

# Performance of a driven hitch-cart for draft animal power under different power take-off torque and ballast levels condition

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## Abstract

The performance of a two-wheel driven hitch-cart designed for draft animal power has been assessed. The cart fits a three-point linkage system and a ground-driven power take-off (PTO). Conventional pneumatic tires and metallic wheels have been tested in dedicated draft trials with increasing torque applied to PTO (7.0 to 70 Nm) at two ballast levels (100 and 200 kg). Draft force varies from a minimum of about 760 N (pneumatic tires and the lowest ballast), up to about 4480 N (metallic wheels and the highest ballast), with a linear increase as a function of the PTO applied torque. In term of global efficiency the better performances was achieved in different conditions. The metallic wheels deliver greater power to the PTO than pneumatic tires. Furthermore, they had global efficiencies higher than pneumatic for high power requirements, while the pneumatics perform better when the required power is low. Slippage rises as a function of increasing torque and decreasing ballast, with metallic wheels allowing delivery of greater PTO torque at the same slippage extent. The performances of the cart are consistent with the use of implements designed for small tractors.

## Introduction

In the twenty-first century draft animal power (DAP) still remain of crucial importance in developing countries. In fact animal power is

widespread in Asia and Latin America, and is expanding in Africa (AGS, 2010; Fuller and Aye, 2012). Surprisingly, a renewed interest for DAP is recently grown in developed countries, spanning from USA to the European modern agricultural systems relying in the context of organic and biodynamic farming. According to some published papers, DAP could be the next step in an ecological, earth-friendly farming system (Rydberg and Jansén, 2002; Mumma, 2008; Leslie, 2013; Mulder and Dube, 2014). This renewed focus is mirrored in the scientific literature by studies underlining the belonging of DAP to the renewable energy sources and focusing on the environmental effects of reintroducing DAP in modern highly mechanised agriculture (Spugnoli and Dainelli, 2013; Cerruti *et al.*, 2014). Indeed, one of the technological solution already developed for DAP is represented by the so-called hitch-carts. They are a range of wheeled tool-carriers that could be used for various agricultural operations. As reviewed by Joubert (2000) the more sophisticated models consist of three or four wheels chassis, a three-point linkage system and a ground-drive power take-off (PTO), allowing the use of a wide range of conventional small size tractor mounted implements. Particularly, these carts can be used for ploughing, harrowing, planting, rolling, cultivating, fertiliser distributing, boom spraying, mowing, racking, and baling. Starkey (1988) stated the broad failure of these devices in the developing countries, mainly because of the technological inappropriateness to the realities of these environments, high operating costs, difficult of finding spare parts and suitable implements. Certainly, all of this does not hold in the realities of developed countries, where organic and biodynamic farms have the potential to use relatively advanced and expensive technologies. In other words, in the latter realities the use of hitch-carts appears a suitable solution to improve DAP work efficiencies. In a previous work, the field performances of a two wheels DAP hitch-cart equipped with a ground-driven PTO system (in the following referred as driven hitch-cart) were characterised (Spugnoli *et al.*, 2008). One of the main findings of that research underlines the importance of wheels slippage, which occurs when increasing the PTO applied torque depending on wheel soil adherence, and suggesting the possible use of metallic wheels as a mean to overcome this problem. Following these evidences, a set of purposely-designed metallic wheels has been realised and tested in a series of dedicated field trials. The results of such experiment are presented in this paper. These information gain importance in the context of modern agricultural systems for an efficient and renewed exploitation of DAP.

