SMALL POWER ELECTRIC TRACTOR PERFORMANCE DURING PLOUGHING WORKS
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PERFORMANŢELE UNUI TRACTOR ELECTRIC DE PUTERE MICĂ ÎN TIMPUL LUCRĂRILOR DE ARAT

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ABSTRACT

Taking into consideration the current trend to mitigate the agriculture's negative impact on the environment, this implies using new technologies and equipment for performing agricultural works. Currently, the most used equipment in agriculture is the agricultural tractor with heat engine. One alternative is represented by electric motors, usually powered by batteries. The main advantage for the environment is that zero emissions are released into the atmosphere during agricultural works. Another advantage consists of the nominal torque which could be sustained from almost zero revolutions of the electric motors resulting in lower loads on the batteries with a proper mechanical transmission. Ploughing represents the agricultural work which exploits most of the performances of an agricultural tractor, in terms of fuel consumption and engine wear. Within this paper are presented the tests performed on an electric tractor during ploughing works, at different depths and with different working speeds, in order to assess its autonomy and efficiency with a single battery charge. The electrical parameters of the tractor were recorded during tests, as well as the tractor draft force. The results were used to establish the optimal working regime of the electric tractor during ploughing works.

REZUMAT

Luând în considerare tendința actuală de atenuare a impactului negativ al agriculturii asupra mediului, aceasta implică utilizarea de noi tehnologii și echipamente pentru efectuarea lucrărilor agricole. În prezent, cel mai utilizat echipament în agricultură este tractorul agricol cu motor termic. O alternativă este reprezentată de motoarele electrice, de obicei alimentate cu baterii electrice. Principalul avantaj pentru mediu este că zero emisii sunt eliberate în atmosferă în timpul lucrărilor agricole. Un alt avantaj constă în cuplul nominal care ar putea fi susținut de la rotații aproape de zero ale motoarelor electrice, ceea ce duce la sarcini mai mici pe baterii cu o transmisie mecanică adecvată. Aratul reprezintă munca agricolă care exploatează cea mai mare parte a performanțelor unui tractor agricol, în ceea ce privește consumul de combustibil și uzura motorului. În cadrul acestei lucrări sunt prezentate testele efectuate pe un tractor electric în timpul lucrărilor de arat, la adâncimi diferite și cu viteze diferite de lucru, pentru a evalua autonomia și eficiența acestuia cu o singură încărcare a bateriei. Parametrii electrici ai tractorului au fost înregistrați în timpul încercărilor, precum și forța de tragere susținută de tractor. Rezultatele au fost utilizate la stabilirea regimurilor optime de funcționare a tractorului electric la lucrarea de arat.

INTRODUCTION

Research and innovation in the bioresources production domain using renewable and clean energy sources will allow digital agriculture to respond to the increasing nutrition needs at international level while mitigating the negative impact on the environment produced by anthropic actions. Thus, worldwide the agricultural machinery producers, especially tractors developers, started designing agricultural tractors which are using hybrid or entirely electric drive systems instead of classic heat engines (*Moreda G.P. et al., 2016*). The use of non-polluting energy has risen as a necessity to the international effort to reduce air, soil and water pollution. Developers of electric tractors are consecrated large firms, with many years of experience in the field (John Deere, Fendt, Escorts Group, etc.), but also start-ups having the main purpose to develop electric vehicles (Soletrac, etc.). According to *https://www.fwi.co.uk/arable/analysis-electric-technology-set-kill-off-*

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diesel-tractors, electric tractors provide three key advantages: increased efficiency (a diesel engine converts thermal to mechanical energy with approximately 35% efficiency while electric motors have an efficiency of 90%), many more opportunities for optimal control and automation given by usage of electric power and finally, the possibility to use renewable energy. Especially for isolated farms, producing electric energy directly on site, using wind, photovoltaic solar or biodigestion energy sources and storing it (*Maican A. et al, 2019*), could be a real source for electric tractors' batteries recharge so that the diesel fuel transportation problems is avoided.

The advantages of using electric engines for tractor propulsion are multiple: zero emissions, possibility of batteries recharge from mobile stations which are using renewable energy (from wind power or photovoltaic panels), reduced noise and vibrations in exploitation, high torque for a wide range of rotating speeds, costs consumption optimization for an agricultural farm. The major disadvantage consists of the reduced autonomy together with the relatively long recharging time for classic batteries and high costs for battery replacement. Taking into consideration these aspects, the issue regarding the autonomy and efficiency of such an electric tractor used for high energy consuming agricultural works like ploughing has to be approached.

