International Journal of Research
Available at https://edupediapublications.org/journals
e-ISSN: 2348-6848
p-ISSN: 2348-795X
Volume 05 Issue 01
January 2018

Determination of Basic Mechanical Parameters of the Tractor Tyre by Using Universal Approach

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Abstract: Rising fossil fuel prices are leading to an increasing awareness of energy efficiency in plant production. Tillage in particular can consume large amounts of fuel. For four tillage implements (reversible mouldboard plough, short disc harrow, universal-cultivator, subsoiler), this study quantifies the effect of different working depths on fuel consumption, wheel slip, field capacity and specific energy consumption. A four-wheel drive tractor (92 kW) was equipped with a data-acquisition system for engine speed, vehicle speed, wheel speed and fuel consumption. Fuel consumption was measured in the fuel system with an integrated high-precision flow-meter. The results show that the area-specific fuel consumption increased linearly with working depth for both the mouldboard plough and the short disc harrow, but disproportionately for the subsoiler. Wheel slip was found to increase fuel consumption and decrease field capacity performance at all depths. The influence of the engine speed was shown in a separate experiment with a universal-cultivator. Increasing the engine speed from 1,513 r min-1 to 2,042 r min-1 results in an increase of 80% for the fuel consumption rate (L/h) and 35% for the area-specific fuel consumption (L/ha). Future measurement of drawbar pull will allow a more detailed analysis of the energy efficiency losses at the engine, the transmission, and at the wheel/soil interface.

Keywords: fuel consumption, wheel slip, mouldboard plough, subsoiler, universal-cultivator, short disc harrow

1.Introduction

Reducing fuel consumption in cropland agriculture is a complex and multifactorial process, where farm management plays a key role (Safa et al., 2010). Conventional tillage with ploughs is one of the most energy-consuming processes in plant production (Stout, 1990; Kalk, 1981). Mouldboard ploughs, tined implements and disc implements are the main implement types for primary tillage (Arvidsson et al., 2004). The intensity of tillage depends on the number of tillage operations, power transmission (active by PTO or passive by drawbar power), implement geometry, and depth of operation (Godwin, 2007; McKeyes, 1985; Loibl, 2006). Compared to conventional tillage systems, fuel consumption can be significantly reduced with conservation tillage systems (Mileusnić et al., 2010; Moitzi et al., 2009; Tabatabaefar et al., 2009). Tillage with a high degree of soil disturbance, e.g. ploughing or cultivating, contributes greatly to soil tillage erosion (Lobb et al., 1999; Sheng et al., 2007). The fuel consumption of soil tillage operations varies widely and can be reduced through proper matching of tractor size, operating parameters, tillage implement (McLaughlin et al., 2008). Of the average fuel consumption for ploughing (25 L ha-1), only 5 L ha-1 of the fuel energy is used for the drawing of the plough (Kutzbach, 1989), while the remaining fuel consumption is due to efficiency losses in the engine, transmission, and

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wheel/soil interface (Jahns and Steinkampf, 1982; Schreiber et al., 2004). The term "fuel" is used here exclusively to denote diesel fuel. Additional, soil related, parameters, such as soil texture and organic matter content, influence fuel consumption in soil tillage (McLaughlin et al., 2002; Moitzi et al., 2009). Depending on the soil consistency the fuel consumption increases by 0.5 to 1.5 L ha-1 per centimetre of ploughing depth (Kalk and Hülsbergen, 1999; Filipović et al., 2004; Moitzi et al., 2006).

2.Materials and methods

Experimental setup The experiments (Table 1) were conducted on arable fields at the research station Gross Enzersdorf (Lower Austria; 48° 15′ N/ 16° 37′ E) of the University of Natural Resources and Life Sciences Vienna. The site is situated in a semi-arid region with an average precipitation of 546 mm and average temperature of 9.8°C. The silty loam soil belongs to the soil type calcic CHERNOZEM.

