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Determination of wheel-soil rolling resistance of agricultural tire

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Abstract

So far many researchers have tried both theoretically and practically to define tire rolling resistance. In this research, two predicting models of tire rolling resistance were evaluated and compared. Bekker model and one of the Waterways Experimentation Station method models were selected as predicting models. Using a single wheel tester, some experimental tests on a controlled soil bin filled with clay loam soil, were performed to validate the selected models' rolling resistance accuracy. Decision tree was used to predict the effect of tire inflation pressure and vertical load on rolling resistance. A towed tire was tested at different levels of inflation pressure (34.5 to 207 kPa) and normal load (0.981 to 4.905 kN). Effects of these factors on rolling resistant were analysed. The models related to WES-method, offers a great number of different models which are applicable for typical soil-tire systems. Wismer and Luth model (as a WES model) showed the better result for rolling resistance prediction. Bekker model (as a semi- analytical model) was unmeet for predicting the rolling resistance. The accuracy of decision tree was 97% for predicting these parameters' effect on rolling resistance. So, the decision tree appeared to be a good method for fast and accurate prediction of rolling resistance.

Keywords: Bekker model, Decision tree method, Experimental data, Single wheel tester, Soil bin, WES model.
Abbreviation: DT: Decision tree, MSE: Mean Square Error, RR: rolling resistance, SWT: single wheel tester, WES-method: Waterways Experimentation Station method, *CI:* cone index.

Introduction

As a vehicle moves across terrain its wheels deform the soil and the tires are also under deformation. A moving vehicle causes the appearance of stress and strain in the soil via its wheel system. Every soil structure is characterized by certain stability with relation to mechanical load. If the load is small, the soil responds in a flexible manner. However, if the load is greater than the stability of the soil structure, irreversible deformation of the soil takes place. Vertical deformation is the result of the vehicle mass, and it causes soil compaction or packing (Ademiluyi et al. 2009; Błaszkiewicz, 2007). 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 RR. The soil and tire deformation give rise to energy losses which contribute in making RR. The accepted view is that RR consists of two components: one is soil deformation and the other one is tire deformation (KISS, 2009). The performance characteristics of a towed wheel are usually described by RR and sinkage. The most important performance parameter of the towed pneumatic wheel is the RR, which is influenced by tire design, system parameters and soil conditions. Generally, the most important parameters to explain the tire performance are three tire parameters (radius, width and tire inflation pressure) and five soil parameters (soil cover, upper soil strength, lower soil strength, clay content, moisture content) and tire loading (Schreiber and Kutzbach, 2007). For prediction of RR, different soil mechanics theories are applied into the modelling of the soil- tire interaction and tire performance in Terramechanics. These models are the WES-method, the Bekker-method and the mathematical method (Saarilahti, 2001). According to WES-method, the soil penetration resistance is measured using a standard penetrometer. This measurement is a simple operation and the analysis of the results is easy. In the Bekker-method the soil parameters are calculated from plate sinkage test results, and the test appointments and the analysis of the results are more complicated than the WES-method. Usually, the mathematical method, based on soil strength tests, is a basic method and seems more appropriate for scientific programmes than for field applications (Saarilahti, 2001). In 1956, Bekker laid the foundation for scientific investigation of soil-wheel interaction mechanism and extended his model in the following years. To quantify the soil-tire interaction, numerous attempts followed in order to set up models for the prediction of traction parameters (Upadhyaya et al. 1993). Kurjenluoma et al. (2009) compared the RR 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. (2005) examined the effect of inflation pressure on motion resistance ratio of a high-lug agricultural tire. Different SWT devices have been developed for these kinds of measurements (McAllistar 1979, Du Plessis 1989, Upadhyaya et al. 1986 and Mardani et al. 2010). Some of these testers are indoor measurement systems and others are field test equipment. Another method for predicting exact values of different actions' outcomes is DT. DT is a diagram that decision makers can create to help select the best of

Table 1. Analysis of variance (ANOVA), for the effect of tire inflation pressure (P) and vertical load (W) on wheel RR.

