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Theoretical research into the power and energy performance of agricultural tractors

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Abstract. The widespread use of a great number of different types and manufacturer brands of tractors in agricultural use raises several important questions. These all concern the implementation of the criteria which may be involved in making the right choice in regard to a particular power unit that is capable of delivering the required result during the subsequent course of that unit's service life. Even more importantly, the result should be an economically sound one. Despite the fact that tractor theory offers a sufficient number of scientifically grounded criteria that characterise agricultural power units with respect to their particular properties, the engine power rating remains the most widely used and decisive figure – and the factor which defines the ultimate choice of power unit. Meanwhile, the traction properties of tractors, especially in case of wheeled tractors, should be of prime importance as these properties determine the maximum measures that can be taken in relation to efficiency levels in power units as parts of various unitised agricultural machines. Currently, in most areas around the world, the traction and energy performance of wheeled tractors is determined using the same common method, one which is based upon the tractor's power balance. But when taking into account the ever-increasing requirements for protecting the soil, the aforementioned method needs corresponding upgrading with respect to the destructive effect of the wheeled running gear of agricultural tractors on the soil's structure. The aim of this study is to develop a new method of determining the minimum required engine power rating for an agricultural wheeled tractor, as well as its operating mass and energy saturation rate when considering the linear type of dependence for its running gear slipping due to the tractive force being generated. The research utilises standard tractor theory and numerical computation methods. The completed study resulted in several updated and new analytical dependences, all of which can be used to define the tractive power of a wheeled tractor, taking into account the linear type of relationship between wheel slip, operating mass, and energy saturation rate. The data that is obtained through computational methods show that the classification of various wheeled tractors with regard to their traction or their traction and power category using the new method will subsequently allow more accurate calculations to be effected when it comes to unitising various agricultural machines, which should help to ensure an improvement in their overall performance levels.

Key words: tractor (agricultural), engine power, drawbar pull force, wheel slip, operating mass, energy saturation rate.

INTRODUCTION

The large number of different types and brands of tractors which are being widely employed in today's agricultural work raises several questions when it comes to the implementation of the criteria that permit the correct choice when it comes to a particular power unit. This is highly important as, when it is applied to agricultural production, it will provide the required results in terms of operation and, even more importantly, an economically sound result (Kutzbach, 2000; Nadykto et al., 2015). Currently, the theory behind tractor usage offers a sufficient number of scientifically grounded criteria that characterise agricultural power units with respect to their particular properties. That said, one of these characteristic values is used most widely and, in the majority of cases, it decides and determines the choice of a particular tractor – this being its engine power rating. Meanwhile, traction properties, which also characterise tractors, especially wheeled tractors, should in many cases be of prime importance since they determine the maximum measures in relation to the efficiency levels that these tractors will provide as parts of various unitised agricultural machines (Zoz & Brixius, 1979; Serrano, 2007; Šmerda & Cupera, 2010; Turker et al., 2012). Presently, the traction and energy performance of wheeled tractors is determined using virtually the same method, one which is based upon the tractor's power balance. But when taking into account the ever-increasing requirements in relation to protecting the soil (Godwin, 2007), and its structure and fertility, the aforementioned method needs corresponding updating with respect to the intensive destruction caused to the soil's structure by the wheeled running gear of agricultural tractors.

A method has been proposed in various papers for determining a tractor's minimum required operating mass (Boikov et al., 1997; Nadykto, 2014a), this mass being W_{tr} (kg) and its engine power rating N_e, (kW), basing this on the analysis of general power balance in terms of the present day understanding of the latter (Kutkov, 2004). A characteristic feature of this method is the due consideration given to the non-linear dependence of the power unit's running gear slip rate δ on the drawbar pull P_{dp}, (N) which is delivered by it. (Wong & Huang, 2006; Tiwar et al., 2010; Monteiro et al., 2013; Cutini & Bisaglia, 2016).

It should be noted that such a point of view of the function $\delta = f(P_{dp})$ has been and still remains undisputed within general tractor theory (Zoz and Grisso, 2003; Kutkov, 2004; Gil-Sierra et al., 2007; Nastasoiu & Padureanu, 2012; Turker et al., 2012; Abraham et al., 2014; Simikič et al., 2014). The maximum slip rate δ of the running gear on a wheeled tractor is restricted in this case to the value that provides its highest traction and energy performance levels, which usually reaches between 22% and 24% (Guskov et al., 1988; Moitzi et al., 2014). At the same time, in order to ensure that the soil's structure remains intact, the slip of a wheeled power unit may not exceed a level between 9% and 15%, as stated in the paper by Nadykto (2014b), at least in the spring and summer campaign period. If we take into account the fact that the great majority of state-of-the-art wheeled tractors produced across the world are all-wheel drive vehicles, which inherently implies better holding properties, then we face the need to revise the currently established point of view when it comes to the behaviour of the dependence $\delta = f(P_{dp})$.

