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Artificial Neural Network estimation of wheel rolling resistance in clay loam soil

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ABSTRACT

Despite of complex and nonlinear relationships imparting soil–wheel interactions, however, logical, non-randomized, and manifold relations tackle to express and model the interactions which are valid for variety of conditions and are likely to be established whereas mathematical equations are restricted to present. A 3-10-1 feed-forward Artificial Neural Network (ANN) with back propagation (BP) learning algorithm was utilized to estimate the rolling resistance of wheel as affected by velocity, tire inflation pressure, and normal load acting on wheel inside the soil bin facility creating controlled condition for test run. The model represented mean squared error MSE of 0.0257 and predicted relative error values with less than 10% and high coefficient of determination (R^2) equal to 0.9322 utilizing experimental output data obtained from single-wheel tester of soil bin facility. These rewarding outcomes signify the fitting exploit of ANN for prediction of rolling resistance as a practical model with high accuracy in clay loam soil. Derived data revealed rolling resistance is less affected by applicable velocities of tractors in farmlands nevertheless is much influenced by inflation pressure and vertical load. An approximate constant relationship existed between velocity and rolling resistance implying that rolling resistance is not function of velocity chiefly in lower ones. Increase of inflation pressure results in decrease of rolling resistance while increase of vertical load brings about increase of rolling resistance which was measured to be function of vertical load by polynomial with order of two model validated by conventional models such as Wismer and Luth model.

1. Introduction

The current study intends to estimate wheel rolling resistance utilizing Artificial Neural Network (ANN). Traction performance is the most imperative characteristic of agricultural tractors. Total traction and rolling resistance should be subtracted in order to acquire net traction. Obviously rolling resistance is the principal attribute affecting traction performance. Moreover, rolling resistance is extremely influential on fuel consumption. Energy loss due to erroneous management of agricultural tires was reported to be about 575 million liters per year in USA [1].

This statistic spotlights the prerequisites on minimizing the rolling resistance to the lowest possible level. Rolling resistance is naturally negative force applied on wheel against with the forward direction of movement. In other words, it is a direct function of required energy to deform the soil under a wheel as well as tire deformation while initiating to roll. Tire deformation generates tire's heating up and consequent energy loss whiles the latter component of rolling resistance (i.e. soil deformation) proceed further concern of soil compaction. Rolling resistance as a major soil–wheel interaction production has been investigated by various researchers.

Bekkar [2] established the relations between wheel and soil while described amount of rolling resistance to be influenced by variety of parameters may be expressed by:

$$R = \frac{3W^{((2n+2)/(2n+1))}}{(3-n)^{((2n+2)/(2n+1))}(n+1)(K_C+bK_\varphi)^{(1/(2n+1))}d^{((n+1)/(2n+1))}} \quad (1)$$

where K_C and K_φ have been yielded from pressure sinkage equation as follows:

$$P = \left(\frac{K_C}{b} + K_\varphi\right) Z^n \quad (2)$$

where P yields pressure-sinkage equation in kPa, W is vehicle weight in kN, n is sinkage exponent, b is the smaller dimension of the rectangular contact area in m, d is wheel diameter in m, Z is

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the sinkage in m, and K_C and K_φ are the soil condition parameters. The required energy to compact the soil beneath the wheel during movement for a definite distance equals with a resistive force against movement multiplied by the distance. This resistive force (i.e. rolling resistance) is suggested to be yielded as:

$$R = b_w \int_0^{Z_{max}} \left(\frac{K_C}{b} + K_\varphi\right) Z^n dz \quad (3)$$

where R is rolling resistance in kN and b_w is wheel width in m and the other parameters are introduced above. Validity of equation above in order to predict rolling resistance based on soil deformation was offered by Wong [3] for wheel diameters more than 50 cm and sinkage levels less than 15% of wheel diameter.

There are numerous parameters affecting rolling resistance of them wheel diameter, tire inflation pressure, multipass, soil texture, sinkage, wheel slip, normal load, and velocity can be included. In 1971, the effect of wheel speed on rolling resistance was verified by Pope at velocities of between 0.1 and 5.5 m/s and reported the reverse relation between speed and rolling resistance [4]. Elwaleed et al. [5] reported the effect of inflation pressure on motion resistance in their experiments. Way and Kishimoto [6] surveyed soil–wheel interaction and approved the influence of velocity on rolling resistance especially for high speeds. Zoz and Grisso [7] reported identical results in their experiments. McAllister [8] observed reduction in the rolling resistance of wheels determining the values of the coefficient of rolling resistance (CRR) for wheels. The results indicated that reductions in CRR can be produced by reducing inflation pressure and vertical load. Coutermarsh [9] claimed that in dry sand, the rolling resistance has linear relation with velocity until the tire starts to plane, and then it becomes stabilized or decreases.