During ploughing or tilling the soil characteristics are not homogenous, fact that leads to changing soil resistance which affects the necessary torque at the wheel, forcing the driver to accelerate in order to compensate the traction power loss (*Guo H. et al., 2017*). The amount of travel reduction ratio or slippage has to be measured in order to obtain the actual drawbar power needed for the work (*Vladut D.I. et al., 2018*).

Xie, Zhang, Chen, Mao and Du (2015) constructed an agricultural machine endowed with an industrial DC motor and performed ploughing tests in different types of soils. The obtained results concluded that as the working depth of the plough increased, the electric motor torque oscillated with great amplitudes corelated with the soil resistance heterogeneity (*Xie B. et al., 2015*). Thus, the research led to finding various ways to design and optimize the drive train system of such electric tractors (*Xiaofei Z., 2017; We Z. et al, 2019*).

This paper presents the results obtained during various tests performed with an experimental model electric tractor during ploughing for different working conditions. The results regarding the tractor's autonomy and transmission efficiency allowed for an optimal choice of the working regime. The paper highlights the fact that tractor with electric propulsion could achieve the same performance, if not better, than the heat engine tractor, having less negative impact on the environment.

MATERIALS AND METHODS

The experiments were conducted on a 28.8 kW experimental model of agricultural electric tractor developed by INMA Bucharest with rear wheels traction. The 17.28 kWh electric battery powering the tractor was fitted with an ORION battery management system (BMS) with possibility of recording the instantaneous power consumption during works. The advantage of the electric motor used for propelling the tractor compared to the diesel one comes from the maximum output torque, even at very low revolutions per minute. The tractor was also endowed with a mechanical transmission with 8 forward gears or reverse shift which allowed for a minimum travel speed of 1.71 km/h and maximum of 26 km/h for a nominal rotational speed of the electric motor of 2350 s^{-1}. The weight of the tractor was 1210 kg. For experiments a 2-coulter reversible plough was chosen, which was set for a working width of 0.5 m and a maximum working depth of 0.2 m.

Fig. 1 - Experimental model of electric tractor with plough mounted on

In order to measure the draft force during ploughing, several strain gauges were placed on the plough frame. The data acquisition system used during the tests for draft force recording was a QuantumX 1615 amplifier. In view of calibrating the strain gauges for draft force measurement, a calibration test was performed in laboratory using a 10 kN hydraulic cylinder which loaded the plough in longitudinal direction while fixed to a test rig which simulated the tractor three-point linkage system.

The values recorded by strain gauges for 2÷10 kN excitation forces were used to calculate the gain and offset factors which should be used in order to measure in real time the draft force necessary for the ploughing process.

We used the 3^k factorial design to prepare the experiments, a factorial arrangement with k factors, each at three levels. (*Montgomery D.C., 2013*). We took into consideration 2 factors: working depth and speed, each at three levels: low, intermediate, and high. So, we imposed 3 mean depths for the plough combined with three mean working speeds (calculated from the gear ratios), each experiment being replicated 3 times, resulting a number of 27 tests. In table 1 are presented the values used as the inputs of the factorial experiment.

Table 1

Factorial experiment – factor levels

Factor Level	Working depth – a, m	Theoretical working speed – v_T, m/s
low	0.1	0.55
intermediate	0.15	1.1
high	0.2	1.6

During the experiments we measured the draft force and the real travel speed, computing afterwards the travel reduction ratio (TRR) also called slippage which is a reduction in speed due to several factors like slip between surfaces (rubber and soil), shear within soil (due to soil structure and humidity) or flexing of the tractive device (*Zoz F.M., Grisso R.D., 2003*).

$$TRR=1-\frac{V_a}{V_T}\text{, [\%]} \tag{1}$$

where: *TRR* – travel reduction ratio, %;
v_a – actual working speed, m/s;
v_T – theoretical working speed, m/s;

The drawbar power P_d necessary to drag the plough through the soil was computed as in formulae (2), while the electric power input P_e used by the motor was computed using formulae (2).

$$P_d=F_d v_a\text{, [W]} \tag{2}$$

where P_d – drawbar power, W;
F_d – mean draft force, N;
v_a – actual working speed, m/s.

$$P_e=UI\text{ , [W]} \tag{3}$$

where P_e –electric power input, W;
U – battery voltage, V;
I – battery current, A.

The power delivery efficiency (PDE) of the system during ploughing was calculated as the ratio between drawbar power and electric power input used for ploughing and was used to identify an optimal set up for the transmission gear in order to optimize the ploughing work.

The ploughing testing was performed on a 16-meter-wide field with a total length of 100 meters, totalizing 0.16 ha surface.