The development of a new method for determining the minimum required engine power rating for an agricultural wheeled tractor, as well as its operating mass and energy saturation rate, subject to the linear type of dependence for its running gear slippage rate on the generated tractive force.

MATERIALS AND METHODS

The study was conducted using tractor theory, along with appropriate software development and numerical computation.

Based on the general provisions that have been stated in a previous paper (Nadykto, 2014b), the slip rate δ for the running gear of a wheeled tractor can be analysed exclusively in its linear interpretation, specifically:

$$\delta = A\frac{P_{dp}}{W_{tr}g} + B, \quad (1)$$

where A, B are approximation constants for the tractor running gear slip process which is represented in the form of a straight line; g is free fall acceleration.

However, this approach changes the nature of the tractor propulsion efficiency. It turns out that under certain conditions, especially in practice, its maximum (optimum) value can be altogether unattainable (Bulgakov et al., 2015). At the same time, the currently effective scientific provisions for the tractor theory r and machine usage stipulate that the maximum productivity of a machine and tractor unit can be achieved at the maximum propulsion efficiency of the tractor. The productivity of a machine and tractor unit is in its turn conditioned by such rated values for the power unit as its operating mass and engine power rating. This implies that, under the linear form of dependence $\delta = f(P_{dp})$, the method of determining these principal parameters for the tractor will become totally different. An examination of the main points of the said method is the topic of this study.

As with the work carried out in a previous paper (Nadykto, 2014a), and taking into account the methodical approaches laid down in (Kutkov, 2004), the equation for the tractor's power balance has to be set up for the consequent theoretical analysis, retaining the four main components of the power balance N_e for the power unit, ie. the agricultural wheeled tractor, which will result in the following power balance equation:

$$N_e = N_{dr} + N_{tr} + N_\delta + N_{mr}, \quad (2)$$

where N_{dr} is the tractive power of the tractor itself; N_{tr}, N_δ, N_{mr} are the power rates that specify energy consumption by friction in the transmission, the slip of the running gear, and the rolling resistance of the power unit.

Each component in the formula (2) can be expressed as follows, in the form of a set of analytical dependences:

$$\begin{aligned} N_{dr} &= P_{dp} \cdot V = P_{dp.n} \cdot (1 + 3 \cdot V_x) \cdot V, \\ N_{tr} &= (1 - \eta_{tr}) \cdot N_e, \\ N_{mr} &= f \cdot W_{tr} \cdot g \cdot V, \\ N_\delta &= (f \cdot W_{tr} \cdot g + P_{dp}) \cdot \delta \cdot V. \end{aligned} \quad (3)$$

The following designations are assumed in the presented equations (3): V is the operating speed of the tractor as part of the particular machine and tractor unit; $P_{dp.n}$ is the rated drawbar pull of the tractor; V_x is the coefficient of variation in the power unit's traction load; η_{tr} is the efficiency coefficient in the tractor's transmission; and f is the rolling resistance coefficient of the power unit.

After substituting the dependences (1) and (3) into the equation (2) and making the respective transformations, the value N_e will be presented as follows:

$$N_e = \frac{W_{tr}^2 D_2 + W_{tr} D_1 + D_0}{W_{tr} D_3}, \tag{4}$$

where
$$D_0 = \frac{A\left[P_{dp.n}(1+3V_x)\right]^2 V}{g},$$

$$D_1 = P_{dp.n}(1+3V_x)V(1+B+fA),$$

$$D_2 = fgV(1+B), \qquad D_3 = \eta_{tr}.$$

RESULTS AND DISCUSSIONS

The optimum value for the tractor's operating mass can be established by means of solving the partial derivative $\frac{\partial N_e}{\partial W_{tr}} = 0$. This results in the following presentation of the tractor's operating mass:

$$W_{tr} = \frac{P_{dp.n}(1+3V_x)}{g}\sqrt{\frac{A}{f(1+B)}}. \tag{5}$$

After finding the tractor's operating mass from the formula (5), and substituting it into the expression (4), its minimum required engine power rating can be calculated.