Table.1: Overview of experimental set-up

	Ploughing	Stubble field skimming	Subsoiling
Soil tillage device	4 furrow reversible mouldboard plough	Short disc harrow (SDH); Universal-cultivator (UC)	Subsoiler
Adjusted mean working depth (cm)	18, 20, 35	SDH: 8, 10, 13; UC: 13, 15	20, 30, 33, 40, 45
Date of experiments	3 November, 2005	31 July, 2008	2 October, 2008
Previous crop	Corn	Winter rapeseed	Corn
Mean water content in the soil (gravimetric)	14.3% (0-30 cm)	18.3% (0-20 cm)	16.9% (0-40 cm)
Mean dry bulk density	1.35 g cm^{-3}	1.40 g cm^{-3}	1.39 g cm^{-3}

Before the experiment was carried out, each field was probed with soil sample rings (height: 4.8 cm; radius: 3.5 cm; volume: 184.73 cm-3) to a depth of 30 cm for the ploughing experiment, 20 cm for the experiment with short disc harrow and universal-cultivator, and 40 cm for the experiment with the subsoiler, respectively. The soil samples were dried in an oven (105°C, 12 h) and afterwards the mean water content (gravimetric) and mean dry bulk density were calculated. The mean working depth of the mouldboard plough was set by measuring the vertical distance between furrow ground and unploughed soil. For the short disc harrow, universal cultivator and subsoiler the mean working depth was calculated by the difference between the vertical distance of the implement-frame to the soil surface in the tillage process and the vertical distance of the implement-frame to a concrete surface.

Specifications for soil tillage implements Table 2 shows the technical data of the soil tillage implements according to manufacturers` specifications.

Tractor and measuring equipment For all experiments a four-wheel drive tractor (Steyr 9125, CNH, St. Valentin, Austria) with a rated engine power of 92 kW (DIN) was used. The four stroke diesel engine with direct injection and exhaust turbo supercharger has six cylinders (vertical in line) with a total

Table.2: Technical data of the mouldboard plough, short disc cultivator, universal-cultivator and subsoiler displacement of 6,596 cm3 .

e-ISSN: 2348-6848
p-ISSN: 2348-795X
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Technical working width, m	3.00	
Number of discs	2 × 12	
Spacing between discs, cm	25	
Disc diameter, cm	46	
Weight, kg	1770	
Adjustable working depth, cm	3–12	
Depth adjustment	Wedge ring roller	
Manufacturer	*Amazone*, Hasbergen, Germany	
	Universal-Cultivator (Cenius™)	
Technical working width, m	3.00	
Number of spiral spring tines	13	
Tool width, cm	7.50	
Number of discs	8	
Disc diameter, cm	46	
Weight, kg	2160	
Adjustable working depth, cm	5 - 30	
Depth adjustment	Wedge ring roller	
Manufacturer	*Amazone*, Hasbergen, Germany	
	Subsoiler (Cultiplow™)	
Technical working width, m	3.00	
Number of fixed tines	4	
Width of subsoiler wing, cm	34	
Weight, kg	773	
Adjustable working depth, cm	20 - 50	
Depth adjustment	Roller harrow	
Manufacturer	*Agrisem International*, Ligne, France	

Process parameters The process parameters were determined using a variety of sensors (Table 3). For the calculation of the wheel slip (s) the parameters "wheel speed" (v0) and "vehicle speed" (v) are required (Equation (2)). 100 0 0 · = v v v s (2) where, v0: wheel speed, km h-1 ; v: vehicle speed, km h-1 ; s: wheel slip, %. The theoretical field capacity (Ctheo, ha h-1) does not account for wheel slip and is defined as: · v · w=0.1 0 C theo (3) where, w is technical working width, m. The effective field capacity (Ceff, ha h-1) accounts for wheel slip by replacing wheel speed v0 with vehicle speed v: 0.1 eff (4)· v· w=C The area-specific fuel consumption (QA1, L ha-1) with slip is defined as: QA Q Ceff / =1 (5) where, Q is fuel consumption rate, L h-1 The area-specific fuel consumption (QA2, L ha-1) without wheel slip is calculated with the theoretical field capacity: QA Q Ctheo / (6)=2 The area-specific fuel consumption with slip (QA1) is calculated with the vehicle speed (v), whereas the fuel consumption without slip (QA2) is calculated with wheel speed (v0).

