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TRACTION PREDICTION FOR AGRICULTURAL TIRES ON CONCRETE

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SUMMARY:

Equations were developed which predict pull and efficiency for tires on concrete as a function of tire size, tire loading and slip. The equations relate well with Nebraska Tractor Test data and can be used to predict tractor performance on concrete using axle dynomometer data.

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INTRODUCTION

Considerable progress has been made in recent years in developing the ability to predict tractor field performance based upon traction test results. Traction equations have been developed that do an excellent job of predicting vehicle performance in the field. [1-5*] However, since official tests are generally carried out on a concrete surface, [5, 6] there has been a need to provide a means to correlate between official tests and field performance. There is recent interest in official axle performance testing and this can provide the information required for field prediction. However, for continuity of official test results, performance data for concrete is required. It is the purpose of this paper to describe the development and use of equations that can be used to provide the connection between axle dyno tests and performance on concrete.

Official performance testing on a hard surface began in Nebraska in 1919. Tests were carried out on an earthen test course that was required for early tractors with steel wheels and lugs and that continued to be used for later tractors with tracks and tires. Considerable time and preparation was required to maintain the test course and for rubber tired tests, the track had much of the same characteristics as concrete. In 1956 a concrete test track was put into use at Nebraska and official tests (except for a few tests on track layers) have been carried out on concrete since that date. During the 50's and 60's when official tests were developed and put into use in other areas of the world, the concrete test track was exported to many areas and is now in use in at least eight countries. While there are some known differences in performance among the various official test tracks, 5 concrete does provide a relatively constant test condition throghout the world. Although there are some subtle variables that can be encountered, concrete does provide a reasonably reproducible tractive surface. Aside from cleanliness of the track surface, which can be a factor, most of the tractive performance differences that can be expected on concrete are due to the tires and ambient conditions and not from the track itself.

The need for traction equations for predicting performance on concrete has existed within the industry for years, primarily related to predetermining the performance to be expected during official tests. They are also useful for making comparisons between tractors of varying powers, weight, and tractive configuartions. Historically, test stations have conducted drawbar test on concrete as it is more straightforward than axle measurements followed by simulation. However, weather does provide a generally uncontrolled variable and because of the increasing number of tractors to be tested, there is increasing interest throughout the world for a laboratory technique.

*Superscript numbers refer to references listed at end of paper.

VARIABLES AFFECTING TRACTION ON CONCRETE

The principal variables affecting agricultural tire performance on concrete are:

- Tire tread bar height
- Tire manufacturer, rubber durometer hardness and/or age
- Tire construction (bias or radial ply)
- Dynamic weight as related to tire size (% of tire carrying capacity)
- Tire rubber conditioning prior to test
- Ambient temperature and track cleanliness

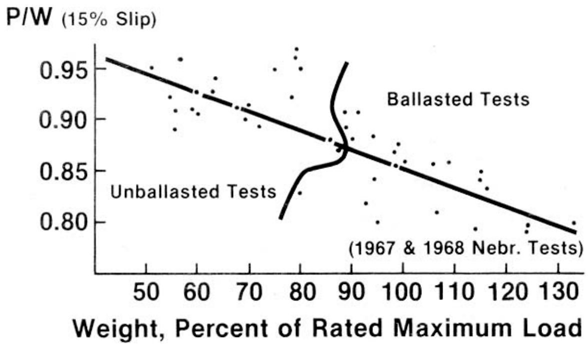
TIRE TREAD BAR HEIGHT - The influence of tire tread bar height as a performance variable was recognized shortly after the concrete test track was put into operation at Nebraska. Consequently, the SAE Agricultural Tractor Test Code (SAE J708c)[7] selected 65% of new tire bar height as a limit based primarily upon the Nebraska Test Lab experience. Traction equations described in this paper assume tire bar height near the 65% limit.

TIRE MANUFACTURER, DUROMETER HARDNESS AND/OR AGE - These factors definately affect performance on concrete. Traction equations presented here assume a somewhat optimal selection. Best selection for use on concrete is not necessarily the best under field conditions.

