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Influence of eccentric drawbar force on power delivery efficiency of a wheeled tractor

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Abstract: Power delivery efficiency shows how much engine power is used for a tractor drawbar. Eccentric traction is a factor influencing the power delivery efficiency of a wheeled tractor. It occurs as a consequence of the offset position of a tractor implement, that is, when the traction line of the tractor and resistance line of the implement are parallel and do not coincide. This paper presents research on the power delivery efficiency of wheeled tractors and its dependence on wheel slippage of central and eccentric drawbar forces on unplowed and plowed stubble. For this purpose, mathematical models and one algorithm were developed. The best power delivery efficiency of the tractor on both unplowed and plowed stubble surfaces was obtained with central drawbar force. Power delivery efficiency of the tractor on unplowed stubble decreased by 5.72% if eccentricity increased up to 0.16 m and by 12.33% if eccentricity increased up to 0.32 m. Power delivery efficiency of the tractor on plowed stubble decreased by 8.88% if eccentricity increased up to 0.16 m and decreased by 19.05% if eccentricity increased up to 0.32 m.

Key words: Eccentric drawbar force, power delivery efficiency, slippage, wheeled tractor

Introduction

The primary purpose of agricultural tractors, especially those in the middle to high power range, is to perform drawbar work (Zoz and Grisso 2003). Drawbar power is defined as the product of drawbar force and actual velocity. Therefore, the ideal tractor converts all the energy derived from fuel into useful work at the drawbar (Grisso et al. 2006).

However, of all of the available tractor energy, 20%-55% is wasted at the tire-soil interface (Burt et al. 1982). A method of predicting improved tractor performance is needed to aid in proper ballasting, matching of implements, selection of tractor configurations, and selection of tires for tractors. Tractor performance is influenced by tire parameters, soil condition, implement type, and tractor configuration (Grisso et al. 1992). Ability to predict and optimize the performance of tractors during field operations has been of great interest to scientists, manufacturers, and users (Grisso et al. 2006).

Under optimal working conditions, the tractor and implement can provide efficient and economical work during which maximum productivity and minimum fuel consumption are achieved (Özarslan and Erdoğan 1996). It is, therefore, of great importance to investigate factors that might improve the tractive

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performance of tractors, and, consequently, the power delivery efficiency of wheeled tractors.

The efficiency of a traction system in which tractive force is transferred onto the attached unit via the drawbar is expressed by the power delivery efficiency of a tractor (Zoz and Grisso 2003). While the efficiency of a traction device is defined as tractive efficiency, the efficiency of a complete tractor is defined as power delivery efficiency (Zoz et al. 2002). Zoz et al. (2002) analyzed the traction performance of wheeled and rubber belt tractors and concluded that power delivery efficiency was the most significant factor for estimating and comparing tractor traction performance. In contrast to tractive efficiency, power delivery efficiency represents the ratio between drawbar power and engine power, which makes it suitable for the comparison of different tractors with different running systems.

Turner (2005) developed a simple instrumental system and test procedure for measuring the power delivery efficiency of tractors during agrotechnical operations in the field. This system does not measure standard tractive efficiency (on the wheel); it measures the power delivery efficiency of the tractor (at the drawbar). This system enables the operator to observe the effects of changes made to a tractor in order to improve power delivery efficiency and gain benefits from the measures undertaken.

Shell et al. (1997) compared the power delivery efficiency and fuel consumption of wheeled and rubber belt tractors with similar power and mass. Six relevant factors were included: tractor configuration (wheeled and rubber belt tractors), soil type (clay and sandy soil), surface (stubble and soil tilled by chisel plow at a depth of 15 cm), engine speed (2 values), torque (3 values), and net traction ratio (0.3, 0.4, and 0.5). In all combinations, the rubber belt tractor showed higher power delivery efficiency than the wheeled tractor, but only by 2% on average. This percentage was higher under poor tractive conditions.

Similar research was conducted by Turner et al. (1997), but with more tractors from various manufacturers. Two wheeled tractors with dual rear wheels and two rubber belt tractors were compared, and the only relevant factor was surface condition. The tractors were similar in power and mass, and the testing was conducted on tilled and untilled clay soil in southern Alberta, Canada. For the interval of net traction ratio ranging from 0.4 to 0.5, wheeled and rubber belt tractors had almost the same power delivery efficiency. Rubber belt tractors showed better traction performance on soft soil, and the net traction ratio was higher than 0.6. Rubber belt tractors of the same weight had higher traction forces at lower slippage values.

Power delivery efficiency is influenced by numerous factors, such as the type and condition of the soil, the mass and distribution of the load, tire type, inflation pressures (Al-Hamed et al. 1994; Sümer and Sabancı 2005; Schreiber and Kutzbah 2008), and eccentric and oblique drawbar force (Stjelja 2002). Eccentric drawbar force is a factor that affects the power delivery efficiency of wheeled tractors (Simikić 2007).

Operating the tractor under conditions of eccentric traction leads to increased driving wheel slippage, greater fuel consumption, and worn out tractor parts, which directly increases production costs and decreases the economic power of farmers (Stjelja 2002).

The aim of this research was to determine the influence of eccentric traction and wheel slippage on power delivery efficiency, to create an algorithm that can be applied to various types of tractors, and to create a new formula for power delivery efficiency of wheeled tractors.

Materials and methods

Preliminaries

Eccentric traction occurs as a consequence of the offset position of the implement in relation to the tractor, that is, when the longitudinal axis of the tractor and the line of the implement draft (drawbar force) are parallel but do not match (Figure 1). In the process of attaching the implement to the tractor, the line passing through the center of resistance of the implement should match the longitudinal axis of the tractor in order to avoid the turning moment and swaying of the front of the tractor. This is accomplished by properly attaching the implement and properly adjusting the implement working width. In practice, eccentric traction occurs most

