Method for calculating walking tractor performance considering operator's energy consumption

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Annotation. The paper proposes a method for calculating the performance of a walking tractor considering the operator’s energy consumption in the dynamics of the tractor movement. The study presents the results of a man's energy consumption determined during physical load. The work has established that the performance of the walking tractor directly depends on the value of operator’s physical action on the cultivator movement. The increase of the operator’s physical effort decreases the performance of the walking tractor, since the operator has to increase the rest time for rejuvenation. The authors have suggested a method for walking tractor performance calculation considering operator’s physical capabilities and his involvement into the tractor operation.

1. Introduction
Recently, small mechanization means are increasingly used in new fields and various human activities. Most frequently, they are used for homesteading and gardening, in greenhouses and on plantations (lawns and flower beds) [1, 2]. Frequently, small machines are used for building purposes. Motor mini-machines on the basis of rototillers and motorized tools are used most often. As per accepted classification, they can be cumulatively referred to as walking tractors. According to works [3, 4], the implementation of walking tractors allows appreciably increasing the work performance as compared to manual work. At the same time, they note that the work with walking tractors relates to hard physical work. Physical load causes a rapid fatigue of the operator and unwanted stops to rejuvenate equipment. During the work on the tractor, the operator controls the course. By pulling, the operator tries to increase the tractor movement speed, thus increasing the performance; however, he gets tired fast and stops for a rest. This reduces the general tractor performance.

The draught force of the walking tractor is generated by two energy sources: energy of the fuel combusted in the engine and operator’s physical force [5]. The operator spends physical forces for:
- ensuring the course (horizontally controlling the arms);
- providing agrotechnical tillage depth of the tractor (vertically controlling the arms);
- manual alteration of the tractor draught dynamics (axially controlling the arms);
- stabilization to prevent the tractor overturning;
- walking over the tilled soil.

The value of physical forces applied by the operator during tilling by the walking tractor depends on a variety of factors, for instance, on physical training and conditioning of the operator, mass and geometry of the tractor, etc. The study does not include the results regarding these factors, but...
practical work with walking tractors testifies that the duration of continuous work is about 0.25–0.5 hours, while the rest duration is about 0.25–0.75 hours [4]. Thus, one can conclude that the performance of the work with walking tractor directly depends on the degree of physical (forceful) participation of the operator in the tractor operation.

The movement dynamics and estimation of draught parameters of tractors is quite fully reviewed and presented in [6, 7]. The draught dynamics and parameters of a walking tractor are formed under the fluctuations in draught resistance of working tools and irregularities of the surface, which constantly alters the reactive moment and the angle of control arms.

The draught properties and course stability of the walking tractor primarily depend on the adherence of the movers to the soil, which interaction is described in detail in [6–9]. The main factors that affect the acceleration characteristics and draught dynamics of the tractor are described in [6, 8, 13]. Operator’s physical action on tractor controls directly impacts his fatigue, which will affect the periodicity and duration of “work-rest” cycles. The studies in this direction are primarily made for sportsmen.

The factor of operator's participation during the calculation of walking tractor performance in existing techniques usually takes into account the labor utilization rate [8, 10] or, at best, the coefficient of time consumption for human physiological needs [11]. These coefficients have a common form for losses of time that exclude physically demanding work.

In this connection, the present work has the goal of developing the method for calculating the walking tractor performance with due consideration of operator's manual labor during working operations.

2. Materials and Methods
Theoretical basics of performance calculation were developed for walking tractors. As the basis, the experimental results of operator's work with the walking tractor in a draught mode were used [4]. The time of work and rest was determined chronometrically. The volume of the work performed was determined by measuring the tilled soil with the use of measuring tools. The force applied by the operator to control arms was measured by tensometric control arms [4].

3. Results and Discussion
The main factors that form the performance of tractors is the operating width of working tools, working movement speed and operation time [10]:

\[ W = 0.36 \cdot V_p \cdot B_p \cdot T_p, \text{ ha} \]  \hspace{1cm} (1)

where \( V_p \) is the movement speed during operation, m/s;
\( B_p \) is the actual tractor operating width, m;
\( T_p \) is time spent for work, h.

It is well known that the tractor operation is accompanied by non-production time losses [11] that lead to the decrease of time of actual operation or affect the shift duration:

\[ T_z = T_p + T_{TL}, \text{ h} \]  \hspace{1cm} (2)

Non-production time losses include:

\[ T_{TL} = T_{PFW} + T_M + T_{TDF} + T_I + T_{VTP} + T_{MF} + T_{OR} + T_{MR} + T_{PN}, \text{ h} \]  \hspace{1cm} (3)

where \( T_{PFW} \) is time for preparatory and final works;
\( T_M \) is time for maintenance;
\( T_{TDF} \) is technological down time (refueling, etc.);
\( T_I \) is time of unproductive move for turnarounds;
$T_{\text{VTP}}$ - down time due to violation of the technological process (cleaning working tools, adjusting the machine, etc.);
$T_{\text{MF}}$ - down time due to malfunction;
$T_{\text{OR}}$ - down time due to organisational reasons;
$T_{\text{MR}}$ - down time due to meteorological reasons;
$T_{\text{PN}}$ - down time due to human physiological needs.