TIRE CONSTRUCTION (Bias or Radial Ply) - This has a definite affect upon concrete track performance. The radial ply tire produces significantly higher pull at the same slip and about 1 to 2 percent higher maximum efficiency. Traction equations presented in this paper were developed for bias ply tires.

DYNAMIC WEIGHT ON TIRE AS RELATED TO THE SIZE OF THE TIRE (Percent of Tire Carrying Capacity) - Best tire performance is obtained, both in field and on concrete, when the tire is not operated near its limit in regard to torque and/or weight carrying capacity. An analysis of Nebraska test data (Figure 1) bears this out. The maximum pull ratio (at 15% slip) from Nebraska test data is plotted as a function of dynamic weight on the tire (% of Tire and Rim maximum load). This plot was developed from Nebraska test data for 1967 and 1968 and includes data from unballasted tests that were still being conducted at that time. A linear curve fit of the data shows 1.036 as the ultimate value that P/W can reach on concrete. This correlates well with test experience and is considered in the traction equations described by this paper.

Figure 1
Nebraska Test Data Showing How Weight Affects Tire Performance



TIRE OPERATION HISTORY - While 65% is the limiting bar height, the method and speed of obtaining the limiting condition is important. High wear rates require high pulls and axle torques and tend to shape the lugs to an abnormal condition. Best test results are usually obtained after several hours of relatively light torque operation. Equations described in this paper are based upon a somewhat optimal conditioning.

AMBIENT TEMPERATURE AND TRACK CLEANLINESS - Best tire performance is obtained with cool air and a clean track. Equations presented by this paper assume near optimal conditions.

EQUATION DEVELOPMENT

The equations presented in this paper were developed from the results of tire tests conducted by John Deere, some of which were substantiated when tested at Nebraska. Additionally, the Nebraksa test data were used in verifying the equations as data are available over a wide range of the variables involved. Using Nebraska test data for the equation development was limited somewhat by the fact that axle power and thus tractive efficiency data are not directly available from the Nebraska tests.

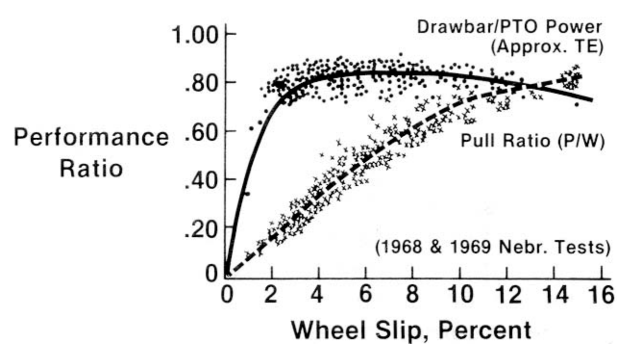
The wheel and tire is basically a method of converting axle torque and rpm into vehicle pull and speed. To completely describe traction phenomenon, four variables are required:

- Axle torque
- Axle rpm
- Drawbar pull (assuming use of a complete vehicle)
- Vehicle travel speed

Data for the last three are available from Nebraska test data (for concrete). However, axle torque data are not available and it is not possible to completely develop a traction equation from official tractor test data alone. Data from tests by John Deere over a period of years were used to supplement the Nebraska data to develop the equations.

The general shape of the traction equation for concrete can be seen from Nebraska test data. Figure 2 is a plot of pull ratio as well as the ratio of drawbar power to PTO power as a function of slip. Maximum PTO power can be assumed a constant for a tractor during test at Nebraska, as ambient and fuel conditions are controlled during drawbar tests to be as close as possible to those during the PTO test. Some variation in conditions can be expected and some change in the effective PTO power level will be experienced. In addition to this, there are inherent differences in the PTO to axle power ratio to be expected from various tractors with differing transmissions and some difference in tire performance can be expected. In spite of these possible variables, the similarity of the DB/PTO power ratio curve to that of tractive efficiency is obvious.