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## Materials and methods

### The driven hitch-cart

A cart belonging to the *category one hitch-cart* as defined by Joubert (2000), has been tested. The cart has two wheels (namely driven hitch-cart; Figures 1A and 2) and was equipped with a three-point linkage system and a ground-driven PTO. The main frame of the driven

hitch-cart consists of a trapezoidal chassis of square section steel tubes, mounting the three point linkage system, supports for harnessing, the driver's seat, and part of the gearing transmission going from wheels to the PTO. The three-point linkage is fitted with a manually operated hydraulic pump placed close to the driver seat. The chassis is mounted on a two wheels rear-axe equipped with a differential gear box. The wheels fit pneumatic tires (measuring 6.50-14, width of 175 mm), corresponding to a whole track of 1750 mm. The whole length of the driven hitch-cart was 1400 mm, with a height of 680 mm at the driver's seat. The empty weight is 175 kg. A peculiarity of the driven hitch-cart is the ground-driven PTO, where the motion is derived from wheels via the differential, connected to a simple sprocket-chain drive system, and a rigid joint (tooth clutch), which allows by a specific lever, to transmit power to the PTO shaft when required or unplugging when unnecessary (manoeuvres, shifting *etc.*). The overall transmission ratio corresponds to 15.75, so that assuming a forward speed of  $1 \text{ m s}^{-1}$  (*i.e.*, the average working speed of a horse), a PTO speed value of about 519 rpm is obtained, representing the theoretical number of revolutions in absence of slippage and for wheels fitting tires with a rolling radius of 290 mm.

### The metallic wheels

A set of two handcrafted metallic wheels, whose technical specifications are summarised in Table 1, was purposely designed for this experiment. Briefly, eighteen steel tubes measuring 76 mm external diameter and 165 mm length (thickness 2 mm), were fixed around a standard tire rim (390 mm external diameter, 165 mm width). Afterward, two annular flat rings were fixed around the tubes giving support for lugs. The latter, were realised with an L-shaped mild steel profile, measuring  $25 \times 25$  mm, thickness 2 mm. Eighteen lugs were fixed on the annular rings with a circumferential angle of  $18.9^\circ$  and a lug angle of  $0^\circ$ . Figure 1 presents a picture of the metallic wheel (Figure 1B).

### Experimental procedure

For the purpose of our experiment we assume that a potential use of the cart could be light working operation for the management of fruit orchards, such as spraying, topping, and inter-row mowing. In these cases the inter row grassing is commonly applied. However, under this soil conditions the wheel slippage could be a potential limit for a proper use of the driven hitch-carts (Spugnoli *et al.*, 2008). Thus the trials were performed on turf soil in an apple orchard inter-row. The soil char-

acteristics were: bulk density  $1.27 \text{ Mg m}^{-3}$ ; moisture content 29.21%; cone index 1.78 MPa; sand 35%, silt 32%, clay 33%. The soil was fully covered by grass (average height 89.5 mm, standard deviation 22.6) and the turf composition was: grass - ryegrass (*Lolium spp.*); meadow grass (*Poa spp.*); tall fescue (*Festuca spp.*); other species. Pneumatic tires and metallic wheels were compared in twenty draft trials, by loading the hitch-cart at two levels of ballast (100 and 200 kg, 10 trials each, by means of an appropriate numbers of 25 kg sandbags), and increasing torque applied to the PTO in the range of about 7 to 70 Nm, in five incrementing steps per each ballast-wheels combination. At this purpose, the PTO was fitted with a previously calibrated hydraulic disc brake, in order to simulate the torque resistance given by driven implements. To balance the higher weight of metallic wheels than pneumatic tires, a subsidiary ballast of 34.2 kg (as a water filled tank) was loaded on the hitch-cart (Figure 1). Draft trials were performed on a 50 m long track.

The driven hitch-cart was pulled by a 4WD vehicle (model Defender 90, Land Rover, UK) at a forward speed of about  $1 \text{ m s}^{-1}$ , simulating the conventional draft of a working horse. The following parameters were recorded during each trial: forward speed (by measuring time to travel

Table 1. Specifications of metallic wheels.