On practice, the non-productive expenditures of time are grouped together and taken as coefficients:
- the coefficient of working time losses for technical preparation of the tractor is:
  $$K_{\text{TL}} = 1 - \frac{T_{\text{PFP}} + T_{\text{M}}}{T_{\xi}},$$  
  \tag{4}

- the coefficient of working time losses for technological preparation is:
  $$K_{\text{TP}} = 1 - \frac{T_{\text{TP}} + T_{\xi}}{T_{\xi}};$$  
  \tag{5}

- the coefficient of time losses for repairs is:
  $$K_{\text{TRL}} = 1 - \frac{T_{\text{VTP}} + T_{\text{MF}}}{T_{\xi}};$$  
  \tag{6}

- the coefficient of working time losses for organisational and meteorological down time is:
  $$K_{\text{OM}} = 1 - \frac{T_{\text{OR}} + T_{\text{MR}} + T_{\text{PN}}}{T_{\xi}}.$$  
  \tag{7}

In certain cases \cite{10}, the non-productive working time losses are estimated as the coefficient of shift time usage:

$$\tau = \frac{T_{\rho}}{T_{\rho} + T_{\text{TL}}}, \text{ or}$$  

$$\tau = K_{\text{TL}} \cdot K_{\text{TP}} \cdot K_{\text{TRL}} \cdot K_{\text{OM}}.$$  
  \tag{9}

The relation of time for rest and operator’s rejuvenation during work with the walking tractor is significantly more than when using conventional tractors \cite{4}; the rest takes about 60-70% of the total working time. During walking tractor performance calculation, the authors have suggested accounting for the time losses for operator’s rest as the coefficient of operator’s rest time:

$$\tau_{\text{BR}} = \frac{T_{\rho}}{T_{\rho} + T_{\text{M}}},$$  
  \tag{10}

Operating width $B_{\rho}$ during the tractor movement increases and decreases. The operating width decreases by the overlapping value during full cultivation and disk harrowing, while it increases during seeding and tillage. The overlapping zone value is estimated as coefficient $\beta$ of operating width usage \cite{10}:

$$B_{\rho} = B_{K} \cdot \beta.$$  
  \tag{11}

The tractor working speed is always smaller that the theoretical one by the value slipping:

$$V_{\rho} = V_{\pi} \cdot (1 - \delta),$$  
  \tag{12}

where $\delta$ is the slipping coefficient.

Then, the actual performance will be:
\[ W = 0.36 \cdot V_T \cdot (1 - \delta) \cdot B \cdot \beta \cdot T_p = 0.36 \cdot V_T \cdot (1 - \delta) \cdot B \cdot \beta \cdot T_L \cdot \tau \cdot \tau_{op} . \] (13)

The time losses for operator’s work and rest depending on the physical intensity are reviewed in [4, 14, 15] and presented in Table 1.

**Table 1.** Dependence of human work and rest duration on the fraction of anaerobic formation of energy in total energy generation system.

| Fraction of anaerobic formation of energy | Work duration without rest [min] | Rest duration [min] |
|-----------------------------------------|---------------------------------|---------------------|
| 0.06                                     | 24-45                           | 5-10                |
| 0.1                                      | 12-20                           | 30-40               |
| 0.15                                     | 8-13                            | 30-90               |
| 0.3                                      | 4-6                             | More than 300       |

Relation (10) is suggested to be estimated by the coefficient of operator’s efficiency:

\[ \eta_{op} = \frac{T_p}{T_p + T_M} = 1 - K_{oppe} = 1 - \frac{E_{EOW}}{E_{EOMAX}} , \] (14)

where \( K_{oppe} \) is the coefficient of operator’s physical energy application intensity;

\( E_{EOW} \) is the energy spent by the operator during work with the walking tractor;

\( E_{EOMAX} \) is maximum possible energy of the operator. The method for its determination is presented in work [4].

The energy spent by the operator for stabilization of the walking tractor draught balance is proposed to be determined by the balance of power. It was assumed that the walking tractor is a draught vehicle and moves along the even surface without inclinations. The required power for the draught operation is:

\[ N_{REQ} = N_{AGR} + N_\delta + N_i + N_{LPT} , \] (15)

where \( N_{AGR} \) is the ergonomically useful power in the draught operation mode of the tractor;

\( N_\delta \) is the power losses for slipping movers,

\( N_i \) is the loss power for overcoming the resistance to motion;

\( N_{LPT} \) is loss power in transmission components.