Figure 2
Nebraska Test Data Showing Similarity To Tire Performance Curves



As discussed previsouly, a number of variables influence tire performance on concrete. Near optimal conditions were assumed for most. Experience has shown however, that traction performance is influenced mainly by wheel slip and tire loading. As indicated by Figure 1:

$$\frac{P}{W} \quad @15\% \quad slip = f(\frac{W}{W_{max}}) \qquad (1)$$

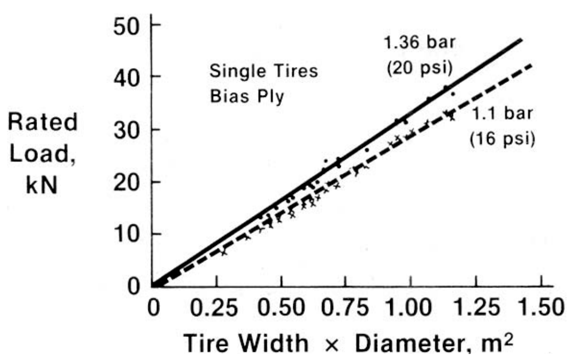
where: P = Drawbar pull
W = Dynamic Load on the Tire
W_{max} = Maximum Rated Tire Load

Tire load information indicates that rated tire load (W_{max}) is lineraly related to tire width x diameter (Figure 3). For a particular inflation pressure:

$$W_{max} = C_1 \, b \cdot d \qquad (2)$$

where: C_1 = constant depending on inflation pressure
= tire section width
= tire section diameter

Figure 3
Rated Load Vs. Tire Width x Diameter



Thus for varying slip, the following fundamental equation can be formed:

$$\frac{P}{W} = f\left(\frac{W}{C1\,bd}, slip\right) \qquad (3)$$

An exponential equation form was suggested by Wismer and Luth[1] for traction in off-road mobility. This function has been used by many researchers with slip replacing the commonly used displacement ratio.

PULL RATIO - A regression of data collected by John Deere and some Nebraska data resulted in the following prediction equatiop for pull ratio:

$$\frac{P}{W} = 1.02\left(1 - e^{-k\left(\frac{bd}{W}\right)S}\right) \qquad (4)$$

where: k = constant = 400 kN/m² (58.4 psi)
S = Wheel Slip, decimal
P,W,b,d as before

Pull is primarily affected by wheel slip as shown in Figure 4. The rate of pull increase, and maximum pull (defined at 15% slip per Nebraska test) is strongly influenced by the tire loading factor ($\frac{bd}{W}$). The maximum value from the equation, 1.02 agrees closely to that suggested by Figure 1.

Units must be consistent to result in dimensionless terms. The constant k of 400 kN/m² is a term relating to rubber hardness. This equation form is similar to that reported by Wismer and Luth[1] for traction in soils where k is replaced by soil cone index.

TORQUE RATIO - Axle torque (Q) is the only variable not measured at Nebraska. However, tests by John Deere indicate that torque requirements can be estimated by assuming motion resistance (M) to be equal to 2.0 percent of dynamic tire load (W).

Since:

$$\frac{Q}{rW} = \frac{P}{W} + \frac{M}{W} \qquad (5)$$

Thus:

$$\frac{Q}{rW} = 1.02\left(1 - e^{-k\left(\frac{bd}{W}\right)S}\right) + 0.02 \qquad (6)$$

where: Q = axle torque
r = rolling radius on a hard surface (effective movement arm)
W, b, d, k, S as before

TRACTIVE EFFICIENCY - Tractive efficiency is defined as"

$$TE = \frac{\text{Drawbar Power}}{\text{Axle Power}} = \frac{\text{Pull} \cdot \text{Velocity}}{\text{Torque} \cdot \text{Axle Speed}} \qquad (7)$$