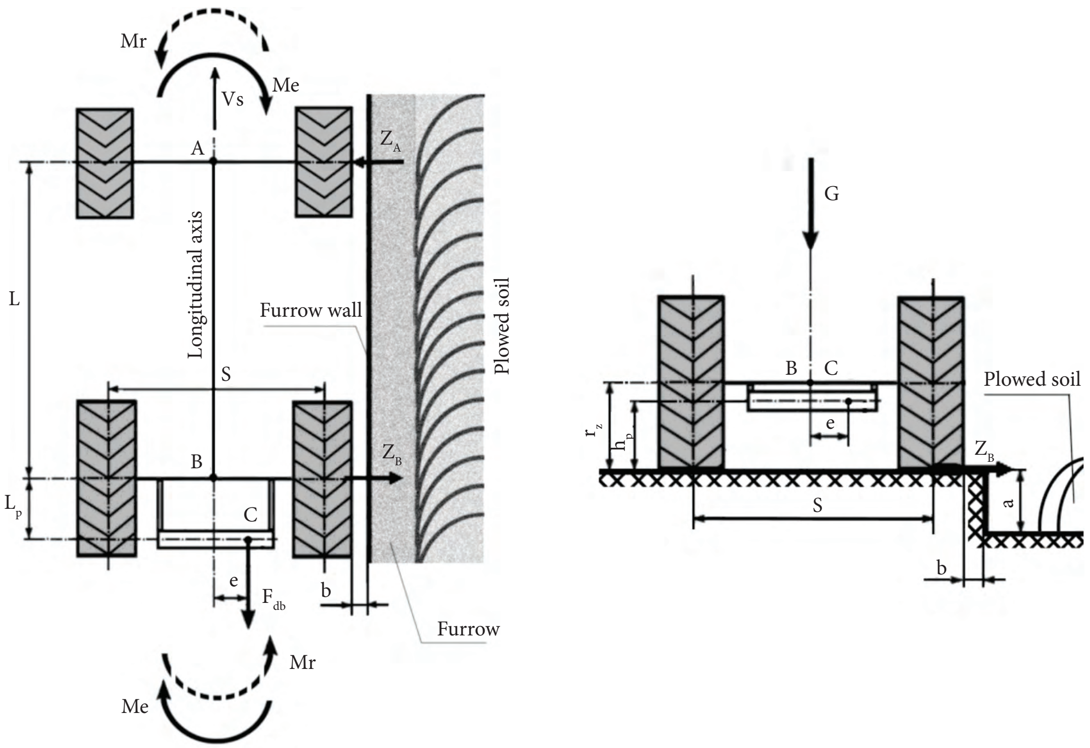

Figure 1. Eccentric offset of a wheeled tractor. Labels: L - wheelbase, L_p - distance between drawbar and tractor's rear axle, b - distance between rear wheel and furrow edge, S - width of rear wheel track, e - eccentricity, r_z - rear wheel radius, h_p - drawbar height, a - furrow depth, Z_A - lateral force on front, Z_B - lateral force on rear, M_r - resistance moment of the soil, M_e - destabilizing moment, F_{db} - drawbar force, G - tractor weight, and v_s - actual tractor velocity.

frequently with asymmetric equipment such as offset plows or the disk harrows used for deep plowing on heavy soil; use of these implements is characterized by great soil resistance in the working width (Stjelja 2002).

The lateral force of the soil on wheels Z_A and Z_B is the consequence of the eccentric force on drawbar F_{db} (Figure 1). Eccentric force F_{db} on arm e creates a destabilizing moment M_e:

$$M_e = e \times F_{db} \tag{1}$$

Moment M_e is equal in magnitude to the resistance moment of the soil M_r:

$$M_e = M_r \tag{2}$$

$$e \times F_{db} = L \times Z_A \tag{3}$$

$$Z_A = \frac{e}{L} \times F_{db}. \tag{4}$$

If $Z_A = Z_B = Z$, it follows that the resistance moment of soil M_r is determined by the following formula:

$$M_r = L \times Z \tag{5}$$

Destabilizing moment M_e can cause a change in the direction of the tractor. In order to annul the influence of destabilizing moment M_e on the direction of the tractor, it is necessary to steer the front wheels in a direction opposite to the destabilizing moment.

Soil properties

The research was conducted on 2 surface types, unplowed and plowed stubble. Unplowed stubble is the type of soil surface that appears after the wheat harvest. In this paper, plowed stubble refers to the type of soil surface obtained after plowing the stubble at a depth of 25 cm. Experimental measuring of the influence of eccentricity on traction characteristics of a wheeled tractor was conducted on flat terrain with chernozem soil; soil texture is given in Table 1. Soil structure was determined by the pipette method from a sample taken at a depth of 20 cm from disturbed soil. The sample was prepared with sodium pyrophosphate according to the method of Thun, and soil texture was classified according to Tommerup (Hadžić et al. 2004). Soil bulk density and moisture content were determined from undisturbed samples taken at depths of 0-10 cm and 10-20 cm with a steel core sampler with a volume of 100 cm^3 (Altikat and Celik 2011). The samples were then dried in driers for 4 days at 105 °C until they reached constant (standard SRPS ISO 11272:2007). Measured soil bulk density and moisture content are given in Table 2. The soil moisture content was determined by weight percent (%, w/w) according to the measured parameters on a dry basis. All measuring was conducted according to the technical scale with an accuracy level of 0.01 g.

Tractor properties

The period of transition in Serbia has been characterized by the enlargement of small farms and the use of tractors with more horsepower. Apart from large farms of over 1000 ha, which make up 10% of the total land, medium-sized farms (family households) are also expanding and are now 100 to 1000 ha in size. Farm expansion has created a demand for tractors with more horsepower so that work can be completed within the optimal agrotechnical deadlines. Tractors with 90-100 kW of power have become more popular for medium-sized farms, and farmers use them universally for various operations. Therefore, a medium category tractor was chosen for the analysis of the influence of eccentric drawbar force on power delivery efficiency. The test tractor was JD 6820 MFWD, a 4-wheel-drive tractor with smaller steering wheels in front (mechanical front-wheel drive, MFWD) and a built-in 99-kW engine (http://www.dlg-test.de/pbdocs/traktoren/John_Deere_6820_AutoQuad_e.pdf). The test tractor had a power-shift transmission and was equipped with 14.9-28 front tires and 18.4R38 rear tires. Front and rear tire inflation pressures were 2 and 1.9 bars, respectively. The tractor weighed 6092 daN, with 41% on the front and 59% on the rear axle. The wheelbase was 2650 mm.

