Soil & Tillage Research 165 (2017) 113–120

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Applying an artificial neural network approach to the analysis of tractive properties in changing soil conditions

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ARTICLE INFO

Article history:
Received 24 June 2016
Received in revised form 8 August 2016
Accepted 9 August 2016
Available online xxx

Keywords:
Traction force
Traction efficiency
Artificial neural network

ABSTRACT

For better performance of a micro-tractor during agricultural operations, it is necessary to select the optimal tractor configuration for the operation. The purpose of this study was to analyse the effects of soil texture, soil moisture and compaction as well as horizontal deformation and vertical load on traction force and traction efficiency. Analysis and mathematical modelling were performed with the use of artificial neural networks (ANN). Accurate mathematical models were obtained with high values of coefficient of determination R^2 for the validation data set ($R^2 = 0.945$ for traction force and $R^2 = 0.963$ for traction efficiency). Based on neural models, analysis of the contribution of independent input variables was performed. Soil texture and soil moisture had the highest influence on traction force and traction efficiency; vertical load significantly affected traction force. Horizontal deformation and soil compaction had minor influences on both dependent variables. Evolutionary algorithm was used for the determination of soil conditions and vertical load which produce high traction force and traction efficiency. The vertical load is considered as an easily managed parameter during agricultural operations. Since the increase in vertical load results in increasing traction force and, at the same time, in decreasing traction efficiency, the appropriate vertical load value was calculated for optimization of traction force and traction efficiency in changing soil conditions, which is crucial for tillage management.

1. Introduction

Tractors are the basic vehicles for performing many agricultural operations and the main machines generating power for field operations in agriculture. The complex topsoil-tyre interaction leads to tyre deflection, soil deformation and energy overconsumption. According to scientific reports, 20–55% of available tractor power is lost because of the interaction between tyres and topsoil (Smerda and Cupera, 2010). This phenomenon directly influences fuel consumption. Minimization of fuel consumption is of crucial importance in tillage management from an economic as well as an environmental point of view. Interaction between tractor wheels and topsoil is affected by several factors, including the mechanical behaviour of the topsoil, wheelbase and drawbar height of the tractor, number of drive wheels, wheel load, wheel slip, tyre inflation pressure and stiffness and tyre dimensions (width and diameter) (Battiato and Diserens, 2013). However, some parameters, such as tyre inflation pressures, wheel slip and vertical wheel loads, are considered as the most significant parameters which influence the performance of drive wheels (Janulevicius and Damanauskas, 2015; Lee and Gard, 2014; Taghavifar et al., 2014). Tyre pressure and wheel load are easily managed parameters. The maximum traction force value and the low power consumption for the MFWD (mechanical front-wheel drive) tractor can be achieved by choosing the lowest permissible air pressures in the tyres as well as the most efficient ballast weights (with minimum kinematic mismatch between the front and the rear drive wheels) (Janulevicius and Damanauskas, 2015). The effects of variations in tyre inflation pressure and wheel load on the traction performance of a 65 kW MFWD tractor on an agricultural clay (C) Vertic Cambisol were investigated by Battiato and Diserens (2013). Improvements in terms of coefficient of traction, tractive efficiency, power delivery efficiency and specific fuel consumption were achieved by tyre pressure decrease. Previous studies have evaluated the influences of velocity, tyre inflation pressure and wheel load on the energy waste of the soil-tyre interface (Taghavifar et al., 2014) and rolling resistance of the wheels (Taghavifar and Mardani, 2013). According to Smerda and Cupera (2010), reduction of tyre inflation can improve the drawbar

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http://dx.doi.org/10.1016/j.still.2016.08.005
0167-1987/

characteristics of the ploughing set, and consequently, fuel consumption.

The majority of the studies on topsoil-tyre interactions was carried out for high-power tractors. Therefore, in this work, we investigated the interaction between soil and the traction device for low-power tractors.

