CALCULATION OF FIELD CAPACITY AND FUEL CONSUMPTION OF MOBILE MACHINERY WITH BUNKERS, TANKS OR OTHER CONTAINERS FOR AGRICULTURAL GOODS
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ОПРЕДЕЛЯНЕ НА ПРОИЗВОДИТЕЛНОСТ И РАЗХОД НА ГОРИВО НА СЕЛСКОСТОПАНСКА ТЕХНИКА С ВМЕСТИМОСТИ

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ABSTRACT
A method and procedure for automatic calculation of field capacity and fuel consumption of mobile machinery with tanks, hoppers and bunkers is suggested. They are based on a combination of two well-founded approaches: East-European and North-American. To increase its calculation area some applications for machines with containers as grain, fertilizer, solution, etc. are added. An example of five linked field operations, namely potato transportation, fertilization, spraying, planting and harvesting is presented. A list of needed information with relations between them and main indices of agricultural aggregates is prepared. For convenience and objectivity calculations are automated with spreadsheets.

РЕЗЮМЕ
Предложени са метод и процедура за автоматично изчисляване на производителността и разхода на гориво от мобилни машини с резервоари, бункери, други вместимости. Те са комбинация от два добре обосновани подхода: източноевропейски и североамерикански. За да се увеличи обхвата на нейното използване, са добавени някои приложения за машини с контейнери за зърно, тор, разтвор и др. Представен е пример за пет свързани полеви операции, а именно транспортиране на картофи, торене, пръскане, засаждане, прибиране на реколтата. Направен е списък на необходимата информация за връзките между тях и основните показатели на селскостопанските агрегати. За удобство и обективност изчисленията са автоматизирани с електронни таблици.

INTRODUCTION
As other areas of management, the agricultural machinery one is about choices. That's why a good decision must be based on well-founded and interrelated steps to a global optimum. To be a choice informed, the potential buyer needs to have enough data including that about technical characteristics of farm machinery (*Spiridonov V., 2018*). Usually, manufactures and traders offer only some information presenting the machines positively, i.e. higher productivity and velocity.

Typically, a statement of the task for effective mechanized agriculture includes as a target machinery work with enough field capacity, required quality, minimum labour and fuel consumption (*Vezirov Ch., 2013*). In principle and in-depth solution of these problems is discussed in (*ASAE 496.3, 2006, ASAE 497.7, 2011, Tutorial, 1978*). The recent research in this area are concerns to the clarification of the proposed dependences for the mechanics of agricultural units (forces, velocities, powers) (*Blinsky Y.N., 2015; Arzhenovskiy A.G., 2017; Vezirov Ch. et al, 2014*). Furthermore with the help of generalized dependencies it becomes possible to calculate fuel consumption more accurately, including for throttle down mode of diesel engines (*Grisso R.D. et al, 2006, Schreiber M., 2006*).

Unfortunately, the practical application of some of these proposals is only possible for a small list of machines and specific operating conditions. For example, there is a lack of enough data to estimate the required power when operating spraying machines, for fertilizing with mineral fertilizers.

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Incorrect results for energy and fuel consumption can be obtained due to the use of equipment with different capacities for harvested products, fertilizers, solutions etc. The situation is similar with different degrees of use of these volumes. Determining the appropriate volume of hoppers and tanks is done from the aspect of the design of such machines without taking into account the specific production conditions (*Dyachkov A.P. et al, 2014*). Other researchers offer various resources to objectify the computational process, which undoubtedly facilitates obtaining the necessary information (*Zaied M.B. et al., 2014; Kumar N. et al, 2015; Revanth K. et al, 2018*).

The positive experience in the application of modern information technologies as well as the need for more accurate determination of the productivity and fuel consumption of equipment with capacities prompted us to try to solve the described task.

MATERIALS AND METHODS

The comparison of the formulas for determining the required power (*ASAE 496.3, 2006, ASAE 497.7, 2011, Tutorial, 1978*) shows similarity. The draft power requirement is

$$P_d = F_i[A + BS + CS^2]WTS \tag{1}$$

where:

F_i is dimensionless soil texture adjustment parameter,
i is 1 for fine, 2 for medium and 3 for coarse textured soils,
A, B, C are machine-specific parameters (*ASAE 497.7*, *2011*),
S is field (working or forward) speed,
W is machine working width, or number of rows or tools,
T is tillage depth for major tools, 1 for minor tillage tools and seeding implements.

