Definition of linear regression models to calculate the technical parameters of Italian agricultural tractors

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Abstract

As it is known, the modern agricultural tractor is no longer just a machine capable of pulling agricultural trailers and operating implements but has evolved into a multi-purpose and mobile energy source with standardized interfaces (mechanical, hydraulic, and electronic) to connect to several typologies of agricultural operating machines. It follows that the selection of the most appropriate tractors for the specific production realities is a crucial aspect for farmers, advisors, contractors, and farm machinery experts. The tractors choice thus must consider different parameters, concerning not only the cost of the machines but also their dimensions, power, weight, technological level, *etc*. The availability of simplified models for estimating the purchase investment and sizing the machine in relation to its mechanical characteristics could be a useful tool in making the choice of tractor more suitable for the specific agricultural context. This study aimed to collect and analyze the technical parameters of tractors present on the Italian market (more than 1300 models), divided into: i) four wheel-drive (4WD) standard tractors; ii) two wheel-drive standard tractors; iii) narrow track 4WD tractors; iv) isodiametric specialized 4WD tractors; v) crawler tractors; and vi) rubber-tracked tractors. This allows for the definition of the most relevant parameter-to-parameter and parameter-to-price relations for updating reference models to calculate the machine price and the weight to engine power ratio. Other relations, including the 3-point hitch efficiency with respect to the tractor's weight and the relationship between the rated engine power and its displacement, are proposed to provide synthetic tools to characterize and compare, from a mechanical point of view, the different categories of agricultural tractors.

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Introduction

For more than 100 years, the tractor has been the key machine of agricultural mechanization. The appearance on the market of the Fordson tractor in 1917 (the first tractor with large-scale production) boosted productivity, working efficiency, and comfort in the subsequent years. According to ISO 12934 (2021), an agricultural tractor is a "self-propelled agricultural vehicle having at least 2 axles and wheels or endless tracks, particularly designed to pull agricultural trailers and pull, push, carry and operate implements used for agricultural work (including forestry work), which may be provided with a detachable loading platform". This definition perfectly describes the original aim for which the agricultural tractor was designed and realized in the late 19th century.

In the following decades, up to the present day, the tractor has evolved into a multi-purpose and mobile energy source with standardized interfaces (mechanical, hydraulic, and electronic) to connect to several typologies of agricultural implements (Renius, 2019).

Indeed, implements have become more sophisticated, requiring additional power. Now, the tractor's engine power must be balanced between the tractive requirements, the power take off (PTO) and hydraulic requirements, and, most recently, the electrical power requirements. Therefore, by properly understanding how tractor power can be used, tractor-implement systems can be optimized (Stoss *et al.*, 2013). In addition, the tractor must be a cheap source of power; consequently, it must be chosen and dimensioned not only in function of the coupled operation machines but also according to the field capacity that must be guaranteed considering the time available for fieldwork, the farm size, *etc*. (Tona *et al*., 2018). From an economical point of view, the tractor is an important resource requiring an accurate cost-benefit analysis since both the investment for the purchase and the operating costs can heavily affect the farm balance sheet. Only a cost-effectiveness assessment, usually based on the methodology defined in the ASABE Standard EP496.3 (2015) for accounting agricultural machinery costs by evaluating the annual ownership costs (*i.e.*, equipment depreciation, interests on the investment, taxes, housing, and insurance) and the operating costs (*i.e.*, labor, fuel and lubricants, repair and maintenance), allows to carry out the best choice between different scenarios and between the several typologies of agricultural tractors available. In fact, given the different types of tractors on the market, an explanation of their characteristics, advantages, and disadvantages could help farmers and contractors make a better choice of the model to consider (Brenna *et al.*, 2018).

