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Influence of Agricultural Tractor parameters on Traction Performance

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Abstract. Agricultural tractors operate in different soil and environmental conditions. Designing and adjusting the tractor parameters for high traction performance is the correct approach to obtain high efficiency in tractor operations. The aim of the study was addressed to measure and evaluate the traction performance of standard tractors for operating the tractor even in high demanding working conditions. A traction load measurement system was refined to measure tractor field data. Standardized trials on a concrete track for assessing the traction performance were executed. Traction performance, including drawbar pull, traction force, travel reduction and net traction ratio were evaluated. Two tractors pertaining to the same family type, designed with the main features equivalent but with different power engine, were compared. To analyze traction performance three parameters were considered, tractor mass, tyre pressure, engine power, for a total of six different operating conditions. The results measured at forward speeds lower than 6 km/h denoted that the net traction ratio increased at the lower tyre pressure in reason of the drawbar pull increase. The mass increase affected the drawbar pull resulting in an increase in traction force across the entire speed range. Comparing the low-power tractor to the high-power one at the low forward speeds, the drawbar pull was similar in the tested configurations, while increasing the forward speed above 4 km/h, the tractor with higher power output showed a significant increase in pulling force and consequently in traction ratio. The travel reduction (slip) was affected mainly by the tractor power. The slip started to have a reduction in between 4 and 5 km/h for the 66 kW and 86 kW agricultural tractors respectively. The traction performance of the tractor was affected by a proper adjustment of the tractor parameters and the results of the evaluation can serve as a guide in tractor design and use.

Keywords: drawbar pull, travel reduction, dynamic traction ratio, tyre pressure, ballast

1 Introduction

The growth in food demand due to the increase in the world population implies that modern agriculture needs contemporarily to increase productivity and efficiency

[1]. Agricultural tractors for powering farming tools and implements are unavoidable in modern agriculture [2] and the tractive efficiency is a main parameter in tractor performance to be improved for field operations [3]. The performance of tractors has always obtained a strong interest among manufacturers and users of the agricultural machinery. To assess tractor performance different testing procedures have been developed in many countries, as in Europe and the United States [4]. In 1959, the Organization for Economic Co-operation and Development (OECD) published the first normalized test code for the performance of agricultural tractors. OECD proposed a standardized procedure for tractor performance aimed to promote the circulation of tractors across the OECD countries [5]. Consequently, since 1959, tractor traction performance was tested worldwide according to the standardized test procedure of the OECD Codes 1 and 2 (OECD Codes 1&2) [6]. Nevertheless, currently only OECD Code 2 is available for tractor testing. In field operations the power of the tractor engine is converted into pulling force by the interaction between the tractor drive wheels and the soil [7] but several studies showed that a percentage ranging between 20 and 55% of tractor power is wasted [7–9] with a consequent tractor tractive efficiency decrease. As described by Battiato and Diserens [10], the parameters affecting the wheel-soil interaction can be divided into three categories: 1) tyre design parameters (i.e., diameter, width, height, inflation pressure and flexibility), 2) soil properties (i.e., soil type, soil moisture, …), and 3) tractor parameters (i.e., wheel load and speed). Experimental results on tractive performance demonstrated the advantages of a correct inflated pressure in tractor tyres. Net traction and tractive efficiency were both increased when inflation pressure was correctly set according to the tyre manufacturers specifications [11]. The influence of the tyre contact area was demonstrated by Kim et al. [12] with four different tyre combinations in paddy field. Wheel-soil interaction is a key subject in evaluating the traction performance [13–15] but, as studied by Kumar et al. [16]by increasing tractors ballast loads higher pulling ability and tractive power efficiency was achieved. Increasing tractor mass affects positively the Net Traction Ratio (NTR) and the stability improving contemporarily the tractor safety in addition to the operating performance. During traction tests the tractor mass influences the dynamic load and the traction force causes slip (travel reduction) due to wheel-ground interaction. Studies demonstrate that the performance of pneumatic tyres is a function of both dynamic load and travel reduction [17]. Different ballasts and ballasting approaches of the tractor are available; however as described by Regazzi et al. [18] tractor front ballasting compared to rear or ventral ballasts decreases the risk of vehicle wheelie. It is noted that in Europe currently the regulation on tractor road circulation requires at least 20% of the tractor total mass on the steering axle [20]. Tractor adhesion is defined as the traction capacity, mainly related to the weight on the driving axle/axles and the features of the contact areas between the ground and the driving components. It has been demonstrated that reducing 37% the tyres inflation pressure and increasing 6 kN the tractor masses, the length of the tyre footprint on the ground increases of 26% and till 39% by adding other 2 kN [21]. The aim of the present study was to evaluate the traction performance of two tractors identical in terms of the design and main features but with different power output. To evaluate how the

engine power, the tractor weight and the tyre inflation pressure affect the drawbar pull, six tractor configurations were studied: three configurations for the 66-kW tractor and three for the 86-kW tractor. In this scenario the testing procedure of the OECD Code 2 was considered. The traction performance of the tractors was evaluated in different gears to cover a speed range from 2 km/h to 11 km/h, pertaining to the working speeds normal operations in the field. The objective was to identify the best configuration of the tractor with respect to the field operation to maximize the traction performance.