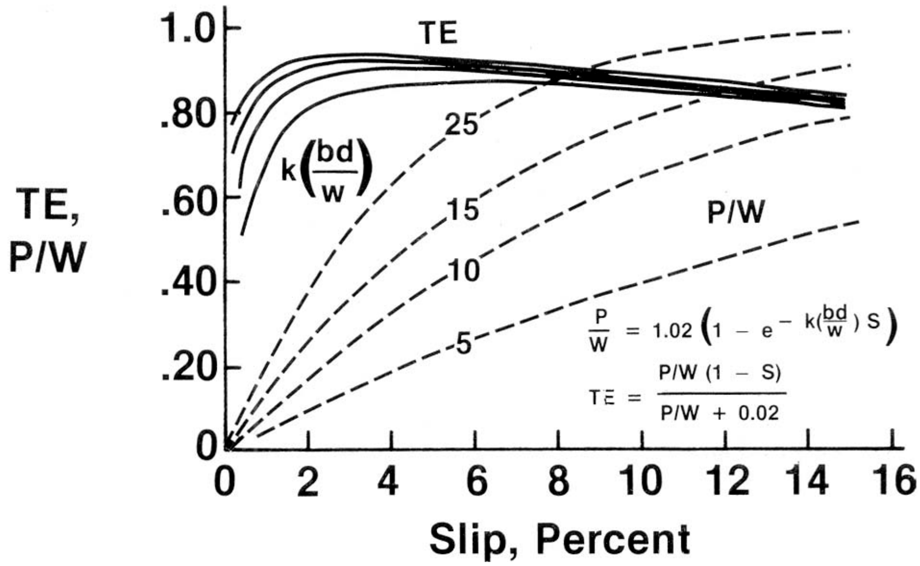
This can be reduced to:

$$TE = \left(\frac{P/W}{Q/rW}\right)(1-S) \qquad (8)$$

Tractive efficiency is plotted in Figure 4 according to equations 6 and 8. TE peaks at low values of wheel slip and is less sensitive to bd/W than the pull ratio. A maximum TE of about 94 percent is all that can be obtained at realistic tire loadings.

Tractive efficiency is plotted against pull ratio in Figure 5. As tire loading decreases (higher values of bd/W), peak efficiencies are obtained at higher pull ratios.

Figure 4
Traction Performance of Tires On Concrete



The equations presented are for dynamic tire loads; that is, the effect of weight transfer is included. In Figure 6 the expected drawbar pull per unit of static weight (RWS) is related to TE, slip and bd/RWS. A weight transfer coefficient of 0.20 (drawbar height/wheelbase) is assumed.

USE OF EQUATIONS FOR SIMULATION

The described traction equations can be used to predict and understand tractor performance on concrete. Variables most pertinent to tractor performance can be studied. Also, recent interest by European official test stations of testing axle power instead of drawbar power emphasizes the necessity of this correlation.

A computer technique for predicting vehicle performance based on the traction equations is illustrated in Figure 7. The method is a double iterative procedure which balances weight transfer, pull, slip and available axle torque. Motion resistance of the front tires is assumed to be 2.0 percent of the dynamic front weight. Performance can be predicted knowing the inputs specified in the diagram.