Parameter	Size
Outer diameter	602 mm
Outer width	227 mm
Rim diameter	390 mm
Rim width	165 mm
Annular rings thickness	5 mm
Annular rings width	30 mm
Lugs spacing	$20^\circ$
Lugs made from mild steel L-shaped size	25 mm height, 25 mm width, 2 mm thick
Lugs length	250 mm
Lugs circumferential angle	$18.9^\circ$
Lugs angle	$0^\circ$
Weight	34.18 daN

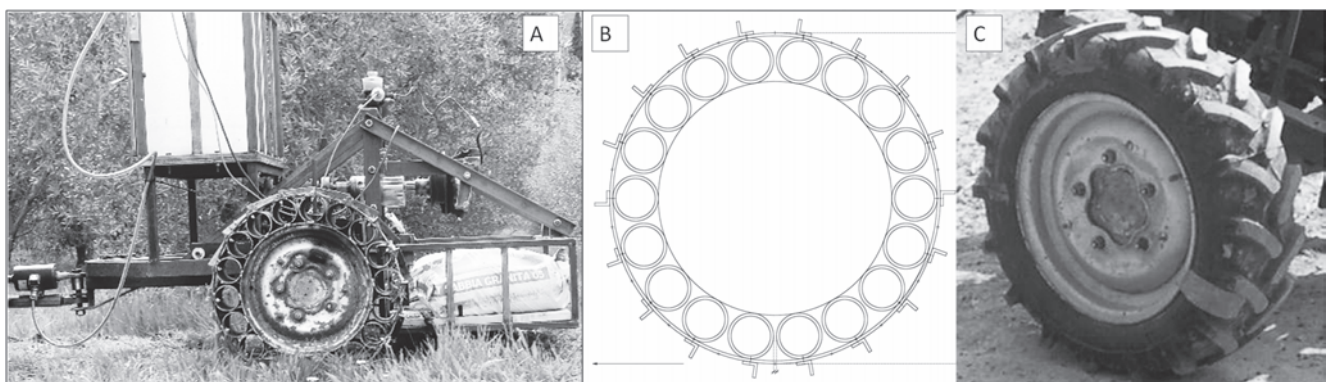


Figure 1. A) The driven hitch-cart; B) sketch of the metallic wheel; C) the pneumatic tire.

the 50 meter track), draft force (by a strain gauge load cell, model U3G1, BLH Vishay Measurements Group GmbH, Germany, response  $3\text{mV V}^{-1}$ , F.S. 50kN), torque applied to PTO and PTO rotational speed [by a BCS, (Italy) rotating torque/speed transducer, model MD 200, response  $1.92\text{ mV V}^{-1}$ , F.S. 250 Nm], number of wheels actual revolutions (by visual direct observation, *i.e.*, by counting the actual wheel revolutions). Two independent observations for each test were recorded for the forward speed and number of wheels actual revolutions, and the average value was taken. The load cell and the torque/speed transducer were fitted to a data acquisition system based on a modular multichannel data logger (model MCDR-M-128, Leane international, Italy) fitted to a laptop computer (MCDR128 acquisition software). The acquisition system was calibrated before every test to avoid any possibility of error attributable to jerks.

### Data analysis

The driven hitch-cart acts as a reverse traction device, where the input power comes from the draft force of pulling, and the output power comes from the torque available at the PTO shaft. Therefore, the global

efficiency (GE) of the driving hitch-cart may be defined as:

$$GE = W_{out} / W_{in} \tag{1}$$

where  $W_{out}$  stay for the output power,  $W_{in}$  stay for the input power.

The input power  $W_{in}$  was computed as product of the measured draft force and the observed forward speed. The output power was computed as product of the measured PTO torque and the PTO rotation speed. According to Wong (1978), GE corresponds to:

$$GE = TE * ME * SE \tag{2}$$

where TE is the gears transmission efficiency, ME is the motion efficiency, SE is the slip efficiency.