Accordingly, the required power take-off

$$P_{pto} = a + bW + cWS \tag{2}$$

where:

a, b, c are machine-specific parameters (*ASAE 497.7, 2011*),
WS is material feed rate.

In such a way F_iAWTS and cWS are functions of working width and forward speed. Furthermore F_iCWTS is different from 0 only for Subsoiler/Manure injector and Mouldboard plough, while in other sources (*Tutorial, 1978*) it is reported directly by an F_iBWTS. Another problem is the impossibility to report idle-power by P_d. To overcome these problems, we propose the machine-specific parameters to be entered with a formula whose velocity is in the denominator.

Regarding the measurement of the influence of the weight of the transported load in the tank or the hopper dependency can be used through resistance force.

$$\frac{Mgf}{(SW)} \tag{3}$$

where:

M is mass of machine including the product in tank or bunkers,
g is gravitational acceleration,
f is motion/rolling resistance ratio for specific terrain.

If the idle-power (only when towing machines from the tractor) does not depend on the speed and working width, then $F_i = 1,\ T = 1$ and

$$P_d = \left(\frac{V}{W}\right)\Psi\rho g f \tag{4}$$

where:

V is volume of tank or bunker,
Ψ is rate of volume use,
ρ is bulk density of the product in tank or bunker.

Since in some data, sources of the traction resistance are given only as a function of the working width, formula (1) assumes the form

$$P_d = \left(\frac{V}{W}\right)\Psi\rho g f + F_iAWTS \tag{5}$$

Additionally, calculations can be made for 1, 2 or 3 types of machines behind the tractor or for up to 2 types of machines together with the self-propelled harvester. Examples: squadron hitch, cultivators and seeders or header, self-propelled grain harvester and straw baler.

Important question in solving the task is the ability to use aggregated data. Such data are available, even before specifying the machines (from which company, what model and modification) for which field capacity and fuel consumption will be calculated. Such summary data for trailers (*Ivanov S., 2019*) are shown in Figure 1.

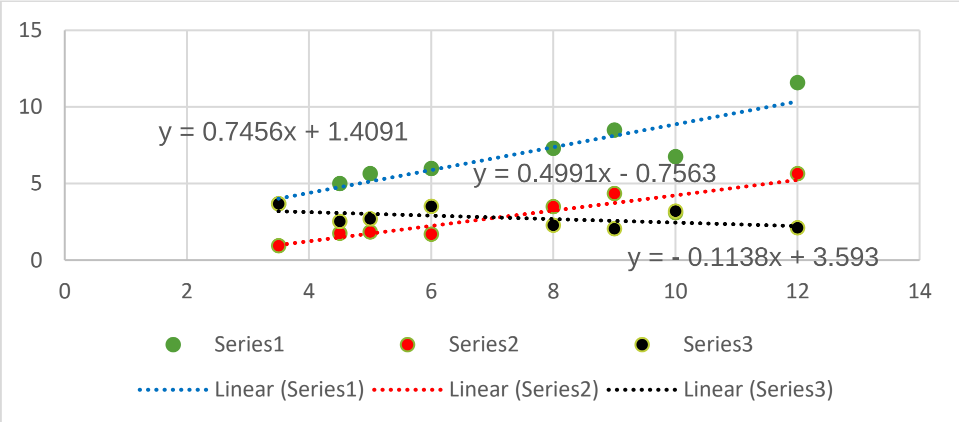

Fig. 1 - Relations for agricultural trailers between x - carrying capacity and y: volume of bodywork - Series1; empty trailer's mass (tare) - Series2; ratio between empty trailer's mass and carrying capacity – Series3

Naturally, the larger volume of the trailer provides greater load capacity - Series1. Greater load capacity also requires more material for trailer body - Series2. At the same time, greater load capacity is achieved with less tare weight, and therefore with lower energy consumption for movement - Series3. For load capacity up to 9 t the dependence is very close to linear. This allows for calculation of Pd through the volumes of trailer's capacities.