RESULTS

During the tests were obtained draft force curves which converged to a mean value of approximately 7 kN, not taking into consideration the start and stop of the test, for the maximum ploughing depth. In Fig. 2 is presented the draft force evolution in time for a test corresponding to a maximum ploughing depth of 0.2 m and an imposed working speed of 1.1 m/s. Because of the slip ratio, the actual working speeds were lower than the theoretical ones.

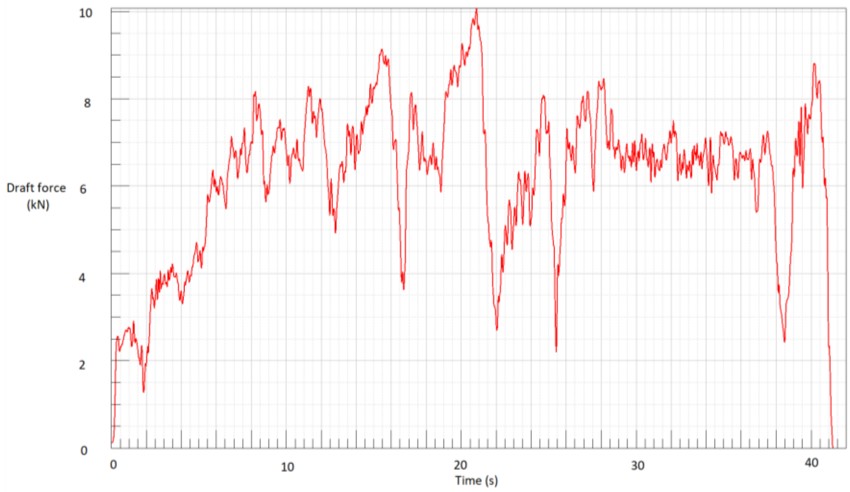

Fig. 2 - Draft force evolution for 1.1 m/s and 0.2 m depth ploughing test

In table 2 are presented the mean results obtained during the tests, for each set of 3 replicas of the experiments. The soil humidity in the tests area was 16%, which is considered to be within the optimal values for ploughing.

Table 2

Experimental results obtained for draft force

Experiment no.	Working depth a, m	Actual working speed v_a, m/s	Mean draft force F_d, N	Travel reduction ratio TRR, %
1	0.10	0.50545	3822	8.1
2	0.15	0.48895	5728	11.1
3	0.2	0.4719	7527	14.2
4	0.10	0.9988	3884	9.2
5	0.15	0.9526	5801	13.4
6	0.2	0.8954	7644	16.6
7	0.10	1.4032	3926	12.3
8	0.15	1.3392	5844	16.3
9	0.2	1.2608	7789	23.2

By analysing data obtained for the travel reduction ratio and the mean draft force mean value from table 2 we observe that they are strongly correlated, with a correlation coefficient R=0.844, which means that the slip increases as the pull of the tractor increases up to the maximum net traction ratio of the tractor.

In fig. 3 is presented the evolution of the tractor traction ratio (draft force/tractor weight) versus travel reduction ratio obtained for the ploughing tests.

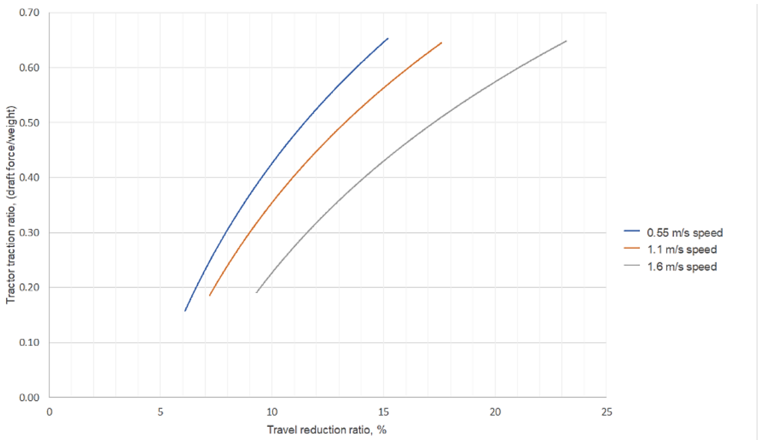

Fig. 3 - Tractor traction ratio versus travel reduction for different theoretical speeds

Looking at the diagrams in figure 3, we can notice a slight difference between the values for the first two theoretical speeds. The slip increases as the working theoretical speed increases corelated with the tractor traction ratio. From the diagram we observe that the tractor loses traction faster at higher ploughing speeds. The maximum pull to weight ratio obtained for ploughing was 0.64, in the case corresponding to maximum working depth of 0.2 m. This value is in the same range as the one obtained for diesel engine tractors, validating the fact that the ploughing performances are similar for both types of tractors. Thus, the advantages of using electric tractors are given by the zero emissions in the atmosphere during works and a much lower costs with the fuel used, such as electricity, being much cheaper than diesel fuel, at the same tractive performances.

