Four wheel drive tractors : field performance in Montana

by John William Ohrmann

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Agricultural Engineering
Montana State University

Abstract:
During the summer of 1978, tests were conducted on four wheel drive tractors in the state of Montana. Measurements were made to determine how farmers are utilizing high horsepower four wheel drive tractors. These measurements were used to determine how efficiently the farmers were using this power. Comparisons were made between the data and the theoretical prediction equations to determine the accuracy of the prediction equations when applied to field conditions. Data gathered provided information on drawbar power, speed, slip, capacity, and energy utilization under various conditions of tractor operation.

The data showed that many farmers are not utilizing the full power potential of their tractors. The drawbar power was often less than half of the rated engine power. Operating speeds were often lower than desired for good tractor performance and optimum life.

Comparison of the field data to the prediction equations showed poor correlation between the two in most cases. Insufficient data and extreme field variation may be responsible. Prediction equations developed for two wheel drive tractors may not be applicable to four wheel drive tractors. Modification of the prediction equation resulted in better correlation in some cases.

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Signature *John Ohrmann*

Date *May 24, 1979*

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ABSTRACT

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GLOSSARY OF TERMS USED TO DESCRIBE TRACTION CHARACTERISTICS

Ballast--Any weight that can be added to or removed from a vehicle or transport device for the purpose of changing its total weight or weight distribution.

Draft--The force to propel an implement in the direction of travel. Equal and opposite to drawbar pull.

Flotation--Ability of the traction or transport device to resist sinkage into the medium being traversed.

Power, drawbar--The product of vehicle velocity and the drawbar pull in the direction of travel.

Pull, drawbar--Force in the direction of travel produced by the vehicle at the drawbar.

Slip--Relative movement in the direction of travel at the mutual contact surface of the traction device and the surface which supports it.

Traction device--A device for propelling a vehicle using the reaction forces from the supporting surface.

Travel reduction--One minus the ratio of distance traveled per revolution of the traction device to the rolling circumference under the specified zero conditions.

Weight, dynamic--Total force normal to the plane of the undisturbed supporting surface, exerted by the traction device under operating conditions.

Weight, static--Total force normal to the plane of the undisturbed supporting surface, exerted by the traction device while stationary on level ground with zero pull and zero torque.

Weight transfer--The change in normal forces on the traction devices of the vehicle under operating conditions, as compared to those for a static vehicle on level ground.

PREFACE

In recent years, large acreage farms have been turning to four-wheel drive (4WD) tractors to increase capacity while simultaneously decreasing the labor force required to raise crops. Many farms have at least one 4WD tractor, with two, three, or more units on one farm being common.

Energy use and availability for agriculture has been of increasing concern. Possible shortages and increasing costs make efficient utilization of energy in agriculture of growing importance. Techniques of saving energy and reducing labor requirements could save farmers a significant amount on an annual and long term basis.

Four-wheel drive tractors have the potential for increased efficiency and reducing costs. These cost savings can only be achieved if this power is being used efficiently. There is concern that the farmer who is used to medium-sized two-wheel drive tractors might not make full use of a large horsepower 4WD unit. If the tractor is operating well below capacity, the efficiency will be well below the tractor's potential.

There is little information available on how a 4WD tractor performs under actual farm use. The information currently available has been obtained from theoretical model studies, and tests conducted under controlled conditions. Test track conditions provide little information about the performance that can be expected by individual operators under farm conditions.

This research project was designed to determine how the farmers are actually using their tractors, and to generate field data which may be used to test the accuracy of the prediction equations.

These results should be helpful to farmers in improving the performance of these operations. Improved performance equations will be useful in predicting field performance.

These tests will benefit both the farmer and the manufacturer. The farmer will in many cases be able to operate more efficiently. Increased knowledge on how the tractors will be used will help the manufacturer build a tractor which better serves the farmers' needs.

1. LITERATURE REVIEW

TRACTION PREDICTION

Traction is defined as the force in the direction of travel developed by a traction device. Extensive work has been done to develop models which describe the expected performance of traction devices.

Soil strength is an important factor in the prediction of traction. Effective pull will be limited to a value somewhat less than the resisting force in the supporting soil. Shearing strength in the soil then becomes a limiting value in developing drawbar pull.

The weight of the tractor is important in predicting traction. Friction between soil particles contributes to the total soil strength, and the effective soil friction is proportional to the normal force produced by the tractor weight.