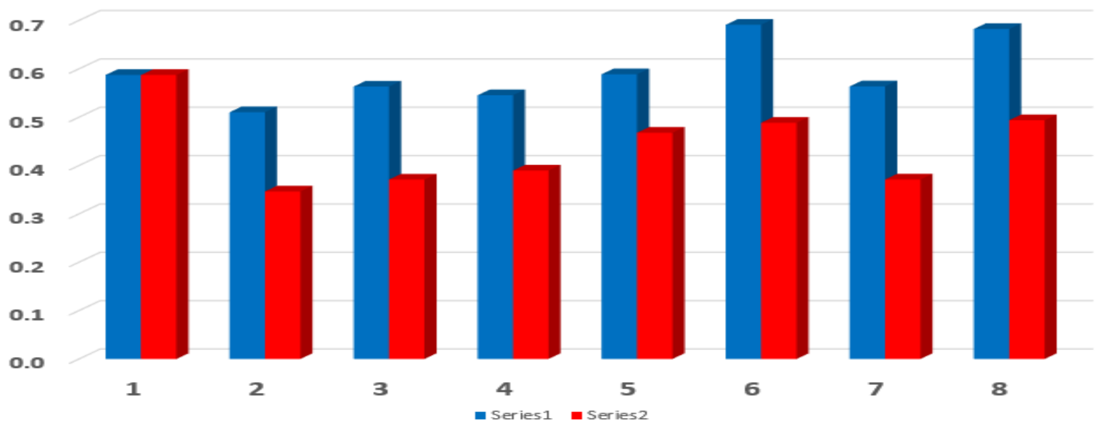

Fig. 2 - Ratios between trailer's volumes: blue colour with blind side extensions to without extensions, red colour with mesh side extensions to without extensions.

Number under the bars means respectively carrying capacity in tons: 1 – 3.5; 2 – 4.5; 3–5; 4–6; 5–8; 6–9; 7–10; 8–12

The Fig. 2 shows that the use of dense and mesh superstructures allows better use of the volume of trailers for loads with lower bulk density. This increase is not enough for straw, hay, tobacco and other plant stems. However, averaged volume data for upgraded trailers can be used.

In a similar way, data are obtained on the ratios of volumes of capacities, own weight to working widths for fertilizers, sprayers, seeders and to engine power of harvesting machines.

RESULTS AND DISCUSSION

We use spreadsheets to perform the calculations. They are suitable due to the following features:

- the change of the entered data and in one cell immediately allow comparison of the result,
- information with formulas can be set in the cells,
- the formulas used and the results shown allow an intermediate verification of the data,
- the formulas are visible and can be updated if necessary, according to the available information.

To implement above mentioned ideas a spread sheet was created, see figure 3.

INITIAL DATA is presented in 2 groups:

A. Input direct in cells with light green background colour;

Operation (column A); distance of transportation (column B); fertilization, spraying, sowing rate, yield (column C); tractors, power machines: brand, model, modification, type of undercarriage, rated engine power (columns D, E, F); implements, other machines, up to 3 types; for each of them: numbers in aggregate/unit, width, volume, rate of volume use of materials in tanks, bunkers, approximately 1; squadron hitch for 2 or more implements together in an aggregate/unit: brand, model, modification, mass/quantity of matter, width of bar for hitching (columns AJ, AK, AL); tilling, sowing or planting depth respectively for 1st, 2nd and 3rd machine/implement (columns AN, AO, AP); type of terrain/soil (ASAE 497.7) (column AR); 1 for machines/implements with information according to ASAE 497.7 about width units in "tools" or "rows" (columns AS, AT, AU); material feed rate (column BP);

B. Input indirect in cells with light yellow background colour by links of a cell in specific sheet. The names of such sheets are shown above related column or columns in row 11.