Assuming a reasonable value for transmission efficiency of 0.88 (corresponding to the overall efficiency of the differential gear box and the sprocket-chain drive system; Stout and Cheze, 1999), Equation 2 can be solved as:

$$ME = GE / (0.88 * SE) \tag{3}$$

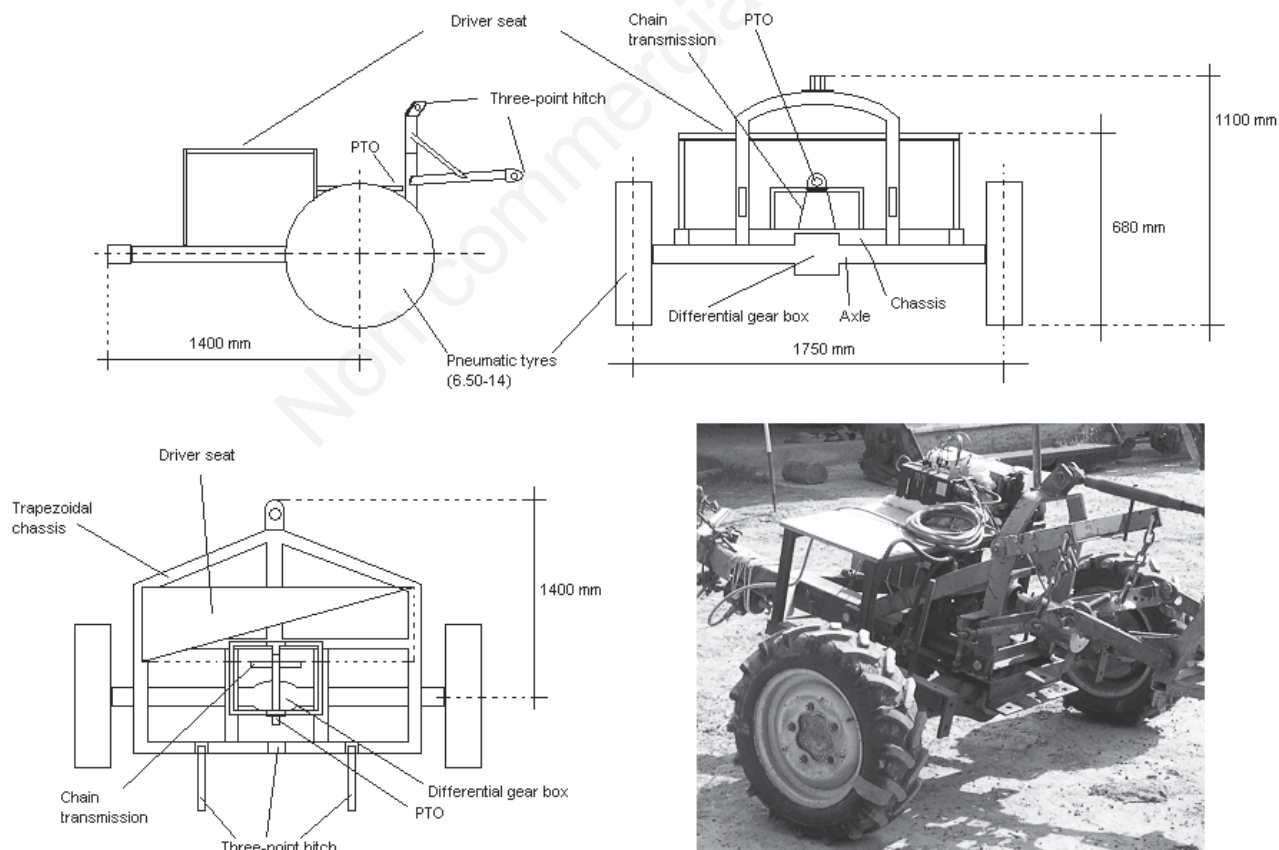


Figure 2. Schematic drawing of the driven hitch-cart structure.

Slip efficiency has been computed as:

$$SE=1-s \tag{4}$$

where s stay for slippage.

Slippage (s) has been computed according to:

$$s=(N_0-N_1)/N_0 \tag{5}$$

where  $N_1$  is the observed number of wheel revolutions and  $N_0$  the theoretical number of wheel revolutions with no slip as derived from the wheel-rolling radius.