2 Materials and methods

2.1 Characteristics of the Tractors

Three tractors were considered: one as braking tractor and two as tested tractors. The braking tractor was a John Deere 6620 weighing 55.72 kN, properly equipped with sensors and a load cell; the tested tractors were pertaining to a family type manufactured by CNH Industrial Italia S.p.A. The two tested tractors, belonging to the same family tractor type, respectively the lowest engine power output tractor and the highest engine power output tractor, were considered as representative of the low-power tractor and the high-power tractor categories.
The first tractor was a CASE IH Farmall 90 C (Fig. 1a), with engine power declared by the manufacturer of approximately 90 HP, corresponding to 66 kW @ 2300 rpm, and the second was a CASE IH Farmall 120 C (Fig. 1b), with engine power of approximately 120 HP, corresponding to 86 kW @ 2300 rpm. Both tractors were Four Wheel Drive (4WD) with maximum forward speed of 40 km/h mounted with mechanical transmission, a synchronized mechanical gearbox with 3 ranges and 8 gears (24x24 Hi-Lo), and a weight of 40.17 kN. The specifications of the tractors in the traction tests are reported in Table 1.

a) b)

Figure 1. The tractors considered: a) low power tractor, b) high power tractor.

Table 1. Specifications of the tractors in the traction performance tests.

Description	Unit
Braking tractor	John Deere 6620 (97 kW)
Weight (kN)	55.72
Pulling tractors	CASE IH Farmall 90 (66 kW) CASE IH Farmall 120 (86 kW)
Weight (kN)	40.17 (unballasted) 42.87 (ballasted)
Wheelbase *Z* (m)	2.285
Tyre (front - rear) (m)	14.9 R24 – 18.4 R34
Tyre width *b* (front - rear) (m)	0.378 – 0.467
Speed Radius Index *RI* (front - rear) (m)	0.60 – 0.775
Rim diameter *D* (front - rear) (m)	0.61 – 0.86
Inflate tyre pressure (front - rear) (kPa)	80/160 – 80/160

2.2 Traction performance

Tests were performed at the official OECD Testing Station in the Laboratory of "Meccanica Agraria" of the Alma Mater Studiorum University of Bologna (UNIBO). The Tractor drawbar power tests were carried out according to the OECD Code 2 procedure. The test procedure required at least 7 gear/speed settings ranging from 2.5 km/h to 17.5 km/h. During all the drawbar tests, the tractor governor control was set for the maximum power and the performance values were recorded only till 15 per cent mean wheel slip, as foreseen in Code 2. This limit was discussed by Smerda and Cupera [9] explaining that a wheel slip exceeding 15% decreases the engine power efficiency transmitted to the ground. Tests were performed in those gear/speed settings, from one giving a travel speed immediately faster than in the gear/speed setting in which the greatest maximum power was developed, down to one immediately slower than the gear/speed setting allowing maximum pull to be developed [6].
Traction performance in terms of the traction force (*TF*) available at the tractor drawbar (drawbar pull), or alternatively in terms of the net traction ratio (*NTR*), was defined as the traction force to tractor weight (*W*) ratio:

$$NTR = \frac{TF}{W} \quad (1)$$

Drawbar power tests allowed for recording the power available at the drawbar of the tractor over a range of gear/speed settings. Drawbar pull varied in the tests, increasing the speed but with a controlled slip, to remain below 15%. The layout of the traction test in steady-state motion in the ring track is depicted in Figure 2.

a) b)

Figure 2. The traction test: a) pulling tractor with a braking tractor, b) load cell.

2.3 Drawbar tests performed

Basing on the main features of the two tested tractors described in paragraph 2.1, ballasts and tyre inflation pressures were modified and the drawbar tests were performed in three different configurations for tractor, corresponding to a total of six configurations and consequently six different tests. The weight (W) of each tractor, differing in the engine power (p), was increased from 40.17 kN (W1) to 42.87 kN (W2) and the tyre inflation pressure (P) was adjusted from 80 kPa (P1) to 160 kPa (P2). The six tractor configurations tested are reported in table 2. The wheel load and tyre pressure values were considered representative for medium powered tractors and were selected according to the indications of the tyre manufacturer. The tractor load on the wheels in the stationary state was measured with 4 scales, one for each wheel (range 0.4 kN – 60 kN).

