Development and evaluation of an in-situ tire testing facility with variable side slip angles

Hamid Abdolmaleki\textsuperscript{a}, Ali Jafari\textsuperscript{a,}\textsuperscript{*}, Ahmad Tabatabaeifar\textsuperscript{a}, Ali Hajiahmad\textsuperscript{a}, Hadi Goli\textsuperscript{b}

\textsuperscript{a}Department of Agricultural Machinery Engineering, College of Agriculture and Natural Resources, University of Tehran, Karaj, Iran
\textsuperscript{b}Department of Agricultural Machinery Engineering, Sanandaj Branch, Islamic Azad University, Sanandaj, Iran

Received 4 December 2013; received in revised form 15 March 2015; accepted 16 March 2015

Abstract

An in-situ tire test rig was developed for field research on tire tractive and maneuverability performances. The Single Wheel Tester (SWT) was mounted on a tractor and a tested wheel was driven by a hydromotor, along a frame of 3 m length. In the SWT, four load cells were utilized to measure longitudinal and lateral forces, input and self-aligning torques, and two optical counters were applied to calculate forward and angular velocities. Response Surface Methodology was used to execute experimental design and to analyze the collected data. Afterwards, reduced form of a 2 Factor Interaction model was extracted to predict rolling resistance using seven factors. The test results show that increasing the normal load and side slip angle will cause an increment of rolling resistance. The incremental growth rate of the rolling resistance due to the normal load increment was observed. At higher cone index values, increasing the angular velocity reduces the rolling resistance, although at lower cone index values, the effect of angular velocity on rolling resistance is in reverse order. In addition, the increasing moisture content effect on rolling resistance at lower side slip angle values was observed.

© 2015 ISTVS. Published by Elsevier Ltd. All rights reserved.

Keywords: Single wheel tester; Rolling resistance; Side slip angle; Normal load; Drawbar pull; Angular velocity; Cone index; Moisture content; Tire inflation pressure; Response Surface Methodology

1. Introduction

Dynamic behavior of off-road vehicles, differs widely from that of road vehicles due to deformability and shearability of contact patch. For many decades, the interaction between ground and off-road vehicles, such as agricultural tractors, has been an important field of study (Muro and O’Brien, 2004; Macmillan, 2002; Pytka, 2010). The performance of tractors greatly depends on the soil–tire interaction. This interaction provides traction, supporting, handling, and braking (Slaughter et al., 2008). The poor interaction between tire and soil, causes nearly 20–55% of tractor power losses (Zoz and Grisso, 2003).

Forces and moments acting on tires should be studied in order to design vehicles, improve traction efficiency, and enhance handling, motion dynamic stability and steerability (Más et al., 2010).

Traction performance analysis can be carried out by the study of a single wheel moving over a deformable terrain in which wheel velocity, lateral and longitudinal slips, applied forces and moments are measurable (ASABE, 2009). Researches on traction performance have been done in soil bin (Gee-Clough and Sommer, 1981; Kawase et al., 2006; Krick, 1973; Tiwari et al., 2009; Yahya et al., 2007; Raheman and Singh, 2004) and on field using a Single Wheel Tester (SWT) Ahmad et al., 2011; Alcock and Wittig, 1992; Way, 2009; Nagaoka et al., 2001; Armbruster and Kutzbach, 1991; Upadhyaya et al., 1985 or via an instrumented vehicle (Pearson and Bevly, 2007;
Baffet et al., 2008; McLaughlin et al., 1993; Gu and Kushwaha, 1994; Shoop, 1992; Gobbi et al., 2005; Goli et al., 2012; Hajiahmad et al., 2013, 2014; Pytka et al., 2011).

Researches based on SWT can be divided into driven and undriven wheels with variable side slip angles or zero side slip angle. Gee-Clough and Sommer (1981) measured steering forces on undriven, angled wheels, using tires with no tread, in a soil bin. They assumed that aligning torque is extremely small and its effect could be neglected in their analysis. Krick (1973) measured the forces of driven wheels with side slip angles (adjustable from 0° to 35°) in a soil bin, by a six degree of freedom recording device. Ahmad et al. (2011) developed a test rig pulled by a tractor for field use on different terrains, to measure motion resistance of towed narrow wheels. They investigated the effect of wheel size, normal load and inflation pressure on the motion resistance. The SWT developed by Armbruster and Kutzbach (1991) was based on a rig connected to a four-wheel-trailer. Tractive and lateral forces on driven tires up to a side slip angle of 16° were measured by a six-component wheel dynamometer.