## Results and discussion

Table 2 summarises the data recorded during draft trials. Draft force varies from a minimum of about 760 N, corresponding to the pneumatic tires and the lowest ballast, up to about 4480 N with metallic wheels and the highest ballast. A linear increment of draft force as a function of the increasing PTO applied torque could be noticed (Figure 3).

Slippage rises as a function of the increasing torque, following an exponential fit ( $r^2$  higher than 0.9, data not showed). Consistently, PTO speed linearly decrease as a function of rising torque, falling below 400 rpm at about torque values of 35 Nm with pneumatic tires, regardless the ballast. The correspondent slippages are 29% and 22% at the lower and higher ballast, respectively. With metallic wheels this PTO speed value was reached over a torque value of about 49 Nm (lower ballast) and 70 Nm (higher ballast), corresponding to slippage of 30% and 58%, respectively.

The requirement of pulling power follows the draft force, varying from about 0.860 kW (pneumatic tires and the lowest ballast), up to about 4.560 kW (metallic wheels and the highest ballast). Bearing in mind that a good draft horse is expected to weigh about 9000 N and that it can provide a pulling force of about 10% of its live weight, an available input power of 0.954 kW could be assumed for a single horse working at about  $1.06 \text{ m s}^{-1}$  (i.e., the overall average of forward speeds adopted in the present trials). This means that only 2 out of the 20 trials may be performed with a single horse, specifically cases 1 and 6 in

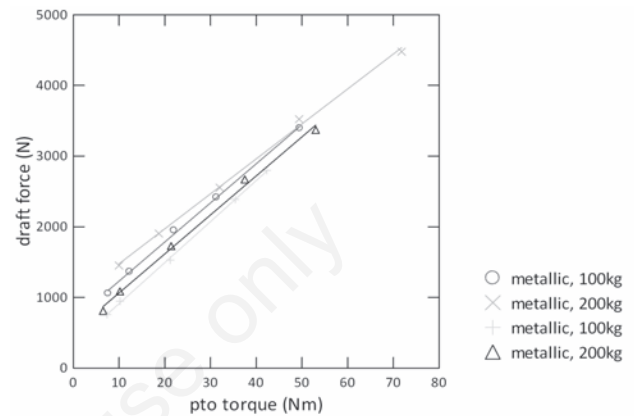


Figure 3. Linear relationship between required draft force and torque applied to power take-off at lower (100 kg) and higher (200 kg) ballast for metallic and pneumatic wheels ( $r^2$  of linear fit are all higher than 0.99).

Table 2. Tractive responses of the driven hitch-cart draft trials.

Trial	Wheels	Ballast (dan)	Forward speed ( $\text{m s}^{-1}$ )	Draft force (n)	Torque (nm)	PTO speed (rpm)	$W_{in}$ (kW)	$W_{out}$ (kW)	GE	SE
1	Pneumatic	98.1	1.13	759.1	7.4	526	0.858	0.408	0.48	0.90
2	Pneumatic	98.1	1.13	945.7	10.2	544	1.069	0.581	0.54	0.92
3	Pneumatic	98.1	1.12	1528.9	21.2	510	1.712	1.132	0.66	0.87
4	Pneumatic	98.1	1.08	2387.8	35.4	402	2.579	1.490	0.58	0.71
5	Pneumatic	98.1	1.07	2797.5	42.3	295	2.993	1.307	0.44	0.53
6	Pneumatic	196.2	1.11	810	6.5	538	0.899	0.366	0.41	0.93
7	Pneumatic	196.2	0.87	1724	21.4	411	1.500	0.921	0.61	0.90
8	Pneumatic	196.2	0.93	1085	10.2	448	1.009	0.479	0.47	0.92
9	Pneumatic	196.2	0.98	2669.3	37.5	399	2.616	1.567	0.60	0.78
10	Pneumatic	196.2	0.91	3369	53.0	133	3.066	0.738	0.24	0.28
11	Metallic	98.1	1.08	1056.3	7.6	519	1.141	0.413	0.36	0.94
12	Metallic	98.1	1.12	1362.4	12.3	536	1.526	0.690	0.45	0.94
13	Metallic	98.1	1.02	1948.6	22.0	473	1.988	1.090	0.55	0.91
14	Metallic	98.1	1.06	2415.8	31.3	476	2.561	1.560	0.61	0.88
15	Metallic	98.1	1.05	3394.8	49.5	375	3.565	1.944	0.55	0.70
16	Metallic	196.2	1.15	1451.5	10.0	558	1.669	0.584	0.35	0.95
17	Metallic	196.2	1.14	1903.3	18.7	547	2.170	1.071	0.49	0.94
18	Metallic	196.2	1.06	3522.3	49.4	467	3.734	2.416	0.65	0.86
19	Metallic	196.2	1.14	2552.4	32.0	518	2.910	1.736	0.60	0.89
20	Metallic	196.2	1.02	4477.1	71.8	220	4.567	1.654	0.36	0.42

