiency of the three drive modes is plotted in Fig. 5. There is no doubt that 4WD is the most efficient mode. Again from the tractive efficiency plot, the RWD mode is more favorable than the FWD mode at most wheel slip levels. Figure 5 also shows the maximum tractive efficiency of the 2WD modes occured at a greater wheel slip as compared with the 4WD mode. A greater slip was needed to produce a certain amount of traction to overcome the motion resistance on the towed wheels.

Motion resistance ratio

Motion resistance was obtained by subtracting the horizontal drawbar pull from the gross traction. The motion resistance ratio

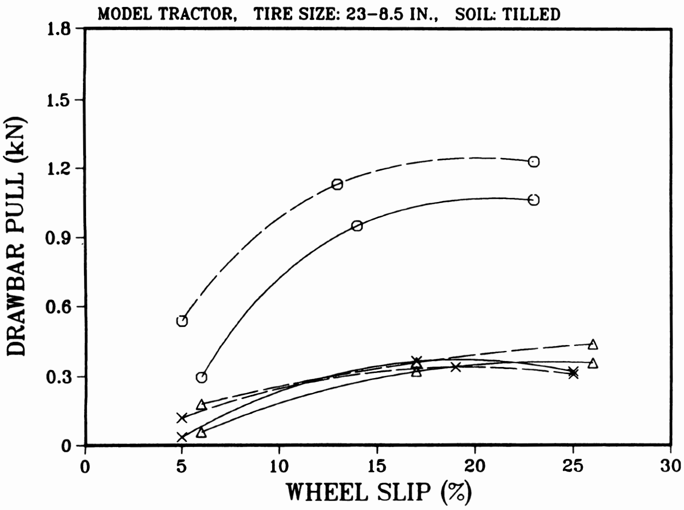

Figure 4. Drawbar pull vs wheel slip with three different drive modes. O, 4WD mode; ×, FWD mode; ▵, RWD mode. —, first pass; ---, second pass.

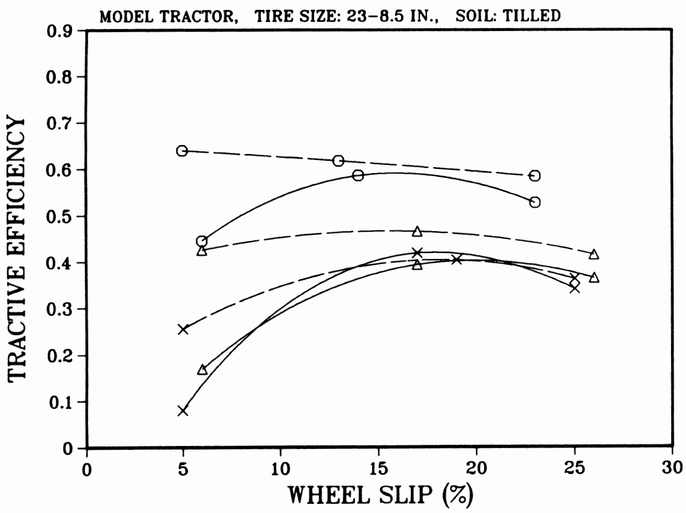

Figure 5. Tractive efficiency vs wheel slip with three different drive modes. O, 4WD mode; × , FWD mode; ▵, RWD mode. —, first pass; ---, second pass.

