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How to select air pressures in the tires of MFWD (mechanical front-wheel drive) tractor to minimize fuel consumption for the case of reasonable wheel slip

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A B S T R A C T

In agriculture, tractor is the most fuel-consuming machine. The research indicates that 20–55% of available tractor power is lost in the process of interaction between tires and soil surface. Tire pressure and vertical wheel load are both easily managed parameters, which play a significant role in controlling the slip, the traction force and the fuel consumption of a tractor. The purpose of the research was to base theoretically and experimentally the tire pressures that ensure a minimum kinematic mismatch between the drive wheels for MFWD (mechanical front-wheel drive) tractor, and thereby reduce the fuel consumption at a reasonable tire slip. Close to one coefficient of kinematic mismatch between the front and the rear wheels was observed when combinations of pressures in the rear/front tires were made, respectively: 150/70, 190/110, and 230/115 kPa. When tractor (MFWD) was driving on a hard road surface without thrust load and with above mentioned tire pressure combinations, the lowest fuel consumption was reached, namely, in the range from 3.75 to 3.8 L h^{-1}.

1. Introduction

Tractors are considered the main machines that generate power for field operations in agriculture. Fuel consumption for the tractor in motion depends on the traction power and the power loss [1]. Agricultural wheeled machines, especially tractors, consume too many energy due to complex topsoil-tire interaction that forms stochastic tire deflection and soil deformation. The research indicates that 20–55% of available tractor power is lost in the process of interaction between tires and soil surface [2,3]. Power loss of the tractor has direct influence on fuel consumption. In turn the fuel consumption can be further processed into greenhouse gas emissions [4]. It is essential to take drastic measures in concern with the minimization of energy loss and maximization of energy efficiency of the agricultural tractors. Vertical wheel loads, tire inflation pressures and wheel slip are the most significant parameters influencing the performance of drive wheels [5–8]. It was observed that only the decrease in tire pressure produced improvements in terms of traction coefficient, power delivery efficiency, and fuel consumption, while the only significant benefit due to the increase in wheel vertical load was a reduction in the fuel consumption [5]. However, low tire inflation does not guarantee better drawbar characteristics in all cases [6]. Taghavifar and Mardani [8] obtained that increase of inflation pressure suggests reverse relation with rolling resistance particularly at higher values of vertical load.

In most cases agricultural tractors are equipped with an all-wheel (four-wheel) drive. Such machines ensure more pull with less slip, because all the weight of machine is utilized for its grip with soil/road surface. Tractors with all-wheel drive perform better in field work, especially when working in loose, wet, saturated areas, as they have better terrain-crossing capacity, although on the dry road a lot of their energy is wasted to drive the second (front) axle [9,10]. Most small and medium-power-range four-wheel-drive tractors are available with different sizes of their front and rear wheels. When the front axle is driven by a mechanical drive and the front wheels are smaller than the rear wheels, such tractors are identified as MFWD (mechanical front-wheel drive) tractors [11].

Most such MFWD tractors are manufactured in such a way that in static conditions rear wheels are loaded by 55–65% of the total weight of the tractor. Tractor researchers recommend maintaining this proportion of vertical wheel loads in working conditions as

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Nomenclature

MFWD mechanical front-wheel drive provides four-by-four capabilities to tractors with different-sized front and rear wheels
B_h hourly fuel consumption (L h^{-1})
d_{ft} and d_{rt} theoretical distances of front and rear wheels' travel during one revolution (m)
d_{fa} and d_{ra} actual distances of front and rear wheels' travel during one revolution (m)
F_v tractor drive force (N)
H height of tire (m)
H_f and H_r heights of front and rear tires (m)
i_f and i_r transmission gear numbers for the front and rear drive axles
k_i coefficient for the ratio between angular velocity of the front and rear wheels, or the transmission gear numbers for the front and rear drive axles
K_s coefficient of kinematic mismatch between the front and rear drive wheels
l_f front axle wheels lead ratio
m_b ballast mass (kg)
M_f and M_r drive torques of the front and rear wheels (Nm)
p air pressure in the tires (kPa)
p_f and p_r air pressures in the front and rear tires (kPa)
$p_f^{\bullet}$ and $p_r^{\bullet}$ nominal air pressures in front and rear tires (kPa)
$P_{\Delta f}$ and $P_{\Delta r}$ power used for normal deformation of the front and rear tires due to active on them vertical loads (kW)
$P_{\tau f}$ and $P_{\tau r}$ power used for tangential deformation of the front and rear tires due to active on them drive (torque) moments (kW)
P_{sf} and P_{sr} power used for slip/slide of the front and rear wheels (kW)
P_{tr} power used for compensation of transmission resistance (kW)
r_0 inner radius of tire (m)
r_{0f} and r_{0r} inner radius of front and rear tires (m)
r_r dynamic radius of tire (m)
r_{rf} and r_{rr} dynamic radiuses of front and rear wheels (m)
r_{rf}^0 and r_{rr}^0 dynamic rolling radiuses of the front and rear drive axle wheels in the mode of driving wheel (m)
R_z normal reaction force of the ground to the tires (N)
R_{zf} and R_{zr} normal reaction forces of the ground to the front and rear tires (N)
Δr deformation coefficient of tire
Δr_f and Δr_r deformation coefficients of the front and rear tire
s_f and s_r slip/slide coefficients of the front and rear drive wheels
v_{tf} and v_{tr} theoretical speeds of the front and rear wheels (m s^{-1})
W normal load of tire (N)
$W_r^{\bullet}$ and $W_f^{\bullet}$ nominal normal load of rear and front tires (N)
ω_f and ω_r angular velocity of the front and rear wheels (s^{-1})
λ tangential elasticity coefficient for the tires
λ_f and λ_r tangential elasticity coefficients for the front and rear tires
$\lambda_f^{\bullet}$ and $\lambda_r^{\bullet}$ nominal tangential elasticity coefficients of front and rear tires
π mathematical constant ($\pi \approx 3.14$)