In figure 4 is presented the theoretical drawbar power (theoretical working speed multiplied by mean draft force) versus actual drawbar power (computed as actual working speed multiplied by mean draft force).

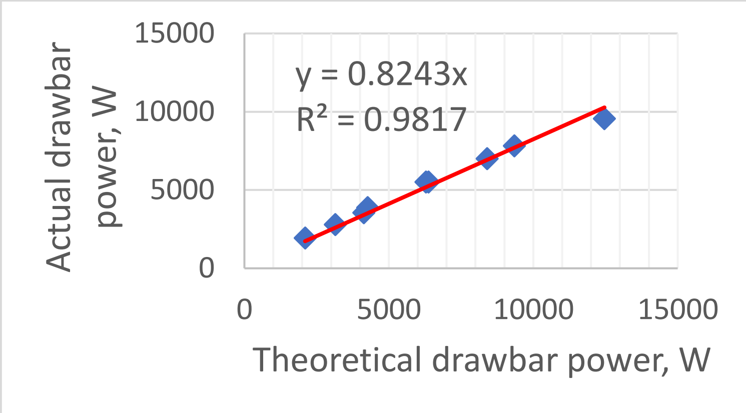

Fig. 4 - Mechanical power loss due to travel reduction ratio

In fig. 4 we observe that the power loss due to slip during ploughing is around 18%, at the same electric power consumption, fact which affects the autonomy of the electric tractor for the same ploughed surface. Thus, the purpose of this paper was to identify the working regime which minimized the losses for this particular experimental model of electric tractor. In order to do this, the power delivery efficiency was chosen as an indicator.

In table 3 are presented the results obtained by computing the experimental data corresponding to each working depth – working speed combination, previously presented in table 2, for obtaining the drawbar power and electric power input, as well as also the power delivery efficiency values. The power needed for the self-propelling of the tractor was measured separately and it was subtracted from the total electric power, so that the electric power input represents only the value used for the ploughing work.

Table 3

Power delivery efficiency for ploughing works

Experiment no.	Drawbar power P_d, W	Electric power input P_e, W	Power delivery efficiency PDE
1	1932	3454	0.55930
2	2801	4594	0.60964
3	3552	7354	0.48300
4	3879	7940	0.48858
5	5526	9702	0.56958
6	7013	12602	0.55647
7	5509	11487	0.47958
8	7826	14435	0.54217
9	9571	19147	0.49988

As shown, the power delivery efficiency values are in the same range for all the studied cases, with a slightly better situation for experiments conducted at the working depth of 0.15 m for all the working speeds and 0.2 m (maximum working depth) for the intermediate working theoretical speed of 1.1 m/s.

Table 4 shows data corresponding to the autonomy of the tractor with a single charge of the 17.28 kWh battery for each experimental case taken into consideration, based on the electric power consumption. The ploughing productivity was computed using the actual working speeds measured during experiments and the working width of 0.5 m of the plough. Also, total ploughed surface was computed as ploughing productivity multiplied by the tractor autonomy, making the hypothesis of working in a straight line, not taking into consideration the time needed to turn over the tractor at the end of the field.

Table 4

Electric tractor autonomy for ploughing works

Experiment no.	Electric power input P_e, W	Tractor autonomy, h	Ploughing productivity, ha/h	Total ploughed surface, ha
1	3454	5.00	0.09	0.46
2	4594	3.76	0.09	0.33
3	7354	2.35	0.08	0.20
4	7940	2.18	0.18	0.39
5	9702	1.78	0.17	0.31
6	12602	1.37	0.17	0.23
7	11487	1.50	0.25	0.38
8	14435	1.20	0.24	0.29
9	19147	0.90	0.22	0.20

CONCLUSIONS

The purpose of the experiments was to identify optimal working regime for a small power experimental model of agricultural tractor during ploughing works. The tractive performances measured during experiments showed that the best power delivery efficiency values bigger than 0.54 were recorded for the intermediate working depth of 0.15 m for all the working speeds, fact that suggests this is an optimum working regime. The tractor autonomy is strongly correlated with the drawbar power which affects the electric power consumption. Thus, even though the draft force is quasi-constant for the imposed working depth, having a very small deviation due to the imposed working speed, the latter has a big influence on the electric tractor behaviour. The increase in speed causes an increase in the travel reduction ratio and for this particular experimental model an exponential increase in electric power consumption.

The maximum pull to weight ratio obtained during experiments was 0.64, value similar to diesel engine tractors fact which confers feasibility to the future development of the experimental model to a prototype.

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