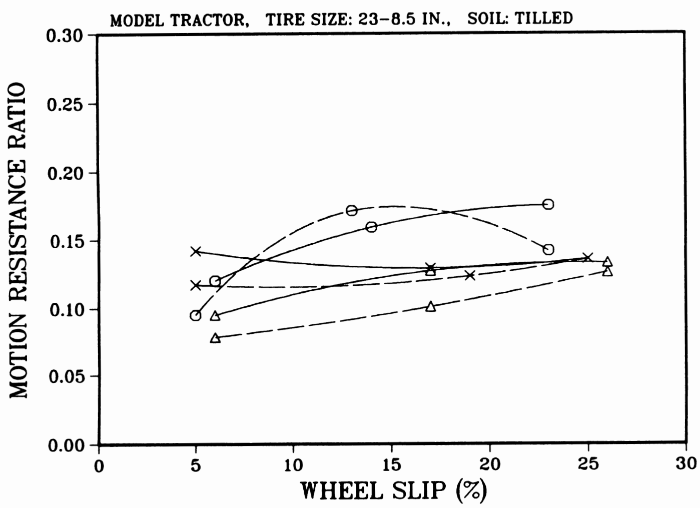

Figure 6. Motion resistance ratio vs wheel slip with three different drive modes. O, 4WD mode; ×, FWD mode; ▵, RWD mode. —, first pass; ---, second pass.

is the ratio of motion resistance to the total tractor weight. The laboratory test results plotted in Fig. 6 show the motion resistance of the 4WD mode is greater than that of the two-wheel-drive modes. From this test, the RWD mode was found most favorable as far as the motion resistance is concerned. It is not known, however, why the motion resistance ratio was higher for the 4WD mode than for the RWD or the FWD mode. This phenomenon may be due to the difference in motion characteristics of towed wheels and powered wheels. As indicated in Fig. 6, the motion resistance increases with slip. Field tests of a full-sized 4WD tractor (Wang 1988) also revealed this phenomenon, that is, the motion resistance increases with slip. Thus, high slip operation of 4WD tractors is not recommmended. Further tests are necessary in order to find a relationship between motion resistance and wheel slip.

First pass vs. second pass

As can be seen from Fig. 4, the drawbar pull increased by about 18% on an average for the second pass as compared with the first pass. The motion resistance ratio was about 15% less on an average for the second pass than for the first pass (Fig. 6). This incereased drawbar pull and decreased motion resistance was due to the increased soil strength. As indicated in Table I, the soil cone index after the first pass is about three times that before the first pass. For the RWD mode, rear wheels travel on the soil compacted by front wheels. This situation increases the tractive ability of the rear wheels. Therefore, the RWD mode has a certain advantage over the FWD mode.

Optimum traction ratio

A tractor should be ballasted to a weight such that the tractor not only produces sufficient pull but also operates at the maximum tractive efficiency. For a single drive wheel, the tractive efficiency can be computed from the following equation (McKyes 1985):

$$\eta = \frac{\tau}{\tau + \rho}(1 - S) \tag{4}$$

where:

τ = traction ratio,
ρ = motion resistance ratio, and
S = wheel slip.

The traction ratio is the ratio of the net traction to the dynamic wheel load. The motion resistance ratio is the motion resistance divided by the dynamic wheel load. From Gee-Clough et al. (1978), the traction ratio can be predicted from an exponential function and expressed as:

$$\tau = \tau_0(1 - e^{-KS}) \tag{5}$$

where:

$$\tau_0 = 0.796—0.92/M \tag{6}$$

$$K = (4.838+0.061M)/\tau_0 \tag{7}$$

Also from Gee-Clough et al. (1978) the motion resistance ratio can be predicted by

$$\rho = 0.049+0.287/M \tag{8}$$

where M is the mobility number (Turnage 1972), which is expressed as:

$$M = \frac{Cbd}{W} \sqrt{\frac{\delta}{h}} \cdot \frac{1}{1 + b/2d} \qquad (9)$$

where:

C = soil cone index,
d = unloaded tire diameter,
b = unloaded tire section width,
W = dynamic wheel load,
δ = tire deflection, and
h = unloaded tire section height.

For a given traction ratio, the wheel slip can be predicted from Eq. 5 which is rearranged as:

$$S = -\frac{1}{K} \ln \left(1 - \frac{\tau}{\tau_0}\right) \qquad (10)$$

To determine the optimum traction ratio, Eq. 10 is substituted into Eq. 4 which becomes:

$$\eta = \frac{\tau}{\tau + \rho} \left[1 + \frac{1}{K} \ln \left(1 - \frac{\tau}{\tau_0}\right)\right] \qquad (11)$$