Studies on vehicle dynamic behavior have been done using instrumentation of a conventional vehicle or development of a prototype vehicle. Gobbi et al. (2005) developed an instrumented wheel hub (connected directly to the rims of a tractor), to measure all forces and moments acting on the front wheels. They applied the longitudinal and the lateral slips and measured the corresponding longitudinal and lateral forces. Baffet et al. (2008) applied a dynamometric hub on a passenger car tires in order to study the dynamic behavior of wheel-road interaction. A few researchers developed prototype vehicles with required instrumentation to study traction performance, vehicle dynamic behavior, etc. (Goli et al., 2012; Hajiahmad et al., 2013, 2014).

However, there were some methods of measuring tire forces and moments in the literature, but they were limited to measuring few parameters or their methods were not economical. This paper presents an in-situ and flexible tire traction testing facility, with minimum time consumption for experiment execution, to obtain reliable data for measuring forces (including lateral) and moments acting on angled driven wheels in each intended surface. In addition, the rolling resistance of a high lug agricultural tire investigated as a function of seven important variables.

2. General description

A general view of the SWT and its components are shown in Fig. 1. A linear bushing is attached to the carrier part which allows the driving system to slide freely in vertical axis guided by a chrome shaft. The driving system, including wheel, hydromotor, gearbox and dynamometric mechanism had been designed. To provide wheel drawbar pull, one end of a wire rope was attached to the carrier part and the other supported a dead weight.

3. Driving system

The wheel was powered by a hydro-motor with a displacement of 165 cm³/rev. A 4.67 reduction ratio gearbox

| Nomenclature |  
|-------------| |
| $d$ | lever arm of $R$ (m) |
| $eh$ | longitudinal distance between wheel center and $R_c$ (m) |
| $rt$ | vertical distance between wheel center and rolling resistance application point (m) |
| $CI$ | cone index value (kPa) |
| $CR$ | carrier resistance (N) |
| $DP$ | drawbar pull (N) |
| $F_{AT}$ | the force acting on the load cell 4 measuring aligning torque (N) |
| $F_T$ | the force acting on the load cell 1 measuring drive axle input torque (N) |
| $F_x$ | longitudinal force measured by load cell 2 (N) |
| $F_y$ | lateral force measured by load cell 3 (N) |
| $F_z$ | wheel normal load (N) |
| $GT$ | gross traction (N) |
| $MC$ | moisture content (%) |
| $NT$ | net traction (N) |
| $Pr$ | tire inflation pressure (kPa) |
| $R$ | resultant of surface reaction force (N) |
| $R_h$ | horizontal surface reaction force (N) |
| $R_r$ | rolling resistance (N) |
| $R_v$ | vertical surface reaction force (N) |
| $R_x$ | longitudinal reaction force applied to chrome shaft by the carrier (N) |
| $R_y$ | lateral reaction force applied to chrome shaft by the carrier (N) |
| $S$ | tire slippage (%) |
| $T$ | input torque (N m) |
| $V_a$ | actual velocity (m/s) |
| $X$ | lever arm of lateral force (m) |
| $Y$ | lever arm of longitudinal force (m) |
| $z_{AT}$ | normal distance between load cell 4 and center of chrome shaft (m) |
| $z_T$ | normal distance between load cell 1 and center of axle (m) |
| $x$ | side slip angle (°) |
| $\theta$ | the angle between $R_r$ and $R$ (°) |
| $\omega$ | tire angular velocity (rpm) |
was used to increase the input torque. The output gearbox shaft was connected directly to the wheel. Using a 4/3 directional control valve, the forward and reverse motions of the driving system were possible. The wheel angular velocity was adjustable from two to 22 rpm using a hydraulic system of a Massey Ferguson 285 tractor (MF 285).

4. The SWT dynamometric design

To measure the tire lateral and longitudinal forces, input and self-aligning torques, S-beam load cells were used. Also, wheel slip was obtained by two opto-counters. The tire vertical load and drawbar pull could be statically applied with dead weights.

4.1. Input torque

To measure the tire input torque, the reaction force method was applied that is well fitted with a drive axle mechanism. In this method, the reaction force generated by the torque exerted on the wheel axle could simply be measured. In the driving system the gearbox housing was connected through a pair of bearings to the support rig (Fig. 1c), as the gearbox and hydromotor can freely rotate about bearing axes.

