An instrumented drive axle to measure tire tractive performance

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Abstract

An instrumented drive axle is introduced for a prototype tractor using in field research on tractor and implement performance. This mechanism was developed to determine whether such an instrumented drive axle is practical. The drive axle was equipped with a set of transducers to measure wheel angular velocity, rear axle torque and dynamic weight, as well as tire side forces. Measuring the drawbar pull acting on the tractor provides data for calculating net traction, motion resistance and chassis resistance for each driven wheel.

1. Introduction

Most tractors and agricultural machinery have no suspension system for isolating the vehicle from irregularities of the ground surface except the tires and springs of the driver seat. Other important duties of the tires include: affording steerability and stability, providing tractive and braking forces and supporting the vehicle weight [1]. Under cornering conditions, the tire develops lateral force [2]. Also, the same force can be a result of driving on banked surfaces, side winds [3], or asymmetric drawbar pull from implements [4].

Tractive force is provided by the torque applied to the wheel which is generated by the engine and transferred through the power train. According to Fig. 1, this force termed as Gross Traction (GT), overcomes Motion Resistance (MR) and drawbar pull or Net Traction (NT) [5]. In contrast, the braking force is provided by the torque locking the wheel to the vehicle chassis. The tire also bears the weight of vehicle or dynamic load \( (W_d) \), including static and any additional forces such as load transfer to the wheel [5]. As wheel dynamic load increases, slip decreases and tractive capacity of tire improves [6]. There are different parameters identifying tractive performance from different points of view. The most important ones are: Travel Reduction Ratio (TRR), Net Traction Ratio (NTR), Tractive Efficiency (TE), Gross Traction Ratio (GTR), and Motion Resistance Ratio (MRR). The traction condition is well illustrated and data will be provided to optimize that when all these parameters are ready. In order to represent these parameters, knowing tire tractive force, input torque, rolling resistance, dynamic load, wheel angular velocity and forward speed is essential. Therefore, measuring the forces and torques acting on the tires is helpful in the study of dynamic behavior, especially the tractive performance of vehicles.

2. Background

Review of the literature shows that dynamic behavior and tractive performance studies can be conducted through theoretical and experimental procedures. Usually, theoretical predictions are verified with experimental results performed in laboratory [7] or field [4,8,9]. Therefore, most researches require measurement of forces and torques...
applied on the tires. Some laboratory experiments have been carried out in soil bins [10–14] while field tests usually need instrumented vehicles [4,15–23]. Fleming [24] reviewed the different methods for measuring torque on rotary axles and summarized them into seven categories. He analyzed specifications, merits and demerits of each category. Oida [22] measured lateral force of an articulated tractor tire by attaching four strain gauges on its driving axle housing, to define the turning behavior of the tractor. Shoop [23] developed a vehicle with triaxial load cells mounted on the wheel axle. It has been used to measure the forces at the tire/soil interface. McLaughlin et al. [21] equipped a 97 kW agricultural tractor with an instrumentation and data logging system which was used in field research on tractor and implement performance. The tractor was fitted with a set of transducers to measure fuel consumption, engine, wheel, and ground speed, front and rear axle torque and weight, and forces in the three-point hitch. Itoh et al. [20] presented his measuring method of vertical, longitudinal and lateral forces, which act on tires of a four-wheel drive and four-wheel steering agricultural tractor. He also measured longitudinal and lateral slip of the tires. Gu and Kushwaha [19] designed and fabricated an instrumented model tractor for the study of the effect of dynamic load distribution on the tractive performance of 4WD tractors. Al-Janobi et al. [16] developed a precision wheel torque and weight transducer for an agricultural tractor replacing its standard wheel center with the developed wheel torque transducer. The wheel torque and weight transducer incorporated three load-sensing clevis bolts. He also measured angular velocity of the wheel using a shaft encoder. Besselink [18] developed a vehicle to study tractive performance and designed a dynamometer consisting of a S-type load cell to measure dynamic force along the longitudinal axis. Baffet et al. [17] applied a very expensive dynamometric hub for measuring forces and moments acting on tires of an on-road vehicle in order to study dynamic behavior of wheel-road interface. Ahmad et al. [15] presented the development of a test rig for measuring motion resistance of towed narrow wheels. The towing force which is equal to the motion resistance will be measured by a Basic Force Gauge (BFG) installed on the test rig. The test rig comprises two parts, one part holding the wheel and the second part hitched to the tractor, between these two, the BFG is measuring the towing force.

