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Modelling Tire Tractive Performance at Lower Inflation Pressures

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ABSTRACT. *When it comes to tractors used in field work, large amounts of energy are lost at the tire/soil interface. The Brixius equations are a set of equations designed to predict tractive performance. These equations were developed based on data acquired in the 1970's and 1980's, and may not accurately represent today's tire and tractor technologies nor accurately scale across a range of inflation pressures. Especially, they may underestimate the benefit of very low pressure conceivable during field work when the tractor is equipped with Central Tire Inflation Systems (CTIS). A two-wheel drive (2WD) tire test tractor fitted with instrumentation was used to pull a load tractor equipped with a ground engaging implement to analyze the ability of the Brixius equations to predict the net tractive performance of radial tires across changes in inflation pressure, soil condition, and ballasting. The drawbar pull produced by the tractor was measured by a load cell, while the torque transmitted through the axle of the tractor was determined using strain gauges. After analyzing the data collected, it was determined that the Brixius equations did not fully account for changes in tire pressure when predicting net tractive force. Similarly, changes in soil conditions were also not completely captured by the Brixius equation.*

Keywords. *tractive performance, Brixius traction equations, tractors, CTIS*

Introduction

Continuous improvement in agriculture, like any industry, originates from a process of gathering of information on current performance, analyzing that information to determine any patterns or correlations, and finally, work towards a way to improve by predicting future performance based on some set of conditions. Information is the key to improvements in any industry. Knowing the current and past performance of field operations gives farmers a baseline with which to work. This information makes it possible for researchers to work towards predicting field performance, such as a tractor's operational performance. A tractor's ability to convert the axle power to drawbar power is essential for row crop production. Methods have been developed to predict this performance based on data collected in the 1970s, but the accuracy of these methods is uncertain when applying them to current tractor and tire technologies and operating conditions. Better understanding accuracy of such predictions could enable optimization of drawbar performance and tractive efficiency.

Tractive efficiency is defined as "the efficiency of the tractive device in converting the axle input power into output power" and can be calculated by dividing the drawbar power by the axle power (Goering, 2003). The ability to determine the tractive efficiency of a tractor gives us a baseline of how well power is being converted from the axle to the drawbar. As much as 20-55% of energy delivered to the axle is lost in the soil-tire interaction of the driving wheels of a tractor (Elwaleed, 2006). Soil compaction can result from a portion of this energy loss and leads to impaired soil conditions that have a negative impact on crop production (Elwaleed, 2006). Tractive efficiency is affected by the amount of slip, or travel reduction, in the interaction between the tractive device and the soil or other deformable media. To determine the amount of slip being produced, the theoretical and actual velocity of the vehicle must be measured (Goering, 2003). The actual velocity of the vehicle is typically measured by a ground speed radar sensor or a GPS receiver. The theoretical velocity of the vehicle is calculated by multiplying the angular velocity of the wheel by the loaded rolling radius of the wheel. Rolling radius is defined as “The distance advanced per revolution of the wheel divided by 2π under the specific zero condition.” (ANSI/ASAE, 2003). The zero condition most used for this calculation is the operation of the vehicle being self-propelled on a hard surface, with zero drawbar load and low travel reduction (Goering, 2003).

In addition to slip, tractive efficiency is affected by the motion resistance to moving the tire through the soil. This motion resistance is due to both energies required to deform the tire and the soil. Reduced soil deformation due to reduced pressure in the contact area due to reduce tire pressure has potential to increase tractive efficiency.

Having the ability to predict the tractive efficiency of a tractor during operation is a useful performance metric of the tractor’s ability to convert power associated with the wheels rotating to that transmitted through the drawbar and delivered to the implement being towed by the tractor. As discussed before, a large amount of energy is lost through soil-tire interaction. The ability to predict the amount of tractive force a tractive device will develop under defined conditions is extremely valuable information. Wismer & Luth developed a method for determining the traction performance and rolling resistance of a tire in soil conditions that were not highly compacted (Wismer, 1974). These equations were generalized for most soil conditions and tire sizes. The Wismer & Luth equations were replaced with a "more generalized expression for tractive characteristics of bias-ply pneumatic tires”, which are known as the Brixius equations (Tiwari, 2010). After gathering data from over 2500 tests which included 121 combinations of tire and soil type, the relationships in the data were investigated using curve fitting procedures (Brixius, 1987).

The objective of this research is to better understand the accuracy of the Brixius traction prediction equations when applied to today’s tractor and tire designs. This includes determining if net tractive effort predictions account for changing tire pressures when using the standard coefficients and assessing the error between the prediction equations and field measurements.

Background

The Brixius traction model used a dimensionless number known as the mobility number, B_n, that captures the effects of soil strength and tire geometry in one factor. It was obtained using a curve fitting methodology. Mathematically, the mobility number was defined by Brixius as:

$$B_n = \frac{CIbd}{W}\frac{1+5\frac{\delta}{h}}{1+3\frac{b}{d}} \tag{1}$$

where:

CI = soil Cone Index (Pa)
b = tire section width
d = overall unloaded tire diameter
h = tire section height
δ = the tire deflection under load
W = vertical load acting on the wheel

Increases in the mobility number corresponded to increases in tractive performance (Brixius, 1987). Capturing this relationship in the mobility number enabled quick predictions of tire performance under given soil conditions. the mobility number was required to determine the motion resistance and amount of pull being produced.

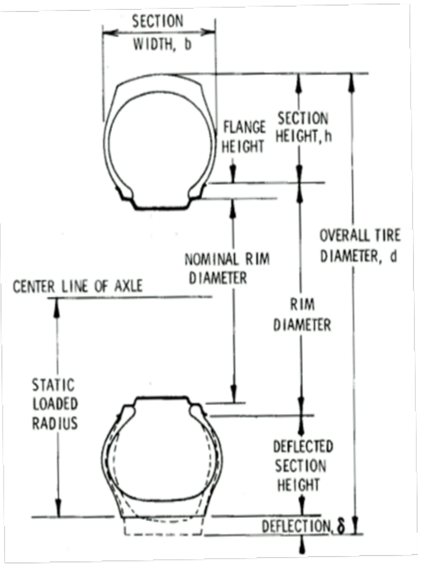

Figure 1. Tire parameters (Brixius, 1987).