According to several researchers (Lazzari and Mazzetto, 2016; Brenna *et al.*, 2018; Renius, 2019), agricultural tractors typically used in Europe can be classified as: i) four wheel-drive (4WD) standard tractors, with engine power ranging between 20 and 470 kW, which include small, multipurpose and very high-power machines; ii) two wheel-drive (2WD) standard tractors, with engine power ranging between 20 and 80 kW, generally used for light operations (*i.e.*, transports and cultivation treatments); iii) narrow track 4WD tractors, with engine power ranging between 30 and 85 kW; specialized machines characterized by a narrow track (until less than 1 m) used to carry out field operations in vineyards and orchards; iv) isodiametric specialized 4WD tractors, with engine power ranging between 20 and 80 kW, suitable for operations carried out in hill and mountain agriculture. This category of tractors is characterized by a greater weight distribution on the front axle to reduce the risk of rollover; v) crawler tractors, with engine power ranging between 50 and 80 kW, suitable for operations requiring high grip and traction force, especially in hill and mountain conditions; vi) rubber-tracked tractors, with engine power ranging between 220 and 500 kW, are characterized by high power and high technological level and are suitable for heavy field operations (*i.e.*, tillage) carried out by operating machines with high field capacity.

The choice of the tractor based on brand equity (national and international reputation), brand loyalty, and reliability of the dealer network limits the farmer's decision-making process and could lead to the purchase of badly scaled machinery both from a dimensional and functional point of view (Walley *et al.*, 2007; Masek and Novak, 2018). This is particularly important for the tractor, which is a machine having a multi-purpose and sometimes unpredictable use (Yezekyan *et al.*, 2018); thus, the tractor selection should consider different parameters, concerning not only the cost of the machines but also their dimensions, power, weight, technological level, *etc*. The availability of simplified models usable as tools for estimating the purchase investment and sizing the machine in relation to its mechanical characteristics could help farmers, contractors, agronomists, and consultants in the choice of the tractor more suitable for the specific agricultural context (Yezekyan *et al.*, 2020). Therefore, this study aimed to collect and analyze the technical parameters of tractors present on the Italian market to define the most relevant parameter-to-parameter and parameter-to-price relations for updating reference models to calculate the machine price and the weight to engine power ratio. Other relations, including the 3-point hitch efficiency with respect to the tractor's weight, are proposed to provide synthetic tools to characterize and compare, from a mechanical point of view, the different categories of agricultural tractors.

Materials and Methods

Data collection and definition of tractors' technical parameters

The reference database involves 1307 commercial models of tractors produced by 15 European manufacturers and by 7 manufacturers in the rest of the world. The dataset has been created referring to the 2022 market year and using as data sources specific publications of farm machinery (*i.e.*, MAD, 2022a; MAD, 2022b); the official reports of tests were conducted according to OECD Code 2 (OECD, 2022), and the websites of manufacturers. Tractors have been classified according to the 6 typologies described in the Introduction. 4WD standard tractors, being the largest sample (774 models) with a wide range of rated engine power and high versatility, were divided into 4 subclasses according to Calcante *et al.* (2019): i) low power (<60 kW, 115 tractors), ii) medium power (61 to 120 kW, 429 tractors), iii) high power (121 to 200 kW, 155 tractors), and iv) very high power (>200 kW, 75 tractors). Narrow track 4WD tractors (334 models) were split into 2 subclasses depending on their technological level: i) low-tech narrow tractors (276 models), equipped with mechanical or power shift transmission, cab or folding safety frame as rollover protective structure (276 models), and ii) high-tech narrow tractors, equipped with continuously variable transmission (CVT) air-conditioner cab, isobus connection, *etc*. (58 models). The database also included isodiametric 4WD tractors (112 models), 2WD standard tractors (34 models), crawler tractors with steel tracks (26 models), and rubber-tracked tractors (27 models). All wheeled tractors included in the dataset are equipped with standard equipment wheels. For each tractor, data were collected on the following variables: i) rated engine power (kW), measured according to ISO TR 14396, ECE R 120 and 97/68/EC standards; ii) engine displacement (dm^3); iii) number of cylinders; iv) weight (kg), without ballast and driver; v) lift capacity (for the rear 3-point hitch), intended as maximum capacity (kg) measured at arms' hitch pins; vi) price list (€) excluding value-added tax, tax and entry road referred to the Italian market. These variables have been used to define the following parameter-to-parameter and parameter-to-price relations and the related reference models.