Table 2. Steady tractor arrangements.

Test number	Power (kW)	Tyre Inflate Pressure (kPa)	Height of the drawbar (m)	Total Weight (kN)	Front Weight (kN)	Rear Weight (kN)	CoG – front wheels distance (m)	CoG - rear wheels distance (m)
W1P1p1	66	80	0.495	40.17	16.23	23.94	1.362	0.923
W1P2p1	66	160	0.495	40.17	16.23	23.94	1.362	0.923
W2P2p1	66	160	0.490	42.87	18.88	23.99	1.279	1.006
W1P1p2	86	80	0.495	40.17	16.23	23.94	1.362	0.923
W1P2p2	86	160	0.495	40.17	16.23	23.94	1.362	0.923
W2P2p2	86	160	0.490	42.87	18.88	23.99	1.279	1.006

The tests were compared the effect of tyre pressure and tractor mass on traction performance. The traction tests were performed on a flat concrete ring track. Runs 5 m wide and 120 m long were marked out in the track. The runs were travelled in steady-state motion recording the drawbar pull developed by the pulling tractor with a braking tractor used as dynamometer. The measurements were carried out on the straight line of the track to neglect the lateral force component due to the drift. Data recorded were the dynamic axle load (W) on the wheel, the drawbar pull, the actual forward speed. A 100 kN load cell (TRQ 100 kN/1-A, sens. 1mV/V - Pavone Sistemi) in between the tested tractor and the loading tractor measured the drawbar pull. Actual forward speed (v_a) was measured by using non-contact sensors with integrated a fiber-optic Gyroscope (CORREVIT Sensor L-CE with Gyro). The engine speed (n_e) as revolution speed of the engine crankshaft was recorded at the CAN-BUS tractor signals. The number of engine revolutions for one revolution of the driving wheels for each gear selected (τ) was provided by the tractor manufacturer because related to the transmission system mounted in the tractor. Basing on the engine crankshaft revolution per minute, the wheels revolution per minute and the engine speed in real time via CAN-BUS, the theoretical forward speed (v_t) at the wheels was calculated, referring to the dynamic index radius (RI) of the tyres (ETRTO Standard):

$$v_t = \frac{n_e}{\tau} \cdot \frac{2\pi}{60} RI \quad (2)$$

The acquisition system in the braking tractor recorded and displayed all parameters. The tested tractor travelled in strait direction with locked differential to allow for the highest traction performance to be achieved. The actual forward speed, reduced by the wheel slip, was affected by the flexibility of the driven wheels, the features of the contact areas, such as rubber and concrete, the shear within the soil; the Travel Reduction (TR) was calculated as:

$$TR = \left(1 - \frac{v_a}{v_t}\right) \cdot 100 \quad (3)$$

3 Results

3.1 Drawbar pull

The results of the drawbar pull force in the six test configurations are presented. The Net Traction Ratio was obtained according to Equation 1. The traction force (Fig. 3) and Net Traction Ratio (Fig. 4) are presented with respect to the tractor forward speed. The results pertaining to the tractor with lower power engine are presented as a line, while the results of the tractor with the higher power engine as dotted line.

3.2 Slip in forward travelling

The trend of slip with respect to the forward speed is shown in figure 5. The slip at low speeds was constant at 15% then the values measured decreased above 4 km/h for the low-power tractor and 6 km/h for the high-power tractor. The same behaviour was verified on all six configurations tested for the two tractors in comparison. The reduction in tire pressure generates a larger tire-ground contact surface. This explains why, at the same forward speed, a tractor with a low tire pressure has less wheel slippage than a tractor with a higher tire pressure. A similar effect is caused by the ballast, as a greater mass of the tractor causes a greater tire-ground contact pressure, resulting in a greater flattening of the tread on the ground.

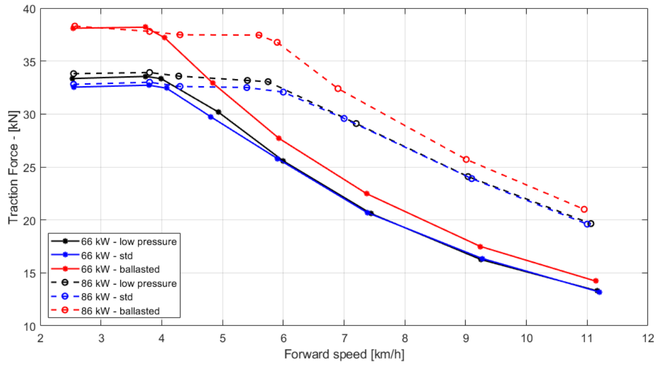

Figure 3. Traction Force vs. Forward speed: pulling force available at the tractor drawbar.

