POWER DELIVERY EFFICIENCY:
A VALID MEASURE OF BELT / TIRE TRACTOR PERFORMANCE?

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Summary:
Traction tests have shown generally better tractive performance for belts when compared to tires. However, total vehicle tests measuring field productivity and fuel consumption have shown little difference between belt and rubber tire tractors. Recent tests of both type of tractors by Southwest Texas State University and the Alberta Farm Machinery Research Centre have used Power Delivery Efficiency, or percent of input horsepower available at the drawbar as a measure of overall tractor performance. This paper will show why this is a valid procedure for making total tractor comparisons.

Keywords:
Power Delivery Efficiency, tractive efficiency, belt, tire

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Power Delivery Efficiency: A Valid Measure of Belt/Tire Tractor Performance?

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INTRODUCTION

Over the last few years, numerous traction performance tests have been conducted on tires and belts. These "tractive efficiency" tests have shown generally better performance for belts over tires. Other researchers have used "Power Delivery Efficiency" as a measure of performance and find very little difference between the two types of tractors. These researchers have also conducted full field productivity and fuel consumption tests which show very little difference between the tire and belt equipped tractors. What is Power Delivery Efficiency, how is it used to measure tractor performance and is it a valid way to make comparisons?

WHAT IS POWER DELIVERY EFFICIENCY?

Power Delivery Efficiency (PDE) has been defined as the percentage of power produced by the engine that is available as tractive power delivered to an implement (1,2). PDE includes not only Tractive Efficiency (TE) but also the efficiency of the entire drivetrain from engine through the PTO and transmission. In contrast to Tractive Efficiency, there is currently no standardized definition for Power Delivery Efficiency.

PDE is computed by dividing the measured drawbar power by a specified input power over the same time period. The input power may be either Power-Take-Off (PTO) or Engine but is usually that which defines the power level of the tractor being tested. For most tractors this would be the PTO power but for four-wheel-drive and some other tractors without PTO, the size of tractor the customer buys may more likely be specified by engine power. Either PTO or engine power may be used in the PDE calculation but it is most important to be consistent between tractors being compared. Engine power will most likely be measured directly in the field whereas regression analysis is required to determine the equivalent PTO power in the field.

TRACTION MECHANICS REVIEW

A review of traction mechanics is helpful in understanding differences in tractive performance as they affect Power Delivery Efficiency. The basic forces involved in a powered wheel are shown in Figure 1. The torque input, Q, develops a gross thrust, GT, acting at the wheel's loaded radius, Lr. Part of the gross thrust is required to overcome motion resistance, MR, which is the resistance to the motion of the wheel, including internal and external forces. The remainder is equal to the net thrust, NT. Dividing by the dynamic weight on the wheel, Wd, results in dimensionless relationships.

\[
\frac{GT}{Wd} = \text{Gross Traction Ratio, GTR}
\]
\[
\frac{NT}{Wd} = \text{Net Traction Ratio, NTR}
\]
\[
\frac{MR}{Wd} = \text{Motion Resistance Ratio} = \text{GTR} - \text{NTR}
\]

The theoretical travel speed, Vt, depends upon effective radius, r, and rotational speed. Input power is the product of theoretical speed, Vt, and gross thrust, GT. Output power is the product of actual travel speed, Va, and net thrust, NT. Tractive efficiency, TE, is the ratio of output power to input power.

Tractive Efficiency (ratio) =

\[
TE = \frac{\text{Net Thrust} \times \text{Actual Speed}}{\text{Gross Thrust} \times \text{Theoretical Speed}}
\]

\[
= \frac{NT \times Va}{GT \times Vt} = \frac{NT}{GT} \times \frac{Va}{Vt} = \left( \frac{NTR}{GTR} \right) \left( \frac{Va}{Vt} \right)
\]

Eq. 1

The mechanics of the belt drive mechanism, shown in Figure 2, is similar to the wheel in many respects; but the distribution of the load is dependent upon vehicle parameters. Location of the dynamic load resultant, eh (dynamic balance ratio) (3) depends upon static weight distribution and vehicle weight transfer characteristics.
TRACTIVE EFFICIENCY

Tractive "inefficiency" is caused by both velocity losses and pull losses. The loss in travel speed is commonly referred to as "slip" although it should more properly be called "travel reduction". It is the result of the theoretical travel speed not being entirely converted to actual speed due to movement within the soil, between the soil surface and the tractive device (a more proper definition of slip), and within the tractive device itself (tire windup or belt slippage). All result in travel or speed loss.