Weight to rated engine power ratio

The primary purpose of agricultural tractors is to develop drawbar power for pulling agricultural machinery or trailers for ploughing, tilling, *etc*. The term tractor, in fact, derives from the Latin *trahere*, which means "to pull". Nevertheless, the traction performance of a tractor varies depending on several factors related to the soil, the implement, the tractor itself, and its tires (or tracks). Travel speed is also known to affect traction but to a lesser extent within the range of operating conditions commonly encountered in farm activities. All other factors being equal, the parameters related to the tractor are its available power and weight. Tractors need specific requirements, both in terms of engine power and weight, to provide the necessary pull and successfully carry out the task. In other words, if tractors do not have a proper weight, they cannot develop the necessary traction force. This weight requirement inevitably results in a corresponding engine power requirement. In fact, the design structure of tractors is such that there is always a positive correlation between the tractor's weight and rated engine power (Bodria *et al.*, 2013; Lazzari and Mazzetto, 2016). This concept is exemplified by the weight to power ratio (kg/kW) that contributes to characterizing an agricultural tractor: a high ratio means that the machine has a greater capacity to develop traction force, while a low ratio corresponds to a versatile and agile tractor that is not suitable for heavy operations.

Price to rated engine power ratio

For agricultural tractors, the purchase price depends mainly on the engine power. The price to power ratio (€/kW) allows both to estimate a plausible price of a tractor in the absence of other information and to provide a "reference cost", homogenous for the various categories of machines, for the public authority when it has to correctly allocate the amounts to purchase new tractors for farmers and contractors. Furthermore, as already mentioned, economic estimation models for machinery cost calculation are based on the annual ownership costs and the operating costs evaluation. The corresponding formulas used to calculate the various items considered the purchase price; the use of the price to power ratio could simplify and reduce the complexity of the estimation, leading to the correct implementation of the model (Hawkins and Buckmaster, 2015).

Price to weight ratio

The price to weight ratio (€/kg) is an indicator of the massif price of a tractor. Since the weight (understood as hardware) has a cost, this ratio allows us to evaluate how much the weight contributes to the price formation of the specific category of tractors.

Lift capacity to weight ratio

This dimensionless ratio is useful to evaluate the lift capacity of the 3-point hitch for a specific category of tractors. This allows us to verify if the tractor is most suitable to operate with mounted implements rather than trailed implements, simplifying the operating machine-tractor coupling.

Rated engine power to displacement ratio

As regards agricultural tractors, in particular multi-utility models, a rather recent trend is the downsizing of combustion engines. Compared to previous engines, displacement has decreased, which is compensated by turbocharging. The development of tractor engines has been characterized by a trend toward higher mean effective pressure at constant displacement. In the range from 100 to 140 kW, smaller 6-cylinder engines (1 to 1.15 dm^3 displacement per cylinder) were increasingly replaced by 4-cylinder systems (Stirnimann and Engelmann, 2017). The rated engine power to displacement ratio is an interesting indicator of the evolution of engines and their implementation in different categories of agricultural tractors.

Data management and statistical analysis

The reference database has been created and managed using an electronic spreadsheet (Microsoft Excel, Microsoft Corporation, Redmond, WA, USA). Statistical analysis was carried out using the JMP Pro 16.2 statistical software (SAS Institute, Cary, NC, USA). Descriptive statistics (mean, standard deviation, minimum, and maximum) were reported for the variables rated engine power (kW), engine displacement (dm^3), number of cylinders, weight (kg), lift capacity (kg), and price list (€) of the different tractors typologies. Linear regression analysis was performed to test the relationship between variables and find linear models for each parameter-to-parameter and parameter-to-price relations. Linear regression models were evaluated using the coefficient of determination (R^2), standard error of regression (S), the root mean squared error (RMSE), and the RMSE-observations standard deviation ratio (RSR) as evaluation metrics. R^2, ranging between 0 and 1, describes the proportion of the variance in the measured data, which is explained by the model, with higher values indicating less error variance. Typically, $R^2>0.5$ is considered acceptable (Santhi *et al.*, 2001; Van Liew *et al.*, 2003); therefore, models with lower R^2 values were discarded from the analysis. The standard error of regression represents the average distance that the observed values fall from the regression line. Smaller values are better because they indicate that the observations are close to the fitted line (McHugh, 2008). The RMSE indicates a perfect match between observed and predicted values when it equals 0, with increasing RMSE values indicating an increasingly poor match (Golmohammadi *et al.*, 2014). The RSR is calculated as the ratio of the RMSE and standard deviation of measured data and varies from the optimal value of 0 to a large positive value. Performance ratings for RSR are the following (Moriasi *et al.*, 2007): $0.00\leq RSR\leq 0.50$ (very good); $0.50<RSR\leq 0.60$ (good); $0.60<RSR\leq 0.70$ (satisfactory); $RSR>0.70$ (unsatisfactory).