Results and discussion

Mouldboard plough Mouldboard ploughs are used in conventional tillage systems, where the furrow slice is turned in an angle of about 139°. The measured fuel consumption rate shows a diminishing increase with increasing working depth (Figure 2), which is the result of shifting the partially loaded engine's operating point closer to the full load range. The engine speed was relatively constant at the different working depths (Table 4), and at partial engine load, the specific fuel consumption (g kWh-1) decreases with increasing power demand. The area-specific fuel consumption (QA) is the quotient of fuel consumption rate and field capacity (Equations (5) and (6)). It also exhibited a possibly diminishing increase with working depth. The area-specific fuel consumption with wheel slip QA1 was approximated slightly more accurately with a quadratic model (R 2 = 0.991) than with a linear model (R 2 = 0.978). Linear functions for this parameter were found in Kalk and Hülsbergen (1999) and Filipović et al. (2004). The slope of the QA1 curve is 0.348 L ha-1 per cm working depth. The y-intercept of QA1 in the linear model (Figure 2), 6.48 L ha-1 , is the basic consumption which results mainly from the rolling resistance between tyre and soil surface. The wheel slip increases from 3.34% at 18 cm working depth to 6.12% at 35 cm working depth (Table 4), which is a result of increased drawbar power demand. For the working depth of 35 cm, this slip between wheel and soil consumes 1.1 L ha-1 of the total area-specific fuel consumption QA1 of 18.29 L ha-1 .

Fig.1: *Measuring tyre contact length*

Coefficient of stiffness can be determined in the following ways:

1. statically, according to the slope of the curve of tyre deflection versus vertical load, and
2. dynamically, according to the natural frequency of tyre vertical vibration.

Damping coefficient can be obtained through the time response of free vertical damped vibration by using logarithmic decrement method. Vibration is excited by the free fall of the tyre from the certain height level ("drop test"), which does not have to be much higher than the static equilibrium height. It is well known from the previous investigations (e.g. [1]) that both tyre stiffness and especially damping are dependent on both excitation frequency and the tyre rolling speed. Therefore, results obtained in this work should be viewed as more or less rough approximation. More broad set of test data in view of free damped vibration response with different mass values (meaning different natural frequencies of the system) would though enable empirical modelling of damping coefficient dependence on excitation frequency.

MEASUREMENTS RESULTS

Vertical load, Tyre Deflection and Contact Length

By using described procedure for the determination of dependence between tyre deflection and the vertical load, results were obtained for full range of tyre loads, dependence between tyre load and the deflection is clearly non-linear. However, considering only limited load range in the area of tyre nominal load (i.e. taking very small loads and deflections out of consideration), Fig. shows that linear dependence between load and deflection for this load range represents very acceptable approximation. Dependence between contact length and tyre deflection is shown in the Fig. Relationship can be well approximated by degressive power growth trendline. Results clearly show that this dependence is of pure geometrical nature, i.e. it is not affected by the tyre pressure or vertical load.