In the above equation, ρ, K and τ_0 are functions of the mobility number as indicated by Eq. 6, 7, and 8. For a given dynamic wheel load, a given soil strength and a given tire, the mobility number is determined. In this case, the tractive efficiency, η, is a function of traction ratio only. To obtain the maximum tractive efficiency for a given mobility number, Eq. 11 is differentiated with respect to traction ratio. Letting the resulting equation equal zero, the final equation obtained is given below:

$$\frac{\tau(\tau + \rho)}{\rho K(\tau_0 - \tau)} = 1 + \frac{1}{K} \ln \left(1 - \frac{\tau}{\tau_0}\right) \qquad (12)$$

For a given mobility number, the optimum traction ratio, corresponding to the maximum tractive efficiency, can be solved from the above equation. A simple computer program was written to calculate the optimum traction ratio for a given mobility number. Table II lists some of the computer results.

As can be seen from Table II, the optimum traction ratio varies with the mobility number. The average value of the optimum traction ratio is 0.36. The model tractor tests were carried out in three soil strength levels and three ballast combinations. Unless the traction ratios of front and rear wheels are equal, a 4WD tractor is not equivalent to a single drive wheel in terms of tractive characteristics. Thus, the model tractor tests were conducted to evaluate the application of the traction theory for a single drive wheel to a 4WD tractor. Table III lists the specifications of ballasts and soil conditions for these tests. Results are presented in Figs. 7, 8 and 9 for tilled, medium packed and heavy packed soils, respectively. In tilled soil, the optimum traction ratio was about 0.28 for a 3724-N tractor weight, and about 0.33 when the tractor weight was 2852 N. In the medium and heavy packed soils, the tractive efficiency was higher when the tractor weight was small. The maximum tractive efficiency was about equal at tractor weights of 3293 N and 3724 N. Generally, from Figs. 7, 8, and 9, the optimum traction ratio increased with soil strength and it fell within the range 0.3–0.4 which agreed with the analytical results given in Table II. On an average, the optimum traction ratio was 0.36, therefore, the optimum weight/pull ratio was about 2.8. Dwyer and Pearson (1976) suggested that a 4WD tractor should be designed so that it can be ballasted to use the full engine power available, at a reasonable working speed, with a drawbar pull equal to 40% of the dynamic tractor weight. This suggestion is equivalent to an optimum traction ratio of 0.4.

Table II. Optimum traction ratio from Eq. 12

Mobility number	Optimum traction ratio	Maximum tractive efficiency	Slip (%)
5	0.373	0.686	11.8
10	0.365	0.737	10.6
15	0.358	0.755	10.1
20	0.353	0.764	9.8
25	0.348	0.770	9.6
30	0.345	0.774	9.5

Table III. Specifications of ballasts and soil conditions for the model tractor tests

Soil condition	cone index (kPa)	Moisture (% DB)	Tractor static vertical load Front (N)	Rear (N)	Total (N)
Tilled	490	14	1676	1176	2852
(100 mm	491	12	2009	1284	3293
deep)	506	11	2352	1372	3724
Medium	571	17	1676	1176	2852
packed	550	16	2009	1284	3293
	607	15	2352	1372	3724
Heavy	700	16	1676	1176	2852
packed	650	20	2009	1284	3293
	764	19	2352	1372	3724

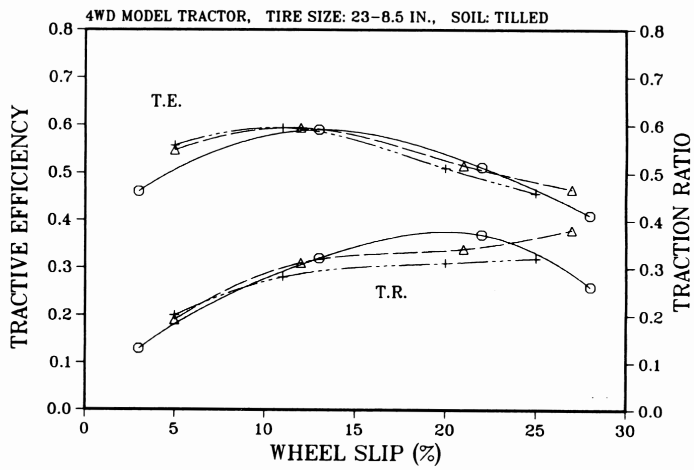

Figure 7. Relationship between tractive efficiency and wheel slip for the model tractor in tilled soil. O, tractor weight 2852 N, static load ratio 1.43; △, tractor weight 3293 N, static load ratio 1.57; +, tractor weight 3724 N, static load ratio 1.72.