Results and Discussion

Of the 1307 tractors considered, 59% (774) are 4WD standard tractors, while only 2.6% (34) are 2WD tractors. This figure is very different from what was reported by Biondi *et al.* (1996) for the Italian market in the period 1960-1989. Of the 1809 tractors examined by these authors, 2WD tractors were 36% of the total, while front-wheel auxiliary drive tractors accounted for 28%. Even if both 2WD and 4WD tractors can perform the same basic tasks, the greater traction, the suitability for rough terrain, and the possibility to efficiently operate heavy-duty implements of 4WD tractors contributed to their increased adoption by Italian farmers over time.

Tables 1-3 summarize the descriptive statistics of all variables defined and used in the study.

Table 1. Descriptive statistics of variables rated engine power and weight for each tractor's typology.

Tractor typology	Number of samples	Rated engine power (kW) Mean±SD	Minimum	Maximum	Weight (kg) Mean±SD	Minimum	Maximum
4WD standard tractors	774	112.4±64.7	18.0	471.0	6078±3161	655	20,856
<60 kW	115	48.6±9.3	18.0	60.0	2675±686	655	4000
61-120 kW	429	88.5±15.7	62.0	120.0	5061±1440	2850	9400
121-200 kW	155	149.8±24.2	121.0	199.0	8125±1148	6000	11,400
>200 kW	75	269.9±57.3	204.0	471.0	12,886±3032	9200	20,856
2WD standard tractors	34	62.4±6.7	48.0	75.0	3086±276	2800	3600
Low-tech narrow tractors	276	66.0±10.5	28.0	82.0	2897±444	1250	3515
High-tech narrow tractors	58	70.7±7.1	53.0	84.0	3280±126	3080	3515
Isodiametric 4WD tractors	112	48.6±13.8	15.0	72.0	1980±431	750	3150
Crawler tractors	26	69.7±8.3	55.0	79.0	4695±648	3505	5450
Rubber-tracked tractors	27	353.3±78.8	228.0	495.0	20,941±3620	15,169	24,620

SD, standard deviation; 4WD, four wheel-drive; 2WD, two wheel-drive.

Table 1 shows the average, minimum, and maximum values of rated engine power (kW) and weight (kg) for every category of tractors considered. On average, rubber-tracked tractors have the highest engine power (353.3 kW) and weight (20,940.6 kg), followed by very high power 4WD standard tractors with values of 269.9 kW and 12,855.9 kg, respectively. The category with the lowest average engine power (48.6 kW) and weight (1980.0 kg) is isodiametric 4WD tractors.

In Italy, between 1951 and 1989, the average power of tractors increased from 28 kW to 51 kW (Biondi *et al.*, 1996). The average power calculated from our tractors' dataset referred to the 2022 market year is about 98 kW, which is more than 48% higher compared to 1989. Greater power means not only development in the technology of engine construction but also higher work capacity (Biondi *et al.*, 1996). Tractors provide machine power to perform farm activities, and a high correlation between farm productivity and available tractor power is recognized worldwide (Spoor *et al.*, 1987; FAO, 2013; Lankenau and Winter, 2018; Ruiz-Garcia and Sanchez-Guerrero, 2022).

Table 2 reports the average, minimum, and maximum values of list prices and lift capacity (for the rear 3-point hitch) for every category of tractor. The highest average price (515,613€) is for rubber-tracked tractors, while the cheaper category is represented by isodiametric 4WD tractors, with 42,300€. Lift capacity is the maximum weight of the implement that the hydraulic system can lift. Although several factors, such as the center of gravity and weight distribution, can affect the lift capacity, this parameter is usually proportional to engine power since a higher power is required to operate the hydraulic pump for heavier loads. Rubber-tracked tractors and 4WD standard tractors, being characterized by the average highest engine power (353.3 and 112.4 kW), show the highest average lifting capacity, equal, respectively, to about 9834 and 6212 kg (Table 2). Isodiametric 4WD tractors with an average engine power of about 48.6 kW (Table 1) have the lowest lifting capacity, equal to about 1818 kg (Table 2). It is interesting to note that the list price of tractors has increased significantly (+10-15%) starting in December 2021 compared to previous months. The reasons concern the increasing cost of raw materials, which was observed before the start of the conflict Russia-Ukraine (February 2022) and the transposition of Regulation No. 2016/1628, which obliged the manufacturers, starting in January 2022, to commercialize only Stage 5/Tier 5 compliant engines for all power ranges (European Commission, 2016). It is clear that this requirement requested a deep reassessment of the tractor's structure since the additional technologies require more space under the bonnet, and the space is a very valuable resource, especially for narrow and specialized tractors. Obviously, all of this is reflected in the tractor's production cost.