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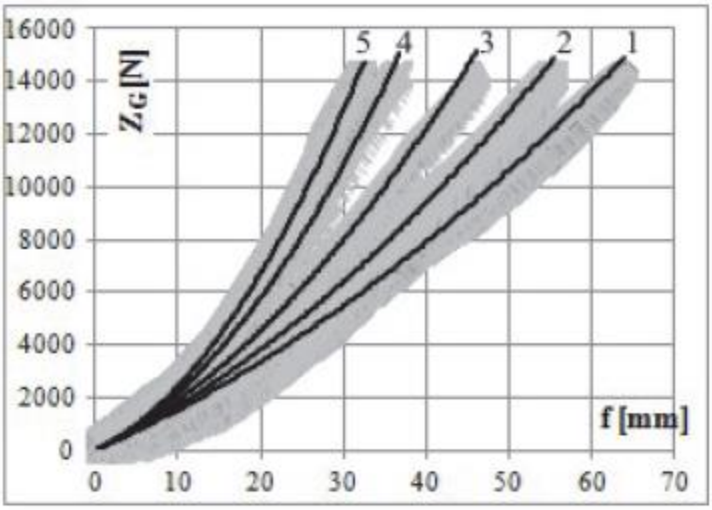

Fig.2: *Dependence between tyre deflection f and the vertical load ZG for different pressure values; 1-0,8 bar, 2-1,1 bar, 3-1,4 bar, 4-1,7 bar, 5-2,0 bar*

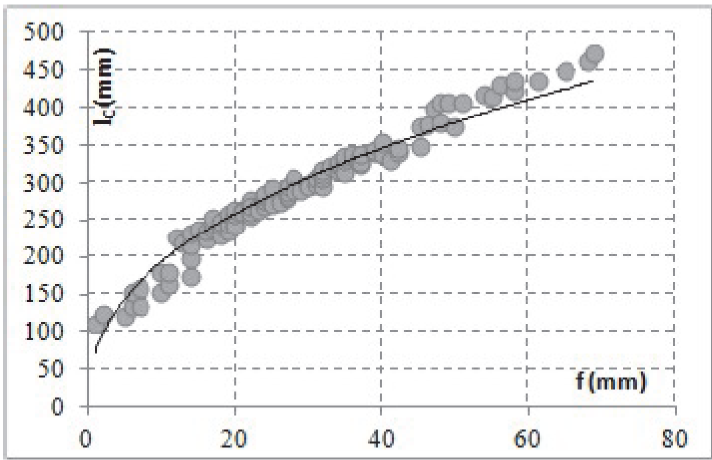

Fig.3: *Dependence between contact length lC and tyre deflection f*

Tyre Radial Stiffness and Damping

Results for the statically determined stiffness coefficients for different tyre pressure values were obtained according to the relation (8), by using curves shown in the Fig. For dynamically determined stiffness, relations (4), (6) and (7) were used. Parameters *TD* and *zi* (expression 4) were obtained from the oscillogramme, i.e. time history of tyre free response after the drop-test. An example of the oscillogramme is shown in the Fig. Both statically and dynamically determined coefficient values for different pressure levels are presented in the Table 2., and their dependence on pressure is also shown graphically in the Fig.

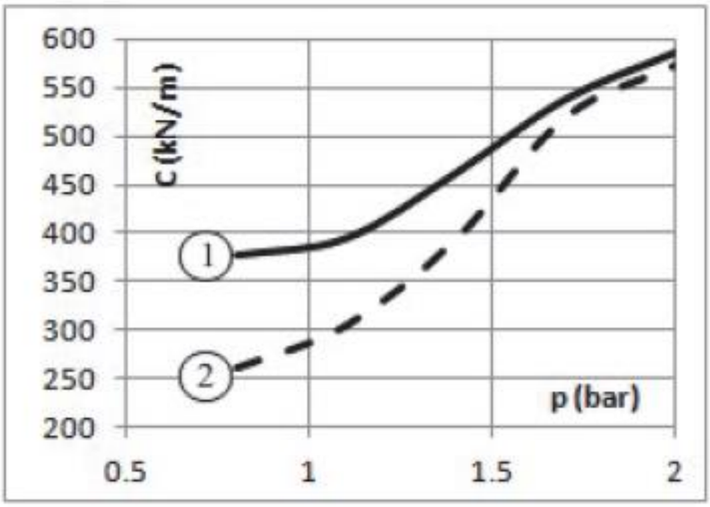

Fig.4: *Dependence of statically and dynamically determined stiffness coefficients on pressure*g

Table.2: *Overall results of the stiffness coefficient Calculations*

From the results in Table 3 a trend toward rise of the stiffness with higher tyre load can be noticed (though with certain deviations). This phenomenon could be attributed to nonlinearity of the dependence between tyre static load and radial deflection (Fig. 5). For higher loads, tyre vibrates about central position corresponding to greater static deflection, exhibiting greater slope of the load-vs.- deflection curve, which corresponds to higher value of linearized stiffness coefficient.