Structure of the experiment

The influence of eccentric traction on the power delivery efficiency of the tractor was determined by examining drawbar power according to OECD test code 2 and standard ISO 789-9:2002, which were adapted for testing in field conditions (Nikolić et al. 2007). Testing traction in the field always requires applying the load to the test tractor. It is possible to use traditional drawbar loading units designed for use on hard surfaces in the field; however, problems may occur. Relatively heavy load units are required for heavy load drafts, and this limits the minimum drawbar pull to the motion resistance of the load unit. As a result, lower portions of the pull-travel reduction curve cannot be attained (Zoz and Grisso 2003). It is preferable to use a second tractor (Figure 2, marked as 8) in combination with the implement (Figure 2, marked as 7). A load tractor was attached to the test tractor via a universal drawbar installed on the test tractor. The implement was operated at the depth suitable for a load tractor to pull, and the drawbar pull applied to the test tractor was adjusted using the throttle of the load tractor. Throttling back on the load tractor increased the load on the test tractor, as the test tractor was forced to pull more of the implement load. Increasing the throttle setting on

Table 1. Soil texture.

Soil texture	Soil aggregate size (mm)	Sample (%)
Gravel	2-0.2	4.98
Sand	0.2-0.02	49.47
Silt	0.02-0.002	32.76
Clay	<0.002	12.79

Table 2. Soil bulk density and moisture content.

Depth (cm)	Soil bulk density (Mg m^{-3})	Soil moisture content (%, w w^{-1})
0-10	1.208	17.42
10-20	1.254	18.86

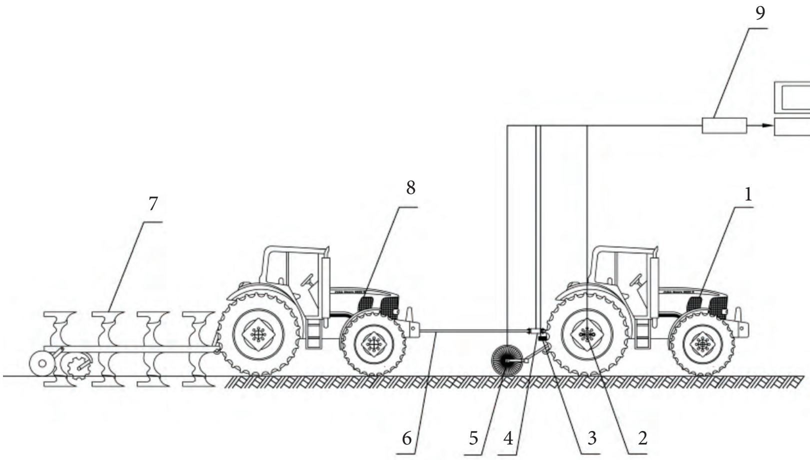

Figure 2. Test tractor with powered tractor and implement as load unit. Labels: 1 - test tractor, 2 - theoretical velocity sensor, 3 - PTO speed sensor, 4 - dynamometer, 5 - actual velocity sensor, 6 - link, 7 - implement load, 8 - load tractor, 9 - acquisition, and 10 - PC.

the load tractor caused it to overtake the test tractor, reducing the drawbar pull as the load tractor pulled the implement (Zoz and Grisso 2003).

The influence of eccentric traction on the traction characteristics of the tractor was tested by measuring the drawbar force, velocity of the tractor, wheel slippage, engine speed, and power take-off (PTO) power (Tables 3 and 4). Drawbar force was measured with an electronic dynamometer D-20 T [Hottinger Baldwin Messtechnik (HBM), Germany] (Figure 2, marked as 4), which had a measurement range up to 20,000 daN and an accuracy level of ±0.05%. Drive wheel slippage was determined by measuring the actual velocity with a sensor on the fifth wheel (Figure 2, marked as 5), while theoretical velocity was measured with a wheel revolution sensor with a toothed wheel (Figure 2, marked as 2) on a rear tractor wheel. Engine speed was obtained by measuring PTO speed with a sensor (Figure 2, marked as 3) and was based on the relationship of PTO speed to engine speed, which was 1:2. Engine speed and theoretical and actual velocity were measured with optocoupler GP1A70R (Sharp) sensors with ±1.67% reliability. Analog signals obtained from sensors for drawbar force, actual and theoretical velocity, and PTO speed were transmitted by 8-channel acquisition PC measurement (Spider 8, HBM) (Figure 2, marked as 9). The acquisition processed the signals and enhanced and transformed them into digital signals that were then processed by software (Figure 2, marked as 10). Every 90 s, the tractor load was changed; the drawbar force was increased, but only the values measured in the last 30 s were recorded as relevant data (only mean values are presented in Tables 3 and 4). During the measurement, data reading was done 10 times per second.

The direction of the drawbar force was moved parallelly beyond the median longitudinal plane of the tractor (e = 0) to the right; eccentricity values were e = 0.16 m and e = 0.32 m (Figure 1).

PTO power measuring was performed with an electric Eggers-Dynamometer, type 301/ME (measurement range up to 220 kW), in accordance with OECD test code 2 and standard SRPS ISO 789-1:1997. Tractor weight was measured on a weighbridge (TRC, Novi Sad) with a measuring range up to 168 kN, HBM sensors (type 4xHLCBC3/4.4t), and reliability of ±0.5 kg. Tire inflation pressure was measured with a TROTEC BY10 (measurement range of 0.35-6.9 bars, reliability of 1% ± 0.05 bars; TROTEC, Heinsberg, Germany). All measurements were performed with equipment from an OECD-accredited laboratory for power machines and tractors in Serbia (http://www.oecd.org/document/55/0,3746,en_2649_33905_1814320_1_1_1_1,00.html).

Statistical analysis

Mathematical models were obtained using experimental data and applying nonlinear regression

Table 3. Experimental (measured) data, unplowed stubble. Power delivery efficiency (PDE) is not from measured data; it is calculated based on Eq. (14).

Eccentricity (m)	Wheel slippage (%)	Tractor actual velocity (m s^{-1})	Drawbar force (N)	Engine speed (min^{-1})	PTO power (kW)	PDE (%)
e = 0	1.7	2.0	5670	2122	87.2	31.87
	6.4	2.1	15,490	2100	91.6	52.75
	8.8	2.1	19,950	2074	92.6	57.31
	15.7	1.8	31,500	1980	98.4	60.66
	22.4	1.6	35,660	1902	98.0	58.03
	26.6	1.4	37,620	1880	97.2	54.81
e = 0.16	2.1	1.9	5050	2115	90.1	28.15
	4.1	2.0	10,970	2060	94.3	44.56
	11.3	1.9	21,170	2056	94.6	55.18
	21.4	1.6	30,420	1948	99.6	54.32
	28.1	1.4	34,200	1915	98.7	51.40
e = 0.32	1.9	1.8	4450	2115	90.1	25.16
	3.8	1.9	9640	2110	90.3	41.49
	12.5	1.8	21,560	2070	93.4	54.18
	22.8	1.5	28,870	1960	99.2	51.07
	32.4	1.3	31,840	1925	98.9	46.07

Table 4. Experimental (measured) data, plowed stubble. Power delivery efficiency (PDE) is not from measured data; it is calculated based on Eq. (14).