The equation for predicting the gross traction ratio, μ_g, the ratio of gross tractive force produced by a wheel to the weight supported by that wheel, was:

$$\mu_g = 0.88(1 - e^{-0.1B_n})(1 - e^{-7.5s}) + 0.04 \tag{2}$$

where:

s = slip or travel reduction ratio which is defined by:

$$s = \frac{V_t - V_a}{V_t} \tag{3}$$

where:

V_t = theoretical velocity vehicle, and

V_a = the actual velocity of the vehicle (Goering, 2003).

Brixius defined the motion resistance ratio, ρ, as a ratio of the towed force to the total weight of the tractor on a per tire basis. This motion resistance ratio is determined by the following equation:

$$\rho = \frac{1}{B_n} + \frac{0.5s}{\sqrt{B_n}} + 0.04 \tag{4}$$

The net traction ratio, μ, the ratio of net tractive force produced by a wheel to the weight supported by that wheel is defined as:

$$\mu = \mu_g - \rho \tag{5}$$

These equations have been used and evaluated for the past 32 years. Whenever possible, it is desirable to decrease traction prediction error. The constants associated with the Brixius equations were determined across a range of test conditions and bias-ply tires that were in use in the 1970s and 1980s. For radial tire usage in lieu of bias-ply ones, a "first estimate" of the appropriate adjustments to apply to the equation constants (Brixius, 1987) led to suggesting reducing the intercept 0.04 to 0.030 - 0.035 in both gross traction and motion resistance ratio equations. The latter's $\frac{1}{B_n}$ is furthermore to be changed to $\frac{0.9}{B_n}$ and the former's $e^{-7.5s}$ to be somewhere between $e^{-8.5s}$ and $e^{-10.5s}$. The following equations are used in this study to predict the gross traction and the motion resistance ratios of the radial tires at the rear axle:

$$\mu_g = 0.88(1 - e^{-0.1B_n})(1 - e^{-9.5s}) + 0.0325 \tag{6}$$

$$\rho = \frac{0.9}{B_n} + \frac{0.5s}{\sqrt{B_n}} + 0.0325 \tag{7}$$

If the application in which these equations are being applied is different than for which they were originally developed, then extrapolation may be occurring, and likely traction will not be predicted accurately. It is also important to observe that tire inflation pressure does not appear directly in the Brixius equation but does enter indirectly through the tire deflection. As the inflation pressure decreases then the tire deflection will increase so that change will affect the mobility number – increasing it and subsequentially increasing gross traction ratio and decreasing the motion resistance ratio. However, a question exists if the magnitude of the change in tractive performance is captured in the Brixius equations.

Materials and Methods

To determine the effects of tire pressure, soil conditions and ballasting of a more recent tractor and tires on the Brixius equations, field tests were conducted. The tractor used for the tests was a 70 kW two-wheel drive (2WD) tractor (John Deere 6420). The tractor rear axle was equipped with Michelin Machxbib tires with standard tire size of 600/70-R30, in which the first number on the left indicates tire width in millimeters, the middle number indicates the aspect ratio as a percentage of the section height to width, the letter R indicates a radial tire construction, and the right-most number indicates the rim diameter in inches.

Four different measurements were recorded during these tests: drawbar pull, axle torque, actual vehicle speed, and axle speed. The rear axle speed of the 2WD tractor was measured with a Hall Effect sensor (LCZ-260, Honeywell International Inc., Golden Valley, Minn.) and gear, which was built into the slip rings. The GPS receiver associated with the tractor determined the actual ground speed of the vehicle and output as NMEA (National Marine Electronics Association) messages. Torque transmitted through the axle of the tractor was determined using strain gauges (187UV, Micro-Measurements, Raleigh, North Carolina). Since the tractor's axle ends were not exposed, 2 adaptors (Figure 2) were needed to have a surface to attach these strain gauges. This adaptor was a set of wheel spacers which were machined down from their original material stock diameter to a smaller diameter to gain a more accurate torque measurement. These strain gauges were placed on these adapters at 180 degrees relative to each other and connected in a full Wheatstone bridge configuration. To cancel out any bending force and acquire a torque reading, the tension side of one strain gauge was connected to the compression side of the second. The same connection was made for the other set of tension and compression sides. These two sets make up the positive and negative excitation lines. The last two connections were the positive and negative sense lines. The amount of force transmitted through the drawbar by the 2WD tractor was measured using a load cell (model SWP-50K, Transducer

Techniques, Temecula, Calif.) with a tension base (TB2-SWP50K, Transducer Techniques, Temecula, Calif.). A load cell transmitter (SST-LV, Transducer Techniques, Temecula, Calif.) was used to calibrate and condition its signal, as well as the axle torque sensors.

Figure 2. Wheel spacer torque sensor consisted of the spacer after Lathing process (left), strain gauge and protective cover installation (center), and torque sensor mounted to the rear wheel of the tractor (right).

A second tractor was used to apply a load to the test tractor's drawbar (Figures 3 and 4) following the method by Zoz and Grisso (Zoz, 2003). The second tractor, known as the load tractor, was a 447 kW four-wheel drive (4WD) tractor (Challenger MT975E). By using a second tractor, the loading process was more versatile since a tractor is self-propelled unlike traditional loading methods and eliminates the restriction on the minimum amount of pull possible to apply to the drawbar of the test tractor. An implement was attached to the load tractor to apply the initial load onto the test tractor. Both the test and load tractor began at equal speeds to represent zero pull or the self-propelled wheel state. As the tractors traveled through the field, the load on the test tractor was increased by engine braking with the load tractor. The optimum set speed for the test tractor was one that enabled it to produce its maximum torque. The test tractor was operated from the self-propelled state to the driving wheel state, at which the maximum amount of pull was developed (Zoz, 2003).

