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A simulation model of 2WD tractor performance

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ABSTRACT

The aim of this study was to develop a model that can accurately simulate the performance of a 2WD tractor with a suspended working implement (cultivator) on various types of soil. The following performance indicators were assessed with the use of the developed model: tractor's overall efficiency, tractive efficiency, specific fuel consumption and soil productivity. The proposed model supports the determination of performance indicators accounting for the overall loss of energy during machine operation. Overall efficiency is such an indicator. The value of this parameter varies significantly subject to changes in tractive force from 0 to 7 kN for the analyzed values of the fuel injector control signal and the total transmission ratio in the third (3L), fourth (4L) and fifth (1H) gear. For this reason, the above indicator may be used to determine the optimal parameters of tractor performance. The above variability was not reported in respect of the coefficient of tractive efficiency.

1. Introduction

Farming tractors and machine units are the basic tools used in field production and internal field transport. Modern machinery, characterized by a growing degree of automation, unification and modular integration, poses new technical, organizational and economic problems, in particular during operation. The effectiveness of tractor performance is one of such problems. Changes in the performance quality of farming machines can be monitored through the rational use of performance indicators. Farming machines operate in varied conditions due to soil diversity, soil deformation as well as changing loads exerted by the working implement. The effectiveness of tractor performance has to be monitored continuously in a varied operating environment.

Various authors have proposed to analyze the effectiveness of tractor performance in view of the drawbar pull criterion (Söhne, 1952; Steinkampf, 1974; Wong, 1986; Wulfsohn et al., 1988; Kuczewski and Wolski, 1990; Souza and Milanez, 1991; Upadhyaya et al., 1991, 1997; Okello, 1992; Komandi, 1997; Osetinsky and Shmulevich, 2004; Sahu and Raheman, 2006; Previati et al., 2007). The problem of drawbar pull efficiency has been discussed in numerous theoretical and empirical studies, many of which analyzed wheel–soil interactions in view of the tractive efficiency ratio.

The first attempts to analyze the force system and moments of force during interactions between a tractor's chassis components and a deformed soil surface were made by Bekker (1956). His work was further elaborated by other authors who developed various models of interaction between pneumatic tires and the soil. A graphical method for predicting the field efficiency of a rear-wheel drive tractor was proposed by Zoz (1972). The tractive efficiency ratio of the drive wheel was expressed as the ratio of drawbar power to axle power. This method is applied to predict the drawbar pull, drawbar horsepower, the speed and slip of drive wheels in various, predetermined field (soil) conditions. Wismer and Luth (1974) proposed an empirical equation for determining the tractive performance of wheels on cohesive soils. The value of the tractive force is calculated by subtracting the rolling resistance force from the tractive force. Equations determining the tractive characteristics of a bias-ply tire during heavy-duty operation were presented by Brixius (1987). An analysis of the above equations indicates that the calculation of drawbar pull efficiency requires the determination of many empirical variables, some of which are used to calculate the tire's tractive coefficient. Brixius's drive wheel performance equations were applied in simulation software to determine a tractor's drawbar pull. Zoz (1987) relied on Brixius's (1987) tractive adhesion equations to develop Lotus templates for predicting the drawbar pull of 2WD and 4WD tractors with bias-ply tires on farming soil. Al-Hamed et al. (1994) verified Lotus-compatible templates for the spreadsheets developed by Zoz (1987). Based on the existing templates, Al-Hamed and Al-Janobi (2001) created a dedicated application in Visual C++ to predict tractor performance. The application was used by Zoz and Grisso (2003) to evaluate the tractive performance of a 4WD tractor.

Catalán et al. (2008) and Kumar and Pandey (2009) modified Brixius's equations describing the tractive parameters of a drive wheel to account for the characteristics of a specific soil