Table 3 shows the average, minimum, and maximum values of displacement and the number of cylinders (only minimum and

Table 2. Descriptive statistics of variables list price and lift capacity for each tractor's typology.

Tractor typology	Number of samples	Price list (€) Mean±SD	Minimum	Maximum	Lift capacity (kg)* Mean±SD	Minimum	Maximum
4WD standard tractors	774	131,974±86,924	16,851	500,280	6212±2975	700	13,600
<60 kW	115	45,792±10,045	16,851	74,187	2,589±1112	700	4525
61-120 kW	429	101,643±33,614	48,695	208,997	5498±2000	2600	9700
121-200 kW	155	182,977±43,759	101,960	299,767	9310±1255	6300	12,000
>200 kW	75	332,202±72,760	192,230	500,280	11,270±1286	9000	13,600
2WD standard tractors	34	54,803±9251	35,753	69,552	3807±529	3000	4525
Low-tech narrow tractors	276	67,978±14,459	19,660	92,640	2513±439	1000	3250
High-tech narrow tractors	58	112,032±4935	101,941	122,550	2997±2997	2415	3800
Isodiametric 4WD tractors	112	42,300±13,751	14,300	89,840	1818±546	500	2400
Crawler tractors	26	69,307±7489	56,415	78,725	2937±304	2600	3510
Rubber-tracked tractors	27	515,613±95,453	390,319	673,185	9834±1742	8800	14,000

SD, standard deviation; 4WD, four wheel-drive; 2WD, two wheel-drive; *related to the rear 3-point hitch.

Table 3. Descriptive statistics of variables displacement and number of cylinders for each tractor's typology.

Tractor typology	Number of samples	Displacement (dm^3) Mean±SD	Minimum	Maximum	Number of cylinders Minimum	Maximum
4WD standard tractors	774	4.8±2.0	0.9	15.0	3	6
<60 kW	115	2.8±0.6	1.4	3.8	3	4
61-120 kW	429	4.2±1.1	3.8	6.8	3	6
121-200 kW	155	6.6±0.7	4.5	8.7	4	6
>200 kW	75	9.3±2.0	6.1	15.0	6	6
2WD standard tractors	34	3.3±0.5	2.8	3.8	3	4
Low-tech narrow tractors	276	3.2±0.5	1.6	4.0	3	4
High-tech narrow tractors	58	3.5±0.5	2.9	3.9	3	4
Isodiametric 4WD tractors	112	2.5 ±0.8	0.9	3.8	2	4
Crawler tractors	26	3.4±0.4	2.9	3.9	3	4
Rubber-tracked tractors	27	12.0±2.7	9.0	16.8	6	12

SD, standard deviation; 4WD, four wheel-drive; 2WD, two wheel-drive.

maximum values) for every category of tractors. Obviously, the greater the engine power, the greater the displacement; therefore, the higher values are related to rubber-tracked tractors, with 12.0 dm^3 of displacement, followed by very high power 4WD standard tractors with 9.3 dm^3. Lower values are observed for isodiametric 4WD tractors (2.5 dm^3) and low-power 4WD standard tractors (2.8 dm^3). The number of cylinders is not a representative variable since a very wide range of engine power rates (from 26 to 456 kW) can be generated using 3-6 cylinders. Only certain models of rubber-tracked tractors are equipped with a 12-cylinder engine.

Table 4 highlights the parameter-to-parameter and parameter-to-price ratios calculated for all categories of tractors. The one-way analysis of variance was carried out considering the category of standard 4WD tractors, previously divided by rated engine power into several sub-categories, as unique.