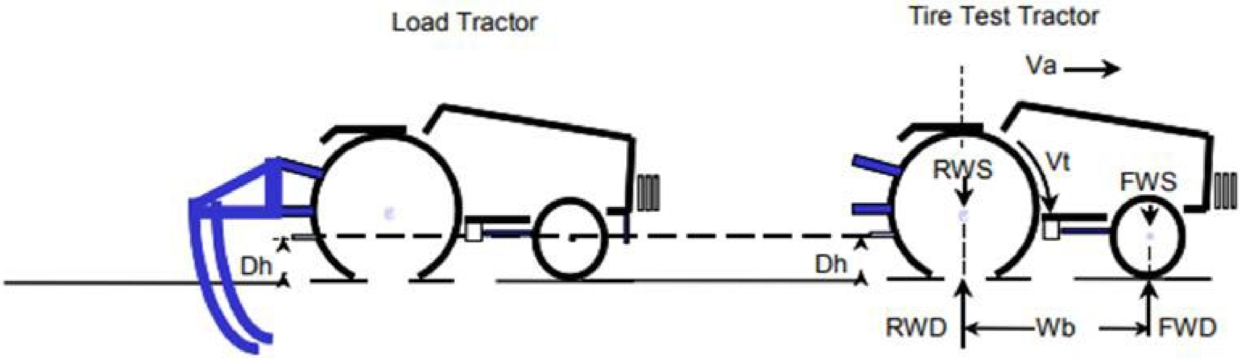

Figure 3. Loading methodology developed by Zoz & Grisso (Zoz, 2003).

The tests were conducted over two different soil conditions: tilled and untilled. The untilled condition was a field in a post-harvested state, while the tilled condition was a freshly tilled portion of the field by a 22-foot, 8 shank disk-ripper attached to the load tractor. To maintain a consistently true course, automatic guidance was used to keep both tractors running in a straight trajectory. The cone index readings were split into two averages: untilled and tilled. These samples were taken beside the soil moisture samples. These cone index values were determined by taking three measurements in the first six inches of the soil for each individual test. These were averaged for a cone index reading for each test. After each test reading was recorded, an average cone index for the tilled and untilled section was calculated. These values included 970 kPa (140 psi) for the untilled condition, while 490 kPa (71 psi) was found for the tilled conditions.

The test tractor had two ballasting conditions. Adding more suitcase nose weights led to a lighter weight on the driven rear axle. The static weights were measured using a set of scales (640XL, Avery Weight-Tronix, Fairmont, Minn.) and are reported in Table 1.

Figure 4. 2WD test tractor attached to 4WD load tractor.

Table 1. Test tractor ballasting configurations.

Front axle weight (lbs.)	Rear axle weight (lbs.)	Condition
4,085	6,176	higher rear axle weight
4,502	6,017	lower rear axle weight

Two pressures were used to establish a significant variation in pressure to see what sort of effect there was on the tractor performance as a function of pressure. The high pressure was admittedly higher than the manufacturer's recommended pressure but is typical to practices by farmers in North American applications. The low pressure was based on the scenario of a tractor equipped with a Central Tire Inflation System (CTIS) and for the field speed of 10 km/h (6 mph). If the tractor was equipped with a CTIS, the tire pressure could be changed within minutes from that used for operating in the field to one optimal for driving on the road. In the higher rear axle weight condition, the 600/70R30 tires set at a pressure of 15 and 9 PSI for the high- and low-pressure setting, while the lower rear axle weight condition had 13 and 7 PSI for the high- and low-pressure setting, respectively (Michelin, 2017).

When designing this experiment, it was known that the Brixius equations were affected by weight transfer, soil condition, and tire size. Because of this, it was decided to test the accuracy of these equations based on the manipulation of each of these variables. The Brixius equations account for the deflection of the tire, which is directly related to tire pressure and load. With this relationship known, it was decided to determine the Brixius equation's ability to predict tractive efficiency based on different pressures. The tests were performed in a field in Boone County, Iowa, in the Garden township, in a 1,300 by 600-foot experimental area (Figure 5), with three primary soil types: Nicollet Loam, Canisteo clay loam, and Harps clay loam.

Figure 5. Test area, 600 ft (183 m) by 1,300 ft (396 m), in Boone County, Iowa.

Because of the test area's size, the width of each pass was determined by the width of the 4WD tractor. Each tractor traveled along the 600-foot width of the field. It was determined that the 2WD tractor travels about 15 feet for every revolution of its driven tires. Under this condition, in a 600-foot pass, the tractor would complete 40 tire revolutions (or more under high slip) to move along the entire pass. Four revolutions per load level applied to the tractor, and then decreasing, would allow there to be five load levels. To consistently change the load level after each of the four revolutions, weigh points were placed on a map (SMS software, Ag Leader Technologies, Ames, Iowa), which was seen on the navigation display in the cab of both tractors.

The tests conducted included three experimental factors: two tire pressures: high pressure and low pressure; two tractor weights: higher and lower rear axle weights; and two soil conditions: tilled and untilled (post-harvest). Three replications of each factor were performed. Each set of tests were arranged by tractor weight. This resulted in three blocks of tests, categorized by the tractor operating in the tilled or untilled soil conditions (Table 2). Within each block, four tests were conducted based on rear axle weight, and tire pressure. Once the untilled soil condition tests were conducted, the same areas were tilled with the disk ripper to develop a tilled soil condition.

Table 2. The Experimental design consisted of three test blocks per soil condition

Block 1				Block 2				Block 3			
higher rear axle weight		lower rear axle weight		higher rear axle weight		lower rear axle weight		higher rear axle weight		lower rear axle weight	
high pressure	low pressure	high pressure	low pressure	high pressure	low pressure	high pressure	low pressure	high pressure	low pressure	high pressure	low pressure

With the weight transfer known, the traction prediction equations were used. As stated before, the Brixius equations calculate the tractive forces on a per tire basis. The weight transfer calculations determined the weight of a tractor on a per axle basis based on measurement of drawbar pull. For a single set of tires, the axle weight needs to be divided by two. The final element that must be determined is the amount of slip, or travel reduction, being developed by the test tractor using the theoretical and actual velocities. With the calculated slip value, the standard motion resistance and gross tractive force were calculated for the rear tires under a specific ballasting and tire pressure. Since the front tires were not instrumented, the diameter of the tire while loaded was measured to determine the static deflection, and a slip value of zero was assumed since they were not driving. These deflections and slip values were used for each test for the front tires. With the deflection known, it was possible to calculate the mobility number of the front tires. The mobility number allowed for the motion resistance to be calculated for the front tires.