Source		Type III SS	df	MS	F	Significant value
Intercept	Hypothesis	1273266.613	1	1273266.613	5.957	0.062
w	Hypothesis	787524.998	4	196881.249	83.752	0.001
p	Hypothesis	96137.007	5	19227.401	8.179	0.001
w×p	Hypothesis	47015.305	20	2350.765	34.559	0.001
	Error	6121.873	90	68.021		

Fig 1. Soil bin, the single wheel tester, linkages, and data loggers.

several alternative courses of action. DT is defined as "hierarchical model based on nonparametric theory where local regions are identified in a sequence of recursive splits in a smaller number of steps that implements divide-and-conquer strategy used in classification and regression tasks" (Alpaydın, 2010). Classification and DT are flexible and robust tools which are well-suited to this task. In addition, they are easy to construct and interpret (Moisen, 2008). In general, other advantages of tree-based regressions are that they can handle missing values, can use continuous and categorical predictors, are robust to predictor specification, and make very limited assumptions about the form of the regression model. Moreover, for large data sets, they have the potential to uncover relatively complex structure that may be difficult to detect with more conventional regression tools. In recent times, the development of the "tree-averaging" techniques like boosting and bagging (Friedman et al. 2000; Breiman, 1996) which fit multiple trees in making any predictions or classifications, have offered potential improvements to the predictive power of DT. Henderson et al. (2005) used DT to predict Australia-wide soil properties, based on compiled national soils point database. In other studies, Quinlan (1993); Uysal and Guvenir (1999) used DT, based on conditions of some rules that they had defined before. In other words, the rules determined, enabled interactions to be handled automatically by allowing different linear models to capture the local linearity in different parts of the predictor variable space. This can often lead to smaller trees and better prediction accuracy than DT. This study was performed with the main objective of developing the empirical models for prediction of towed tire RR, according to experimental soil bin observations. The DT method was used to examine the possibility of predicting the RR in constant ground condition and tire dimension, with different inflation pressures and applied vertical loads.

Results and discussions

Using experimental data obtained from single wheel tester, some multiple regression models were developed to estimate the average ground pressure. Fig. 2 showed the relation of tire contact area pressure with vertical load and tire inflation pressure. The tire contact pressure has a direct relation with vertical load and inflation pressure of tire. The contact area for all tests was in the range of 60-490 cm^2. Average contact pressure increased nearly linearly with increase in vertical load and increase in inflation pressure. Comparing the results of contact area of tire-land with the results of Cesbron et al. (2008) whose research about tire contact area showed that there is not much different between tire contact areas in static and dynamic conditions (about 20%), conforms that we can generalize the results of tire contact area in static mod for dynamic mode. Table 1 shows the analysis of variance (ANOVA), for the effect of tire inflation pressure (P) and vertical load (W) and the interaction of them on wheel RR. This table shows that both of these two parameters have significant effect on RR changes. More ever the interaction of independent variables (P, W) on dependent variable (RR) was significant with the probability rate of %99. A typical plot of vertical load versus RR is shown in Fig. 3. In general, at constant level of soil compaction, the RR was found to increase within the increase of vertical load, and in all inflation pressures, the effect of vertical load seems to be similar. Figure 4 showed the effect of inflation pressure on RR. The increase in inflation pressure caused RR to decrease, but this effect was not significant at low levels of vertical load. Kurjenluomar et al. (2009) reported "reduction of tire

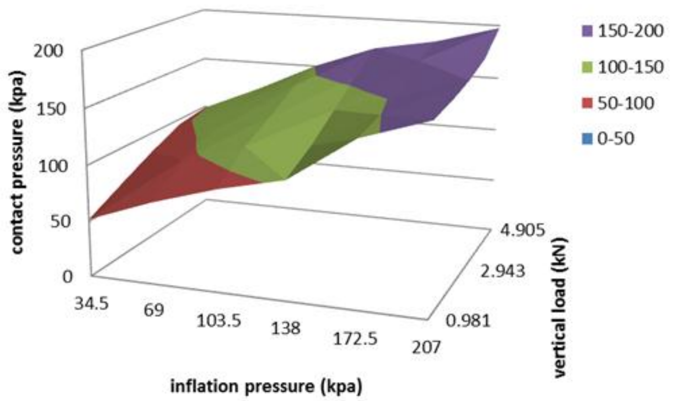

Fig 2. The relation of tire contact area pressure with inflation pressure and vertical load.