Eccentricity (m)	Wheel slippage (%)	Tractor actual velocity (m s^{-1})	Drawbar force (N)	Engine speed (min^{-1})	PTO power (kW)	PDE (%)
e = 0	2.5	1.8	5140	2180	87.8	21.56
	7.3	1.9	13,470	2108	90.4	39.71
	11.3	1.7	18,940	2066	94.7	44.06
	16.3	1.6	24,890	1968	99.0	46.89
	23.7	1.3	30,470	1914	98.5	45.20
	30.2	1.1	33,240	1892	97.7	41.73
e = 0.16	2.5	1.8	5020	2114	90.2	20.97
	8.9	1.8	12,470	2054	95.2	35.89
	12.4	1.6	18,940	2045	96.8	42.35
	30.1	1.4	25,510	1947	99.6	39.42
	38.4	0.9	31,100	1924	98.8	33.20
e = 0.32	3.1	1.8	4880	2217	84.2	20.78
	10.2	1.7	14,210	2098	92.5	37.96
	14.2	1.5	18,320	2050	96.1	39.84
	28.2	1.3	21,500	1959	99.6	34.85
	37.5	0.9	27,500	1922	98.8	30.83

analysis (Strasser 1985). An experimental data table was created for each type of soil, and mathematical models were estimated based on these data. For each mathematical model, nonlinear regression analysis provided regression coefficient estimation, t-test, and F-test values. A coefficient of determination (R^2) was also introduced for validation of each regression equation. Mathematical operations and graphs of the functions were performed with Mathematica 6 (Wolfram 1991), while statistical analysis was performed with Statistica 10. These software packages have been very useful in many other agriculture-related papers (Babić et al. 2011, 2012; Dedović et al. 2011; Tomic et al. 2011; Zorić et al. 2011).

Algorithmic approach

Power delivery efficiency η_v of the tractor is the ratio of drawbar power to PTO power, and it is defined as:

$$\eta_v(\%) = \frac{P_{db}}{P_{pto}} \times 100 \qquad (6)$$

where P_{pto} is PTO power expressed in kilowatts and P_{db} is the power at the drawbar, also expressed in kilowatts.

Tractor manufacturers generally specify the power output at the PTO and drawbar. PTO power is the most commonly used power specification for tractors. For each tractor model, the rated horsepower information provided is at rated engine speed. Typically, this power output is measured at PTO and is referred to as rated PTO power (Grisso et al. 2011). Engine power can be estimated as PTO power because, for most tractors, there is minimal gearing between the engine and the PTO power; consequently, minimum transmission losses occur between them (Ortiz-Cañavate et al. 2009).

The power on the drawbar is defined by:

$$P_{db}(\mathrm{kW}) = \frac{F_{db} \times v_s}{1000} \qquad (7)$$

where F_{db} is the drawbar force expressed in N, and v_s is the actual velocity of the tractor expressed in m s^{-1}.

The aim of the research was to create a new formula for the power delivery efficiency of wheeled tractors. Therefore, the algorithm will be presented. The algorithm entry data were: the tractor weight (G); a coefficient (ξ) equal to the ratio of torque during idle engine speed (nonload torque) to torque at rated speed [between 0.03 and 0.05, see Chudakov (1972)]; an efficiency coefficient of the ith pair of the gear in transmission ($\eta_{i,n}$), where n is the number of gear pairs; torque at rated engine speed (M_n); transferred torque (M_k); a motion resistance coefficient (f), which depends on the type and condition of the surface and the drivetrain design (stubble: $f = 0.084$, plowed stubble: $f = 0.173$) (Nikolić 1983); drawbar force (F_{db}); and eccentricity (e).

Other values calculated in the algorithm were P_f (loss of power due to motion resistance), P_{trt} (loss of power due to transmission to driving wheels), P_δ (power loss due to wheel slippage), and P_{db} (drawbar power). The transmission efficiency coefficient (η_{tro}) in the load function is calculated by the formula:

$$\eta_{tro} = \left(1 - \xi \times \frac{\mathrm{M}_n}{\mathrm{M}_k}\right) \times \prod_{i=1}^{n} \eta_{i.n}. \qquad (8)$$

Transmission efficiency coefficient η_{tro} changes depending on the torque, which is transferred by transmission. Increased transferred torque leads to an increase in the transmission efficiency coefficient (Chudakov 1972). On the basis of Eq. (8), where $\eta_{tro} = (1 - 0.04/0.8) \times 0.985 \times 0.985 \times 0.975 \times 0.975 \times 0.975 = 0.854$ (2 pairs of spiral gears and 3 pairs of cylindrical gears), 80% of the torque at rated speed ($M_n/M_k = 1/0.8$) is transferred (Chudakov 1972). Considering the fact that resistance of the implements is highly dependent upon soil type and condition, it was assumed that 80% of the torque at rated engine speed was transferred to the transmission in order to have the reserve moment that prevents engine overload. However, the presented model is flexible and can even be used to transfer 100% of the torque to the transmission. In addition, $\xi = (0.03 + 0.05)/2 = 0.04$ was chosen. In order to obtain the graphs in Figures 3 and 4, $G = 6210$ kg × 9.81 m s^{-2} = 60,920.1 N was used.

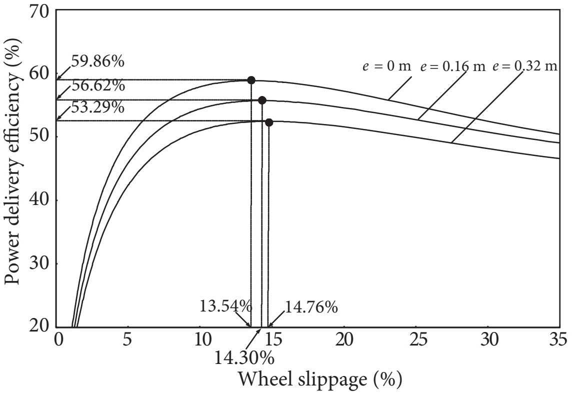

Figure 3. Power delivery efficiency dependence on tractor wheel slippage for different values of eccentricity (*e*). Maximum power delivery efficiency at corresponding wheel slippage in unplowed stubble.