Measurements from each sensor were sampled at 400 Hz. With such a high sampling rate, many data points were acquired. Since the distance sensors were recording measurements on a fixed position on the rim, there were only a few measurements of tire deflection in each revolution of the tire. Because of this limitation, the mean of all measurements per revolution of the driving tire was used in the subsequent analysis, except for the deflection. This approach allowed for an equal comparison between the predicted and actual net traction force.

Results and Discussion

Drawbar Force

When plotting the actual drawbar force produced against slip, a noticeable difference between the high- and low-pressure conditions could be seen (Figure 6). The lines seen in each plot are smoothing splines generated by the statistical program determined by the lambda value of 2. Regardless of tire pressure or axle weight, less drawbar force was produced in the tilled condition compared to the untilled. While the untilled condition showed a maximum drawbar force of about 5,300 lbs., the tractor was limited to producing approximately 4,700 lbs. during the tilled condition. The highest drawbar pull produced was seen while using a low tire pressure, under a higher rear axle weight in untilled soil.

At low slip values, 5 to 15 percent, a higher drawbar force was measured while using the low tire pressure with the heavier axle weight and operating on an untilled soil. While the drawbar force was in the range of 1,500 lbs. to 3,000 lbs. while using the high pressure, the low-pressure condition yielded a drawbar force from 2,300 lbs. to 3,600 lbs. (Figure 6, a). As slip increased, the low tire pressure consistently produced higher drawbar pull. A maximum drawbar force of approximately 5,300 lbs. was observed for the low-pressure condition, while the high pressure was found to produce a maximum force of 4,900 lbs.

When operating with the lighter rear axle weight on an untilled soil (Figure 6, b), a low-pressure tire condition continued to result in higher drawbar forces. At 5 percent slip, the tractor subjected to high tire pressure produced less than 2,000 lbs. of force and less than 2,500 lbs. at 10 percent slip, while the use of the low-pressure condition resulted in drawbar forces from 2,400 lbs. to 2,900 lbs. The low-pressure condition consistently produced approximately 700 lbs. more force than the high pressure above 30 percent slip.

With the tractor at a heavier rear axle weight operating on a tilled soil condition, using high tire pressure tended to produce more drawbar pull than the low pressure (Figure 6, c), but mostly there was no observable difference between 10 and 25 percent slip. At 5 to 10 percent slip, the drawbar force produced under low tire pressure conditions ranged from 1,000 to 1,900 lbs. while the drawbar force observed under the high tire pressure condition was between 1,300 and 2,000 lbs. Beyond 25 percent slip, the drawbar pull continued to be higher when the tractor used the high tire pressure with the maximum drawbar force being measured at 4,800 lbs. while under the low-pressure condition it was measured at 4,200 lbs.

With the lighter rear axle weight and in a tilled soil condition, the use of the low tire pressure condition resulted in more drawbar force across the slip range than that observed when the tractor was subjected to a high tire pressure condition (Figure 6, d). The maximum drawbar force observed under the low-pressure condition was approximately 4,700 lbs., while the maximum drawbar force associated with the high-pressure condition was about 4,200 lbs.

Tractive Efficiency

The tractor's tractive efficiency showed similar results (Figure 7) as those observed for the drawbar force. The lines seen in each plot are smoothing splines generated by the statistical program determined by the lambda value of 0.4. Under each condition, regardless of rear axle weight or soil condition, a higher tractive efficiency was seen when a low tire pressure was used. Seventy-two percent tractive efficiency was observed to be the maximum value under untilled conditions, while fifty-eight to sixty-three percent was observed for the tilled soil. At lower slip values, around ten to fifteen percent, the use of low tire pressure was seen to have increased tractive efficiency by an average of ten percent. Although a similar amount of drawbar pull was produced regardless of tire pressure with the heavier rear axle state in a tilled soil condition, a higher tractive efficiency was seen under these same conditions while using a low tire pressure.

When analyzing the tractive efficiency seen with the heavier axle weight in untilled condition (Figure 7, a), the use of the low pressures resulted in a tractive efficiency of 68 % at 10 % slip and at 15 % slip. At 10 % slip, when the tractor was subjected to the high-tire inflation pressures, the tractive efficiency was 62 % while a 64% tractive efficiency was observed at 15 percent slip. As slip increased above 20 percent, regardless of the tire pressure used on the tractor, the tractive efficiencies declined at the same rate, and the differences between the two pressure conditions were negligible.

With the lighter axle weight and an untilled soil condition, the tractive efficiency produced by the tractor with a low tire pressure at low slip values (below 10 percent) was seen to be approximately 70 percent (Figure 7, b). When it comes to the use of the high pressure, slip values below 10 percent yielded an efficiency below 65 percent. From 10 percent slip and on, the tractor produced equal efficiencies under both pressure conditions.

When observing the effects of the tractor subjected to heavy rear axle and tilled soil conditions, higher efficiency was seen from the use of low tire pressure above 8 percent slip (Figure 7, c). Maximum efficiency by the tractor using the low-pressure condition was seen at 16 percent slip, 63 percent efficiency.

At 10 percent slip, when the tractor operated with the lighter rear axle in a tilled soil, 56 % tractive efficiency was observed while using a low tire pressure, while the use of the high tire pressure condition resulted in approximately 50% tractive efficiency (Figure 7, d). On the other hand, when the tractor was subjected to a low tire pressure condition, a tractive efficiency of 57 percent was produced under a 13 to 15 percent slip.