The walking tractor operates due to two sources: fuel combustion energy that creates effective motor power and power from axial operator’s pushing:

\[ N_M + N_{opp}^s = N_{REQ} , \] (16)

Then, the draught balance will be:

\[ N_M + N_{opp}^s = N_{AGR}^s + N_\delta + N_i + N_{LPT} , \] (17)

\[ N_{opp}^s = (N_{AGR}^s + N_\delta + N_i + N_{LPT}) - N_M . \] (18)

Obviously, the deficit of power is compensated by the operator. The operator axially applies pushing force to the tractor’s arms in the case if \( N_{REQ} - N_M > 0 \). From practice with walking tractors, it should be noticed that the gripping is usually insufficient, which is expressed by increased slipping and appreciable decrease in motion speed.

The operator’s force, applied to control arms is random numbers, has stochastic character and is subjected to the random value distribution law. At a certain time, power spent by the operator can be determined as:

\[ N_{opp}^s = P_T \cdot V_T = P_T \frac{ds}{dt} , \] (19)

Then, the energy spent by the operator is:
\[ E_{op}^R = P_t \cdot V_p \cdot t = P_t \frac{dx}{dt} \cdot W \cdot s \]  

(20)

where \( dx \) is elementary axial displacement over time \( dt \).

Taking into consideration that the operator by muscle force applied to control arms ensures axial course according to a set trajectory and corrects the agrotechnical depth of working tools in the soil:

\[ E_{op}^{MAN} = E_{op}^Y + E_{op}^Z, \]

where \( E_{op}^Y, E_{op}^Z \) is the energy spent by the operator for ensuring control in axial and vertical directions, respectively.

In this case, the energy required for control and spent over instantaneous moment of time is:

\[ E_{op}^{MAN} = \bar{P}_y \frac{dx}{dt} + \bar{P}_z \frac{dx}{dt} - \sqrt{P_y^2 + P_z^2} \frac{dx}{dt}. \]

(22)

In the non-dimensional form, the walking tractor efficiency can be expressed as:

\[ \eta_{AGR} = \frac{W_d}{W_v} = \frac{0.36 \cdot V_y \cdot (1 - \delta) \cdot B_y \cdot \beta \cdot T_c (1 - K_{op})}{0.36 \cdot V_y \cdot B_y \cdot T_c} = \eta_o \cdot \eta_T \cdot \eta_{op}, \]

(23)

where \( \eta_o \) is slipping efficiency;
\( \eta_T \) is tool width efficiency;
\( \eta_{op} \) is operator’s efficiency.

4. Conclusions

When calculating walking tractor performance, in addition to main components, such as tractor’s operating width, actual speed, working time, the level of operator’s physical load should be considered, which changed the draught dynamics of the tractor depending on his physical capabilities. This indicator was suggested to be considered as the coefficient of the intensity of operator’s physical participation in the tractor operation. This coefficient is calculated as the relation of energy spent to maximum possible energy for a given person.

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References

[1] Lara-lopez and Chancellor W J 1993 Regional Network for Agricultural III 95-114
[2] Lara-lopez A and Chancellor W J 1999 Handbook of Agricultural Engineering, Plant production Engineering III 95-114
[3] Keller N 2003 Tractors and agricultural machines 4 7-10
[4] Ovsyannikov S 2013 Motrol 7 45-50
[5] Ovsiannikov S and Remarchuk N 2010 Agricultural machines, Collection of research articles. Lutsk, Lutsk National Technical University 20 234-242
[6] Guskov V V, Velev N N, Atamanov Yu E 1988 Tractors: theory (Maschinostroyenie)
[7] Macmillan R H 2002 The mechanics of tractor-implement performance: theory and worked examples: a textbook for students and engineers Printed from: http://www.eprints.unimelb.edu.au
[8] Lovei`kin V and Romasevich U 2012 Motrol 14-3 158-163
[9] Malesa V 2012 Motrol 13 136-144
[10] Karabanitskiy A P and Kochkin E A 2009 Theoretical basis of industrial exploitation MTP. Kolos 152.
[11] Popov L A 2004 Exploitation of the machine and tractor park in the agrarian complex. Syktyvkar Forest Institute 152
[12] Kuzmin NV 2005 Mechanization and electrification of agricultural machinery production 10 6–8
[13] Ademiluyi Y S Ozoemena Ani A, Ugwuishiwu B O and Oyelade O A Nigerian journal of technology 26(1) 59–66
[14] Ahlborg B, Bergstrom J, Ekelund L G. and Hultman E 1967 Acta Physiologica Scandinavica 70 129-142
[15] Carrithers J A, Williamson D L, Gallagher P M, Godard M P, Schulze K E and Trappe S W 2000 Journal of Applied Physiology 88 1976-1982