Pressure level	Stiffness [N/m]	
	Static	Dynamic
1 (0,8 bar)	261088	377384
2 (1,1 bar)	304957	394732
3 (1,4 bar)	364064	461916
4 (1,7 bar)	520127	537827
5 (2,0 bar)	573638	585737

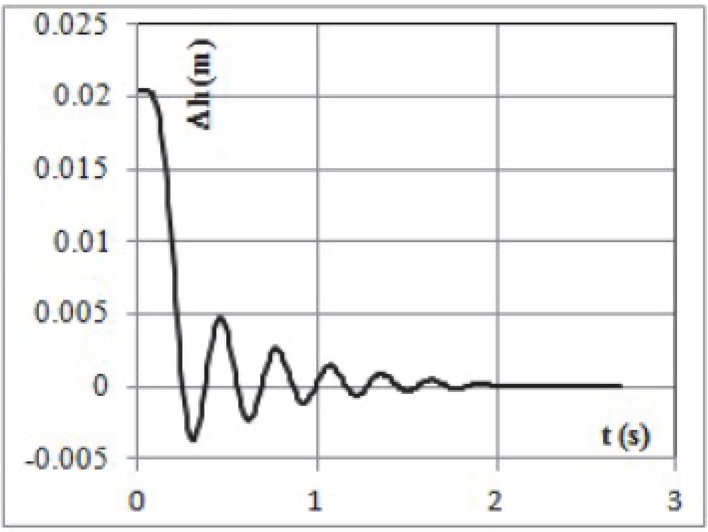

Fig.5: *An example of the oscillogramme - time history of tyre free response after the drop-test; t- time, ∙ h- tyre height with respect to static equilibrium*

Results presented in the Table 2 for dynamically determined stiffness coefficient values represent mean values of measurements for three different levels of tyre static load e.g. system mass/weight (according to Table 1). Results for individual values of tyre static load are shown in the Table 3.

Table.3: *Results of dynamically determined stiffness coefficient calculations*

Pressure level	Dynamic stiffness [kN/m]		
	m=660kg	m=960kg	m=1440kg
1	339,2	377,2	415,7
2	355,1	398,0	431,0
3	403,6	512,0	470,2
4	462,6	619,4	531,5
5	486,4	683,7	587,0

CONCLUSION

This paper describes procedures for determination of some basic tractor tyre parameters by using simple test facility and universal measuring techniques. Dependences between tyre vertical load, static radial deflection and contact length on the hard level ground, as well as stiffness and damping, were investigated. All described measuring procedures were repeated for different values of tyre pressure and vertical load, which enabled investigation of impact of these two important tyre operational parameters on its behaviour from the observed points of view. Measurement results shown acceptable level of deviation, so that they were easy for analysis and interpretation. Dependence between deflection and ground force shown nonlinearity, although linear behaviour can be used as good approximation in the area of nominal tyre load. It was observed that the dependence between tyre deflection and contact length is of purely geometrical nature, i.e. it is not affected by the tyre pressure and vertical load. Some discrepancy was observed between statically and dynamically obtained results for linearized stiffness coefficient, which is ascribed to non-linear nature of tyre response. Linearized stiffness and damping coefficient values can be used in certain applications of tyre viscoelastic structure modelling. Caution is though needed as real tyre exhibits dependence of these values on rolling speed and excitation frequencies. Relationships between tyre load, deflection and contact length can be useful when investigating tyre geometric or filtering properties such as enveloping behaviour.

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