Figure 1.1 illustrates the basic forces associated with a traction device (3).* The drawbar pull is the difference between the horizontal force developed by the traction device and the rolling resistance on

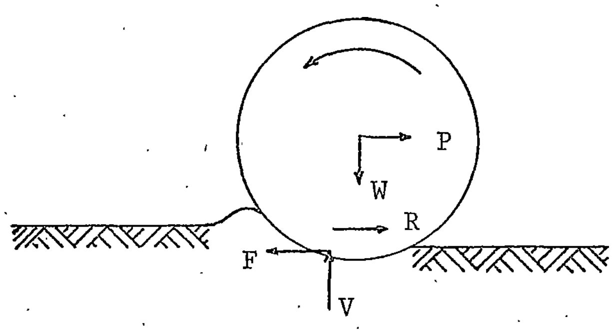

Figure 1.1. Free-body diagram of a driving wheel of a traction device

*Numbers in ( ) refer to literature cited in the bibliography.

the traction device. It can be determined by the equation:

$$P = F - R \qquad [1.1]**$$

where P = drawbar pull, N;

F = total force developed at soil tire interface, N;

R = rolling resistance, N; and

V = vertical soil reaction, N.

If the soil has some cohesion, the theoretical soil thrust on the tire is given (3) by the equation:

$$F = Ac + W \tan \phi = A(c + \rho \tan \phi) \qquad [1.2]$$

where A = area of soil-tire contact, m^2;

c = cohesion of the soil, N/m^2;

W = dynamic load on the traction device, N;

ϕ = internal friction angle of the soil; and

ρ = pressure exerted on the soil by the tire, N/m^2.

If the tire contact surface is assumed to be an ellipse, then:

$$\rho = \frac{W}{0.78\ bx} \qquad [1.3]$$

where b = tire section width, m;

x = length of tire track or footprint, m; and

ρ, W as previously defined.

**Numbers in [ ] refer to equation number.

Rolling resistance is a value which is somewhat more difficult to determine. Barger (3) has derived a formula in which the rolling resistance is defined by the following formula:

$$R = \frac{2}{(n + 1)(K_c + bK\phi)^{1/n}} (W/2x)^{(n+1)/n} \qquad [1.4]$$

where K_c = cohesive modulus of soil deformation, N/m^{n+1};

$K\phi$ = frictional modulus of soil deformation, N/m^{n+2};

n = coefficient of Z, dimensionless;

Z = wheel sinkage, m; and

R, x, b, W as previously defined.

If the sinkage, Z, is large in proportion to the tire deflection, the equation developed by Bekker (5) is more applicable. In this case, the rolling resistance is defined as:

$$R = \frac{(3W/b^{0.5})^{(2n + 2)/(2n + 1)}}{(3 - n)^{[(2n + 2)/(2n + 1)]}(n + 1)(K_c + bK\phi)^{1/(2n + 1)}} \qquad [1.5]$$

Knowing the rolling resistance, the expected pull can be determined by solving Equation [1.1].

The main objection to using Equations [1.2] and [1.5] for the determination of pull is the number of soil variables involved. For each soil, an analysis of c, ϕ, K_c, $K\phi$, and n must be made. Bekker indicates that this analysis may be carried out by using a pressure plate and a recorder to obtain a plot of pressure verses sinkage (4). The information must then be transferred to log-log paper in order to find the variables K_c and $K\phi$. Presumably, c and ϕ are already known (which is reasonable if the type of soil and moisture conditions are known).

Wismer and Luth (17) used dimensional analysis to simplify the prediction equations. The set of dimensionless ratios for the variables is:

$$\frac{TF}{W}, \frac{P}{W}, \frac{Q}{rW} = f\left(\frac{CIbd}{W}, \frac{b}{d}, \frac{r}{d}, S\right) \qquad [1.6]$$

where TF = towing force, N (used in towed wheel condition);

W = load (vertical reaction at soil-tire interface), N;

P = pull, N;

Q = torque on wheel, N-m;

r = rolling radius of wheel, m;

CI = cone index of soil, N/m^2;

b = tire section width, m;

d = overall tire diameter, m; and

S = slip, dimensionless.

Traction equations are then developed using these variables.

The dimensionless ratios given in Equation [1.6] can be applied to the performance of a towed wheel, a self-propelled wheel, or a driving wheel. Since the tractor is intended to create a net pull, the driving wheel equation applies. This equation is:

$$\frac{P}{W} = 0.75\ (1 - e^{(-0.3\ C_n S)}) - (\frac{1.2}{C_n} + 0.04) \qquad [1.7]$$

where P = wheel pull parallel to soil surface, N;

W = dynamic wheel load, normal to soil surface, N;

C_n = dimensionless wheel numeric, $\frac{CIbd}{W}$; and

CI, b, d, S as previously defined.

