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A Mathematical Model for Determining Rolling Resistance of Agricultural Tire to Control Energy Losses

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Abstract: One of the most important performance parameter of the towed pneumatic wheel is the rolling resistance, which is influenced by tire design, temperature, soil conditions and etc. The rolling resistance of tires is one of the major sources of energy losses of any moving vehicle and accordingly vehicle fuel consumption. In this research we tried to determine the rolling resistance of transport type agricultural tire on firm soil terrain roads. The tire was tested at different levels of inflation pressure (34.5 to 207 kPa), normal load (0.981 to 4.905 kN) and forward speed (3 to 7 km/h). These tests were conducted on firm clay loam soil in a soil bin by means of single wheel tester having single tire test carriage with four-bar parallel linkages. Different combination of vertical loads, inflation pressures and forward speeds were considered to observe the respond of rolling resistance toward these combinations. Effects of these factors on rolling resistance were analyzed separately and also the interaction of the factors was acquired and finally a mathematical model was developed to predict the rolling resistance of tire. The mathematical model was able to predict the rolling resistance under this test condition in an acceptable manner and it showed that such models would be used as useful tools for assessment of tire efficiency before choosing for any specific use.
Key words: single wheel tester, energy losses, mathematical model, agricultural tire

INTRODUCTION

At every turn of the wheel the rubber compounds in a tire deform as they come into contact with ground and move away from it. As the rubber deforms, it heats up and energy loss occurs. This is the source of most of the tires rolling resistance. The soil and tire deformation give rise to energy losses which contribute in making rolling resistance. The accepted view is that rolling resistance consists of two components: one is soil deformation and the other one is tire deformation (Kiss et al., 2009). Rolling resistance reduction is nowadays a great challenging subject according to the worldwide trend for developing the energy- efficient vehicles (Ebbott et al., 1999; Hublau et al., 2008).

According to Carman (2002), Wheel sinkage and tire deflection due to load results in energy wastage in overcoming rolling resistance forces. For a vehicle moving on a hard surface, the tire flexing component of the rolling resistance is dominant. Under off-road conditions, in contrast, the rolling resistance due to vertical soil compaction and horizontal soil displacement, i.e. rut formation, make up the largest part of the motion resistance force. The performance characteristics of a towed wheel are usually described by rolling resistance and sinkage. The most important performance parameter of the towed pneumatic wheel is the rolling resistance, which is influenced by tire design, system parameters and soil conditions.

Some of the factors that affect on rolling resistance of a tire (especially agricultural tires) are out of our control, but some others are under our control and by maintaining attention can have important effects on fuel consumption reduction of agricultural vehicles. For instance as a result of an study (DOT, 2001) of the 11,000 vehicles inspected at randomly selected gas stations throughout the US, only 30% of surveyed drivers check the pressure in their tires at least once a month and 7% do not check the pressure at all. Overall the survey found that about 26% of passenger cars and 29% of light trucks had the pressure in at least one tire 25% below the pressure recommended by the vehicle manufacturer. Also, another study in Saudi Arabia concluded that the pressure in 21% of the inspected tires was 25% or more below the vehicle manufacturer's recommended inflation settings (Ratrout et al., 2005). In the same, way energy loss in agricultural tires because of inaccurate management was reported to be about 575 million liters per year in USA (Wulfsohn, 1987).

If the agricultural engineers and operators of tractors and agricultural vehicles would be able to predict the effects of different operational and environmental factors on their machine performance they would be able to make remarkable saving in energy need for this job. One of the controllable parts of a vehicle is its tires. So, the aim of present study is to determine the effect of 3 different factors that may affect on rolling resistance of agricultural tire which is used for transporting agricultural goods between farms on firm soil terrain road and try to predict the effect of each factor using mathematical models.

To quantify the soil-tire interaction, numerous attempts have been made in order to set up models for the prediction of traction parameters (Upadhyaya et al., 1993). Also, different soil mechanics theories are applied into the modeling of the soil- tire interaction and tire performance. These models are the WES- method, the Bekker-method and the mathematical method (Saarilahti etal., 2001). Bekker (1960) laid the foundation for scientific investigation of soil-wheel interaction mechanism and extended his model in the following years. Compare with Bekker model, Wismer & Luth model is considered to be quite simple and convenient to use in the field as it involves less number of parameters and also yields reasonably good prediction. WES-method can be extended to evaluate the tire rolling resistance. It seems that Bekker model's weakness to estimate the RR of tire is because of ignoring the effect of inflation pressure and assuming the rolling resistance of wheel as energy used to deform the soil (Gharibkhani et al., 2012). Kurjenluoma et al. (2009) compared the rolling resistance of towed flotation implement tires at different tire inflation pressures (100-200 kpa), and static wheel loads (35.4–36.4 kN). Shoop et al. (2006) examined four types of tire models for evaluating suitability of tire to roll on deformable terrain. Elwaleed et al. (2006) examined the effect of inflation pressure on motion resistance ratio of a high-lug agricultural tire. Also different soil-wheel test devices have been developed for these kinds of measurements (McAllistar, 1979; Du Plessis, 1989; Upadhyaya et al., 1986; Mardani et al., 2010). The decision tree was used for predicting rolling resistance of a tire subjected to different vertical loads and inflation pressures, and the decision tree was able to predict the rolling resistance with accuracy of 97% (Gharibkhani et al., 2012).