When a torque is exerted on the wheel, a reaction force is generated tending to rotate hydromotor and gearbox in the opposite direction. This reaction force is measurable by load cell 1, located between hydromotor and support rig. Therefore, input torque could be derived through multiplying this force by its normal distance from the rotation axis (Fig. 2), or:

\[ T_w = F_T \cdot z_T \]  

4.2. Gross traction

Gross traction is a force acting against the wheel forward motion and equals the sum of net traction and motion resistance \( (\text{ASABE, 2009; Grisso et al., 2006}) \).

\[ GT = T_w / rt \]  

The correct torque radius is not directly measurable. There is no general agreement among traction researchers as to what radius to use \( (\text{Zoz and Grisso, 2003}) \). Thus, with an expected error, the traveled distance by a rotation of the tire without drawbar pull divided by \( 2\pi \) was used instead \( (\text{Goli et al., 2012}) \).

4.3. Net traction

Net traction is a force applied to the wheel induced by drawbar pull. Drawbar pull may be applied to the wheel using constant drawn implements or dead weight. In the latter case the moving carrier was lifting dead weights by a wire rope \( (\text{Fig. 1a}) \). As the wheel drives, the dead weights were lifted up to 3 m above the field surface to provide constant drawbar pull in the traveled distance. According to Fig. 3, net traction is computable using Eq. (3).
4.4. Carrier resistance

Besides net traction, another force is counteracting with wheel motion. This force appeared when the carrier is moving along the rail named as carrier resistance, therefore, the longitudinal force can be written as:

\[ F_x = NT + CR \]  \hspace{1cm} (4)

As shown in Fig. 3, load cell 2 was installed between two plates with four linear bushings and guide rods allowing longitudinal force to be exerted along load cell 2 axis. So, the effects of other forces would be absorbed and CR could be measured.

4.5. Rolling resistance

The rolling resistance accounts for all energy losses caused by the deformation of the tire and the terrain (ASABE, 2009). The free body diagram of a driven wheel is illustrated in Fig. 4a. The vertical load on the wheel was provided by dead weights placed on the support rig (Fig. 2). The vertical reaction force is not directly under the axle centerline and is offset by the distance \( eh \). Therefore, an opposing torque will be exerted on the wheel. Moving the application point of the reaction force \( R_v \) under the wheel center, needs to apply a torque to satisfy the static equilibrium. This torque is usually generated through a virtual longitudinal force known as rolling resistance (Fig. 4b) acting on the wheel in the distance of rolling radius from the wheel center.

The gross traction can be rewritten as:

\[ GT = F_x + R_v = (NT + CR) + R_v \]  \hspace{1cm} (5)

And rolling resistance is calculated as:

\[ R_v = GT - F_x = GT - (NT + CR) \]  \hspace{1cm} (6)

4.6. Lateral force

When the tire experiences side slip angle a lateral force will be exerted on the tire. To measure this force a mechanism was developed (Fig. 3) in which an S-beam load cell (Load cell 3) was coincided with wheel axis. Inner rings of two spherical roller bearings surrounded the load cell axis to keep it from rotating in order to prevent signal wire from twisting with tire rotation.

4.7. Aligning torque

The reaction force method was applied to measure aligning torque (Eq. (7)). As wheel drives on uneven surfaces, load cell 4 freely slides vertically using two linear bushings and guide rods (Fig. 1c). The guide rods were rigidly connected to the carrier. One end of the “L-shape part” was fastened to the chrome shaft, and the other end was jointed to the load cell 4. The side slip plate which had two circular guiding slots, allowed the wheel to move at different side slip angles. The aligning torque mechanism has been shown in Fig. 3.

\[ M_z = F_x \cdot y + F_y \cdot x - F_{AT} \cdot z_{AT} \]  \hspace{1cm} (7)
4.8. Slip

As the carrier moves, an opto-counter (Fig. 1c) attached to the carrier slides along a notched plate with 3 m length and 600 teeth. Therefore, the counter pulses were being sent to a Data Acquisition System (DAQ), to calculate the real velocity of the tire.

The input power calculation requires input torque and angular velocity values to be known. The angular velocity is also needed to obtain tire tractive performance. Therefore, the SWT was equipped with an angular velocity transducer. According to Fig. 1c, a notched circular strip of 90 teeth was installed concentric with the wheel axis between sender and receiver of an opto-counter. Knowing actual and angular velocities, the slip could be calculated using Eq. (8).

\[
S = 100 \times \left(1 - \frac{V_a}{rt \cdot \omega}\right)
\]  

(8)

5. Dynamometer calibration

The force transducers were calibrated under static conditions to find linearity and accuracy of each measurement system. Specified forces were applied to some determined points of the SWT and corresponding forces were recorded for each load cell. Load cell readings were taken in microvolts by the DAQ and calibration curves were fitted.