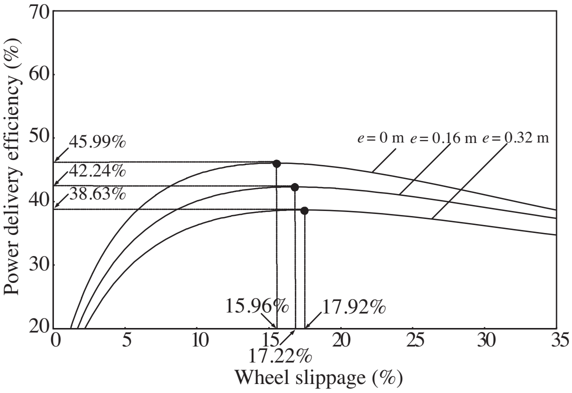

Figure 4. Power delivery efficiency dependence on tractor wheel slippage for different values of eccentricity (*e*). Maximum power delivery efficiency at corresponding wheel slippage in plowed stubble.

The traction performance of the test tractor (John Deere 6820 MFWD) was determined on unplowed and plowed stubble at central and eccentric traction. In order to express power delivery efficiency dependence on drawbar force (and later on wheel slippage) and eccentric traction, tractor velocity and wheel slippage dependence on drawbar force and eccentricity should be determined. By using the experimental data (Tables 3 and 4) on tractor velocity (v_s), drawbar force (F_{db}), and eccentricity (e) and by applying nonlinear regression analysis, the interdependence of the observed values was obtained. It is presented in Eqs. (9) and (10) for unplowed and plowed stubble, respectively:

$$v_s(F_{db}, e) = b_1 + b_2 \times F_{db} - b_3 \times F^2_{db} - b_4 \times e \qquad (9)$$

and

$$v_s(F_{db}, e) = b_1 - b_3 \times F^2_{db} - b_4 \times e\,. \qquad (10)$$

Considering the actual velocity data as a dependent variable and the drawbar force data as an independent variable (Tables 3 and 4), for each eccentricity it was concluded that these data could be approximated by a concave quadratic function, as presented in Eqs. (9) and (10) for unplowed and plowed stubble, respectively. It was also concluded that higher eccentricity implied lower actual velocity; therefore, term $-b_4 \times e$ was added.

On the basis of experimental data [wheel slippage (δ), drawbar force (F_{db}), and eccentricity (e)], it was concluded that wheel slippage could be expressed as a function of drawbar force and eccentricity:

$$\delta(F_{db}, e) = -\frac{1}{b_5}\times \mathrm{In}\left(-\frac{1}{b_6}\times\left(\frac{F_{db}\times(1+b_7\times e)}{G}-b_8\right)\right) \qquad (11)$$

where G is the weight of the tractor (N). Eq. (11) is actually a consequence of the following equation:

$$F_{db}(\delta, e) = \frac{G\times(b_8 - b_6 e^{-b_5\times\delta})}{1+b_7\times e}$$

which was formed based on the experimental data for each eccentricity, where drawbar force is a dependent variable and wheel slippage is an independent variable. It was concluded that the experimental data could be approximated by a function containing $-b_6 \times e^{-b5 \times \delta}$. Coefficients b_5 and b_6 influence the slope of $-b_6 \times e^{-b5 \times \delta}$, while coefficient b_8 is used for the graph translation. An increase in eccentricity reduces the drawbar force, which is why $b_7 \times e$ is a term in the denominator of the fraction. To avoid dividing by 0 (in case $e = 0$), 1 was added. Drawbar force directly depends on weight G of the tractor, and therefore G is in the nominator of the fraction.

Since P_{pto} depends on engine speed (m), based on the measured experimental data, it can be expressed as a concave quadratic function:

$$P_{pto}(m) = -b_9 \times m^2 + b_{10} \times m + b_{11} \tag{12}$$

In order to obtain P_{pto} in the function of wheel slippage (δ) and eccentricity (e), the following linear interdependence was determined:

$$\delta(m, e) = -b_{12} \times m + b_{13} + b_{14} \times e \tag{13}$$

where m is the engine speed (min^{-1}). Next, m from Eq. (13) was determined and used in Eq. (12). The estimation of empirical regression coefficients in Eqs. (9), (10), (11), (12), and (13) are given below. All necessary background for the algorithm presentation is provided in Figure 5.

Results

Research results confirmed that power delivery efficiency is dependent on soil surface and the proper attachment of the implement. The estimations of regression coefficients b_1, b_2, b_3, and b_4 are given in Tables 5 and 6 for unplowed and plowed stubble, respectively. The estimations of empirical regression coefficients b_5, b_6, b_7, and b_8 from Eq. (11) are given in Tables 7 and 8 for unplowed and plowed stubble, respectively. The estimations of empirical regression coefficients b_9, b_{10}, and b_{11} from Eq. (12) are given in Tables 9 and 10 for unplowed and plowed stubble, respectively. Finally, the estimations of empirical regression coefficients b_{12}, b_{13}, and b_{14} from Eq. (13) are given in Tables 11 and 12 for unplowed and plowed stubble, respectively. Validation of each regression equation is presented by R^2 in the corresponding Tables.

Graphs in Figures 3 and 4 were obtained using the algorithm (Figure 5) and the output result:

$$\eta_v(F_{db}, e) = \frac{F_{db} \times v_s(F_{db}, e)}{1000 \times P_{pto} \times (1+\eta_{tro} \times (\delta(F_{db}, e)-1)) + v_s(F_{db}, e) \times (f \times G + F_{db})} \times 100 \tag{14}$$

Function η_v, which depends on δ and e, should be formed using Eq. (14). Thus, v_s should be replaced with:

$$v_s(F_{db}, e) = 1.958 + 0.297 \times 10^{-4} \times F_{db} - 0.117 \times 10^{-8} \times F^2_{db} - 0.98 \times e \tag{15}$$

which is obtained from Eq. (9) by using the coefficients from Table 5. Using the coefficients from Table 7 and Eq. (11), F_{db} can be expressed as:

$$F_{db} = \frac{0.714 - 0.721 \times exp(-0.076 \times \delta)}{1 + 0.779 \times e} \times G \tag{16}$$

Finally, by inserting Eqs. (15) and (16) into Eq. (14), $\eta_v = \eta_v(\delta, e)$, where depends on δ and e, is obtained. For different values of eccentricity (e = 0 m, e = 0.16 m, e = 0.32 m), the equation defines, , $\eta_v(\delta, 0)$ $\eta_v(\delta, 0.16)$, and $\eta_v(\delta, 0.32)$ (Figure 3). Using the calculated values for power delivery efficiency from Eq. (14) (Table 3, last column), the coefficients of determination are R^2 = 97.62%, R^2 = 97.74%, and R^2 = 96.96% for $\eta_v(\delta,0)$ $\eta_v(\delta,0.16)$ and $\eta_v(\delta,0.32)$, respectively.