Specific sheets are for: bulk density of grain, solution, fertilizer, manure, seeds, etc. (columns S, T, U) – "density"; motion resistance rate for undercarriage on specific terrain (columns Y, Z, AA) – "Femc"; field width efficiency (column AB) – "β§η"; maximum speed for specific operation and machine or squadron hitch (columns AF, AH, AG, AI) – "V&χm&ao"; motion resistance rate for squadron hitch (column AM) - "Femc"; field time efficiency (column AQ) - "T"; soil parameter Fi (*ASAE 497.7, 2011*) (column AV); machine-specific parameters for 1st, 2nd and 3rd machine/implement for draft power requirement (*ASAE 497.7, 2011*) (columns AW, AX, AY; BB, BC, BD; BG, BH, BI respectively); machine-specific parameters for PTO power requirement (*ASAE 497.7, 2011*) (columns BM, BN, BO); maximum acceptable energy use rate less than 1 (column BQ);

RESULTS are presented in 3 groups:

C. In cells with white background colour - intermediate data:

To check the numbers obtained before the final results (columns AZ, BA; BE, BF; BJ, BK); calculated specific draft/drawbar resistance for aggregate/unit (column BL); acceptable forward field speed (column BR); real working width of aggregate/unit (column BS); power take-off (column BT); draft power requirement (column BU); sum of two powers mentioned before (column BV); required power for aggregate/unit including tractive one and needed for PTO (column BW); engine power according to type of undercarriage and tractive condition (column BX); ratio of numbers in previous two columns BW and BX (column BY); specific fuel consumption (column BZ); fuel consumption for entire shift time (column CA);

D. In cells with light pink background colour:

Field efficiency and specific fuel consumption for autonomous operation without relation with transportation (exception for fuel for tractors and self-propelled harvesters) (columns CB, CC);

E. In cells with light blue background colour:

Field efficiency and specific fuel consumption for linked operations (columns CE, CF). The columns CD, CE, CF are not used in this example because of the nature of specific agricultural operations.

Result of above-described procedure for five linked field operations, namely potato transportation, fertilization, spraying, planting, harvesting is presented in the same figure 3. First step was to select tractor, trailer, planter, sprayer, spreader and harvester, i.e. (*Complex, 2020*). They have to be compatible, as appropriate hitch system, PTO with equal rotational speed and numbers of splines etc. For example, trailer's mass with full load has to be less than tractor's mass for off road transportation. On the other hand, there is a relation between tractor's rated tractive force on unpaved farm road, and maximum trailer's carrying capacity: 0.9–4 t, 1.4–6 t, 2–9 t, 3–12 t, 5–21 t (*Ivanov S., 2019*).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
10																		
11				rated effective power ↓														
12	agricultural operations	distance of transportation, km	fertilization, spraying, sowing rate, yield, t/dka	tractors, power machines														
13				brand, model	type: 1 - 4x2 2 - MFDW 3 - 4x4 4 - crawler	Pen, W	brand, model			numbers in aggregate			width, m			volume, m³		
14										n1	n2	n3	B1	B2	B3	1.	2.	3.
15	Transportation of fertilizer	3.4	0.1	Tractor	2	60000	Trailer	Telescopic crane		1	1		1.0			6.15		
16	Spreading of fertilier		0.1	Tractor	2	60000	Spreader			1			10.8			5		
17																		
18	Transportation of potato	3.4	0.25	Tractor	2	60000	Trailer	Telescopic crane		1	1		1.0			6.15		
19	Potato planting		0.25	Tractor	2	60000	Planter			1			3.0			4		
20																		
21	Transportation of solution for spraying	3.4	0.03	Tractor	2	60000	Tank semi trailer			1			1.0			4		
22	Spraying		0.03	Tractor	2	60000	Sprayer			1			10.8			1.2		
23																		
24	Transportation of fertilizer	3.4	0.015	Tractor	2	60000	Trailer	Telescopic crane		1	1		1.0			6.15		
25	Under root fertilisation		0.015	Tractor	2	60000	Row dependent soil cultivator			1			0.75			0.9		
26																		
27	Potato harvest		2.5	Tractor	2	60000	Harvester			1			1.5			4		
28	Transportation of potato	3.5	2.5	Tractor	2	60000	Trailer			1			1.0			6.15		
29																		

Fig. 3. Segment of spreadsheet for calculation of field capacity and fuel consumption - part 1