The dimensions of CI, b, d, and W must be chosen so that the wheel numeric is dimensionless. If the cone index is in newton per square meter, then b and d must be in meters, and W must be in newtons.

The cone index of the soil must be determined for Equation [1.7] developed by Wismer and Luth (17). This measurement is accomplished by driving a cone of standard size into the ground at a prescribed rate, and measuring the force necessary to drive the cone. The value determined is actually a composite measurement, combining factors such as soil cohesion, angle of internal friction, and soil-to-metal friction (17). Since these factors are also important in determining the total soil thrust against the tire, the cone index can be used as a factor for predicting traction.

Bekker's equations contain variables for soil characteristics such as internal friction angle and soil cohesion. The Wismer and Luth equations combine all these factors into one simple soil measurement which provides the value directly. Cone index is easy to measure and use. The Wismer and Luth equations are therefore more easy to use as traction prediction equations than Bekker's analysis.

The wheel numeric, C_n, which introduces the cone index into Equation [1.7], includes a characteristic area of the tire footprint, bd, and the load on the soil, W. The area of contact is important when developing traction on cohesive soils, such as clay. On frictional soils such as sand the load on the soil determines the traction which can be developed. Both factors may be involved on many soils, as shown by Equation [1.2].

Various references (17), (8), (16) recommend different methods for determining the cone index for a particular soil. In most cases, the cone index will vary with depth and with different sites in an area. A value which in some way averages the several measurements obtained is therefore necessary. Generally, measurements taken at 2.5 centimeter increments of depth, and averaged over a 15 centimeter penetration depth is recommended. If the tire sinkage is greater than 7.5 centimeters, then the average of the measurements 7.5 centimeters above and 7.5 centimeters below the depth of sinkage is recommended.

The dynamic weight on the tires is included in both Bekker's analysis and the Wismer and Luth equations. The usual method to determine dynamic weight is to treat the tractor as a free body unit. A moment diagram using static front and rear weights plus drawbar pull is used to determine the weight transfer. The following equation is used:

$$V_F = W_F - \frac{P\,y}{w} \qquad [1.8]$$

where V_F = dynamic load on front axle, N;

W_F = static weight on front axle, N;

P = total drawbar pull, N;

y = drawbar height, m; and

w = wheelbase, m.

The method outlined above would be accurate if the tractor were stationary, and producing only enough torque on the wheels to provide a stationary pull equal to the given drawbar pull. According to Smith and Murillo-Soto (13), however, this method is not entirely correct. Some accounting for the accelerations involved during operation must be made. The complete equation for determining dynamic weight according to Smith, et. al. is as follows:

$$V_F = W_F + \frac{P\,r_o}{w} - \frac{P\,y}{w} - \frac{T_F}{w} - \frac{T_R}{w} - \frac{H_F\,y'}{w} \qquad [1.9]$$

where r_o = effective wheel radius, m;

y' = difference in sinkage between front and rear wheels, m;

H_F = horizontal force developed by front axle, N;

T_F = torque developed by front axle, N-m;

T_R = torque developed by rear axle, N-m; and

V_F, P, w, y, W_F as previously defined.

The axle torques, horizontal force, effective wheel radius, and sinkage all require specialized equipment for their measurement. The necessary instrumentation was not available, and if available, it would have been difficult to adapt this equipment to the variety of tractors tested. Also, the time required to install the equipment on each tractor would have been excessive.

The error involved in using Equation [1.8] to determine the dynamic weight rather than the exact method given by Equation [1.9] is relatively small. As a check, Smith's equation was solved using actual test data, assuming the front axle torque was equal to the rear axle torque and assuming the difference in sinkage between front and rear wheels was 7.5 centimeters. The approximate method was within one percent of the exact method. For these reasons, the approximate method of calculating dynamic axle loads was used rather than the more exact method described by Smith, et. al.

SLIP PREDICTION

Developing traction in a deformable medium such as soil requires that there is some distortion of the soil. The tractive force is a function not only of the vertical load and the dynamic properties of the soil, but also of the displacement between the device and the soil (9). The traction device will displace the soil until the soil has built up enough stress to either equal the necessary tractive force, or fail. If the tractive force is attained, the vehicle will develop pull. If failure occurs, the vehicle will be incapable of forward motion. This displacement is related to the travel reduction and slip. Travel reduction refers to the difference between the distance traveled per revolution of the wheel and the distance which would be traveled if there were no displacement. Slip refers more specifically to the relative motion between wheel and soil at the interface. The two terms are often used interchangeably.