MATERIALS and METHODS

In this study some experiments were performed on a soil bin tester, filled with clay-loam soil. The test bed consists of a wheel carriage that can be adjusted both horizontally and vertically. The facility has a moving carriage that moves on rails using two chains, well above a soil Channel. The single wheel tester has a four parallel linkages mechanism and as the rolling resistance is the vector sum of the four reaction forces of the links, it was calculated by vector summing of the data obtained from load cells placed on these linkages (Figure 1). The single wheel tester has the capability to apply different loads up to 5kN using a power screw which helps to push the tire to the surface and the various forces on the tire could be measured using a vertical load cell. The soil in the soil bin was compacted by passing the single wheel tester again and again on a same track to obtain the penetration resistance of soil which was similar to the farm soil terrain roads. A digital RIMIK mark penetrometer was used to determine soil penetration resistance (cone index). The values obtained at depth range of 20cm were used as a mean of penetration resistance based on (Carman, 2002) method. Some physical properties of the soil used to feel the soil bin are given in Table 1.

Table 1: Some physical properties of soil used in the experiments

Soil physical property	Value
Sand (%)	35
Silt (%)	22
Clay (%)	43
Bulk density (kg/m^3)	2630
Frictional angle (degree)	32
Cone index (in depth of 20 cm)	700
Cone index (in depth of 50 cm)	1500

Figure 1. The single wheel tester and tire

To conduct the experiments, the agricultural towed tire was inflated at different levels of inflation pressure (34.5, 68.97, 103.46, 137.94 and 207 kPa). Then for each inflation pressure tire was exposed to five different normal loads (0.981, 1.962, 2.943, 3.924 and 4.905 kN) and was towed with three different forward speeds (3, 5 and 7 km/h) and each experiment had 3 replications. During each experiment the data coming from all load cells were measured and saved using data acquisition system.

Some different mathematical models were examined to obtain the best model for predicting the rolling resistance of tire under this working condition. The objective is to allow agricultural engineers to prepare the agricultural tire accordingly to meet the operating conditions and so optimize the fuel and energy consumption of tractors and other agricultural vehicles. In each model inflation pressure, vertical load and forward speed was taken into consideration. The R square, standard error and p-value were considered for choosing best fit model. In addition, there are some statistical test methods to evaluate the goodness of fit of the models. Among these, mean bias error E_{MB}, root mean square error E_{RMS} and reduced chi-square x^2 are the ones widely used in many modelling studies (Mardani et al., 2010). These statistical tests are defined as follows.

$$E_{MB} = \frac{1}{N}\sum_{i=1}^{N}(M_{RR_{pre,i}} - M_{RR_{exp,i}}) \quad (1)$$

$$E_{RMS} = [\frac{1}{N}\sum_{i=1}^{N}(M_{RR_{pre,i}} - M_{RR_{exp,i}})^2]^{1/2} \quad (2)$$

$$x^2 = \frac{\sum_{i=1}^{N}(M_{RR_{pre,i}} - M_{RR_{exp,i}})^2}{N-n_1} \quad (3)$$

Where: $M_{RR_{pre,i}}$ is the ith experimental rolling resistance; $M_{RR_{exp,i}}$ is the ith predicted rolling resistance; N is the number of observation; n_1 is the number of constants. The higher the value of the R^2, and lower values of the E_{MB}, E_{RMS} and x^2, the better the goodness of the fit.

RESULTS and DISCUSSION

The relation between vertical load and rolling resistance is shown in figure 2. In general, at constant level of soil compaction, the rolling resistance was increased under the effect of the increase of vertical load, and in all inflation pressures, the effect of vertical load seems to be similar. Figure 3 showed the effect of inflation pressure on rolling resistance value. The increase in inflation pressure caused the rolling resistance to decrease, but when the inflation pressure passed 170 kPa, the increase in it led to increase in rolling resistance which can be interpreted by increase in sinkage of tire into the soil.