	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ
10								field width effciency↓											mass↓ ↓ = (n1-1)*B1							
11		density						Feмc			β§η				V&χм&ao							Feмc				T
12	other machines																		squadron hitch				depth, m			field time efficiency, T
13	m³	bulk density, kg/m³			rate of volume use			motion resistance rate			β	numbers of rows in a machine			max speed, m/s				brand, model	Gc, kg	Φc, m	fc	1. machine	2. machine	3. machine	
14	3.	1.	2.	3.	1.	2.	3.	f1	f2	f3		1. machine	2. machine	3. machine	V1	V2	V3	of squadron								
15		800			1			0.1			1.00				9.7											0.84
16		800			0.48			0.11			1.00				2.8											0.75
17																										
18		640			1			0.1			1.00				9.7											0.84
19		640			0.48			0.11			1.00				2.0											0.67
20																										
21		1000			1			0.05			1.00				9.7											0.84
22		640			0.48			0.06			1.00				2.8											0.67
23																										
24		800			1			0.05			1.00				9.7											0.80
25		1000			0.48			0.12			1.00				2.8											0.75
26																										
27		660			0.48			0.06			1.00				2.3											0.70
28		660			0.48			0.05			1.00				9.7											0.84
29																										

Fig. 3. Segment of spreadsheet for calculation of field capacity and fuel consumption - part 2

	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ
10					V&χM&ao RM = Fi * (A + B * V + C * V²) * Ba * ao														
11					Fi	1. machine					2. machine					3. machine			
12		1 - small machines, seeders				A	B	C			A	B	C			A	B	C	
13/14	terrain: 1 - firm 2 - tilled 3 - soft 4 - concrete	1. machine	2. machine	3. machine	–	N/ (m*cm)	N*s/ (m²*cm)	N*s²/ (m³*cm)	inter mediate	N/m	N/ (m*cm)	N*s/ (m²*cm)	N*s²/ (m³*cm)	inter mediate	N/m	N/ (m*cm)	N*s/ (m²*cm)	N*s²/ (m³*cm)	inter mediate
15	1				1.00	1760			1760	6587				0	0				0
16	1				1.00	140			140	332				0	0				0
17									0	0				0	0				0
18	1				1.00	1760			1760	5621				0	0				0
19	2				0.94	840			790	1232				0	0				0
20									0	0				0	0				0
21	1				1.00	670			670	2632				0	0				0
22	1				1.00	40			40	60				0	0				0
23									0	0				0	0				0
24	1				1.00	880			880	3293				0	0				0
25	3				0.94	2190			2059	2737				0	0				0
26									0	0				0	0				0
27	1				1.00	1490			1490	1987				0	0				0
28	1				1.00	880			880	1836				0	0				0
29																			

Fig. 3. Segment of spreadsheet for calculation of field capacity and fuel consumption - part 3

	BK	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH
10		Ppto ≈ a + b* Ba + c * F					↓maximum acceptable energy use level																	
11			Ppto			0	β§η					power engine load ↓												
12	N/m	χм	a	b	c	F	ηmax	Vmax	Ba*β	Ppto	Pd	Pd+Ppto	Peo	Pen	η	gp	Gсм	Wсм	g	is enough width of squdron hitch bar	for linked operations		ΔV	Δη
13–14		N/m	kW	kW/m	kWs/kg	kg/s	–	m/s	m	kW	kW	kW	kW	kW	–	kg/kWh	kg/ shift	dka/ shift	g/dka		Wсм, dka/ shift	9, g/dka		
15	0	6587					0.96	5.45	1.0	0	36	36	49	51	0.96	0.226	74	119	620				4.27	0.00
16	0	332			11	2.89	0.90	2.68	10.8	31.8	10	41	46	51	0.90	0.226	62	563	110				0.10	0.00
17	0	0					0.00			0	0	0												
18	0	5621					0.96	6.40	1.0	0	36	36	49	51	0.96	0.226	74	139	530				3.32	0.00
19	0	1232					0.88	2.00	3.0	0	7	7	12	51	0.23	0.590	36	104	340				0.00	0.65
20	0	0					0.00			0	0	0												
21	0	2632					0.96	9.72	1.0	0	26	26	35	51	0.68	0.261	61	212	280				0.00	0.28
22	0	60			4.4	0.9	0.94	2.78	10.8	3.96	2	6	6	51	0.13	0.745	26	521	40				0.00	0.81
23	0	0					0.00			0	0	0												
24	0	3293					0.96	9.72	1.0	0	32	32	43	51	0.85	0.229	64	202	310				0.00	0.11
25	0	2737			5	0.03	0.92	2.78	0.8	0.16	6	6	10	51	0.19	0.640	37	41	910				0.00	0.73
26	0	0					0.00			0	0	0												
27	0	1987		10.7			0.85	2.30	1.5	16.1	7	23	27	51	0.52	0.326	49	63	770				0.00	0.33
28	0	1836					0.96	9.72	1.0	0	18	18	24	51	0.47	0.354	57	212	270				0.00	0.49
29																								