Slip is expressed as either a percentage or as a decimal. The basis for calculation can be velocity, as given by Gill, et. al. (9):

$$S = \frac{v_o - v}{v_o} \qquad [1.10]$$

where S = slip expressed as a decimal;

v_o = velocity of the vehicle without slip, m/s; and

v = actual velocity of the vehicle relative to the earth, m/s.

The reduction in distance traveled per wheel revolution is defined as travel reduction and is often used as a basis for calculating slip:

$$S = \frac{\text{No-load advance per wheel revolution} - \text{Loaded advance per revolution}}{\text{No-load advance per wheel revolution}} \qquad [1.11]$$

If a common distance is used for both the loaded and no-load conditions, Equation [1.11] simplifies to:

$$S = \frac{\text{Number of wheel revolutions, loaded} - \text{Number of wheel revolutions, no-load}}{\text{Number of wheel revolutions, loaded}} \qquad [1.12]$$

The no-load condition considers the traction device as a self-propelled vehicle, with no pull at the drawbar, and negligible rolling resistance. A hard surface, such as concrete, is necessary for the no-load condition if the slip measurement is to be completely accurate (7). If a softer surface, such as soil, is used for all tests, then the measurement is more accurately called travel reduction, and the slip measurement is actually a measurement of the difference between the no-load slip and the loaded slip. Presumably, the no-load slip will be negligible compared to the loaded slip.

Slip can be predicted if the proper variables are known. Equation [1.7] can be rearranged as follows:

$$S = \frac{1}{0.3\, C_n} \ln \frac{0.75}{0.75 - (\frac{P}{W} + \frac{1.2}{C_n} + 0.04)} \qquad [1.13]$$

This equation, and Equations [1.11] and [1.12] yield slip as a decimal value.

PREDICTION OF TILLAGE TOOL DRAFT

An idea of the magnitude of the expected draft on a tillage tool is necessary to properly match the tillage tool to the tractor. In Agricultural Machinery Management Data, ASAE D230.3 (2) equations are presented which can be used to predict the draft on various tillage tools with varying soil conditions. These equations incorporate implement speed and depth of tool penetration in the draft prediction equation. Variations of ten percent about the mean values are indicated as common variations.

Sial and Harrison (12) showed an increase in draft with an increase in speed or in depth. Vertical and lateral reactions on the individual tools also increased in magnitude with greater speed and greater depth.

MATCHING TILLAGE TOOLS TO TRACTORS

Efficient use of the power of a tractor is possible only if the tractor is matched with an implement of the appropriate size. An implement which is too small will not put enough load on the engine for efficient operation, while an implement which is too large may cause excessive wear on the drive train of the tractor. Excessive wear may be caused by high torques on the drive train. In order to pull an implement which is too large for the tractor, the farmer will have to operate in a low gear. In a low gear, power is transferred to the traction wheels at low speeds. Power is proportional to the product of torque and angular speed, therefore slow angular speeds (associated with low ground speeds) require high torque for full power to be transferred to the traction wheels. Bowers (6) suggests matching implements to tractors so that field speeds will be in the 7.25 to 10.0 kilometers per hour range.

Drawbar power is proportional to the product of ground speed and drawbar pull. Therefore, if the recommended ground speed and the usable drawbar power which can be expected from a given tractor are known, then the drawbar pull which the tractor can be expected to develop can be calculated. Implement draft per unit width can be estimated from Agricultural Machinery Management Data, ASAE D230.3 (2) or Bowers (6). The implement with the proper width will produce a draft equal to the drawbar pull which the tractor can be expected to develop. By using a ground speed in the range recommended by Bowers it is possible to calculate the width of an implement which would be well matched to the tractor.

Bowers (6) has investigated the relationship between usable power at the various levels in the drive train. A "rule of thumb" conversion factor of 0.86 was developed for comparing one power level to the next. The consecutive power levels referred to, as well as the relative power at each level, are given below:

Maximum engine power	= max eng power x 0.86^0
Maximum PTO power	= max eng power x 0.86^1
Maximum drawbar power, concrete	= max eng power x 0.86^2
Maximum drawbar power, firm soil	= max eng power x 0.86^3
Usable drawbar power, firm soil	= max eng power x 0.86^4
Usable drawbar power, tilled soil	= max eng power x 0.86^5
Usable drawbar power, soft soil	= max eng power x 0.86^6

The expected usable drawbar power can be determined for any tractor with a known power rating if the soil conditions are known. It should be noted that Bowers de-rates the maximum power by 14 percent in going from a maximum power to a usable power for each soil type, or operating condition. This would give a normal operating load of 86 percent of the maximum available power under each condition.

