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Tire inflation and its influence on drawbar characteristics and performance – Energetic indicators of a tractor set

T. Šmerda, J. Čupera *

Department of Engineering and Automobile Transport, Mendel University in Brno, Brno, Czech Republic

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Abstract

This work deals with the influence of tire inflation on tractive characteristics and performance-energetic parameters of a ploughing set. The test was conducted using two tire sets with different tire pressures under field conditions. Measurements of tractive properties were performed by setting travel speeds to 5, 8, and 10 kph, respectively. The ploughing set was operated at 8 kph, according to the manufacturer's recommendation. The measurement results were processed graphically and mathematically into the Vehicle Traction Ratio, drawbar power, and slip characteristics. The tire inflation, reduced from 180 to 65 kPa and/or 75 kPa, of tires with wide treads (low-profile) resulted in increase of the front tire footprint by 24.7% and rear tire footprint by 31.1%. This change had a positive impact on the specific tractive fuel consumption that decreased in the range from 3.4% to 16.0%, depending on the travel speed. The results of performed measurements revealed that reducing the tire inflation of appropriate tires can improve the drawbar characteristics and consequently the fuel consumption.

Keywords: Tractor; Radial-ply tire; Tire inflation; Slip

1. Introduction

Tractive efficiency is considered as the most important factor of tractor aggregation, especially in crop production. Research studies indicate that about 20–55% of the energy transferred to the drive tractor wheels is wasted in the tire–soil interaction. Not only is this energy useless or causes soil compaction, but it also may have a devastating effect on crop production [3]. The increasing tractive efficiency means more effective usage of the internal combustion engine's mechanical work. In other words, possibilities of higher efficiency lie in power dissipation reduction.

The common speed of a tractor during field operation ranges from 3 kph to 15 kph. Unfortunately, it is the range of the speed where the wheel slip gets its maximal value; therefore, the aim should be focused on reducing the tire slip, which can bring more tractive efficiency. There are two essential ways how to reduce the slip in terramechanics. The first one lies in increasing the tractor's weight by adding ballast. The other possibility is to enlarge the contact area between tires and surface.

Enlargement of the tire contact area reduces negative effect of tractor's movement on the field and it restricts physical degradation of soil characteristics (structure damage, compaction, etc.) In addition, a larger contact area makes rolling resistance smaller in soft soil [4,5]. Gaultney et al. [6] found 50% corn yield reductions with severe compaction and 25% yield reductions with moderate compaction.

In this context, there is an intensive effort of research and development to find out optimal operational parameters which might improve net traction ratio as well as tractive efficiency. The tire inflation was found to be one of the most important factors affecting traction [7]. In general, for traction in loose or soft soils, a decrease of inflation

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* Corresponding author. Address: Department of Engineering and Automobile Transport, Mendel University in Brno, Zemedelska street 1, 613 00 Brno, Czech Republic. Tel.: +420 545 132 942.
E-mail address: xcupera@node.mendelu.cz (J. Čupera).

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Nomenclature

A	tire footprint
b	width of tire footprint
c	cohesion
DP	drawbar power
F_g	gross traction
j	shear displacement
K	shear modulus of deformation
L	footprint length of tire
p	inflation pressure
q_s	mean contact pressure
SFC	specific fuel consumption
s	slip
VTR	vehicle traction ratio
φ	angle of internal friction
σ	normal stress
$\tau_{\max}$	maximum shear stress
τ	shear stress

pressure results in the improvement of distributions of both normal and tangential, inferential stress in the traction of the tire performance [10]. A tire inflation pressure range of 40–50 kPa is recommended to avoid harmful soil compaction in moist to wet soil conditions [8]. Advantages of using low pressure tires, especially the positive influence on traction ability and soil compaction, made manufactures of farm machinery and tires together develop very low pressure radial tires with inflation capacities of 40 kPa without impacts on lifetime or durability.

The goal of this work is to evaluate the advantages of low-pressure inflation decreased to 40 kPa and the effect on the drawbar pull during the test and application of obtained results in measurement with a mounted plough.

2. Theoretical analysis

Gross traction moving the tractor forward is a result of interaction between soil and the engine torque transferred onto the tire's circumference. Mechanical characteristics of the soil are one of the major factors, determining drawbar characteristics of tractors [10]. The transfer circumference force causes the soil shear stress, which is a direct proportional tangential force, and the indirect proportional shear area, in which the force acts.

$$\tau_{\max} = \frac{F_{g\max}}{\sum_{i=1}^{n} A_i} \,(\mathrm{Pa}) \tag{1}$$

where $F_{g\max}$, maximum gross traction (N), $\sum_{i=1}^{n} A_i$, sum of shear areas (m^2).

Shear stress increases with a growing tangential force up to the moment when soil failure occurs. The maximum shear stress and soil movement is described by above-introduced Eq. (1). From the results of Coulomb's Soil Failure Theory, the value of maximum shear stress is not constant; but depends on the size of normal stress in a level of failure, and in the general case it has two components: internal friction described by the angle of internal friction φ and cohesion c [9].

Maximum shear stress formulated by Coulomb can be written in the following way:

$$\tau_m = c + \sigma \cdot \mathrm{tg}\varphi \tag{2}$$

where c, cohesion; σ, normal stress; φ, angle of internal friction.

Soil failure will occur, if the shear stress τ achieves the value of maximum shear stress τ_m. The size of the biggest gross traction, transferred onto the surface and respecting the shear stress maximum, represented by Coulomb, can be rewritten in the form:

$$F_{g\max} = (c + \sigma \cdot \mathrm{tg}\varphi) \cdot \sum_{i=1}^{n} A_i = f\left(\sigma, \sum_{i=1}^{n} A_i\right) \tag{3}$$

That equation can be further modified using knowledge of the exponential approximation in dependence of shear stress τ to shear displacement respecting of Coulomb's law [2,12,13]:

$$\tau = \tau_{\max} \cdot (1 - e^{-\frac{j}{k}}) = (c + \sigma \cdot \tan\varphi) \cdot (1 - e^{-\frac{j}{k}}) \tag{4}$$

K is the shear deformation parameter of the terrain, which determines the shape of the shear stress–shear displacement curve. Substitution into the basic equation (1) and its solving yields in the final formula, where dependence of the slip-tire size and maximum length of the slip surface L are present:

$$F_h = \int_0^L \tau_{\max} \cdot b \cdot dx \tag{5}$$

$$F_h = b \cdot \tau_{\max} \int_0^L (1 - e^{-\frac{j}{k}}) dx \tag{6}$$

$$F_h = F_{h\max} \cdot \left(1 - \frac{k}{\delta \cdot L} \cdot \left[1 - e^{-\frac{\delta \cdot L}{k}}\right]\right) \tag{7}$$

Usually it is assumed that the maximal value of the shear force occurs at the maximum slip, which results from previous equations. This statement cannot be taken unconditionally as can be seen from the results obtained by Grečenko [1]. Wong et al. [11] further noted that the derivation is valid for the flat contact area and movement on hard surfaces.

Decrease of normal stress can be achieved by the reduction of weight, tire pressure, or by using low tire pressure. In all cases, the effect is based on the change of the contact footprint, which is the area where shear stresses are generated. Weight reduction causes a fall of normal stress and an area transferring tangential force. It increases slip and