Weight to rated engine power ratio

Crawler tractors and rubber-tracked tractors show the highest weight to engine power ratio, equal to 67.5 and 60.4 kg/kW, respectively (Table 4), confirming the aptitude of these machines to carry out operations requiring high traction force.

The difference between 4WD standard tractors and 2WD standard tractors is about 5.5 kg/kW due to the absence, in these latter, of the frontal drive axle, including the related differential and braking system. This leads to a weight to power ratio of 49.7 kg/kW compared to 55.2 kg/kW for 4WD standard tractors. Within the 4WD standard tractors, the weight to power ratio reduces significantly ($p<0.01$) from 56.7 kg/kW of <60 kW tractors to 47.9 kg/kW of tractors with rated engine power >200 kW. This latter ratio agrees with that reported by Estrada *et al*. (2016). Over the years, the weight to power ratio has reduced, and this trend is related primarily to the increase in the average power of the tractors and to a general lightening and improvement in tractor design and construction materials (Renius, 1994; Biondi *et al*., 1996; Schlosser *et al*., 2005). As for the 4WD tractors, a lower weight to power ratio entails the use of additional ballast since these tractors are designed to work with heavy implements, requiring increased demand for traction (Estrada *et al*., 2016). According to Márquez (2012), in 4WD tractors, the weight to power ratio with ballast should approach 60 kg/kW.

Concerning the narrow tractors, the high-tech versions show a weight to power ratio higher than the low-tech models (46.8 kg/kW *versus* 44.2 kg/kW). This significant difference is essentially due to the absence of the cabin in many low-tech narrow tractors, whereas all high-tech models are equipped with an air-conditioned cab. The presence of the cabin, in addition to the largest number of onboard equipment, increases the weight of these latter particular machines up to 385 kg compared to the low-tech narrow tractors. Isodiametric 4WD tractors present the lowest weight to power ratio, with only 42.2 kg/kW, confirming their usefulness for small, specialized, and hobby farms.

Table 5 (Bodria *et al*., 2013; Lazzari and Mazzetto, 2016) summarizes the values of weight to power ratio reported in the literature, which are compared to those obtained in the present study, although limited to 2WD, 4WD, and crawler tractors.

The values obtained in the present study are quite different from those obtained by Bodria *et al*. (2013) and Lazzari and Mazzetto (2016). Despite only a few years have passed since the above studies, the current values are generally lower, especially for 4WD standard tractors and crawler tractors. This is probably due to an increase in rated engine power for the same weight of these categories of tractors. On the contrary, results for 2WD standard tractors are more discordant.

Results from the linear regression model that tested weight *versus* power for every type of tractor are reported in Table 6.

The best results were found for 4WD standard tractors and isodiametric 4WD tractors. The high R^2 values (respectively of 0.90 and 0.85) and the reasonably low RSR values (respectively of 0.30 and 0.36) suggest that the linear regression models can accurately estimate the weight of these tractors from their rated engine power.

Table 4. Parameter-to-parameter and parameter-to-price ratios calculated for each tractor's typology. Values are expressed as means±standard deviation.

Tractor typology	Weight/power (kg/kW)	Price/power (€/kW)	Price/weight (€/kg)	Lift capacity/weight (-)	Power/displacement (kW/ dm^3)
4WD standard tractors	55.2±8.9[b]	1131.7±229.0[b]	20.8±4.2[c]	1.1±0.20[b]	21.3±4.3[b]
2WD standard tractors	49.7±3.7[c]	874.0±91.2[d,e]	17.7±2.3[d]	1.2±0.11[a]	19.2±2.3[c]
Low-tech narrow tractors	44.2±5.0[d]	1029.2±154.0[e]	23.4±3.1[c]	1.0±0.1[c]	16.4±3.5[d]
High-tech narrow tractors	46.8±4.5[c]	1597.1±124.4[a]	34.2±1.8[a]	0.9±0.1[c]	19.9±2.3[b,c]
Isodiametric 4WD tractors	42.2±5.8[d]	874.1±124.7[c]	21.0±3.6[b]	1.0±0.1[c]	19.2±3.1[c]
Crawler tractors	67.5±6.2[a]	998.5±68.8[c]	14.9±0.9[d]	0.6±0.1[d]	20.4±1.7[b,c]
Rubber-tracked tractors	60.4±8.5[a]	1485.5±194.9[a]	24.8±3.0[b]	0.5±0.2[d]	28.8±3.4[a]

4WD, four wheel-drive; 2WD, two wheel-drive; [a,b,c,d,e]values in the same column with different superscripts differ significantly ($p<0.05$).