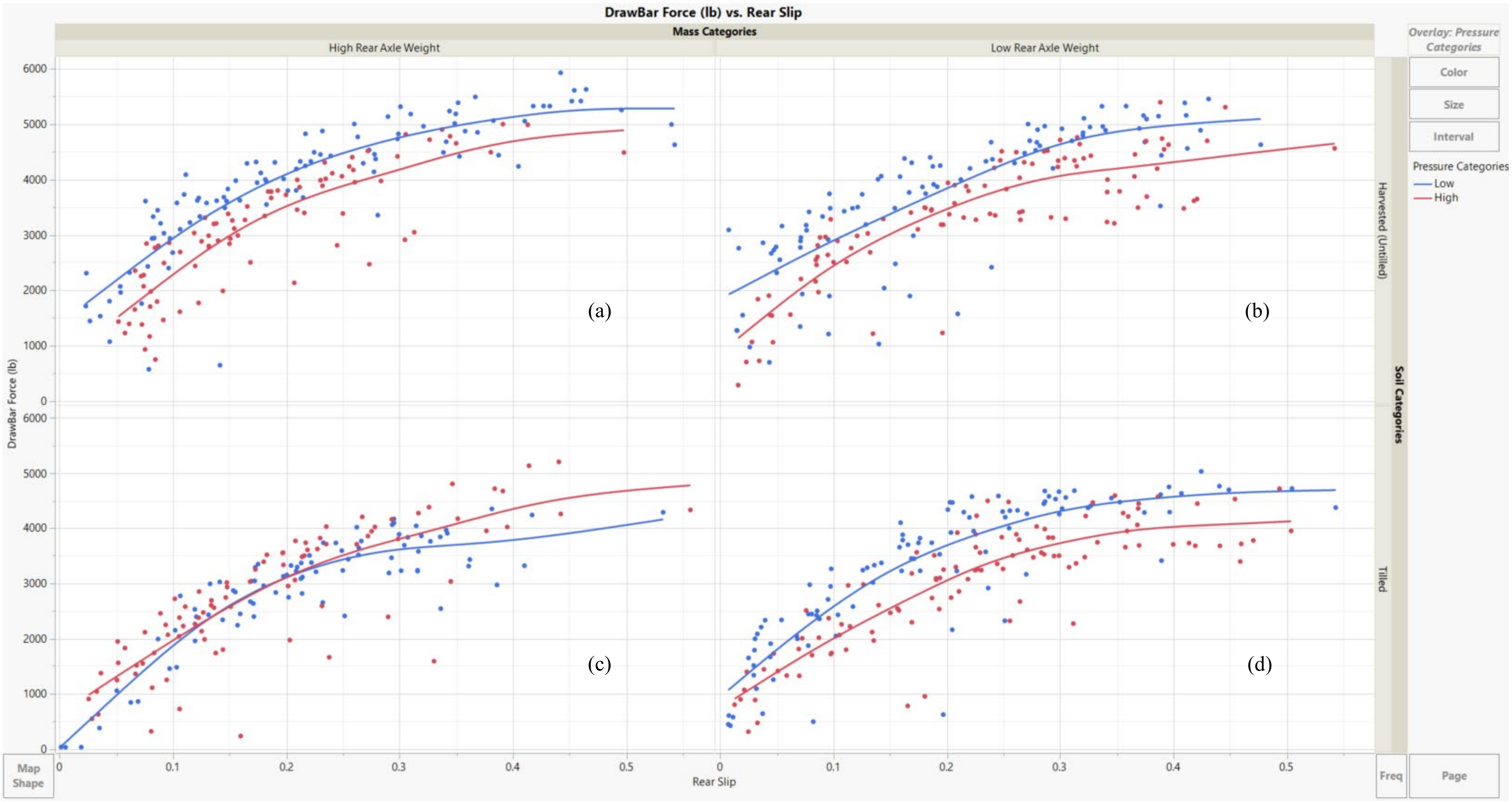

Figure 6. Horizontal drawbar force (lbs.) as a function of slip for both the low and the high tire pressures in (a) high axle weight and untilled soil conditions, (b) low axle weight and untilled soil conditions, (c) high axle weight and tilled soil conditions and (d) low axle weight and tilled soil conditions