Although several methods for measuring tire forces and moments have been reported in the literature, they are either limited to measuring a limited number of parameters [18,19] or methods are not economical [17,21]. This paper presents a low cost flexible method for measuring forces (including lateral) and the torque acting on the driving wheels.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>A</td>
<td>normal distance between shear type load cell</td>
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<td></td>
<td>and tire center plane (m)</td>
</tr>
<tr>
<td>D</td>
<td>lever arm of R (m)</td>
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<tr>
<td>eh</td>
<td>longitudinal distance between wheel center and</td>
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<tr>
<td></td>
<td>R, (m)</td>
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<tr>
<td>I</td>
<td>the ratio of forward axle weight to the tractor</td>
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<td></td>
<td>weight (–)</td>
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<tr>
<td>rt</td>
<td>vertical distance between wheel center and MR</td>
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<td></td>
<td>application point (m)</td>
</tr>
<tr>
<td>t</td>
<td>tractor wheel base (m)</td>
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<tr>
<td>CR</td>
<td>chassis resistance (N)</td>
</tr>
<tr>
<td>Fc</td>
<td>chain tension force (N)</td>
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<tr>
<td>FT</td>
<td>force acting on the load cell measuring drive</td>
</tr>
<tr>
<td></td>
<td>axle input torque (N)</td>
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<tr>
<td>Fy</td>
<td>wheel side force (N)</td>
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<tr>
<td>GT</td>
<td>gross traction (N)</td>
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<tr>
<td>MR</td>
<td>motion resistance (N)</td>
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<tr>
<td>NT</td>
<td>net traction (N)</td>
</tr>
<tr>
<td>R</td>
<td>resultant of surface reaction force (N)</td>
</tr>
<tr>
<td>Re</td>
<td>vertical component of the surface reaction</td>
</tr>
<tr>
<td></td>
<td>force (N)</td>
</tr>
<tr>
<td>Ta</td>
<td>input torque acting on drive axle (N m)</td>
</tr>
<tr>
<td>Tw</td>
<td>input torque acting on drive wheel (N m)</td>
</tr>
<tr>
<td>Va</td>
<td>tractor actual velocity (m/s)</td>
</tr>
<tr>
<td>Vt</td>
<td>tractor theoretical velocity (m/s)</td>
</tr>
<tr>
<td>W</td>
<td>tractor weight (N)</td>
</tr>
<tr>
<td>Wa</td>
<td>drive axle weight (N)</td>
</tr>
<tr>
<td>Wd</td>
<td>wheel dynamic load (N)</td>
</tr>
<tr>
<td>ZT</td>
<td>normal distance between torque load cell and</td>
</tr>
<tr>
<td></td>
<td>center of axle (m)</td>
</tr>
<tr>
<td>θ</td>
<td>the angle between Rc and R (°)</td>
</tr>
<tr>
<td>ω</td>
<td>tire angular velocity (rpm)</td>
</tr>
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</table>

Fig. 1. Basic velocities and forces on a wheel, including resultant soil reaction force [5].
3. Dynamometric design of the driving wheel

Forces acting on the driving wheel and its input torque were measured on a prototype tractor in which the front wheels were steerable and the rear axle was driven by a differential of 1:3.3 reduction ratio. In order to measure the tire input torque and side force, S-beam load cells were used while the vertical load was measured using shear type compression load cells.

3.1. Input torque (T)

Through a survey on the methods mentioned by Fleming [24], for measuring drive axle input torque, the reaction force method was selected due to its conformity to the drive axle mechanism, low cost, and high precision. The reaction forces generated by the torque exerted on the axle can be measured easily using this method. In drive axle mechanism, the axle housing is connected through two pairs of tapered roller bearings instead of direct connection to tractor chassis as depicted in Fig. 2a. This allows the axle housing to freely rotate about the axes of the bearings.

When a torque is exerted on the drive wheel by the differential input shaft, a reaction force is generated tending to rotate the axle housing in the opposite direction. This reaction force is measurable by fixing the differential input shaft to the chassis through load cell 1. Input torque can be derived through multiplying this force by its normal distance from the rotation axis, or:

\[ T_a = F_T \cdot zT \]  

Obviously, all of the forces acting on the differential housing parallel to load cell 1 axis cause errors in torque measurement. Therefore, as shown in Fig. 2b, two laterally installed equal sprockets were used to transmit the power from the gearbox output to the differential input. This prevents chain tension \( F_c \) from affecting the load cell reading \( F_T \).