Figure 5
Pull Ratio Vs. TE on Concrete

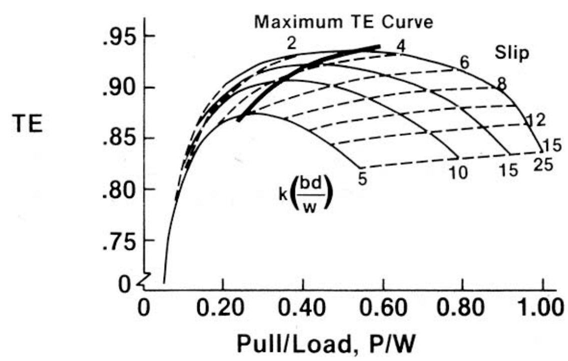


Figure 6
TE Vs. Static Weight Pull Ratio

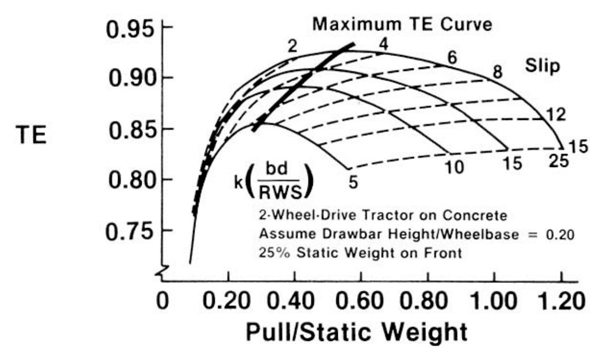
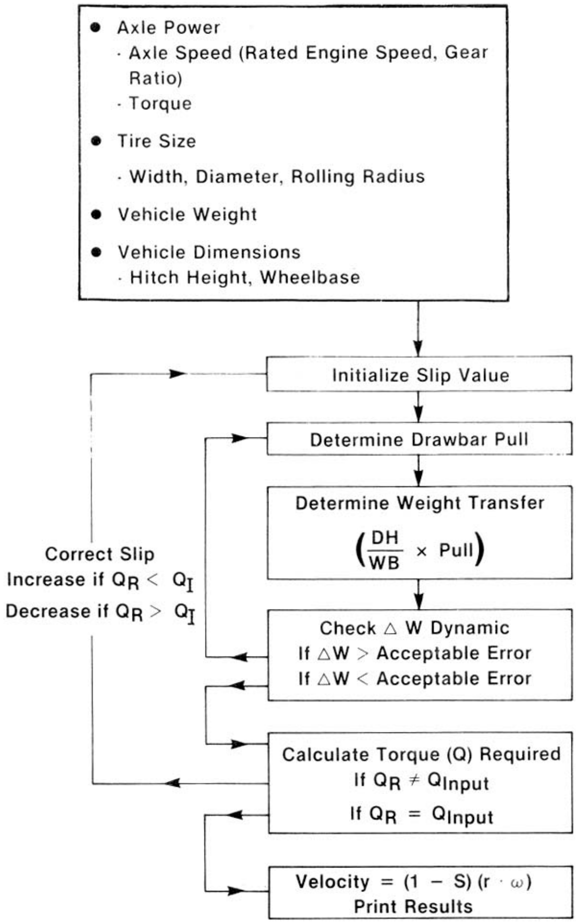


Figure 7
Vehicle Simulation Flow Chart



SUMMARY

1. Equations were developed which predict tire pull and efficiency for tires on concrete as a function of tire width, diameter, rolling radius, tire load and slip. Equations were developed from tests on concrete and Nebraska test data.
2. The relationships can be used to simulate vehicle performance on concrete and to study variable effects on performance.
3. The developed equations relate well with Nebraska test data and past experience.

RECOMMENDATIONS FOR FUTURE WORK

1. Investigate the assumption that motion resistance is equal to 0.02 times tire toad and determine whether it is affected significantly by tire loading, lug shape, tread wear and wheel slip.
2. Determine the effect of weight transfer and axle torque on rolling radius, or the effective moment arm.
3. Further study the accuracy of predicting drawbar performance from axle power measurements. Improved simulation methods incorporating the results from the above recommendations should be developed.

REFERENCES

1. Wismer, R. D. and Luth, H. J., "Off-Road Traction Prediction of Wheeled Vehicles" ASAE Paper No. 72-619, December 1972.
2. Zoz, F. M., "Predicting Tractor Field Performance", ASAE Paper No. 70-118, July 1970.
3. Brixius, W. W. and Zoz, F. M., "Tires and Tracks in Agriculture", SAE Paper No. 760653, September 1976.
4. Domier, K.W. and Willians, A. E., "Tractive Efficiency--Maximum or Optimum?", ASAE Paper No. 77-1053, January 1978.
5. Manby, T. C. D. and Matthews, J., "Development and Operation of OECD Tractor Test Code", SAE Paper No. 730762, September 1973.
6. Splinter, W. E., Steinbreugge, G. W.; Lane, D. E., Larsen, L. F. "Nebraska Tractor Test--Programs and Philosophy", SAE Paper No. 730763, September 1973.
7. SAE Standard, Agricultural Tractor Test Code--SAE J708C., SAE Handbook.
8. Brixius, W. W. and Wismer, R. D., "The Role of Slip in Traction", ASAE Paper No. 78-1538, December 1978.