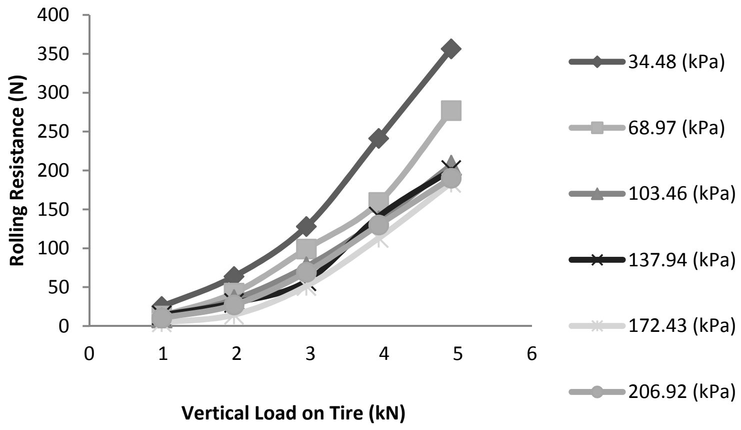

Figure 2. The relation between vertical load and rolling resistance

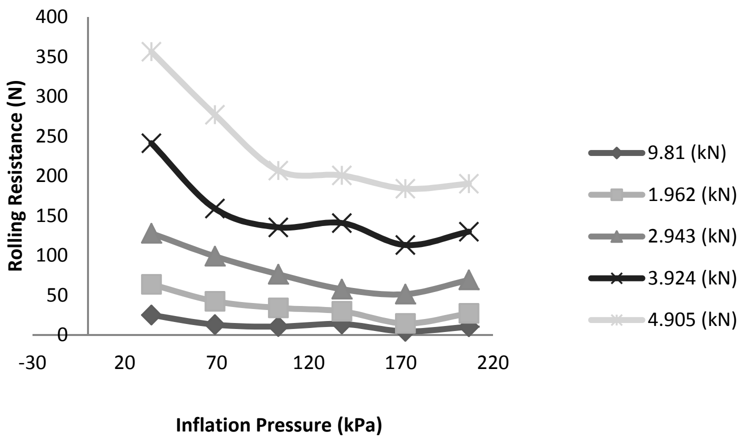

Figure 3. The relation between inflation pressure and rolling resistance

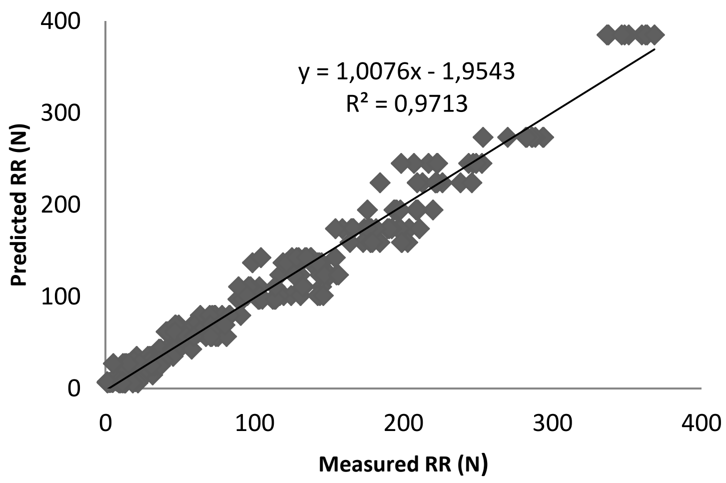

Figure 4. Comparison of measured and predicted rolling resistance

The data taken from the acquisition system was used for creating predictive models. As data loggers registered data with frequency of 20Hz, lots of data were obtained from each experiment. So in order to get a very realistic result for rolling resistance, all data were used for predicting model. The results indicated that the highest values of R^2 and the lowest values of E_{MB}, E_{RMS} and X^2 could be obtained when the logarithmic model was used. This model is shown as

$$RR = 10^{1.957} . W^{2.028} . P^{-0.501} \quad (4)$$

Where *RR* is the rolling resistance of tire; *W* is vertical load on the wheel and *P* is the tire inflation pressure. As it can be seen in the equation 4, the forward speed of tire is not placed in the equation. It means that our results showed no meaningful effect of forward speed of tire (*V*) on the rolling resistance ($p<0.05$). It can be interpreted from the model that when the agricultural transport tires work at low speeds (under 7 km/h) the effect of forward speed can be neglected. The R^2, E_{MB}, E_{RMS} and x^2 values for this equation are 0.90, 0.00116, 0.05666 and 0.000247, respectively. The R^2 value can be acceptable for this model due to the large number of data used for predicting model.

CONCLUSION

The results show that using logarithmic model a good model can be produced for predicting rolling resistance of agricultural tires (Figure 4). It can be interpreted from the model that the forward speed of agricultural tires does not affect on the rolling resistance in the experimented range, so it is advisable to use the maximum limit of speed for transporting agricultural goods on firm soil terrain road to get the best efficiency in time and fuel consumption depending on the capacity of engine and vehicle. Also, it was seen that the inflation pressure and vertical load on the wheel are two indispensable determining factors which should not be neglected.

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