PTO, power take-off;  $W_{in}$ , input power;  $W_{out}$ , output power; GE, global efficiency; SE, slippage efficiency.

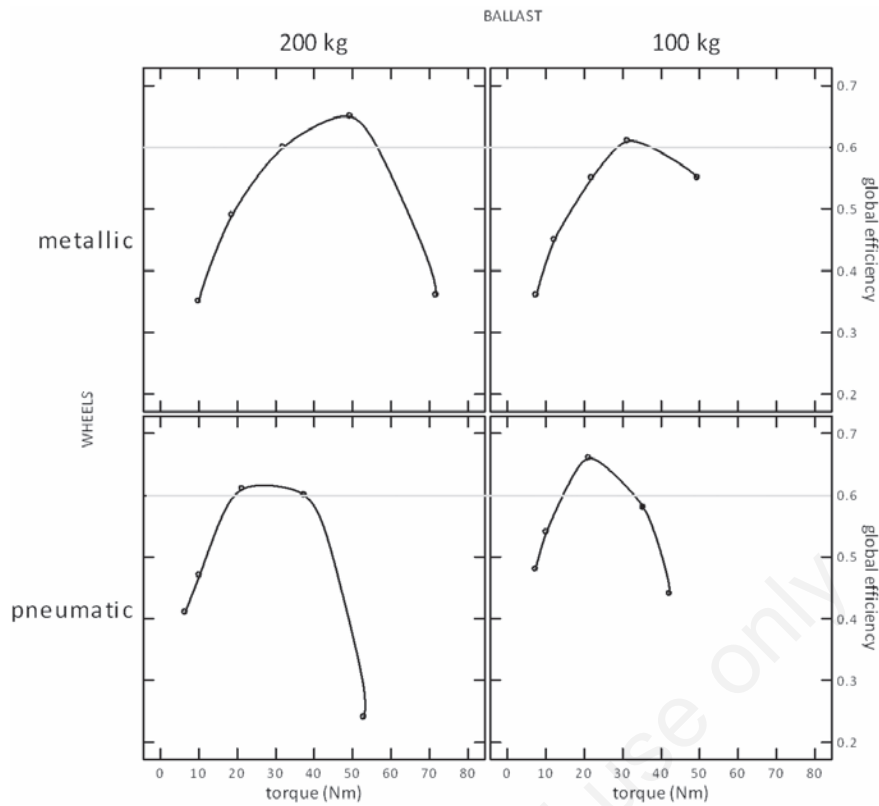


Figure 4. Global efficiency of the driven hitch-cart as a function of power take-off delivered torque, fitting different ballast load (100 kg and 200 kg) and two kinds of wheels (pneumatic tires and metallic wheels).