Table 5. Weight to power ratios proposed by different authors compared to those obtained in this study.

Tractor typology	Weight/power (kg/kW)		
	Bodria *et al*., 2013	Lazzari and Mazzetto, 2016	Present study
4WD standard tractors	56.0	60.0	55.2
2WD standard tractors	45.8	55.0	49.7
Crawler tractors	76.4	70.0	67.5

4WD, four wheel-drive; 2WD, two wheel-drive.

Nevertheless, when segmenting 4WD tractors by power range (<60, 61-120, 121-200 and >200 kW), R^2 and RSR values ranged respectively between 0.57-0.69 and between 0.46-0.50, indicating a lower correlation and agreement between measured and estimated weights.

In high-tech narrow tractors, the rated engine power is not a predictor of weight (R^2=0.14), probably because these tractors are characterized by a reduced range of weight (from 3080 to 3515 kg) in the face of a rated engine power ranging from 53 to 84 kW. In this way, it is possible to find on the market tractors with similar weight but equipped with increasing engine power. On the other side, these tractors are designed for specialty crops, where it is most important to provide adequate power for the operating machines (often coupled to the 3-point hitch) in the form of PTO torque, hydraulic, *etc*. rather than to develop a high traction force. For the other tractor typologies, R^2 values between 0.53-0.66 and RSR values between 0.47-0.50 suggest that the rated engine power is a satisfactory but not optimal predictor of weight.

Price to rated engine power ratio

The more expensive tractors per kW of engine power belong to the categories of high-tech narrow tractors, due to their high technological level, and rubber-tracked tractors because of the high performance they can provide (Table 4). The most economical ones are the 2WD standard tractors and the isodiametric 4WD tractors, with an average price to rated engine power ratio of 874.0 €/kW and 874.1 €/kW, respectively, mainly due to the simple construction characterizing these 2 typologies of tractors. It is interesting to note that isodiametric 4WD tractors and crawler tractors do not show significant differences. On the other side, these tractors have similar characteristics: low center of gravity, low speed, mechanical transmissions, the same distribution of weight on the axles, and low-medium-rated engine power.

The price to rated engine power ratio for 4WD standard tractors amounts to 1131.7 €/kW, but it increases significantly by about 26% from 949.4 €/kW for low-power machines (<60 kW) to 1239.4 €/kW for tractors with rated engine power >200 kW. This is probably due to the technological level that increases with raising engine power: indeed, high and very high-rated engine power tractors are often equipped with isobus connections, on-board computers, CVT transmissions, a high number of hydraulic distributors, *etc*., besides the structural over-dimensioning necessary to perform heavy field operations. Results from the linear regression model tested for price *versus* power for every type of tractor are reported in Table 7.

The high R^2 value (0.91) and the low RSR value (0.28) highlight the excellent correlation and agreement between measured and estimated prices for 4WD standard tractors when the linear regression model is built using the whole dataset. On the contrary, when segmenting 4WD tractors by power range (<60, 61-120, 121-200 and >200 kW), lower R^2 values and higher RSR values

Table 6. Results from the linear regression model tested weight *versus* power.

Tractor typology	Weight/power equation	p	R^2	S	RMSE	RSR
4WD standard tractors	W=46.4·P+867	0.00	0.90	0.55	946.1	0.30
30-60 kW	W=55.6·P-26	0.00	0.57	4.58	341.5	0.50
61-120 kW	W=76.2·P-1684	0.00	0.69	2.49	668.4	0.46
121-200 kW	W=36.3·P+2694	0.00	0.59	2.46	567.0	0.49
>200 kW	W=43.7·P+1094	0.00	0.68	3.50	1423.4	0.47
2WD standard tractors	W=31.6·P+1116	0.00	0.58	4.72	138.1	0.47
Low-tech narrow tractors	W=30.8·P+861	0.00	0.53	1.74	222.1	0.50
High-tech narrow tractors	-	-	0.14	-	-	-
Isodiametric 4WD tractors	W=28.7·P+583	0.00	0.85	1.15	154.1	0.36
Crawler tractors	W=58.9·P+593	0.00	0.57	10.40	327.4	0.50
Rubber-tracked tractors	W=37.2·P+7783	0.00	0.66	5.38	1752.0	0.48

4WD, four wheel-drive; 2WD, two wheel-drive; W, weight (kg); P, power (kW); R^2, coefficient of determination; S, standard error of regression; RMSE, root mean squared error; RSR, RMSE-observations standard deviation ratio.