To start off, it can be concluded from the analysis of the formula (5) that, when the tractor's coefficient of rolling resistance f increases, its operating mass W_{tr} should decrease. In effect, this is not the case and the reason is as follows. The rising coefficient f implies the deteriorating conditions of adhesion between the power unit's running gear and the soil. When the moisture content of the soil is normal, this effect can also take place because the soil itself is considerably loosened. This is why the tractor's coefficient for rolling resistance f is always lower on hard soil (for example, on stubble), than it is on tilled soil (for example, soil that has been prepared for planting).

The path of a tractor that is travelling with the same pulling force on hard soil as it is on loosened soil will, in the latter case, feature a greater degree of running gear slippage. Analytically speaking, this will be added to the picture through the respective values of the aforementioned approximation constants, A and B.

The results of the analysis of traction performance for a number of wheeled tractors indicates that the growth of the coefficient A has the greatest effect on the value W_{tr}, which is something that cannot be said about the growth of the coefficients f and especially B. Moreover, the rate of growth for the approximation constant A prevails to such an extent that, as a result, with the parameters $P_{dp.n}$ and V_x in the formula (5) remaining unaltered and the value of the tractor's rolling resistance coefficient f increasing, its operating mass W_{tr} will grow.

The necessary and most desirable level of reliability in the application of the formulae (4) and (5) for specific calculations can be achieved only in the case of a sufficient quantity of data being available with respect to the values of constants A and B for the linear approximation of slippage in the running gear of a wheeled tractor under the conditions of having to function on different types of cultivated land. So far, no one has managed to obtain any such traction performance data for tractors.

Nonetheless, despite this fact we will try and apply the formulae (4) and (5) for actual calculations. For this purpose, the values for the components of these expressions first have to be set. This applies to the upper limit for the operating travel speeds of machine and tractor units. In the course of practical operation, it has been revealed that the average value of that parameter for the majority of state-of-the-art tilling and sowing agricultural machine and tractor units is approximately equal to 9 km h^{-1}. In this case, the coefficient of the tractor's traction load variation can have a value that is between 12% and 18% (Guskov et al., 1988). Taking that into account, the value $V_x = 0.15$ will be assumed for the calculations.

Furthermore, as an example, consideration will be given to the wheeled power units in traction category three, which are fairly common on European farms. They have integrated design layouts, and locked wheel drives on the front and rear axles. According to data that has been obtained from the drawbar tests on a broken stubble field at a coefficient of rolling resistance of $f = 0.11$ and a maximum running gear slip of 12%, their average rated drawbar pull is $P_{dp.n} = 32$ kN. The coefficients for the approximation of the slippage process for these tractors in the form of a straight line are as follows: $A = 0.301$; $B = 0.001$. The transmission efficiency factor is $\eta_{tr.t} = 0.93$ (Kutkov, 2004).

The results of the computation for the formula (5) show that, with such basic data, the operating mass of a traction category three tractor should be 7.8 t. This is at least 0.3 t less than the actual operating mass of those power units that are produced by most of the manufacturers in Europe.

For a comparison, the authors of a past paper (Guskov et al., 1988) propose that the tractor's operating mass be estimated using the following formula:

$$W_{tr} = \frac{\Delta_{\lim} \cdot F_{kr.n}}{\left(\varphi_{dop} - f\right) g} \tag{6}$$

where $\Delta_{\lim}$ is a factor of the tractor's potential tractive effort overload. In this case $\Delta_{\lim} = 1 + 3V_x$; $F_{kr.n}$ is the rated tractive effort of the power unit, ie. it is equal to $P_{dp.n}$; φ_{dop}, the adhesion coefficient of the between the tractor's running gear and the soil which is acceptable under the existing agrotechnical conditions. The maximum value of this parameter as suggested by previous authors (Guskov et al., 1988), ie. $\varphi_{dop} = 0.75$, will be assumed.

With the following initial data: $V_x = 0.15$; $F_{kr.n} = P_{dp.n} = 32$ kN; $\varphi_{dop} = 0.75$ and $f = 0.11$, it follows from the formula (6) and the data that has been obtained by computation on a PC that the operating mass of a traction category three tractor has to be equal to 7.4 t. This is only 400 kg less than its value as obtained in our computation of the formula (5).

As regards engine power, the minimum rating here has to be almost 174 kW (ie. 237 hp), which follows from the calculations with the use of the formula (4). A detailed account of the method used in selecting the full engine power rating of the tractor is given in a previous paper (Nadykto, 2014a).