A model for predicting soil–traction interaction is a useful tool for researchers and engineers in solving problems regarding tractor performance under a wide range of conditions; it can be used for tractor operational parameters optimization without expensive and time-consuming field tests. Tyre–soil interaction models can be based on empirical, semi-empirical and analytical methods (Tiwari et al., 2010). Analytical models require the knowledge of the distribution of normal and shear stress at the soil-tyre interface and the geometry of the 3D contact surface. This approach has been used by some researchers for the prediction of traction parameters (Fervers, 2004; Nakashima and Oida, 2004; Yong et al., 1980). Tiwari et al. (2010) emphasise the fact that there are difficulties in the widespread use of analytical models caused, inter alia, by the complexity of the interaction between tyre and soil. Semi-empirical models are based on two parameters: the vertical deformation of soil, which is similar to the deformation under a sinking plate, and the shear deformation of soil under a traction device, which is similar to the shear due to a torsional shear device or a rectangular grouser unit (Tiwari et al., 2010). The parameters of equations used in semi-empirical models are determined experimentally. A semi-empirical model for the prediction of traction performance of a tractor driving wheel was proposed by Rosca et al. (2014) and based on the super ellipse equation, describing the shape of the tyre–ground contact surface. Empirical models are more simple than analytical and semi-empirical models; they are developed based on traction data recorded from operating vehicles. Consequently, the applicability of empirical models is limited to cases with similar conditions to the ones from which experimental data were obtained. Therefore, in the model proposed in this research, one of the parameters is the coefficient describing soil texture.

Since the topsoil-tyre interaction is non-linear and complex, the development of high precision models based on experimental data was complex and challenging. Therefore, some methods other than linear and non-linear regression techniques are proposed for prediction models describing soil-machine dynamics. The 3D finite element–discrete element method was proposed for analysis of rigid tyre traction performance on a sandy soil (Zhao and Zang, 2014); the data envelopment analysis and hybrid statistical-mathematical modelling approach of RSM (response surface methodology) for optimization of the energy waste of off-road vehicles (Taghavifar et al., 2014); the fuzzy logic approach for soil compaction prediction under pneumatic tyres (Carman, 2008). As an alternative method of topsoil-tyre interaction modelling, the artificial neural networks (ANNs) were employed by some researchers (Taghavifar and Mardani, 2014; Taghavifar et al., 2013; Çarman and Taner, 2012). The development of high precision ANN model provides additional opportunities in topsoil-tyre interaction analysis. Several methods can be used to determine the contribution of independent input variables, resulting in knowledge about predictor variables importance (Li et al., 2015; Reddy et al., 2015; Tohidi and Sharifi, 2015). An ANN model can be easily implemented into some optimization algorithms, such as evolutionary algorithms (Di Scala et al., 2013), and enables the determination of optimum traction conditions.

In this paper, we present artificial neural networks for the prediction of traction force as well as traction efficiency of low-power tractors with the inputs of vertical load, horizontal deformation and certain soil parameters. Based on high precision models, the analysis of predictor variables importance was conducted and an evolutionary algorithm was employed for traction conditions optimization.

2. Materials and methods

2.1. Experimental data acquisition

The tests were carried out for four different soil types: sand, fine sandy loam, sandy loam and silty clay loam. In order to obtain an universal model which can be used for different soil types, soil texture was determined according to USDA (Brady and Weil, 2008) and soil coefficient was calculated as follows:

$$s_c = \frac{c_1 + c_2 + c_3}{100} \quad (1),$$

where: s_c is the soil coefficient [−], c_1 is the share of medium silt in the test sample [%], c_2 is the share of fine silt in the test sample [%] and c_3 is the share of clay in the test sample [%].

Based on Eq. (1), the values of coefficients calculated for investigated soils are as follows: sand – 0.08; fine sandy loam – 0.21; sandy loam – 0.33 and silty clay loam – 0.68. We chose four moisture levels for each soil texture: 1.25 field water capacity, field water capacity, beginning of plant growth inhibition and strong inhibition of plant growth. The values of soil moisture for different soil types are presented in Table 1.

Soil moisture was changed in a controlled manner by water addition. and established using a drier method with the use of a scale-drier WPE – 300S. Soil moisture of the five samples was measured and the final value was calculated as the arithmetic mean. Soil compaction was changed by means of stand presented in Fig. 1.

The soil compaction device was motorized by a single-phase electromotor connected with the cam through a transmission belt; vibration frequency equalled 38 Hz and an amplitude of 0.01 m. Different degrees of soil compaction were obtained by altering compaction time.

A soil bin testing facility presented in Fig. 2 was used in the laboratory to provide the

controlled environment for evaluating the interaction between soil and tyre of micro-tractor.

The vertical load of the wheel was changed by means of a wheel bevameter. The wheel was motorized by a hydraulic system with a servo-motor working both sides, providing constant angular velocity and power necessary to perform measurements in all

Table 1
Values of soil moisture [%].

	1.25 field water capacity	Field water capacity	Beginning of plant growth inhibition	Strong inhibition of plant growth
Sand	15.31	12.25	10.00	7.00
Fine sandy loam	24.38	19.50	16.00	11.20
Sandy loam	25.63	20.50	18.00	12.60
Silty clay loam	37.81	30.25	27.00	18.90