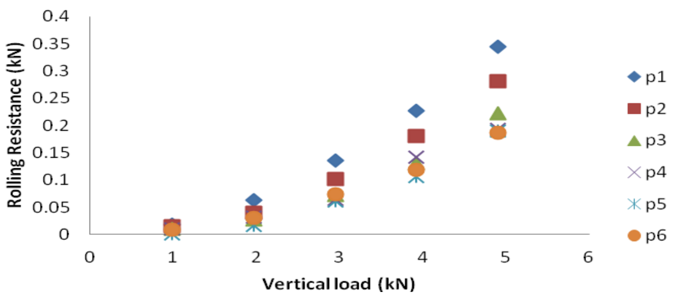

Fig 3. Effect of vertical load on RR of tire at different inflation pressures.

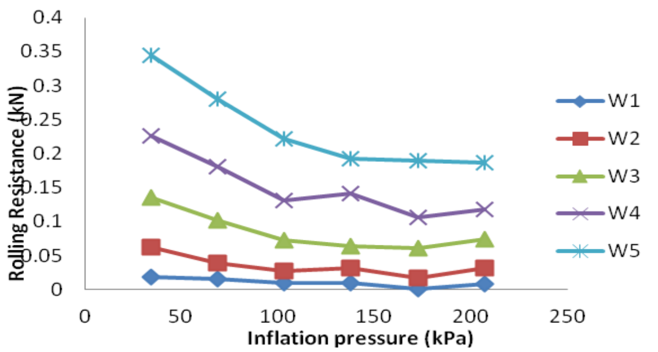

Fig 4. Effect of inflation pressure on RR of tire at different vertical loads.

inflation pressure reduced RR and rut depth only on soft soil, when the soil strength was low, and in hard soil conditions the effect was opposite on RR" and as our experiments were conducted in hard clay loam soil, our results conforms the result of their research, and shows that reduction in inflation pressure increases the RR of tire. Also Elwaleed et al. (2006) reported that reduction in tire inflation pressure by 28 kPa from the recommended value resulted in decrease of tire motion resistance ratio by 5.01%. However, further reduction by 55 kPa resulted in an increase in tire motion resistance ratio by 9.96%, but their experiments were conducted on loosened soil condition which was different from this test condition. The comparison between measured and predicted values of RR using two different models for the selected tire is shown in Figs. 5 and 6. We can see that that the model based on wheel numeric approach could predict the RR within an accuracy of 20 percent, while the model based on Bekker approach was found to over predict most of the experimental values of RR beyond + 20%. The poor prediction results of Bekker approach may be due to the reason that Bekker equation has been developed for a rigid rectangular uniformly loaded area, while the contact area observed under the test tires has been found to be elliptical in the present study and other reports. On the other hand, the Bekker approach is based on work done in vertical soil deformation disregarding to the soil deformation in lateral and longitudinal directions. The DT which is based on 80% of data is as Fig. 7. In this DT Chance Nodes are represented by triangles and End Nodes by squares. As mentioned before, the performance of DT can be assessed in terms of a number of key indicators. These include the number of points used in the model, the R^2, the (rank) correlation, and the MSE which gives an estimation of the standard deviation of the errors to determine if the result of DT is reliable enough or not. Fig.8 is the comparison between measured RR and predicted RR of DT, and also the coefficient of determination is 97%. This level of R^2 shows that DT is able to predict RR accurately. Also MSE value measured by equation No.4 was about 0.042 based on normalized error that shows low error for estimation obtained by DT method in this study.

Materials and Methods

The wheel must compact the soil, when moving horizontally, and RR is the horizontal force needed to compact the soil. The RR depends on tire sinkage, which is related to the tire loading and tire deflection, determining the tire contact pressure, and the soil bearing capacity. There are different approaches to model the tire RR. Some models describe the RR as the soil sinkage and soil deformation. One of the first and most important models of soil sinkage has been introduced by Bekker (1960) and Wong (1984). The vertical and horizontal soil deformations in wheel-soil interaction are described by pressure-sinkage characteristics and shear tension displacement characteristics, respectively. The pressure-sinkage relationship, as proposed by Bekker, is described as equation No.1.

$$P = \left(\frac{k_c}{b} + k_\phi \right) z^n \qquad (1)$$

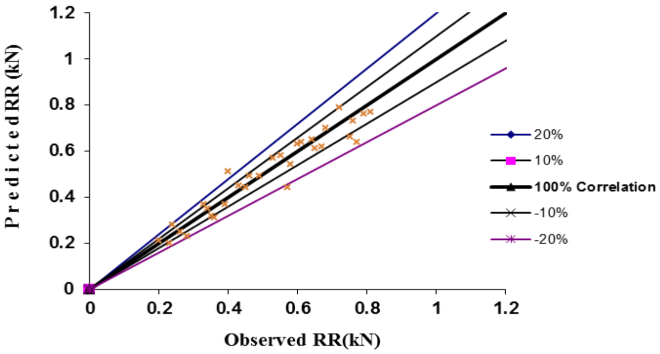

Fig 5. Comparison between observed and predicted values of RR (kN) based on mobility number approach.