Fig. 3. Segment of spreadsheet for calculation of field capacity and fuel consumption - part 4

Some problems arose because of aggregated information about time efficiency, soil and terrain (only 3 or 4 condition), calculation for only one mode (soil and plants processing), exclude: turning, run idle (no load), loading or unloading of materials, etc. The specific input values, i.e. machine-specific parameters, was changed by coefficients taking into account soil cone index, field length, coherence of agricultural and transport machinery, etc. Part of input data has been verified by comparing different sources. The other one has been adjusted based on formal experience with similar operations and machinery.

Because some data for machine-specific parameters are with width units in “tools” or “rows”, the tillage depth was relatively precise.

To comply with the requirements for operation’s forward speed and maximum engine power use level, values have been changed in columns BR manually or by Solver add-in. Optimization criteria was the closeness of calculated forward speed and rate engine power use to the acceptable values. This Microsoft Excel program can be used for what-if analysis too. Other way to meet these requirements was reducing the rate of volume use for trailer, tank, bunker capacity (columns V, W, X) or increasing the trailer volume by using blind or mesh side extensions (columns P, Q, R). The possibility of transportation with more than one trailer in aggregate/unit was checked also (it is not shown in the figure).

This procedure and spreadsheet were used for calculations for other crops and technologies too. It was found that there is no enough data in most recommended sources *Tutorial, 1978, ASAE 496.3, 2006, ASAE 497.7, 2011*, for such operations like spraying, fertilization, gathering up and loading straw, root crops from field, a lot of stationary systems, cargo handling, with electrical engines. It is obviously that collecting large volume of information of this kind is practically impossible. Our practice shows that in such situation analogy approach may be effective.

In few cases, field experiments are required. They are aimed at determining the appropriate forward speed to ensure quality work, effective load of engine and undercarriage, wheel slip or speed reducing ratio of tractor, car or self-propelled harvester. The simplest way to evaluate these indicators is by tachometer, speedometer, even by naked eye. Of course, these experiments can be realized with available similar machinery in analogical soil and plants conditions. If selected machines are bought such trials make sense to precise machine-specific parameters and other input data.

Finally, we must emphasize that only by these two indices, namely filed capacity and fuel consumption, it is not possible to evaluate machines’ efficiency of machine and tractor fleet. It is important to find the global extremum for all farm operations.

The fact that above-described procedure is realized by such widespread software Excel as a part of Microsoft Office makes it even easier to use. Furthermore, each cell with formulas is visible and may be changed by users. Similarly, more than 12 sheets with specific data are available and may be supplemented and improved. In other words, this free computer software can be distributed under terms that allow users to run the software for any purpose as well as to study, change, and distribute it in any adapted versions.

CONCLUSIONS

The above presented procedure for determination of field capacity and fuel consumption of mobile machinery with tanks, hoppers, bunkers allows a semi-automated informed choice. By it, the effect of main factors such as type of tractor, harvester, trailer and their technical parameters, goods, terrain, on field speed, energy consumption and time efficiency is reproduced. All this information can be achieved from official standards, manuals or simple experiments. The procedure allows specifying concrete values and relations according to practice. Application of spreadsheets makes the process easier, quicker and well-founded.

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