Larsen (10) makes use of Nebraska Tractor Test Data (11) in the prediction of available drawbar horsepower. The available drawbar power can be determined from the following formula:

$$\text{DBHP in the field} = Z \times \text{DBHP on concrete, Nebraska Tractor Test} \qquad [1.14]$$

where Z = 0.58 for soft soils,

Z = 0.70 for filled soils,

Z = 0.85 for firm soils, and

Z = 1.00 for concrete.

These numbers are quite close to the values shown by Bowers (6). They are, however, related to the maximum power that should be available for each soil condition and should be derated to usable power to be comparable with the information from Bowers.

If the Nebraska Tractor Test Data was not available, Larsen used maximum continuous power with accessories as published in the Implement and Tractor Red Book (8) as an estimate of the available engine power. The estimating formula was then expressed as:

$$\text{DBHP in the field} = Y \times \text{continuous engine HP with accessories} \qquad [1.15]$$

where Y = 0.45 for soft soils,

Y = 0.55 for tilled soils,

Y = 0.66 for firm soils, and

Y = 0.78 for concrete.

The recommendations set forth by Bowers and Larsen may be used in matching implements to tractors, or used as a guide to determine if farmers are operating with properly matched tractor-implement units.

A comparison of the maximum drawbar power from the Nebraska Tractor Tests with Maximum Engine Horsepower from the Implement and Tractor Red Book shows a wide range of variability. Data was compared for engines in 4WD tractors which were tested between 1976 and 1979. The ratio of maximum DBHP from the Nebraska Test to the maximum engine horsepower varied over the range of 0.59 to 0.83. The average value was 0.73.

This would indicate that prediction of drawbar power as a percentage of Nebraska Tractor Test power is quite valid since the Nebraska Test is run under standard conditions. Prediction of drawbar power as a percentage of maximum engine power is questionable due to the variability either in the procedures used by the manufacturers to rate the engines or in the performance of the engines when placed in a tractor.

2. TRACTORS AND IMPLEMENTS TESTED

SELECTION OF UNITS

The tractor-implement units used in these tests were owned by farmer-cooperators throughout Montana. County agents and equipment dealers were contacted, and through them a list of potential cooperators was obtained. These farmers were contacted, and appointments were made with those interested in the study. No effort was made to choose farmers with particular brands of tractors or implements. There was an effort, however, to locate cooperators over a wide area within the state.

TRACTORS

All tractors tested were 4WD units. Figure 2.1 shows a typical 4WD tractor. Most of the tractors were of the articulated frame type. Four of the tractors were a solid frame type, with individual steering for front and rear wheels. Twelve tractors were equipped with dual tires, while four tractors were operated with singles. Two of the wheel steer tractors were equipped with single tires.

Power ratings for the tractors based on maximum engine power ratings ranged from 104 to 448 kilowatts. Static weights of the tractors varied from 8.3 to 24.5 metric tons. Static weight distribution varied from 53 percent of the total weight on the front axle to 65 percent of the total weight on the front axle.

Accessories on the tractors were limited to air conditioning units and dozer blades. All the tractors tested were equipped with air conditioning. Frames for dozer blades were mounted on six of the tractors. The dozer blades were not mounted during field work, but were used for winter snow blowing and light grading work during the summer.

IMPLEMENTS

The tractors involved in this project were often used with a variety of implements for general field work. For the performance test, however, in all cases they were operated with towed, tool bar type field cultivators. Figure 2.2 shows a typical tool bar field cultivator.

All cultivators tested were towed implements. No three point hitch mounted implements were encountered. The actual tillage tools were primarily sweeps mounted on 30.5 centimeter centers. The sweep width ranged from 35.5 to 40.6 centimeters. One cultivator was equipped with twisted shank chisels rather than sweeps. Tillage tools were connected to the implement frame by spring shanks. No rigid shanks were encountered. Overall implement widths ranged from 6.4 to 16.6 meters. Implement weights ranged from 2.4 to 6.4 metric tons.

Accessories on the implements were limited to spring tooth harrows or rod weeders, mounted to the rear of the implement. Five of the sixteen implements tested were equipped with spring tooth harrows. One of the implements was equipped with a rod weeder.

Most of the farmers were operating the implements at depth of 10 to 12.5 centimeters, with one farmer operating at tillage depth of 20 centimeters.