Since differential mechanism equalizes the input torque on the driven wheels, the wheel torque is half of the axle torque; i.e. \( T_w = T_a/2 \).

3.2. Gross Traction (GT)

Drawbar pull and motion resistance are the two forces acting against the wheel forward motion which should be overcome by wheel torque. This torque appears in the contact patch and generates gross traction. Therefore, GT is the result of wheel torque divided by the distance between the wheel center and the contact patch (Eq. (2)).

\[ GT = \frac{T_w}{rt} \]  

Fig. 2. Schematic view of the prototype tractor driven wheel, (a) drive axle assembly, (b) input torque measurement by load cell 1, (c) vertical load measurement, (d) free body diagram of the driven wheel, and (e) equivalent static system including MR.
The correct torque radius is not directly measurable. There is no general agreement among traction researchers as to what radius to use [25]. Thus, with an expected error, the distance traveled in one rotation of the tire without drawbar pull divided by \(2\pi\) is used instead.

### 3.3. Net Traction (NT)

Net traction is applied to the wheel by implements drawn by the vehicle and can be measured with an S-beam load cell situated between the vehicle and the implement. When net traction of a single wheel is measured through drawbar pull measurement of a vehicle, to ensure that the left and right wheel traction values are equal, two points are important:

1. Drawbar pull direction should be parallel to the ground surface and coincide with tractor longitudinal axis.
2. Measurement should be conducted when the tractor is moving straight.

### 3.4. Vertical load (\(W_d\))

The traction parameters involving forces are all normalized by dividing by the vertical load (\(W_d\)). \(W_d\) includes static axle weight and any weight transfer, i.e. the total reaction force [25]. Vertical load acting on each drive wheel was measured, according to Fig. 2c, through two shear type compression load cells installed between the chassis and tapered roller bearings hub. Forces indicated by the load cells are not equal to the tire vertical load (\(W_d\)) because the application points of these forces are not on the center plane of the tires. Since these load cells are not able to measure weight of the part standing under them with a desirable assessment, half of the axle weight is added to each tire vertical load. Therefore, vertical reaction force on each wheel is calculated through static analysis as follows:

\[
R_{v2} = \frac{W_3 \cdot a + W_5 (t - a)}{t} + \frac{W_a}{2}
\]

\[
R_{v3} = W_2 + W_3 + W_a - R_{v2}
\]

Vertical loads on left and right wheels are not equal when the tractor is turning (especially at high speeds) and traversing slopes. This inequality can also be found through the mentioned equations.

### 3.5. Motion Resistance (\(MR\)), chassis resistance (\(CR\)) and horizontal distance between vertical force and center of contact patch (\(eh\))

The free body diagram of a drive wheel is illustrated in Fig. 2d. Since the vertical reaction force (\(R_v\)) is not directly under the axle centerline and is offset by the distance \(eh\), an opposing torque will be exerted on the wheel. Moving the application point of reaction force (\(R_v\)) under the wheel center applies a torque to satisfy the static equilibrium. This torque is usually generated through a virtual longitudinal force known as motion resistance (Fig. 2e) acting on the wheel at the distance of torque radius (\(rt\)) from the wheel center. In other words:

\[
MR \cdot rt = R_v \cdot eh
\]

In addition to motion resistance, another force is countacting the rotation of driven wheel. This force is termed as chassis resistance (\(CR\)), mostly due to the un-driven wheels motion resistance and aerodynamic forces exerted through vehicle chassis to drive axle [26].

Since the algebraic sum of the moments of the forces about wheel center must be equal to zero, Eq. (6) holds:

\[
T_w - R \cdot d = 0
\]

where the direction and magnitude of the resultant force (\(R\)) are derived from Eqs. (7) and (8).

\[
\theta = \tan^{-1}\left(\frac{NT + CR}{R_v}\right)
\]

\[
R = \sqrt{(NT + CR)^2 + R_v^2}
\]

In addition, wheel torque can also be written as Eqs. (9) and (10).

\[
T_w = (CR + NT) \cdot rt + R_v \cdot eh
\]

\[
T_w = (CR + NT) \cdot d \sin \theta + R_v \cdot d \cos \theta
\]

With a simple geometric analysis, the following equation relating parameters \(d\), \(\theta\), \(rt\) and \(eh\) is obtained:

\[
d = eh \cdot \cos \theta + rt \cdot \sin \theta
\]

Now, based on dynamic analysis, a system of equations has been developed by the above equations, in which knowing \(R_v\), \(T_w\), \(rt\) and \(NT\) will result in the calculation of CR and \(eh\) values.