CONCLUSIONS

A model tractor was tested in a soil bin to evaluate the traction performance in three drive modes. An analysis was conducted for the optimum traction ratio. Analytical results were compared with the model tractor tests in 4WD mode. The following conclusions are drawn from this study:

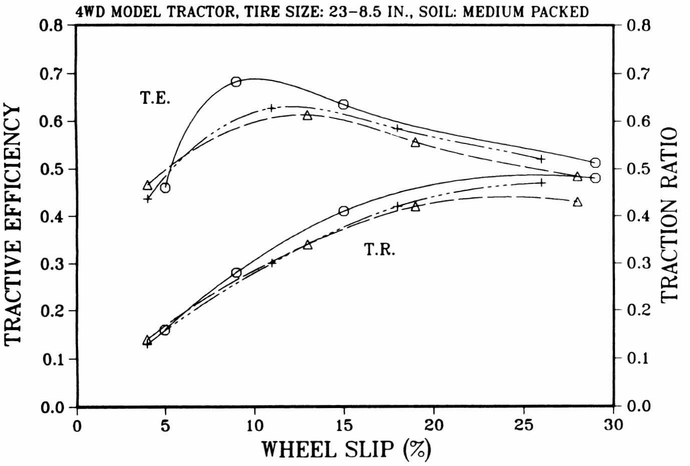

Figure 8. Relationship between tractive efficiency and wheel slip for the model tractor in medium-packed soil. O, tractor weight 2852 N, static load ratio 1.43; Δ, tractor weight 3293 N, static load ratio 1.57; +, tractor weight 3724 N, static load ratio 1.72.

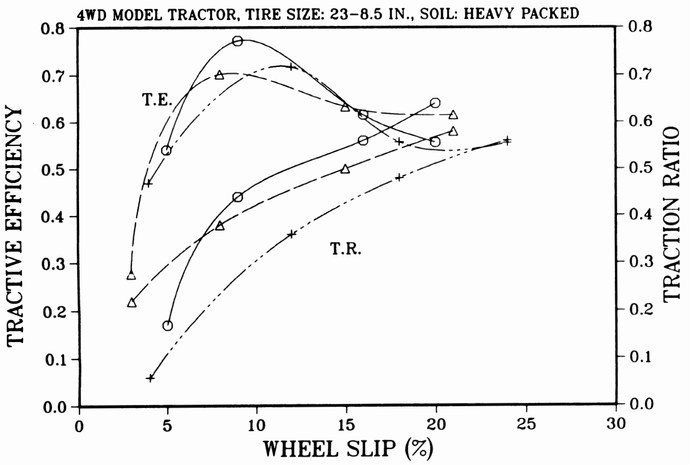

Figure 9. Relationship between tractive efficiency and wheel slip for the model tractor in heavy-packed soil. O, tractor weight 2852 N, static load ratio 1.43; Δ, tractor weight 3293 N, static load ratio 1.57; +, tractor weight 3724 N, static load ratio 1.72.

1. The four-wheel-drive mode produced a drawbar pull about three times that produced with the rear-wheel-drive or the front-wheel-drive mode.
2. The rear-wheel-drive mode was found to be more favorable than the front-wheel-drive mode as far as the motion resistance and drawbar pull were concerned.
3. The motion resistance ratio of the four-wheel-drive mode was greater than that of the two-wheel-drive mode from these test results. This situation was due to the increasing of motion resistance of powered wheels with slip. Further investigation should be conducted to find the difference in motion resistance of powered wheels and towed wheels.
4. The range of traction ratio for maximum tractive efficiency was from 0.3 to 0.4. On an average, a tractor should be ballasted to a weight of 2.8 times the desired horizontal drawbar pull.

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