The other component of tractive inefficiency, which is less visible and often overlooked, is a loss of pull when motion resistance reduces the amount of gross thrust that is converted to useful output (net traction). This is especially relevant to belts as internal losses within a belt are greater than those within the tire. On soft soils the internal belt losses are generally compensated for by the lower external motion resistance of belts over tires.

The following is a generalized plot of the traction relationships using radial ply tires and the Brixius (4) traction equations. While traction data has been traditionally plotted with "slip" as the independent variable, it's becoming more evident that pull, that is, net traction is the independent variable. For a properly ballasted and inflated farm tire, tractive efficiency tends to maximize at a Net Traction Ratio of approximately 0.40. This was also recognized by Dwyer (5). Motion resistance tends to be a linear function of either slip or NTR unless (slip) sinkage becomes a factor.

The travel and pull losses making up tractive inefficiency do not have official terminology. The simplest way to understand them is to look at a "Velocity Ratio" and "Pull Ratio". From Eq 1, 

\[ TE = \left( \frac{NTR}{GTR} \right) \left( \frac{Va}{Vt} \right) = \text{Pull Ratio} \times \text{Velocity Ratio} \]

The Velocity Ratio is shown as a function of Net Traction Ratio in Figure 4. At zero NTR (zero pull) the actual velocity, Va, is about equal to the theoretical velocity, Vt, (depending somewhat on the definition of "zero" slip (6)), and the Velocity Ratio is near unity. As pull increases, slip increases and Velocity Ratio decreases. Velocity Ratio losses depend upon the characteristic shape of the pull-slip curve.

Pull Ratio is also shown as a function of NTR in Figure 4. At zero pull, the ratio of Net Traction Ratio to Gross Traction Ratio approaches zero (the difference between GTR and NTR is motion resistance which is in the range of 0.05 to 0.15). Due to motion resistance, Net Traction Ratio can never equal Gross Traction Ratio and Pull Ratio approaches but never reaches unity.
The overall tractive efficiency cannot be greater than either the Pull or Velocity Ratio. Thus it reaches a maximum value at NTR of about 0.4 with radial ply tires. A similar but slightly higher NTR value exists for belts.

Pull Ratio, Velocity Ratio and overall tractive efficiency are shown for real data in Figure 5. Data is for radial ply tires in medium (tilled) tractive conditions. The curves are the result of regression analysis (7) of the field test data. Both velocity (slip) and pull (motion resistance) losses contribute to overall tractive (in)efficiency.

Figure 6 shows the same data as Figure 5 plotted in the more traditional way using slip ratio as the independent variable.

Figures 8 to 10 show the performance of three belt widths from one manufacturer in comparison to dual tires on three surfaces. Under firm un�험 conditions (Figure 8), there is little performance difference between the four treatments at normal field pulls (NTR approx. 0.4 to 0.5). Duals tend to drop off more at higher pulls and the wider belt provides higher maximum NTR (limited by slip).
The difference between belts and tires becomes greater as the soil becomes soft and loose with belts maintaining their relative position with each other (Figures 9 and 10). Note that the maximum tractive efficiency for tires still comes at an NTR of about 0.4 whereas the belts tend to maximize at a slightly higher pull and demonstrate a wider range of pulls at near maximum efficiency. It should be noted that all these tests were carried out with a minimum of steering. Matching implements at higher NTR on a skid steer belted machine may result in limited steering control under load.

**POWER DELIVERY**

Previous discussions of tractive performance consider only the difference between axle and drawbar performance. In actual use, tractors are generally sized and purchased by either engine or PTO rather than axle power. Tractive Efficiency considers only the losses between axle and drawbar. Power Delivery Efficiency considers the entire vehicle from engine or PTO to drawbar including all hydraulic and drivetrain power losses. When using PDE as a performance comparison tool, either engine or PTO power can be used for the comparative calculations depending on what is available and convenient. The important thing is that tractors being compared both use the same power measurement. Directly measuring engine power with a torque meter is preferable. This power can be used directly in the PDE calculation or can be used to determine the effective PTO power through regression analysis. If the tractor is not equipped with an engine dynamometer but has a PTO, then dynamometer runs are made prior to field testing to determine PTO power as a function of engine speed and other parameters such as injection pump rack position. In the field the equivalent PTO power can then be predicted from the results of regression analysis (8).