Similarly, the curves in Figure 4 were obtained by replacing $v_s(F_{db}, e)$ in Eq. (14) with

$$v_s(F_{db}, e) = 2.039 - 0.088 \times 10^{-8} \times F^2_{db} - 0.912 \times e \tag{17}$$

which was obtained from Eq. (10) using the coefficients from Table 6. Furthermore, F_{db} is expressed as follows after applying the coefficients from Table 8 to Eq. (11):

$$F_{db} = \frac{0.642 - 0.646 \times exp(-0.061 \times \delta)}{1 + 1.094 \times e} \times G \tag{18}$$

After inserting Eqs. (17) and (18) into Eq. (14), $\eta_v(\delta, 0)$, $\eta_v(\delta, 0.16)$, and $\eta_v(\delta, 0.32)$ were defined (Figure 4). Again, using the calculated values for

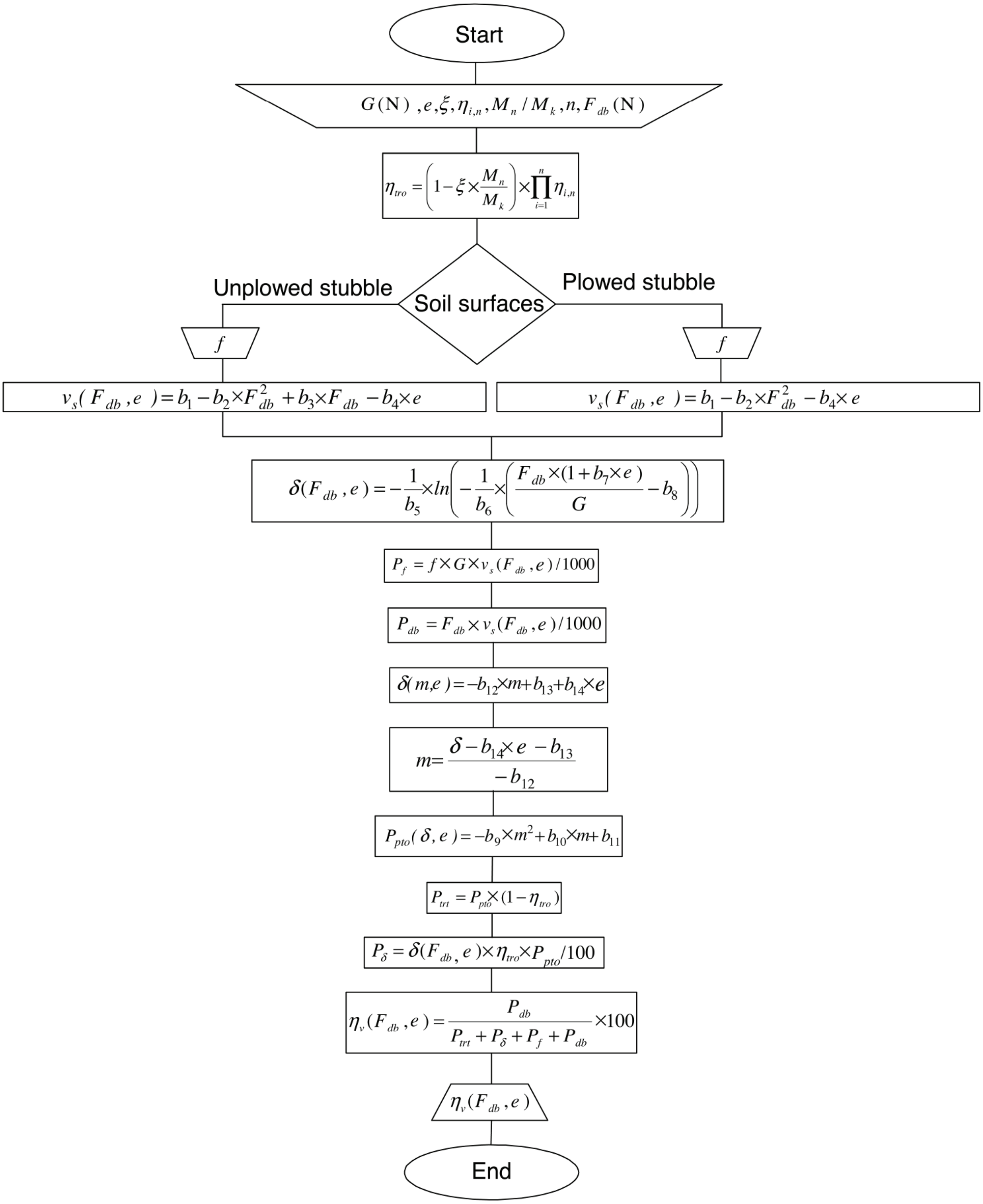

Figure 5. Calculation of power delivery efficiency of a wheeled tractor: algorithm. Labels: G - tractor weight, P_{pto} - PTO power, ξ - coefficient of torque at idle engine speed compared to the torque at rated engine speed, $\boldsymbol{\eta}_{i,n}$ - efficiency coefficient of the ith pair of the gear in transmission, n - number of gear pairs, M_n - torque at rated engine speed, M_k - transferred torque, F_{db} - drawbar force, e - eccentricity, $\boldsymbol{\eta}_{tro}$ - transmission efficiency coefficient in the load function, f - motion resistance coefficient, v_s - ground speed of tractor, $\boldsymbol{\delta}$ - wheel slippage, m - engine speed, P_f - loss of power due to motion resistance, P_{db} - drawbar power, P_{trt} - loss of power from the transmission to driving wheels, P_δ - loss of power from wheel slippage, and $\boldsymbol{\eta}_v$ - power delivery efficiency.