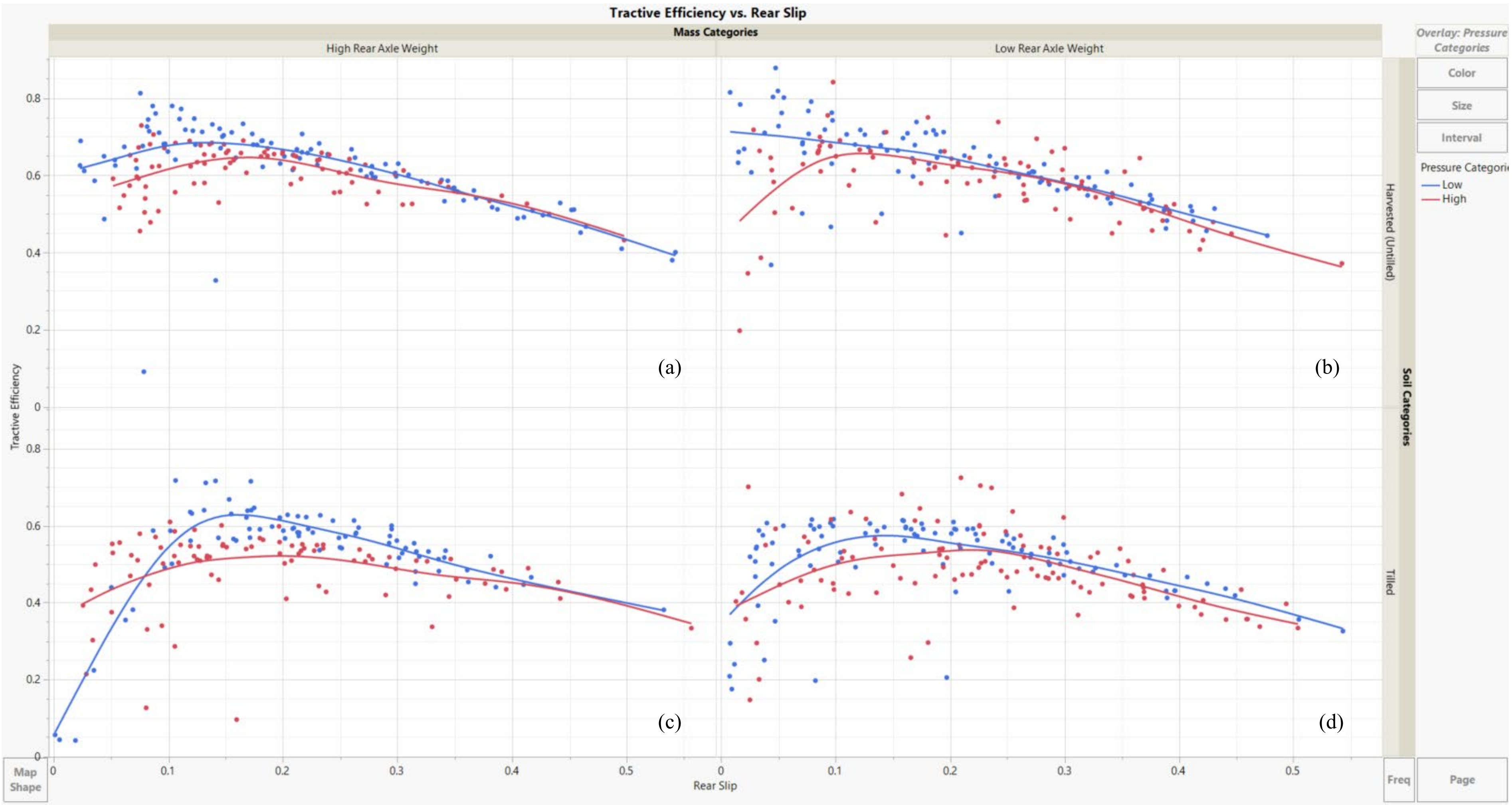

Figure 7. Tractive Efficiency as a function of slip for both the low and the high tire pressures in (a) high axle weight and untilled soil conditions, (b) low axle weight and untilled soil conditions, (c) high axle weight and tilled soil conditions and (d) low axle weight and tilled soil conditions

Predicted Net Tractive Force Vs. Actual Drawbar Force

After applying the Brixius traction prediction equations to the measurements gathered from the field tests, comparisons were made between the actual drawbar force produced and the estimated net tractive force.

High tire pressure setting (Figure 8): With the heavier rear axle, in untilled condition, the prediction equations over-predicted the drawbar force produced (Figure 8, a). With the lighter rear axle in untilled soil conditions (Figure 8, b), the prediction equation was more accurate at 0 to 8 percent slip values. From 8 percent slip and higher, Brixius would continuously overpredict the net tractive force. With the heavier rear axle and operated in tilled soil, Brixius more accurately predicted the drawbar force produced (Figure 8,c). From 3 to 12 percent slip (figure 28) the prediction equations were able to stay within 200 lbs. of the actual force produced. While from 12 to 40 percent slip the prediction equations were able to stay within 400 lbs. of the actual force produced – predicting accurately the 4,000 lb. force at 30 percent slip. The accuracy of the prediction equations was also acceptable when a lighter rear axle was subjected to tilled soil (Figure 8, d). From 5 to 12 percent slip, the Brixius equations were able to stay within 200 lbs. of the actual force produced – predicting accurately the 1,800 lb. force at 8 percent slip. When comparing the tilled (Figure 8, c & d) to the untilled soil condition (Figure 8, a & b), the prediction error decreased substantially. The error seems less sensitive to the difference in the rear axle weight.

Low tire pressure setting (Figure 9): With the heavier rear axle and in untilled soil, an increased in the accuracy of the equations was seen at low slips. From 3 to 15 percent slip, Brixius was within 200 lbs. of the actual force produced – predicting accurately the 2,700 lb. force at 8 percent slip. (Figure 9, a). As slip increased from 15 to 50 percent, the predicted drawbar force began to be slightly overpredicted, but well within 400 lb. of the actual drawbar force produced. With the lighter rear axle weight in the same untilled soil condition, the net tractive force was more accurately predicted between 7 and 12 percent slip – it was underestimated below and overestimated above. (Figure 9, b).With the heavier rear axle weight in tilled soil condition (Figure 9, c) the prediction equations overestimated the drawbar force from 5 of 50 percent slip but only by few hundred lbs. With the lighter rear axle on a tilled soil, Brixius was quite accurate above 8 percent slip. At low slip values, the net tractive force produced seemed to be under predicted. Slip values of 10 percent and higher showed predictions within 250 lbs. of the actual force produced – predicting accurately the 3,300 lb. force at 16 percent slip. (Figure 9, d).