It should be stressed that, currently, this rating at its maximum value for traction category three tractors is equal to a mere 175 hp to 180 hp, which is 26% below the estimated level. It has been proven thanks to the operating practice employed by the majority of agricultural wheeled tractors in traction category three that it is the shortfall of their engine power that curbs the speed performance of these power units in state-of-the-art tillage and crop sowing. This has an adverse effect on both the productivity and the economic feasibility of the farm operations which they carry out.

Apart from the operating mass W_{tr} and engine power rating N_e, there is one more important design parameter for a tractor, which is its energy saturation rate E_{tr}. Analytically speaking, a wheeled tractor's energy saturation rate can be represented by the following expression:

$$E_{tr} = \frac{N_e}{W_{tr}} = \frac{W_{tr}^2 \cdot D_2 + W_{tr} \cdot D_1 + D_o}{W_{tr}^2 \cdot D_3}. \quad (7)$$

According to the formula (7), a wheeled tractor's energy saturation rate has a dimension of (kW t^{-1}). Recently, a number of authors have been considering this parameter as the ratio between the tractor's engine power rating and its operating weight (Kutkov, 2004; Rebrov & Samorodov, 2010). In that case the dimension is (kW $(kN)^{-1}$). It is easy to show that the latter dimension represents the translational velocity of the tractor, ie. in effect the dimension is (m s^{-1}).

Our opinion is that the dimension (kW t^{-1}) better reveals the essence of the energy saturation rate E_{tr}, by showing how much of the tractor's engine power N_e is accounted for as a unit of its mass. At the same time, the dimension of (m s^{-1}) provides little information since the translational velocity of the tractor as part of a particular machine and tractor unit can be limited not by the power unit's engine potential, but by the agronomical and/or other requirements.

It is emphasised in a study by Nadykto (2012) that a tractor with an energy saturation rate of 14–15 kW t^{-1} is a traction concept power unit; in the case of higher energy saturation rates the traction and power concept is applicable. The latter stipulates that designers of agricultural tractors have to develop a system that utilises via various parts of the machine and tractor unit that part of the engine power which cannot be utilised through the drawbar pull.

The calculations for the formula (7) have shown that in order for a tractor as part of a particular machine and tractor unit to be able to utilise a tractive effort of 32 kN at an operating speed of 9 km h^{-1} and the linear form of the dependence of its running gear slipping on the tractive force, the energy saturation rate for the tractor has to be at a level of 22.3 kW t^{-1}. With that figure in mind, the tractor becomes a power unit that fulfils the traction and power concept. Meanwhile, in practice the power units in the overwhelming majority of traction category three wheeled tractors still remain exponents of the traction concept, since their energy saturation rate E_{tr} remains within 16 kW t^{-1}.

As the parameter E_{tr} is determined by the ratio between the tractor's installed engine power and its operating mass, it remains constant over the whole service life of the power unit. Or at least over a time interval within which the value N_e remains constant.

When the tractor's traction load is variable (which turns out always to be the case), in practice its installed engine power cannot be utilised completely, as stated by Kutkov (2004). That implies that the tractor's energy saturation rate is a potential property and, as opposed to the statement by Rebrov & Samorodov (2010), it does not depend on the mode of travel for the machine and tractor unit. It can only be changed by installing in the tractor an engine which has another power rating or by ballasting the power unit, or applying the first and second measures simultaneously. In terms of the compacting effect on the soil medium, the overall prospects of tractor ballasting are rather poor and this approach is undesirable even if the tractor is designed in accordance with the principles of traction and power. This problem is further examined in a study by Nadytko (2013).

CONCLUSIONS

When a certain level of drawbar pull ($P_{dp.n}$), in mode (V, V_x) and under the conditions (f, A, B) in the operation of a wheeled tractor are targeted, the formula (5) enables the operating mass E_{tr} to be determined, while the expression (4) stipulates the minimum required engine power rating N_e.

When operating within these specifications it is possible to specify the train of agricultural machines or implements that need to be unitised with a tractor that features such principal design parameters, subject to the linear type of slip rate variation which it may experience with the generated tractive force. The principles of selecting the composition of the machine and tractor unit for a particular rated drawbar pull of tractor are commonly known.

The tractor's energy saturation rate as the ratio between the installed engine power rating and the operating mass of the power unit is the criterion of its belonging either to the traction or the traction and power concepts, each of which feature their own system of unitising agricultural equipment. This criterion should be understood by the designers of any new mobile power units for operation in the agricultural industry.

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