well [12,13]. If the tractor work includes pull operations, the vertical load distribution between the front and the rear wheels is adjusted by ballast weights [14,15]. If exact distribution is not possible to obtain, deviation in proportion of vertical loads between front and rear wheels should not exceed the recommended by more than 10% [16].

Purpose of the tractors is to pull various agricultural machinery, implements, and trailers. Normal speed of a tractor in field operations ranges from 0.8 m s^{-1} to 4.2 m s^{-1}. Unfortunately, such speeds fall into the range where the wheel slip gets its maximal value; therefore, the aim should be focused on reducing the wheel slip. The wheel slip is a critical parameter for fuel consumption and field performance. The traction control system in ploughs reduces fuel consumption between 10 and 11.5% [17]. Normally, slip of drive wheels should not exceed 15%, otherwise it causes lower productivity, cost-effectiveness, and intensive destruction of the soil [3,18]. If slip of drive wheels in the soil is low (less than 5–7%), it is also unacceptable, as the traction power is not utilized and energy consumption per unit of performed work increases. Slip is low when drive wheels are loaded with too big weight force. In this case the power is used to carry the excess mass and press the soil, and fuel consumption may increase by 15% [11,15]. Analysis of research materials shows that optimal tractor slip in soil should be in the range of 8–12% [11,17]. Nowadays, slip is usually reduced by loading the tractor with ballast weights and decreasing the pressure in the tires. The results of tests show that in tillage works draft can be increased by up to 15% depending on the value of ballast weights and the place where they are mounted [14,16]. Over-ballasting a tractor, however, wastes fuel due to increased rolling resistance and soil compaction. Under-ballasting a tractor wastes fuel due to excessive tire slip, and causes premature tire wear. To reduce slip, tractor operating professionals often recommend reducing tire pressures, thus increasing contact area between the tire and the soil. With this purpose in mind, tire manufacturers and researchers are looking for solutions to further lowering the pressure in the tires, while tractor manufacturers are already introducing automatic tire pressure control systems.

Technical literature analysis shows that tire deformation changes are inevitable when ballasting a tractor (attaching additional weights to the tractor), reducing tire pressure, using traction control systems, etc., leading to changes in rolling radiuses [5]. Disproportion in change of rolling radiuses for MFWD tractors creates kinematic mismatch between drive wheels and alters the lead of the front drive wheels [19–21]. These problems, in turn, make a negative impact on the operating parameters of the tractor: traction force, wheel slip, fuel consumption, productivity, harmful effect on the soil, etc.

Variations in soil structure and surface roughness affect the variations in implement resistance and pulling force [17]. Pulling force and soil surface hardness variations, in their turn, change the tire slip of the tractor. Therefore, slip varies in wide range for the tractors working in the fields. Often, for the average slip of 9–11%, the lowest slip value may fall to only 5%, and the highest slip value may exceed the permissible limit slip value of 15% [22,23]. In such conditions, kinematic mismatch between the front and the rear wheels have a serious impact to the efficient operation of the tractor. While kinematic mismatch caused by tire deformation does not make significant harmful effect for the case of the largest tire slip, kinematic mismatch of the same size significantly adds to power loss when slip decreases. Research results show that in order to reach the maximum traction force and the lowest power consumption for the MFWD tractor, the following is needed: one, to choose the lowest possible air pressures in the tires; two, to choose the efficient ballast weights;