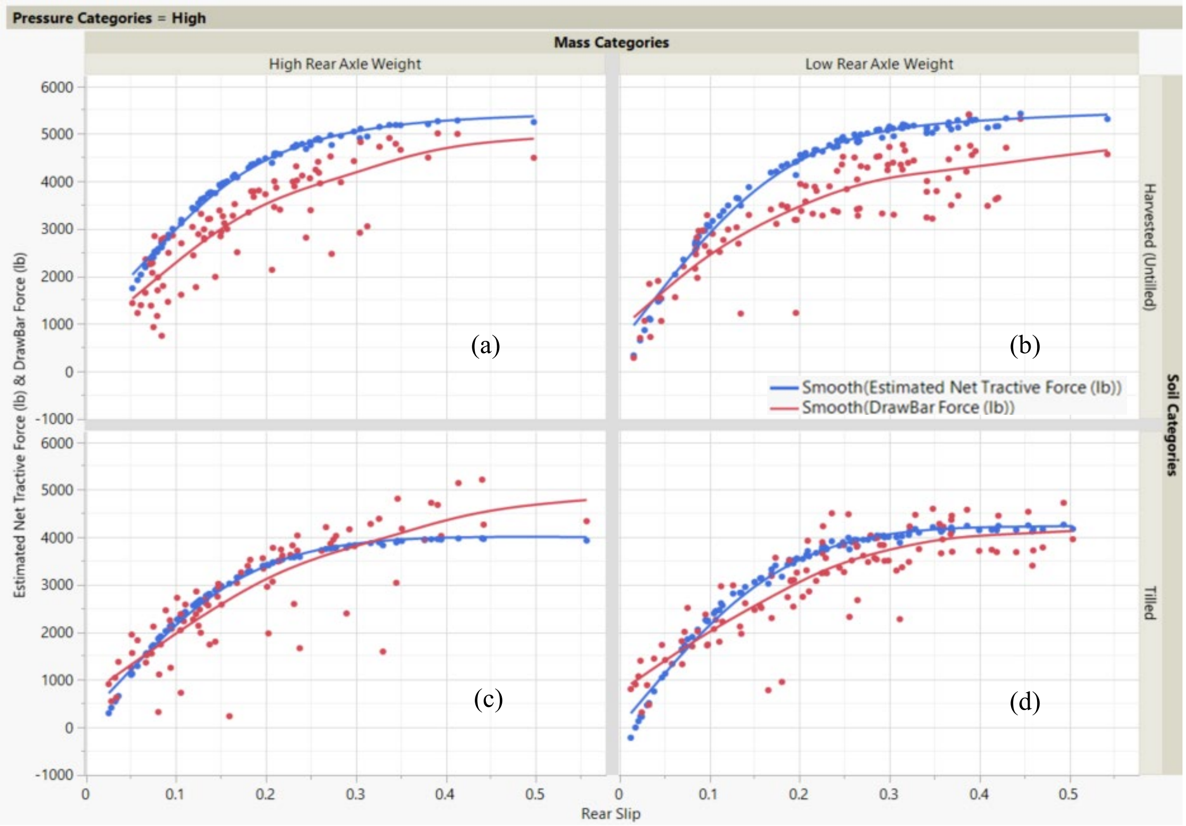

Figure 9. Drawbar Force Produced and Predicted Net Tractive Force as a function of Slip with high tire pressures for (a) high rear axle weight and untilled soil, (b) low rear axle weight and untilled soil, (c) high rear axle weight and tilled soil, and (d) low rear axle weight and tilled soil cases.

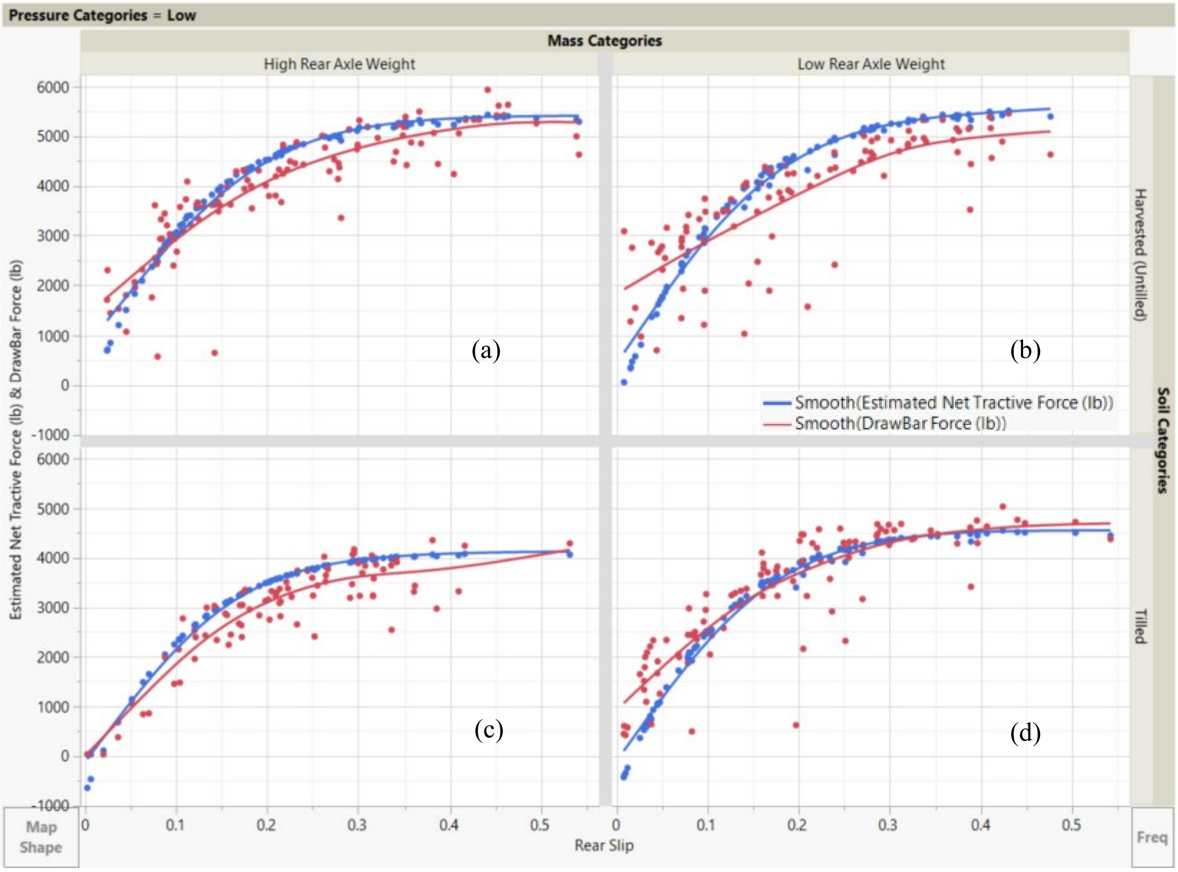

Figure 8. Drawbar Force Produced and Predicted Net Tractive Force as a function of Slip with low tire pressures for (a) high rear axle weight and untilled soil, (b) low rear axle weight and untilled soil, (c) high rear axle weight and tilled soil, and (d) low rear axle weight and tilled soil cases.

