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Research Paper

On the modeling of energy efficiency indices of agricultural tractor driving wheels applying adaptive neuro-fuzzy inference system

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Abstract

The objective is to assess the potential of adaptive neuro-fuzzy inference system (ANFIS) for the prediction of energy efficiency indices of driving wheels (i.e. traction coefficient and tractive power efficiency). The output parameters were evaluated as affected by the tire parameters of wheel load at three different levels, velocity at three different levels and slippage at three different levels with three replications forming a total of 81 data points. ANFIS with a hybrid method of the gradient descent and the least-squares method was applied to find the optimal learning parameters using various membership functions (MFs). Statistical performance parameters of mean square error (MSE) and coefficient of determination, R^2, were considered as the modeling evaluation criteria. The implementations divulged that Gaussian membership function (*gaussmf*) and Trapezoidal membership function (*tramf*) configurations were found to denote MSE of 0.0166 and R^2 of 0.98 for traction coefficient while MSE equal to 1.5676 and R^2 equal to 0.97 for the tractive power efficiency were obtained.

Keywords: ANFIS; Energy efficiency; Traction coefficient; Tractive power efficiency

1. Introduction

Off-road vehicles especially agricultural wheeled machines are of major sources of energy consumption due to their massive size and complex soil-wheel interaction that forms stochastic tire deflection and soil deformation [1]. As documented in literature, the soil-tire interface is responsible for approximately 20–55% of the losses of tractor power, a factor that drastically affects the amount of fuel used in drawbar – implement applications [2,3]. In addition, Gill and Vanden Burg [4] estimated a national annual fuel loss of 575 million liters due to the mismanagement of off-road vehicles at the soil-traction interfaces in agricultural applications alone. It is essential to take drastic measures in concern with the minimization of energy loss and maximization of energy efficiency of the off-road vehicles. Of the significant parameters administering the performance of driving wheels are tire parameters such as wheel load, velocity, slippage, and tire inflation pressure. For the agricultural tractors the term net traction, which is the subtraction of gross traction created at the soil-tire interface and rolling resistance, is the most prominent objective to be increased. However, net traction is affected by numerous soil and tire parameters added with soil-interaction products such as contact area, tire deflection, and soil sinkage. For a certain farmland, however, administration of tire parameters is more beneficial than those of terrain specifications. In order to assess the influence of different applied parameters on the overall tractive performance of driving

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wheels, indices such as traction coefficient and tractive power efficiency are utilized. It is reported that the traction properties of agricultural tires are of special importance because the tractive efficiency varies in a wide range to a maximum of 75% [5]. This confirms the lowest energy waste of at least 25% in the optimal operating condition which is more in the real term situation.

There are many studies dedicated to the investigation of the effect of tire parameters on tractive performance of driving wheels [5–11]. The attempts in these studies were focused on experiments to get a better insight into the soil-wheel interaction and then to propose mathematical-based models or to assess the previously introduced equations. However, these equations were afflicted to unavoidable simplifications due to the complexity of analytical models. Furthermore, elastic–plastic characteristic of soil substance along with the stochastic behavior of wheel dynamic should be added to the difficulties of predicting by conventional models [1]. It is well-documented that soil-machine traction equations are an essential part of vehicle performance simulation [12]. Wismer and Luth attempted to predict the traction of off-road machines by developing a number of mathematical equations. However, various artificial intelligence (AI) techniques are applied to solve stochastic problems in different science and engineering disciplines.

Roul et al. [13] considered a 5–9–1 artificial neural network (ANN) structure, with a back propagation learning algorithm, to simulate draught requirements of different tillage implements in a sandy clay loam soil under varying operating and soil conditions. Çarman and Taner [3] applied a 1-4-6-2 ANN topology with a back propagation learning algorithm to estimate the tractive performance of a driven tire in a clay loam soil under varying operating and soil conditions. The input parameter of the network was only travel reduction (slippage) where the output parameters of the network were net traction ratio and tractive efficiency. There are studies documented in the literature regarding the application of various artificial intelligence techniques for tractive performance of wheels [14–18].

To the best knowledge of authors, literature lacks the assessment of energy efficiency indices of driving wheels (i.e. traction coefficient and tractive power efficiency) as affected by wheel load, slippage and forward velocity employing artificial intelligence techniques, particularly ANFIS as a promising approach in this realm. In Ref. [3], the authors included only the travel reduction as the input parameter of their study which detracted the reliability of the model since there are many influential parameters affecting the tractive performance parameters of off-road vehicles such as wheel load and velocity. In contradictory to Ref. [3], the present study is aimed at inclusion of wheel load, slippage and forward velocity in the proposed model for introducing a more general model using a supervised ANFIS model rather than ANN technique owing to the inherent drawbacks of ANN.

2. Experimental data acquisitioning

A soil bin facility featuring 24 m length, 2 m width and 1 m depth was adopted to carry out the considered experiments. The soil bin system consisted of a single-wheel tester, a carriage device, control panel, and soil processing equipment. At both sides, a rail road was used to assist the motioning of the carriage and the attached single wheel-tester along the soil channel. To pull the carriage through the chain system an electromotor with the power of 22 kW at the nominal rotational speed of 1457 rpm was applied. A SV 220IS5 – 2 N O, 380V model of LG inverter (brand LS) for rotational speed of the engine was applied that provided the speed control for the carriage using the chain system. This facility assisted the forward and reverse movements of the carriage hub.

An L-shape frame connected the wheel-tester and the carriage. An induction motor of 5 kW, 3-phase, 1430 sync rev/min was applied to provide driving power for the wheel. The speed of the motor was primarily reduced by a gear box (7.5:1) then decreased by a gear reduction unit (4.5:1) and the latest reduction ratio was (33.75:1). The difference between the velocity imposed to the single-wheel tester and the carriage velocity provided various slippage levels. A general view of the soil bin facility and single-wheel tester is demonstrated in Fig. 1. The tire was directly driven by the electromotor. An electric motor and an inverter were used to impose desired rotational speed for wheel. The difference between imposed rotational speed for wheel-tester and carriage speed provided preferred slippage levels. The utilized tire for experimentations was a 220/65R21 driving tire. The inflation pressure was adjusted at 19 psi (131 kPa) suggested by the manufacturer. As appreciated from Fig. 1, tester hub and the L-shape frame of carriage are linked through a four-bar mechanism each of which are horizontally situated and accommodate a load cell for the measurement of wheel tractive performance. The data acquisition system for the test is placed on the carriage. Four load cells were positioned on four parallel arms to measure the horizontal forces to determine the net traction force and another load cell was located on a bolt power of wheel to measure the vertical load on the wheel. The vertical load cell transmitted data to a separated digital indicator. Load cells sent data to a Bongshin digital indicator BS722 model and from output digital indicator by RS232 port to a data logger. In addition to synchronization, data were sent by USB port to a computer and then were stored. The general experiment plan and soil properties and are given in Tables 1 and 2, respectively.

After the data were obtained, it was intended to compute the energy efficiency indices of driving wheels (i.e. traction coefficient and tractive power efficiency). As defined by [19] tractive power efficiency is obtained as following:

$$\eta_t = \frac{\text{Output power}}{\text{Input power}} = \frac{P \times V}{H \times V_0} \tag{1}$$