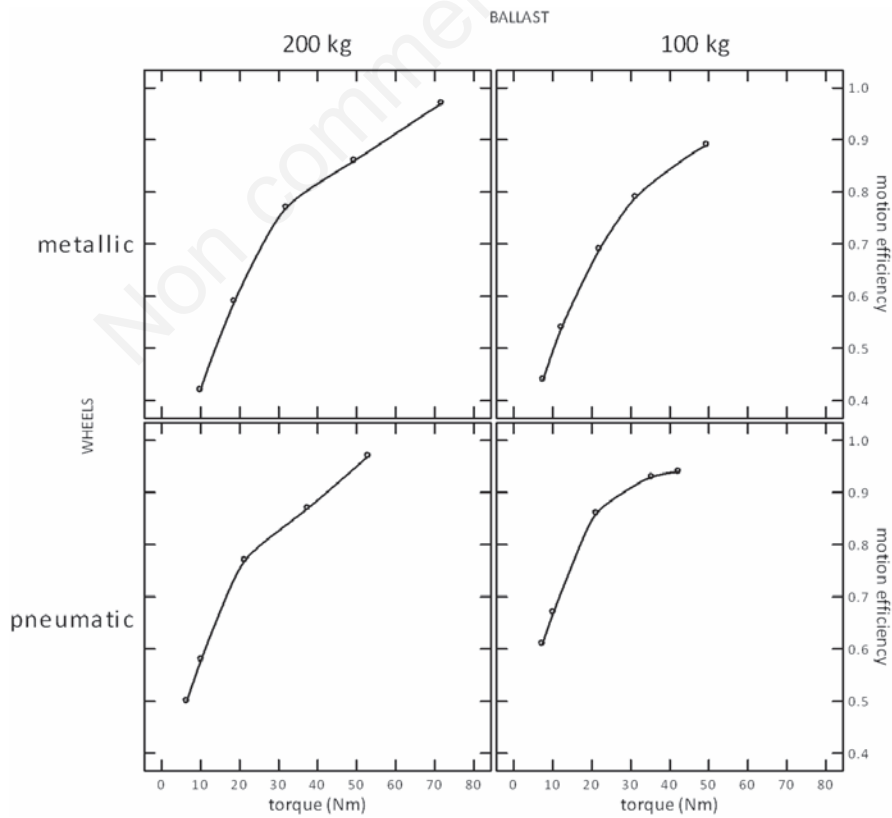


Figure 5. Motion efficiency of the driven hitch-cart as a function of power take-off delivered torque, fitting different ballast load (100 kg and 200 kg) and two kinds of wheels (pneumatic tires and metallic wheels).

Table 2, whereas in the remaining cases a team of horses should be used from 2 up to 5 animals. Further, useful information about the performances of the hitch-cart can be obtained by analysing the working efficiencies as a function of the PTO applied torque (Figures 4-6). With regard to the global efficiency, a reference value of 0.6 can be assumed according to Wong (1978) as a good working performance. As showed in Figure 4, the peaks of the recorded global efficiencies exceed the 0.6 reference value in all the tested ballast-wheels combinations, spanning from 0.64 (metallic wheels at the lowest ballast and tires at the highest ballast) to 0.66 (metallic wheels at the highest ballast and tires at the lowest ballast). Global efficiencies were optimised at different torque values, specifically 24 and 40 Nm for tires, and 30 and 50 Nm for metallic wheels, at the lowest and highest ballast, respectively. Hence, despite the greater requirement in input power, metallic wheels, as well as increasing ballast, allow the global efficiency maximisation at greater PTO applied torque. Some final considerations can be drawn in view of the slippage efficiency showed in Figure 6. In fact, if we assume that for a proper working (*i.e.*, do not waste energy merely to overcome rolling resistance) the extent of slippage should not exceed the limit of 20%, with a global efficiency not below the limit of 0.6, only 5 out of the 20 cases presented in Table 2 would be really applicable. These cases require a number of horses from 1 (cases 3 and 7, by pneumatic wheels and 100 and 200 kg ballast, respectively) to 3 (case 18, by metallic wheels and 200 kg ballast), to deliver a PTO power from 0.9 to 2.4 kW. Hence, the highest powers could be obtained only with metallic wheels and the highest ballast.