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Nomenclature

$A_1, A_2, \ldots A_6$	coefficients of correlation $\mu = f(s)$
a_n	soil cutting depth (m)
B_1, B_2	empirical coefficients of tool resistance
b_n	soil cutting width (m)
C_a	soil productivity (ha/h)
D	tractor's drawbar pull (kN)
e_f, e_r	arm of interaction between the soil and the front/rear wheel (m)
F_a	force of grade resistance resulting from tractor mass and horizontal surface inclination (N)
F_c	fuel consumption per hectare (L/ha)
F_{rf}, F_{rr}	rolling resistance force of the tractor's front/rear wheels (N)
F_t	tractive force acting on the tractor's rear wheels (N)
f_f, f_r	rolling resistance coefficient of front/rear wheels
g_e	specific fuel consumption (g/kW h)
h_C	distance between the tractor's center of mass and the traveled surface (m)
h_D	distance between the point of application of the resultant force exerted by the implement on the tractor and the traveled surface (m)
I_{wr}	mass moment of wheel inertia (kg m^2)
i_{c3}, i_{c4}, i_{c5},	total transmission ratio in third 3L, fourth 4L and fifth 1H gear
l	drive wheel axle base (m)
l_C	distance between the tractor's center of mass and the front wheel axle base (m)
l_D	distance between the point of application of the resultant force exerted by the implement on the tractor and the rear wheel axle base (m)
m	tractor's mass with implement (kg)
P_e	power of engine (kW), determined based on the resultant torque and the angular velocity of the crank
Q_a	normal force resulting from the tractor's mass and horizontal surface inclination, acting on its center of gravity (N)
Q_f	calorific value of fuel (J/g)
R_f, R_r	force of the resultant interactions between the surface and front/rear wheels (N)
R_t	resultant resistance force exerted by the implement on the tractor (N)
r_{df}, r_{dr}	dynamic radius of front/rear wheel (m)
s	drive wheel slip
T_e	torque of engine (N m), calculated as a function of the fuel injection control signal and the angular velocity of the crank
T_w	drive shaft torque (N m) should be supplied by an internal engine via the transmission system to the drive wheel
u_e	fuel injector control signal (%)
v	tractor's linear velocity (m/s)
α	angle of surface inclination relative to the level traveled by the tractor (rad)
γ	angle between the direction of the resultant force exerted by the implement on the tractor and the direction of force component, D, parallel to the surface (rad)
$\eta_e, \eta_m, \eta_t, \eta_o$	engine efficiency, mechanical efficiency of the power transmission system, tractive efficiency of the drive wheel, overall tractor efficiency
μ	coefficient of net traction,
φ_{wf}	angular displacement of the front wheel (rad)
φ_{wr}	angular displacement of the rear wheel (rad)
ω_e	angular velocity of the engine shaft (rad/s)
ω_w	angular velocity of the drive wheel (rad/s)

environment. The modified equations were applied to create a Visual Basic application which was verified and used to determine tractor performance indicators, including tractive efficiency and wheel slip.

Żebrowski (2010) defined the drawbar pull coefficient as the product of three factors: kinematic efficiency, dynamic efficiency and mechanical efficiency. The kinematic efficiency equation is a function of slip, and dynamic efficiency is a ratio of drawbar pull to tractive force.

The physical, chemical and mechanical properties of arable soil in north-eastern Poland vary significantly. For this reason, the efficiency of tractor performance is an important and a complex consideration. Tractor performance is determined by various dynamic input functions that change over time. At present, there are no methods for continuously monitoring tractor efficiency that account for all energy losses. In order to support the optimization of tractor performance, the above indicators have to be determined on-line.

Presented here is a simulation model of tractor performance that can accurately simulate the performance of a 2WD tractor with a suspended working implement (cultivator) on various types of soil (stubble field). The proposed model supports the selection and determination of performance indicators accounting for the overall loss of energy during machine operation.

2. Materials and methods

The described experiment investigated tractor performance during soil (stubble field) cultivation. The machine was a Ursus MF 235 rear-wheel drive tractor. A three-point suspension system was used to mount the working implement (cultivator) to the tractor. A method was developed for determining the coordinates of the suspended device relative to the tractor and the resultant force exerted by the implement on the tractor.

2.1. Tractor model

A diagram of external forces and moments of force applied to a rear-wheel drive tractor with implement load is presented in Fig. 1. A flat frame of reference has been adopted, and the conditions of equilibrium produced three equations of external forces and moments of force acting on the tractor:

– from the sum of projections of force acting on the surface, in the direction of the x axis;

$$\sum F_{xi} = 0 = F_t - m\dot{v} - F_{rf} - F_a - D \tag{1}$$

– from the sum of projections of force in the direction of the y axis;

$$\sum F_{yi} = 0 = R_f - Q_a + R_r - D\ \tan\gamma \tag{2}$$

– from the sum of moments relative to point O_1,

$$\sum T_{O_1} = 0 = Q_a(e_f + l_C) + h_C(m\dot{v} + F_a) - R_r(e_f + l - e_r) + D(h_D + (e_f + l + l_D)\tan\gamma) \tag{3}$$