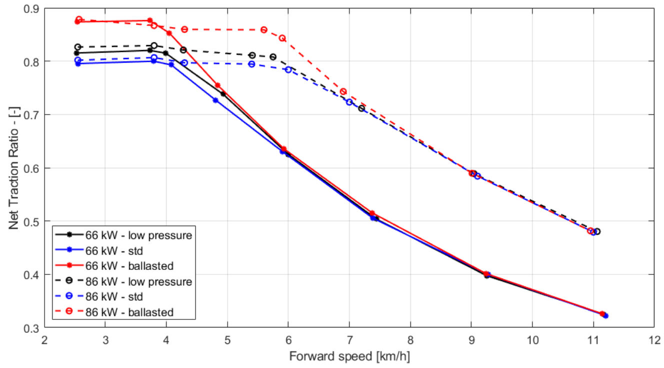

Figure 4. Net traction ratio vs. Forward speed: traction force TF to tractor weight W ratio.

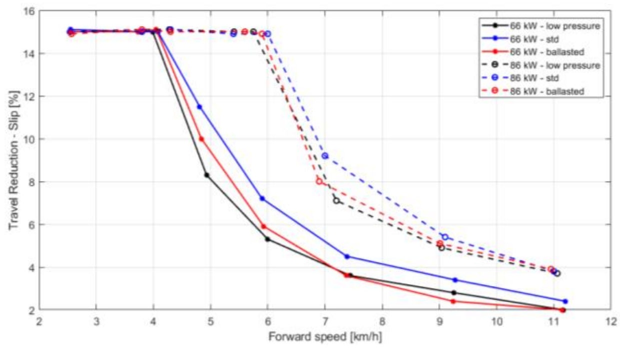

Figure 5. Travel Reduction vs. Forward speed. Where possible the slip was kept constant at a value of 15%.

4 Discussion

The Drawbar tests results allowed for evaluating the performance of the tractors with respect to the engine power and forward speed. The results highlight how tyre pressure and ballasting affect the performance of the tractor, both in terms of TF and NTR. At low forward speeds, until 4 km/h, the TF strongly depends on the weight of the tractor (fig. 3). As the speed increases, above 5-6 km/h the force trends were different since TF has a higher dependence on the engine power supplied by the tractor (fig. 3). In fact, the TF is a parameter related to the mass of the tractor and the interaction between the tire and the ground but is affected by the engine power. In terms of NTR, both ballasting and pressure change had a positive effect at low speeds, as they modify the wheel-ground interaction, as speeds increased the influence on NTR was not observed (fig. 4). Comparing the slip behaviour as the forward speed increased, the lower pressure and the ballasting allowed for an actual speed closer to the theoretical one, resulting in less wheel slippage (fig. 5). The slip value of 15% in the low power tractor was maintained until approximately 4 km/h while in the high-power tractor until approximately 6 km/h. If this behaviour can be seen as a negative effect, since the actual speed is lower due to the slipping, it is however positive for the TF because with high slipping values TF is high too (fig. 3).

5 Conclusions

Two tractors of different power output were considered in the performance evaluation. Tractors were evaluated in three different configurations: standard tractor configuration, tractor adjusted with low tyre inflation pressure and ballasted tractor. Analyzing the performance results in terms of traction, clearly the three parameters affected the pulling force while increasing the forward speed. The results denoted that the tyre inflation pressure decrease improved the performance at the drawbar. The drawbar pull measured on the tractor with low tyre pressure was higher with respect to the standard tractor pressure adjustment until the speeds of 4 km/h and 6 km/h respectively for the 66- and 86-kW tractors. Above these forward speeds the drawbar pull data recorded was equivalent in both tractor pressure configurations. Analyzing the ballasted tractors, the results of measurements demonstrated the effect of increasing the tractor weight on the drawbar pull; it was higher in all the speed range evaluated. Analyzing the Net Traction Ratio, it is worth observing how until the forward speed of 4 km/h the tyre pressure and, even more, the ballast positively influenced the NTR. Between 4 and 6 km/h, NTR was influenced by the tyre pressure and the ballast only in the high-power tractor. NTR above 6 km/h was influenced only by the engine power output. The results denote that the tractor with the highest engine power can guarantee a maximum tractive force over a larger speed range than the tractor with the lowest engine power. However, the maximum tractive force was not related to the power output and therefore up to a specific forward speed the tractors with different power had the same performance. The findings will be complemented in a future evaluation performed in actual field conditions to obtain performance data with an added valuable practical use.

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