When using measured engine power, the PDE calculation is straightforward

\[
PDE = \frac{DbPower}{EngPower}
\]

When using regression analysis other factors must be considered. Assuring that engine power output is the same for PTO and drawbar tests is inherent to the measurement procedure. Figure 11 shows field data where PTO power was calculated from an engine torque meter and from an engine speed regression analysis. In this case there was good correlation with an \( R^2 = 0.98 \), confirming use of PTO regressions in the analysis.
Both PTO and Axle power are dependent upon engine power and drivetrain and hydraulic losses. PTO or transmission drivetrain and hydraulic losses will reduce power at the PTO or axle respectively.

\[
\begin{align*}
PTO\text{Power} &= \text{EngPower} - \text{PTODriveLoss} - \text{HydLoss}_{\text{pto}} \\
\text{AxlePower} &= \text{EngPower} - \text{TransDriveLoss} - \text{HydLoss}_{\text{trans}} \\
\text{DrawbarPower} &= \text{AxlePower} \times \text{Tractive Efficiency Ratio}
\end{align*}
\]

Assuming that engine power output is the same for both PTO and drawbar operations,

\[
\text{PDE} = \frac{\text{DbPower}}{\text{PTOPower}} = \frac{\text{TransDriveEff} \times \text{TtractiveEff}}{\text{PTODriveEff}}
\]

Hydraulic losses during PTO operation are fairly constant for any given tractor. Hydraulic losses during field operations include those necessary for both tractor and implement operation and can vary widely. Effort is usually made to limit steering while data is being taken but, even then, power is usually required for the steering system itself. This power may be different during drawbar operations than it was while sitting stationary during PTO tests. Power Delivery Efficiency depends upon transmission and PTO drive efficiencies (including hydraulic losses) as well as tractive efficiency.

One of the more common comparisons of Power Delivery performance comes from Nebraska or OECD tests and can serve as an example of how PDE is determined. Maximum drawbar and PTO power are both shown in these test reports. Dividing drawbar power by PTO power gives a measure of the overall efficiency of power transmittal (on concrete) regardless of tractor size or type. The maximum drawbar power value is usually the only one of interest. For example, Nebraska Test 1722, Caterpillar Challenger 75D, shows 284.30 PTO hp @ 2097 engine rpm. Maximum drawbar power at the same engine rpm occurred in 3rd gear with 254.52 drawbar hp. Dividing 254.52 by 284.30 gives a Power Delivery Efficiency of 89.5%.

When using Nebraska tests to compare drawbar to PTO power delivery, one of the basic assumptions is that engine power output was the same in each case. This means the same ambient conditions for PTO and drawbar tests as well as the same fuel temperatures and tractor warmup procedures (same oil temperatures). Since the concrete track should be the same for everyone, useful comparisons can be made between models from different companies.

Power Delivery Efficiency calculations from Nebraska tests are usually based upon a single full load, full power data point. Test data in the field is usually compared over a range of engine speeds, loads and gears. The same procedure used in the field can be applied to Nebraska test data.

Figure 12 shows PTO data from Nebraska Tests for the John Deere 8400 MFWD, plotted as a function of engine speed. Data is from the variable load portion of the tests and from performance at reduced engine speeds. A best fit curve is applied separately to the two portions of the data, each with PTO power as a function of engine speed.
Also shown in Figure 13 is the Caterpillar 45 belted tractor, using the same procedure on data from OECD tests. Thus we are comparing two types of tractors of two different power levels from two different test locations using both ballasted and unballasted test conditions. The PTO and drawbar powers are quite different but the Power Delivery Efficiencies are nearly the same (in this example, on concrete).