To further investigate the effective of the Brixius equations in estimating net tractive force, the estimates were plotted against the measured drawbar force values (Figure 10). A linear regression analysis was performed which resulted in a model with produced an RMSE of 983 lbs. and an R^2 of 0.65. It was observed that large amounts of variation can be seen from the line of fit at low drawbar forces. As the drawbar force increased, the variability off of the line decreased. Values of 3,000 lbs. and above showed less scatter from the regression line than those drawbar forces below 3,000 lbs.
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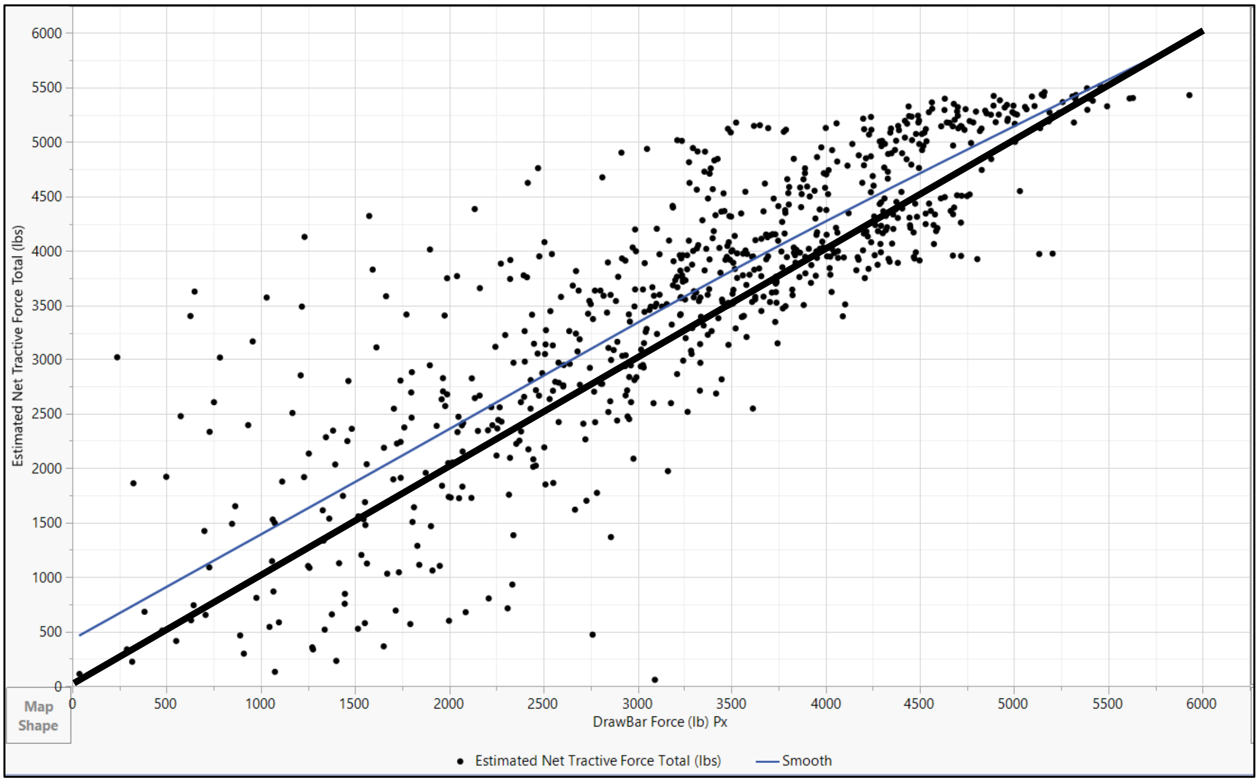


Figure 10. Estimated net tractive force as a function of the Measured Drawbar Force over all test conditions with linear regression model and a one-to-one line.

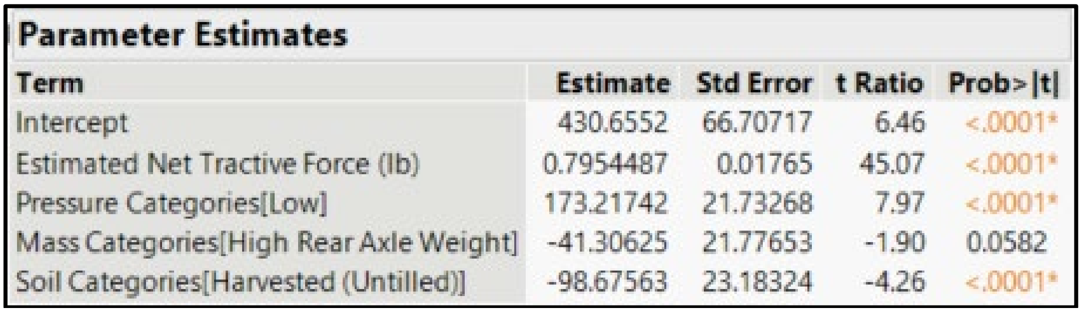
Furthermore, a regression analysis was completed to better understand which experimental factors explained variation in the measured drawbar force that was not accounted for in the Brixius equation. A linear model was used to explain variation in measured drawbar force as a function of the tire pressure, soil conditions, Brixius predicted net tractive force, and rear axle weight. Mathematically, the statistical model can be written as:

$$DBF = a_0 + a_1 BF + a_2 SC + a_3 P + a_4 M$$

where:

DBF is the measured drawbar force in lbs.,
BF is the net tractive force predicted by the Brixius equations in lbs.,
SC are the soil conditions represented categorically (Harvested/Untilled, Tilled),
P is the tire inflation pressure represented categorically (High, Low),
M is the rear axle weightre presented categorically (High Weight, Low Weight, and
a_0, a_1, a_2, a_3, and a_4 are the model coefficients.

Table 3. Regression analysis produced values, P-values, and coefficients



Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	430.6552	66.70717	6.46	<.0001*
Estimated Net Tractive Force (lb)	0.7954487	0.01765	45.07	<.0001*
Pressure Categories[Low]	173.21742	21.73268	7.97	<.0001*
Mass Categories[High Rear Axle Weight]	-41.30625	21.77653	-1.90	0.0582
Soil Categories[Harvested (Untilled)]	-98.67563	23.18324	-4.26	<.0001*

From the regression analysis, the resulting model had an RMSE of 590 lbs and an adjusted R^2 value of 0.75 indicating that 75% of the error was being accounted for between the predicted net tractive force, soil condition, tire pressure, and tractor weight factors. From this analysis, Brixius net tractive force estimates, tire pressure, and soil condition were found to be significant factors ($p<0.0001$) in explaining variation in drawbar force. On the other hand, there was no evidence of rear axle weight being a significant factor in predicting drawbar force. These results suggest that there is additional information in the tire pressure and soil condition factors not used by the Brixius equations. Note that both of these factors will affect the Brixius equations through the mobility number suggesting that the formulation of the mobility number should be investigated and perhaps modified to better include the effect of these factors on net tractive force. The rear axle weight of the tractor, on the other hand, was being accounted for within the Brixius equations.

Conclusions

From this research, it can be concluded that:

1. The Brixius equations do not completely account for the changes in tire pressure when predicting net tractive effort,
2. Information from the categorical till and untilled soil conditions was not completely accounted for by the Brixius equations, and
3. the 2WD tractor's ability to produce drawbar force was increased when using a low tire pressure. Similarly, the tractive efficiency for lower tire pressure was greater than that associated with the higher tire pressure, particularly under lower slip conditions.

It is recommended that the mobility number used in the Brixius equations be adjusted to better account for changes in tire inflation pressure and soil condition. Even though the mobility number is indirectly affected by tire inflation pressure through tire deflection the strength of this functional relationship is not sufficient.

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