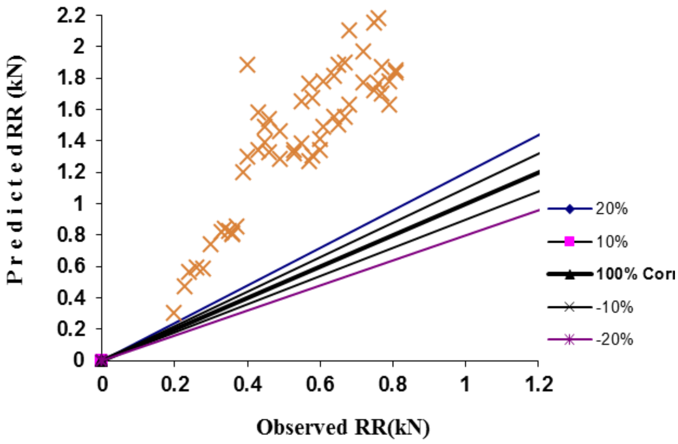

Fig 6. Comparison between observed and predicted values of RR (kN) based on Bekker's approach.

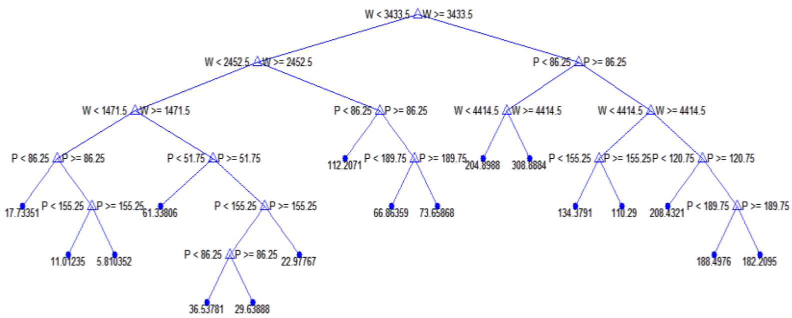

Fig 7. The decision tree based of 80% of data.

Where p is the pressure, b is the smaller dimension of the rectangular contact area, z is the sinkage, and n, kc, Kφ are the soil condition parameters. An attempt was made by using the Bekker's semi-empirical approach to predict the RR and sinkage of the test tire. The total RR of a pneumatic tire, according to this method, is the sum of the RR caused due to compacting the soil and tire flexing. This model defines the soil compaction resistance as equation No.2.

$$R = \frac{b}{(n+1)\left(\frac{k_c}{b}+k_\phi\right)^{1/n}}(P)^{(n+1)/n} \quad (2)$$

The other part of total tire RR is the tire flexing resistance that was determined experimentally on a rigid surface at the same inflation pressure and normal loads as used in tire performance tests (Keshaw and Tiwari, 2006). The following equation involving vertical load, tire flexing resistance and inflation pressure is available.

$$\frac{R_f}{W} = \frac{u}{P_i a} \quad (3)$$

Where R_f is tire flexing resistance, W is vertical load, Pi is inflation pressure (kpa), and also u and a are empirical coefficients that are determined during some experimental tests. Bekker model is a semi-analytical method for determining the sinkage and RR of tire but there are some models (such as WES models) based on experimental methods. As mentioned, the WES-method is widely studied, and there are a great number of reports on it. Wismer and Luth is one of these models and this model is a conventional model for agricultural tires. Wismer and Luth (1974) used the Cone Index (*CI*) as the only soil parameter to find Wheel Numeric (C_n) and considered the tire width (*b*) and tire diameter (*d*) in the wheel numeric as equation No. 4. Kurjenluomar et al. (2009) reported that the soil strength which is represented by *CI*, has influence on coefficient of RR. They found that coefficient of RR and rut depth of pneumatic towed wheels, correlate closely with *CI*.