One of the basic assumptions necessary to make the Power Delivery Efficiency procedure work is to be certain that the engine output is the same under PTO and drawbar test conditions. In the field this means careful control of the variables and/or including them in the regression analysis of PTO power. The examples shown thus far use only engine rpm in the regressions. This is because the data came from official tests where no other data was available and where it is assumed the primary variables of ambient temperature (also controlling viscous fan drive speeds) and fuel temperature are being controlled. There are other reasons engine power may vary from PTO to drawbar or field tests such as differing throttle position or differing fuel blends.

The effect of engine power variation on a Power Delivery Comparison is shown in Figure 14. The values have been calculated from the Nebraska test data on a JD9400 and Cat 85D. Both these tractors have engine derate systems, one functioning on PTO tests and the other in certain gears in the field.

FIELD DATA

The following plot, Figure 15, shows an example of a Power Delivery performance map over a range of pulls and speeds. Tests were conducted by varying the load in selected gears (near vertical lines), and by keeping the load constant and varying the gear to change the travel speed (horizontal lines). Drawbar power levels are shown.
by the curves and the numbers indicate PDE (calculated as percent of PTO power at the drawbar) at the pull-speed intersection points (left of the values). This shows the overall affect of transmission, PTO drive, and tractive efficiencies. Drivetrain efficiencies drop off at lower power levels as losses become a more significant factor. Tractive efficiency peaks in the range where pull is approximately 40 to 50% of the tractor weight.

The following graphs, Figures 16 and 17, show the tractive performance of a belted and an MFWD wheel tractor in two soil conditions. Tractive performance considers only the losses between axle and drawbar. The lines show the regression curve for each case. Tractive efficiency of the belted tractor exceeds that of the wheel tractor at all pull levels and there is greater difference as soil conditions deteriorate (secondary tillage). This data suggests that the belted tractor should exceed the wheel tractor in engine power delivered to the drawbar or in fuel required per area worked.

Figure 15. A Power Delivery Performance Map

Figure 16. Tractive Performance - Primary Tillage

Figure 17. Tractive Performance - Secondary Tillage
Figures 18 and 19 show Power Delivery Efficiency for the same tractors and tests as shown in Figures 16 and 17. Power delivery efficiency is inherently lower than Tractive Efficiency for both belted and rubber tire tractors because it includes PTO and transmission drivetrain losses. While there is a wider scatter in the data points, there is little difference between belts and wheels in the normal range of pull for field operations, 0.3 to 0.5 VTR. This data suggests a different conclusion than the tractive efficiency data. In primary tillage, even though the TE was higher for the belted tractor across the full range of VTR, the PDE for the belted tractor is lower than the wheel tractor below .5 VTR. In the softer secondary tillage, the PDE of the belted tractor is lower than the wheel tractor below .2 VTR and equivalent through about .4 VTR. This data would suggest that in engine power delivered or in fuel required per area worked, when the tractors were operating below .5 VTR, the belted tractor would at best be equal to the wheel tractor and could actually be worse at lower VTR.

Another confirmation of the validity of Power Delivery Efficiency was derived from full field productivity and fuel consumption tests. This procedure, described by Turner (2), involved the uniform tillage of a measured area of approximately 40 acres (16.2 hectares). The primary measurements were area tilled, fuel consumed, and time to complete the measured area but PDE measurements were also made during the test. Tillage depth was held constant and the width of the implement was varied to allow each tractor to operate near its maximum tractive efficiency. Steering was held to a minimum by using rectangular shaped fields and lifting the implement for turning. As shown in Figure 20, this test showed little difference in Workrate or Specific Fuel Rate between comparable rubber belt and rubber tire tractors. This was congruent with the equivalent average values of PDE that were measured for the tractors during the tests.
CONCLUSIONS

Power Delivery Efficiency can provide valid tractor performance comparisons. When comparing tractors with drivetrain designs that are significantly different, as is the case for belted versus wheel tractors, PDE provides more accurate total machine performance comparisons than does Tractive Efficiency. Computing PDE using measured engine power gives data with the least amount of variation. When engine power cannot be measured it can be computed from engine speed using a laboratory derived PTO power regression. However, because engine power is dependent upon a number of field variables, this will increase variability in PDE data. Tight control of the variables or including them in the PTO performance regressions can reduce this variability.

Power Delivery Efficiency comparisons show there is less overall difference in performance between belted and rubber tired tractors than would be implied by tractive efficiency comparisons alone.

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