6. Experimental field condition

A 5.00–12, 4-ply, high-lug agricultural tire, was used to evaluate the SWT and its performance. The field tests were done on a bare agricultural soil surface after using a moldboard plough to a depth of 15–20 cm and a disk harrow to make the field ready for experiments. Nine equal regions of the field were selected to satisfy three compaction levels (plowed, 2 and 5 passes of roller packer) and 3 moisture content levels (8 ± 0.52%, 11 ± 0.37% and 14 ± 0.61%). Soil samples for moisture content determination were taken at 0–10 cm depth, associated with the corresponding cone index readings (penetration up to 10 cm depth). The organic matter percentage, texture, and bulk density of the soil are shown in Table 1.

The mean and standard deviation of 20 sample readings of cone index values (for each treatment level) are tabulated in Table 2. A photograph of the SWT on the field surface is displayed in Fig. 5.

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Clay, Silt, Organic matter (%)</th>
<th>Bulk density in dry based (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay loam</td>
<td>28, 42, 30, respectively</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.35</td>
</tr>
</tbody>
</table>

Table 2

Cone index values (kPa) at different moisture contents and compaction levels.

<table>
<thead>
<tr>
<th>Compaction level</th>
<th>Moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8%</td>
</tr>
<tr>
<td>Plowed</td>
<td>774 ± 31.4</td>
</tr>
<tr>
<td>2-Pass compacted</td>
<td>1012 ± 36.1</td>
</tr>
<tr>
<td>5-Pass compacted</td>
<td>1219 ± 25.9</td>
</tr>
</tbody>
</table>

6.1. Experimental design and data analysis

The Response Surface Methodology (RSM) was utilized to model and analyze the collected data using Design-Expert Software 8.0.7.1. To choose the best model, which is able to accurately predict the response of given data, the residual error between the experimental and the predicted responses should be minimized. A guideline for selecting the correct power law transformation provided by Box–Cox plot. A recommended transformation is found at the minimum point of the curve, in a Box–Cox plot, generated by the natural logarithm of the sum of squares of the residuals. Checks need to be made in order to determine whether the model actually describes the experimental data. Also,
the adequacy of the model is investigated by the examination of residuals using the normal probability plots of the residuals and the plots of the residuals vs. the predicted response. The experimental data were analyzed and fitted into the suggested model or its reduced form (stepwise model) in order to minimize the number of the factors affecting on the rolling resistance. In the software, after targeting a face centered Central Composite Design (CCD), the number of experiments and corresponding values of each variable, in these experiments, were determined. Five variables, including angular velocity, inflation pressure, moisture content, normal load and side slip angle have three levels. While variables CI and DP have specific conditions (Table 2), having 6 extra levels in historical design. The

\[
y = 1.0027x - 0.0646 \\
R^2 = 0.9994
\]

\[
y = 0.9745x + 1.5455 \\
R^2 = 0.9972
\]

\[
y = 1.0036x - 0.8182 \\
R^2 = 0.9991
\]

\[
y = 0.992x + 1.0909 \\
R^2 = 0.9996
\]

**Table 4**
Summary statistics of 2FI reduced form.

<table>
<thead>
<tr>
<th>Standard deviation</th>
<th>Mean</th>
<th>C.V. %</th>
<th>R-squared</th>
<th>Adj R-squared</th>
<th>Degree of freedom</th>
<th>Sequential p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.098</td>
<td>4.7</td>
<td>2.11</td>
<td>0.9163</td>
<td>0.9084</td>
<td>13</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

**Fig. 6.** Calibration curves for load cells, (a) load cell 1, (b) load cell 2, (c) load cell 3, and, (d) load cell 4.

**Fig. 7.** (a) Perturbation diagram of rolling resistance values vs. each independent variable, (b) rolling resistance values vs. experimental values.
range of the affecting variables and corresponding coded values (only maximum and minimum) are given in Table 3.

7. Results and discussion

7.1. Calibration results

The calibration curves of each load cell are shown in Fig. 6. As illustrated, the load cell data are highly correlated with the exerted force values.