Soft computing technology is an interdisciplinary research approach which includes statistics, machine learning, Artificial Neural Network (ANN) and fuzzy data analysis in computational science to analyze data [10]. Hence, the methods of artificial intelligence have greatly been used in the different fields of the agricultural applications [10]. Of soft computing approaches, ANNs are used which are constituted from several elements known as neurons and is an idea of data processing inspired from human neural network. ANNs feature the capability of finding out the correlation between the input and output data [11] and has the ability to deal with manifold variables as well as linear and non-linear relationships [12]. ANNs have been carried out in the fields of pattern, recognition, modeling, and control in an effectively manner [13]. Roul et al. [14] successfully applied ANN representation predicting the draught requirement of tillage implements under varying operating and soil conditions. A neural network is adjusted for a definite task such as model distinguishing and data classification during a training process. Extensive aptitude of this approach for accurate estimations of complicated regressions contributes more advantage compared to classical statistical techniques. Each input to the ANN is multiplied by the synaptic weight, added together and dealt with an activation function while ANNs are trained by frequently exploring the best relationship between the input and output values creating a model after a sufficient number of learning repetitions, or training known as epochs [15]. After training, the neural representation has generalization capacity with new input values to predict, simulate and re-establish the condition identified as testing procedure. Tire movement progression on soil is necessarily sophisticated behavior encountering numerous variables.

There have been three variables in the present research including forward velocity, vertical load applied on wheel, and tire inflation pressure. The experimental investigation was carried out in a soil bin facility. Moreover, soil resistance described with cone index (CI) is a complicated variable and is difficult to be repeated with the purpose of test replicates. Soil processing, however, is more complex to achieve the same soil condition for soil resistance parameter and regarding the dependence of conventional statistical methods to test repetitions, ANNs facilitates this predicament since it is free of dependence to a constant variable during repeated tests.

This study was conducted developing the objectives of investigating the effect of velocity, tire inflation pressure, and vertical load on rolling resistance in a soil bin facility and utilizing ANNs to predict and model the inter-relations between each variable and the objective parameter with acceptable performance, high coefficient of determination, low MSE and simple topology.

2. Materials and methods

2.1. Data acquisition

A long soil bin was built in 2010 in the Faculty of Agriculture, Urmia University, Iran. This soil bin has 23 m length, 2 m width and 1 m depth [16]. This long channel had the ability to hold a wheel carriage, a single-wheel tester, and different tillage tools to be moved altogether in the length of the soil bin. The facility to fill the channel with various soil textures and different moisture contents provided higher advantage in comparison with uncontrolled conditions. A three-phase electromotor of 30 hp was used to move a carriage through the length of soil bin by means of chain system along with the wheel-tester when the carriage had the ability to traverse at the speed of about 20 km/h. The output shaft of the electromotor was connected to the drive shaft of the chains that pull the carriage forward or reverse. An inverter providing variable frequencies was used to supply power of electromotor in order to reach varying velocities. Another advantage of this system is the facility of adjusting braking and starting acceleration of electromotor which results in decrease of inertia forces. Four S-shape load cells with the capacity of 200 kg were calibrated and then were placed at proper places horizontally in parallel pattern between carriage and single-wheel tester and these load cells were interfaced to data acquisition system included a data logger, enabled monitoring the data on a screen and simultaneously, the data were sent to a computer with frequencies of around 30 Hz. A single-wheel tester was assembled to the carriage system with four S-shape load cells to measure the rolling resistance alterations caused by motion of wheel in various treatments being tested. The utilized driven tire was Good year 9.5L-14, 6 radial ply agricultural tractor tire. The system set up is shown in Fig. 1

The measured volume of soil bin was assessed to be 46 m^3 and consequently was filled with soil. To initiate the process, the electromotor generated power for the carriage movement based on adjusted velocity by an inverter by connection between the shafts of electromotor and chain system. An optic tachometer was used to measure the speed of carriage while an inverter could produce variety of velocities for the carriage. The movement of carriage by chain system generated traction of single-wheel tester in the soil bin and accordingly, load cells sent signals to the data acquisition system which were indicators of rolling resistance of wheel and eventually, data acquisition system enabled monitoring these data and also transferring them to the computer. Transmitted files were recorded as txt files and subsequently transferred to MATLAB software (version 7.6, 2008, Mathworks Company) for being processed. Summary of treatments being tested is shown in Table 1.

The soil bin was filled with clay-loam soil to simulate the real condition of farms that exists in most of regions in Urmia, Iran. Particular equipments were employed to organize soil bed including leveler and harrow since it is exceedingly crucial to have well-prepared soil inside soil bin for acquiring reliable and precise results