$$C_n = \frac{CI \cdot b \cdot d}{W} \quad (4)$$

Crossley et al. (2001) confirmed earlier researches on the relationship between mobility number and RR. This model describes the RR coefficient as the following equation.

$$RR = 0.04 + \frac{1.2}{C_n} \quad (5)$$

To validate the selected RR models, some experiments were performed on a soil bin tester. This test bed consists of a wheel carriage that can be adjusted both horizontally and vertically (Fig 1). The facility has a moving carriage that moves on rails using two chains, well above a soil Channel. The SWT has a four parallel links mechanism and RR is the vector sum of the four reaction forces of the links. These forces are measured using four load cells. Different loads can be applied, using a power screw which helps to push the tire

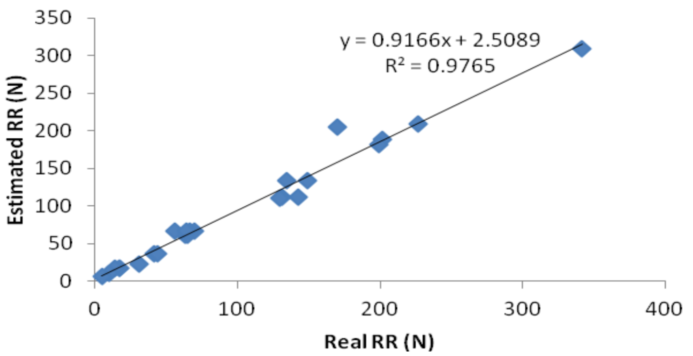

Fig 8. comparison of the measured RR and predicted RR.

to the surface and the various forces on the tire can be measured using a vertical load cell. A data acquisition system was used to measure and save the forces of load cells. The tire has an unloaded overall diameter of 71cm and a section width of 20cm. To determine the tire flexibility and tire load-deflection relationship, some experiments were performed at loads close to those used in the tests. To determine the tire contact area, the wheel mounted on the SWT machine was placed on a hard surface, and footprint area was calculated by planimeter from an inked imprint of the footprint on a paper taped to surface. The ratio of tire load to contact area of tire-surface, determines the average contact pressure of tire. A digital RIMIK mark penetrometer was used to determine soil penetration resistance. The values obtained at depth range of 20cm, were used as a mean of penetration resistance (Carman, 2002). Using the carriage speed controlling, the tire forward speed was maintained at 3 km/h. As Hossain and Inagaki (2011) expressed, there is a relationship between the stress implied to the soil and vertical displacement of the soil, so while the wheel was moving, the total carriage displacement (sum of tire deflection and tire sinkage) was measured by means of an encoder mounted on one joint of parallel tire arms. The joint rotation value indicates the total wheel sinkage. DT which is from a Univariate type of tree was created and trained by 80% of data and tested with 20% of remained data. In this tree, inputted data were tire inflation pressure (P) and applied vertical load to the tire (W), and outputted data was RR. In order to estimate the error of the tree, Mean Square Error and coefficient of determination (R^2) were measured for two groups of data's (trained and tested data). The *MSE* (Mean Square Error) of an estimator is one of ways to quantify the difference between values implied by an estimator and the true values of estimated quantity. *MSE* is a risk function, corresponding to the expected value of the squared error loss or quadratic loss. MSE is measured by the equation No.6.

$$MSE(\hat{x}) = E\left((\hat{x} - x)^2\right) \qquad (6)$$

Where $\hat{X}$ is estimated parameter, x is real parameter and *E* is mathematical expectation value.

Conclusions

There are different approaches to model the RR, a force resisting against the forward movement of the wheel. During this study, two soil- tire models were compared with experimental soil bin tests result. In addition, an analytical method has applied for evaluating the RR data. 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 RR. 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 RR of wheel as energy used to deform the soil. Of course, it is noticed that different models can be added for local conditions to improve the validity of the models. By taking to consideration the complicated interactions in tire-soil contact area and the variety of effective parameters in this interaction, the various use of experimental data and sufficient number of experiment repeats are very useful to approach to accurate models for prediction of RR, and one of theme is models depended on neural network. The DT model can be used as a useful model for predicting RR under affect of various factors, and according to value of MSE and R^2 it is an accurate method for RR prediction.

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