Table 5. Regression coefficients for Eq. (9) on unplowed stubble.

Level of confidence: 95.0%, determination coefficient: $R^2 = 95.17\%$.				
	Estimation	t-test	Confidence interval	F-test
b_1^*	1.958	32.33	(1.826, 2.090)	3241.4
b_2^*	0.297×10^{-4}	4.289	$(0.146 \times 10^{-4}, 0.448 \times 10^{-4})$	
b_3^*	0.117×10^{-8}	7.017	$(0.081 \times 10^{-8}, 0.153 \times 10^{-8})$	
b_4^*	0.980	8.076	(0.716, 1.244)	

*Significant coefficients at significance level of $P < 0.05$.

Table 6. Regression coefficients for Eq. (10) on plowed stubble.

Level of confidence: 95.0%, determination coefficient: $R^2 = 89.87\%$.				
	Estimation	t-test	Confidence interval	F-test
b_1^*	2.039	33.26	(1.907, 2.172)	1010.5
b_3^*	0.088×10^{-8}	10.56	$(0.070 \times 10^{-8}, 0.106 \times 10^{-8})$	
b_4^*	0.912	4.217	(0.445, 1.380)	

*Significant coefficients at significance level of $P < 0.05$.

Table 7. Regression coefficients for Eq. (11) on unplowed stubble.

Level of confidence: 95.0%, determination coefficient: $R^2 = 99.69\%$.				
	Estimation	t-test	Confidence interval	F-test
b_5^*	0.076	15.99	(0.066, 0.087)	2772.3
b_6^*	0.721	44.98	(0.686, 0.756)	
b_7^*	0.779	23.40	(0.707, 0.852)	
b_8^*	0.714	52.08	(0.684, 0.744)	

*Significant coefficients at significance level of $P < 0.05$.

Table 8. Regression coefficients for Eq. (11) on plowed stubble.

Level of confidence: 95.0%, determination coefficient: $R^2 = 98.29\%$.				
	Estimation	t-test	Confidence interval	F-test
b_5^*	0.061	6.665	(0.041, 0.081)	947.0
b_6^*	0.646	19.37	(0.573, 0.718)	
b_7^*	1.094	6.307	(0.716, 1.472)	
b_8^*	0.642	15.85	(0.554, 0.730)	

*Significant coefficients at significance level of $P < 0.05$.

Table 9. Regression coefficients for Eq. (12) on unplowed stubble.

Level of confidence: 95%, determination coefficient: R^2 = 97.83%.				
	Estimation	t-test	Confidence interval	F-test
b_9^*	0.335×10^{-3}	9.515	$(0.259 \times 10^{-3}, 0.411 \times 10^{-3})$	47,851.9
b_{10}^*	1.303	9.220	(0.997, 1.608)	
b_{11}^*	-1168.5	-8.250	(-1474.4, -862.5)	

*Significant coefficients at significance level of $P < 0.05$.

Table 10. Regression coefficients for Eq. (12) on plowed stubble.

Level of confidence: 95%, determination coefficient: R^2 = 95.67%.				
	Estimation	t-test	Confidence interval	F-test
b_9^*	0.153×10^{-3}	5.151	$(0.089 \times 10^{-3}, 0.217 \times 10^{-3})$	
b_{10}^*	0.582	4.787	(0.319, 0.843)	43,649.7
b_{11}^*	-452.7	-3.657	(-720.2, -185.3)	

*Significant coefficients at significance level of $P < 0.05$.

Table 11. Regression coefficients for Eq. (13) on unplowed stubble.

Level of confidence: 95%, determination coefficient: R^2 = 92.58%.				
	Estimation	t-test	Confidence interval	F-test
b_{12}^*	0.116	12.72	(0.096, 0.135)	
b_{13}^*	245.4	13.43	(205.9, 284.9)	163.8
b_{14}^*	12.67	2.174	(0.079, 25.25)	

*Significant coefficients at significance level of $P < 0.05$.

Table 12. Regression coefficients for Eq. (13) on plowed stubble.

Level of confidence: 95%, determination coefficient: R^2 = 87.02%.				
	Estimation	t-test	Confidence interval	F-test
b_{12}^*	0.115	9.258	(0.088, 0.142)	
b_{13}^*	247.7	9.857	(193.4, 302.0)	99.38
b_{14}^*	20.61	2.274	(1.032, 40.196)	

*Significant coefficients at significance level of $P < 0.05$.

power delivery efficiency from Eq. (14) (Table 4, last column), the coefficients of determination are R^2 = 98.86%, R^2 = 92.79%, and R^2 = 90.41% for $\eta_v(\delta, 0)$, $\eta_v(\delta, 0.16)$, and$\eta_v(\delta, 0.32)$, respectively.

Table 13 shows the maximum power delivery efficiency on unplowed and plowed stubble for the corresponding values of wheel slippage, actual velocity, drawbar force, and eccentricity. For example, in the case of central traction (on unplowed stubble, e = 0), function $\eta_v(\delta,0)$ from Eq. (14) reaches its maximum of 59.86% for δ = 13.54%. Eq. (16) defines F_{db} (13.54,0) = 27,847.5 N, and Eq. (15) defines v_s (27,847.5,0) = 1.878 m s^{-1}. The data obtained are in accordance with other research results (Nikolić 1983; Nikolić at el. 1994; Nikolić et al. 2007).

The best power delivery efficiency of the tractor on unplowed and plowed stubble was observed at central traction. The maximum power delivery efficiency on unplowed stubble decreased by 5.72% if eccentricity was increased to 0.16 m, and it decreased by 12.33% if eccentricity was increased to 0.32 m. The power delivery efficiency of the tractor on plowed stubble decreased by 8.88% if eccentricity was increased to 0.16 m and it decreased by 19.05% if eccentricity was increased to 0.32 m.

Different surfaces influencing the change in the power delivery efficiency of tractors indicated the following:

- Maximum power delivery efficiency of the tractor on plowed stubble decreased by 30.16% in comparison to the maximum power delivery efficiency of the tractor on unplowed stubble at e = 0 m.
- Maximum power delivery efficiency on plowed stubble decreased by 34.04% in comparison to unplowed stubble at e = 0.16 m.
- Finally, if e = 0.32 m, maximum power delivery efficiency of the tractor on plowed stubble decreased by 37.95% in comparison to unplowed stubble.