7.2. Model selection

To evaluate SWT performance and investigate rolling resistance model, 152 tests were executed. For selecting the best predicting model, a set of different polynomial models were compared (using Design Expert software). The best model was chosen with respect to a good balance between the highest coefficient of determination, and the lowest standard deviation, p-value and degree of freedom. Due to the aforementioned reasons, 2 Factor Interaction (2FI) model was selected. Finally, in order to reduce and optimize the number of variables included in the 2FI model, stepwise analysis was conducted (Table 4).

The final model of natural logarithm of rolling resistance is represented by Eq. (9), in which the coefficients are in coded unit form. The most appropriate power transformation (lambda) for responses is detected by the Box–Cox diagram that results the minimum residual sum of squares in the transformed model (Fig. 7b).

\[
\ln(R_r) = 4.71 + 0.020 \times MC - 0.18 \times CI + 0.62 \times F_z \\
+ 0.16 \times \omega + 4.039E - 004 \times \omega + 0.012 \times DP \\
+ 0.016 \times Pr + 0.015 \times MC \times F_z - 0.021 \times MC \\
\times \omega + 0.053 \times CI \times F_z + 0.016 \times CI \times \omega \\
- 0.028 \times CI \times \omega - 0.020 \times CI \times Pr
\]  

(9)
7.3. Statistical analysis graphs

To compare the effect of all the factors at a particular point (midpoint (coded 0) of all the factors) in the design space, perturbation plot of rolling resistance model vs. each independent variable are illustrated in Fig. 7a. It is clear that the variation of the wheel angular velocity has the lowest impact on the rolling resistance, while the wheel normal load has the highest. All the independent variables, cone index excepted, are positively correlated with the rolling...
resistance when all the factors are at their midpoint values. Also, the actual values of rolling resistance vs. predicted values using final model are displayed in Fig. 7b.

Some of graphical summaries for case statistics (model diagnostic and influence plots) are shown in Fig. 8. These plots indicate that the model satisfies the assumptions of the analysis of variance reasonably well.

7.4. Output graphs

The rolling resistance behavior of the high-lug agricultural tire are displayed in Fig. 9a–d. These 3D surface plots represent the rolling resistance across the other two variables indicated on each graph. Increasing normal load will result in rolling resistance increment with a non-linear relation (Fig. 9a, c and e). Also, it can be observed that, with an increase of the side slip angle that leads to increases in longitudinal slip, the rolling resistance increases, but the increment is higher at higher normal loads. As displayed in Fig. 9f, the increasing pressure effect on rolling resistance at lower CI values is stronger. Similar observations were reported by Gee-Clough and Sommer (1981), Raheman and Singh (2004), who found that rolling resistance values increase with increasing side slip angles, normal loads and inflation pressures. This is due to the increment of one or more of the following reasons: total contact length, total contact area, buldozerfing effect, wheel ground penetration, slip, sinkage, or other reasons, which may increase the amount of soil in front of the wheel along the pass. In addition, increased inflation pressure resulted in increasing soil contact pressures of tire at lower CI values.

At higher CI values, increasing angular velocity reduces rolling resistance while at lower CI values, the effect of angular velocity is reverse order for the tested soil condition (Fig. 9b). The increasing moisture content effect on rolling resistance at lower side slip angle values is stronger than the higher ones (Fig. 9d). The effect of drawbar pull on $R_r$ showed a slight increase with the increasing drawbar pull as shown in Fig. 9a.

When the soil cone index value increases (i.e. in the second pass of movement) this leads the rolling resistance increment (see Fig. 9b and f), because in a soft soil, sinkage is more profound and the tire lugs become more influential. This finding is supported by Gu and Kushwaha (1994). It can be observed that the rolling resistance are diminished as CI value increases, especially at higher normal loads. At lower cone indices, the rolling resistance is more sensitive to the tire inflation pressure and this effect vanishes as the CI value increases.

8. Conclusion

Single Wheel Tester (SWT), is an essential facility for field research on tire tractive and maneuverability performances. To sum up, the conclusions drawn from the study are as follows:

1. The natural logarithm of rolling resistance was found as a function of seven independent variables, with degree of freedom of 13, using the reduced form of a 2FI model.
2. Increasing normal load and side slip angle increase rolling resistance, however increasing cone index value reduces rolling resistance.
3. At lower CI values, increasing angular velocity increases rolling resistance, although at higher CI values, the reverse effect of angular velocity on rolling resistance was observed.
4. The effect of moisture content increasing on $R_r$ at lower side slip angle values is stronger than the higher ones for the tested soil condition.
5. Increasing drawbar pull demonstrates slight rise in rolling resistance.

References