### 3.6. Lateral force (\(F_y\))

Due to the importance of the side force acting on tires, especially when cornering and moving on slopes, a mechanism (Fig. 2a–c) was developed to measure this force. In this mechanism S-beam load cells 4 and 5 are mounted to coincide with the wheel center in such a way that side forces are exerted along the load cells axes and other forces are absorbed by ball bushings and guide rods. Inner rings of two spherical roller bearings surrounded the load cells axes to keep them from rotating in order to prevent signal wires from twisting with tire rotation.

### 3.7. Angular velocity (\(\omega\))

Input power calculation on each driven wheel requires input torque and angular velocity values to be known. Angular velocity is also necessary to obtain vehicle tractive performance. Therefore, driven wheels of the prototype tractor were equipped with angular velocity transducers.
A notched strip of 90 teeth, formed into a ring (Fig. 2a) was installed concentric with each wheel axis, between the transmitter and receiver of an opto-counter. By sending pulses from the counter to an electronic processor unit, angular velocity was precisely calculable.

4. Dynamometer development

Derivation of input torque, gross traction, net traction, motion resistance, chassis resistance and the \(eh\) distance values requires solving of the equations given in the previous section. These equations contain constants which are dependent on the prototype tractor and its drive axle specifications. These are given in Table 1.

Load cell 1 measures the torque exerted on the drive axle. This torque is provided by a motorcycle single cylinder gasoline engine with a volume of 150 cc. The maximum torque gain coefficient occurs in the first gear and is about eight. A spiral gearbox with a speed reduction ratio of 7.5 (as shown in Fig. 2a) is used to additionally increase the torque and a 90° conversion in power transmission direction. In addition, this torque is again increased with a coefficient of 3.3 in the differential mechanism. Therefore, maximum input torque on the drive axle is:

\[ T_a = 9 \times 8 \times 7.5 \times 3.3 = 1782 \text{ N m} \quad (12) \]

Using the normal distance between load cell 1 and axle housing \((Z_T)\), the maximum force exerted on this load cell is obtained to be 8910 N; hence, a 1000 kgf (9810 N) load cell was used.

Load cells 2 and 3 are installed to measure the dynamic load exerted on the right and left drive wheels. Using the values of \(W, i, W_a\) given in Table 1, the static force acting on each load cell on a flat surface is 850 N. Therefore, two load cells of 150 kgf (1470 N) capacity were used in order to withstand the impacts on uneven surfaces, traversing on slopes and cornering (Fig. 2b).

Load cells 4 and 5 measure side forces acting on the drive wheels (Fig. 2c). The side forces are mainly a result of motion on slopes and tire lateral slip when cornering. The prototype tractor drive wheels are not steerable, thus, side forces are smaller when cornering than traversing along slopes. Therefore, selection of these load cells was carried out assuming traversing on a 30° maximum:

\[ F_y = W \times (1 - i) \times \sin \theta = 1200 \text{ N} \quad (13) \]

Eq. (13) is written assuming the friction coefficient between the tire and ground is negligible for one of the drive wheels, and the whole side force is exerted on the other wheel.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Prototype tractor and its drive axle specifications.</th>
</tr>
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<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>(a)</td>
<td>0.235 m</td>
</tr>
<tr>
<td>(d)</td>
<td>0.510 m</td>
</tr>
<tr>
<td>(h)</td>
<td>0.087 m</td>
</tr>
<tr>
<td>(i)</td>
<td>0.4</td>
</tr>
<tr>
<td>(rt)</td>
<td>0.230 m</td>
</tr>
</tbody>
</table>

*Fig. 3. Experimental instrumented drive axle, (with a 4.00-12, 6 ply tire) (a) vertical load and angular velocity transducers, (b) torque transducer, and (c) side force measurement.*
Hence, the capacity of load cells 4 and 5 are equal to 150 kgf (1470 N) (see Fig. 3).

5. Conclusions

The instrumented drive axle developed in this study demonstrates the feasibility of online measurement of tractive performance and tire side force. In this mechanism, ordinary low cost load cells have been used which is more accurate compared to strain gauges manually installed on structure; however, it is complicated and needs more development. The cost of the load cells used is lower than that of dynamometric hubs, while their precision is sufficient.

Rolling resistance is expected to introduce some error because of its unknown application point. Another mechanism must be developed to measure moments about the vertical axis; which enables determination of the accurate position of this force.

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