Figure 6 shows the dependence of tractor power delivery efficiency on eccentricity for F_{db} = 20,000 N. The curves in Figure 6 were obtained from Eq. (14) by using Eq. (15) instead of $v_s(F_{db}, e)$ for F_{db} = 20,000 N, when the chosen soil type is unplowed stubble. Here, it must be mentioned that in Eq. (14) should be replaced with:

$$\delta(F_{db}, e) = -\frac{1}{0.076} \times \text{In}\left(-\frac{1}{0.721} \times \left(\frac{F_{db} \times (1 + 0.779 \times e)}{G} - 0.714\right)\right) \tag{19}$$

which is formed by applying the coefficients from Table 7 to Eq. (11). In the case of plowed stubble, the function in Eq. (14) should be replaced by Eq. (17), again for F_{db} = 20,000 N. Here, becomes:

$$\delta(F_{db}, e) = -\frac{1}{0.061} \times \text{In}\left(-\frac{1}{0.646} \times \left(\frac{F_{db} \times (1 + 1.094 \times e)}{G} - 0.642\right)\right) \tag{20}$$

which is formed by applying the coefficients from Table 8 to Eq. (11).

Table 13. Maximum power delivery efficiency η_v for various eccentricities (e).

Soil type	Maximum η_v (%)	At wheel slippage (%)	At velocity (m s^{-1})	At drawbar force (N)	Eccentricity (m)
Unplowed stubble	η_v = 59.86	δ = 13.54	v_s = 1.878	F_{db} = 27,847.5	e = 0
	η_v = 56.62	δ = 14.30	v_s = 1.797	F_{db} = 25,582.4	e = 0.16
	η_v = 53.29	δ = 14.76	v_s = 1.699	F_{db} = 23,439.4	e = 0.32
Plowed stubble	η_v = 45.99	δ = 15.96	v_s = 1.518	F_{db} = 24,326.5	e = 0
	η_v = 42.24	δ = 17.22	v_s = 1.480	F_{db} = 21,643.9	e = 0.16
	η_v = 38.63	δ = 17.92	v_s = 1.420	F_{db} = 19,262.8	e = 0.32

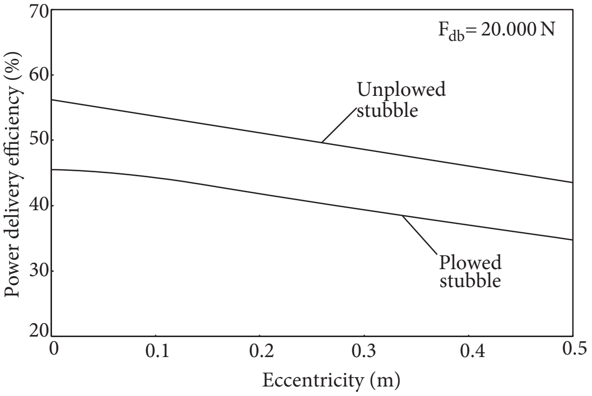

Figure 6. Power delivery efficiency dependence on eccentricity on unplowed and plowed stubble (F_{db} = 20,000 N).

Discussion

The test tractor achieved maximum power delivery efficiency at central traction (*e* = 0) on stubble, and it was 59.86% at slippage of 13.54% (Figure 3). With regard to the obtained results, other research showed higher or lower values for power delivery efficiency depending on the type of tractor and soil surface. Belorussian tractors MTZ 1221 (MFWD) and MTZ 1523 (MFWD), which have power and weight similar to that of test tractor JD 6820, achieved maximum power delivery efficiencies of 54.20% (MTZ 1221) and 53.30% (MTZ 1523) at 20% slippage on unplowed stubble (http://www.ortz.ru/info3.php?id=mtz1). Tractor HTZ 17221 (4WD) achieved a maximum power delivery efficiency of 66.8% at 8.29% slippage on stubble (Samorodov and Rebrov 2008).

The maximum power delivery efficiency that the test tractor achieved on plowed stubble was at central traction (*e* = 0), although it was lower in comparison to the unplowed stubble and it was 45.99% at 15.96% slippage. Nikolić (1983) also emphasized that maximum power delivery efficiency depends on surface conditions and moisture. He determined that the MFWD tractor type had maximum power delivery efficiency of 63.50% at 12.04% slippage on unplowed stubble and a power delivery efficiency of 48.50% at 16.40% slippage on plowed stubble.

Increased eccentricity at the drawbar reduced power delivery efficiency of the tested tractor on the examined soil surfaces. This was also confirmed by Stjelja (2002), who compared the influence of eccentric traction on the power delivery efficiency of a John Deere 4755 tractor on unplowed and plowed stubble. He found that at *e* = 0.32 m, power delivery efficiency was reduced by 17.1% on unplowed stubble and 23% on plowed stubble.

Maximum power delivery efficiencies increased as soil moisture decreased and soil firmness increased. It ranged from 58% in wet secondary tillage conditions to 80% in dry primary tillage conditions (Turner 1999).

Casady (1997) claimed that the highest drive wheel tractive efficiency can be achieved on concrete, followed by firm soil (stubble, soybean field, sunflower field), tilled, and soft or sandy soil. It should be mentioned that drive wheel tractive efficiency is proportional to the power delivery efficiency of tractor (Zoz and Grisso 2003).

For MFWD and belted tractors, Shell et al. (1997) discovered that power delivery efficiency increased by 6.2% on untilled surfaces compared to tilled surfaces. They showed a 6.1% power delivery efficiency advantage in sandy soils over clay soils.

Higher power delivery efficiency can undoubtedly be achieved if radial front tires are used instead of bias-ply (Al-Hamed 1994; Casady 1997). Generally, tractor manufacturers mix radial rear tires with bias-ply front tires, although one manufacturer does not encourage mixing. A limited number of radial tires are produced in the sizes needed for MFWD, and therefore mixing is often necessary (Grisso 1995).

In conclusion, the dependence of power delivery efficiency on soil characteristics and eccentric traction was observed. The efficiency of tractor systems, when the traction force is transferred onto the implement through the drawbar, is expressed as the power delivery efficiency of a tractor. A mathematical model was developed for the evaluation of power delivery efficiency. The best power delivery efficiency of tractors on both unplowed and plowed stubble surfaces was observed with central traction.

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