## Conclusions

The results contribute to a better characterisation of the working performances of a wheeled tool-carrier designed for draft animal power. In general, the performances of the cart are consistent with the use of implements designed for small tractors or for motocultivators. The metallic wheels allow extending the range of use of the cart in terms of power available to the PTO with acceptable slippage.

Summarising: i) the draft force ranged between about 750 N and 4500 N; ii) the available PTO power ranged from about 0.410 kW to 1.500 kW for pneumatic tyre, while from 0.410 to 2.400 kW for metallic wheel; iii) the best performance in term of global efficiency was 0.66 for pneumatic tyre obtained at about 20 Nm torque and the lower ballast; for the metallic wheels the best performance was 0.65 obtained at about 50 Nm torque and the higher ballast; iv) in our experimental conditions a threshold of about 30-35 Nm could be established from data; below this threshold pneumatic tires show better performances in term of GE, while over metallic wheels have better GEs.

Although simple in concept and developed several years ago for the realities of developing countries, this class of agricultural machines is still far from an optimised and performing design, fitting modern agricultural system of developed country. Several improvements of great potential could be implemented such as a system for dynamic balancing of the cart which allows balancing the weight of different mounted implements, or the introduction in the transmission drive-chain of a gearbox which allows adjusting the PTO speed as a function of animals' forward speed.

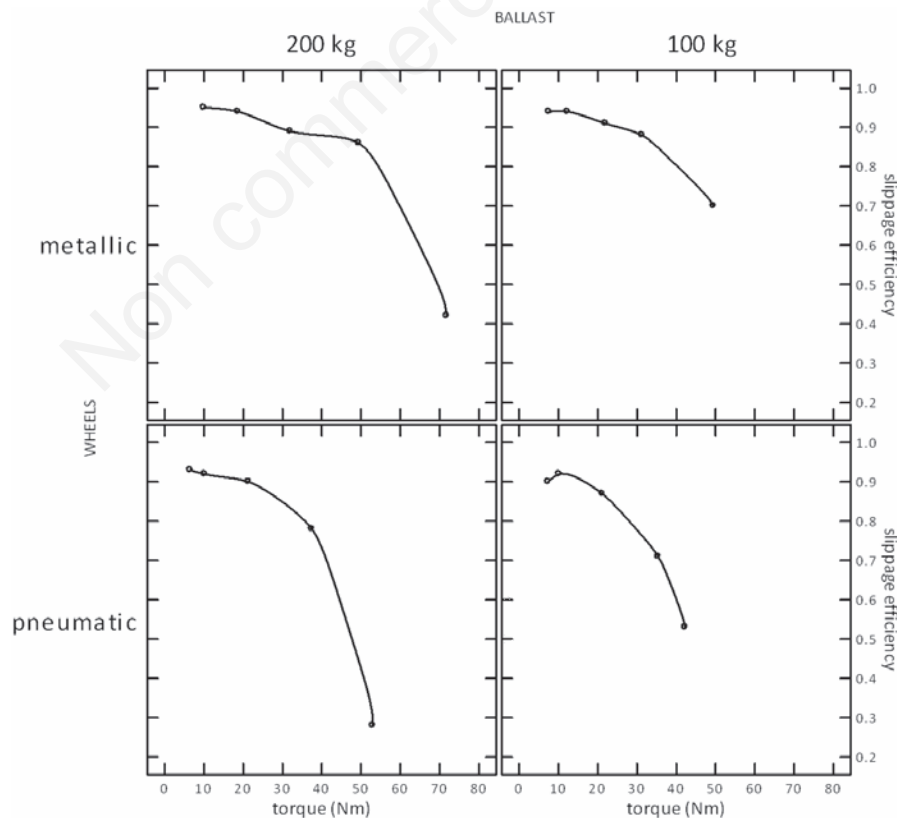


Figure 6. Slippage efficiency of the driven hitch-cart as a function of power take-off delivered torque, fitting different ballast load (100 kg and 200 kg) and two kinds of wheels (pneumatic tires and metallic wheels).

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