Table 7. Results from the linear regression model tested price *versus* power.

Tractor typology	Price/power (€/kw) equation	p	R^2	S	RMSE	RSR
4WD standard tractors	Pr=1283.8·P-12,340	0.00	0.91	14.21	24,433	0.28
30-60 kW	Pr=799.6·P+6958	0.00	0.55	68.65	5024	0.50
61-120 kW	Pr=1749.5·P-53,173	0.00	0.66	60.24	14,898	0.47
121-200 kW	Pr=1335.4·P-17,037	0.00	0.55	98.27	21,854	0.50
>200 kW	Pr=991.6·P+64,603	0.00	0.61	93.03	35,751	0.49
2WD standard tractors	Pr=1148.6·P-16,909	0.00	0.69	137.50	4362	0.47
Low-tech narrow tractors	Pr=986.5·P+2872	0.00	0.52	57.79	7239	0.50
High-tech narrow tractors	Pr=518.8·P+75,370	0.00	0.59	57.46	2446	0.50
Isodiametric 4WD tractors	Pr=868.0·P+110	0.00	0.76	46.34	6748	0.49
Crawler tractors	Pr=758.6·P+16,456	0.00	0.71	98.60	3463	0.46
Rubber-tracked tractors	Pr=904.8·P+195,960	0.00	0.56	161.05	48,343	0.51

4WD, four wheel-drive; 2WD, two wheel-drive; Pr, price (€); P, power (kW); R^2, coefficient of determination; S, standard error of regression; RMSE, root mean squared error RSR, RMSE-observations standard deviation ratio.

were found, indicating a less accurate price prediction from their rated engine power. Ruiz-Garcia and Sanchez-Guerrero (2022) obtained similar findings by applying parametric regression models. For isodiametric 4WD tractors (R^2=0.76, RSR=0.49) and crawler tractors (R^2=0.71, RSR=0.49), a good estimate of their price can be done knowing their rated engine power, while for the remaining tractor typologies, the rated engine power can be considered a satisfactory but not optimal predictor of price, as suggested by the lower R^2 and RSR values.

Price to weight ratio

By referring to Table 4, the maximum massif price has been observed for high-tech narrow tractors (34.2 €/kg) because of their high market price, related to their technological level, and their relatively low mass. On the contrary, crawler tractors present the lowest value of price to weight ratio (14.9 €/kg). This is because, besides the high weight, these machines have low-medium-rated engine power and a limited number of mechanical components (mechanical transmission with a low number of gears, absence of front brake and steering systems, absence of the front differential, *etc.*) that reduce the purchase price. For these particular tractors, therefore, the low price to weight ratio is due essentially to the considerable metallic mass necessary to provide high traction force, whose value is significantly lower with respect to the price of technology. It should be noted that 2WD standard tractors have a price to weight ratio statistically similar to that of crawler tractors. The reason is mainly due to the low technological level and the absence of the already mentioned mechanical parts (frontal drive axle with differential and braking system). This reduces both the weight of the 2WD tractors and, especially, their price list, returning, as a price to weight ratio, a value of only 17.7 €/kg. For 4WD standard tractors, the price to weight ratio amounts to 20.8 €/kg. In these tractors, when segmenting by engine power range, it is possible to notice the same trend already observed for the price to power ratio: the higher the rated engine power, the greater the price to weight ratio. In detail, the price to weight ratio increases significantly, by about 47%, from 17.7 €/kg of low-power machines (<60 kW) to 26.0 €/kg of tractors with rated engine power >200 kW. Despite the increase in weight linked to the different classes of rated engine power, in this case, the different values of the price to weight ratio are substantially due to the increase in the list price. Indeed, as the engine-rated power increases, the technological level and quality of the project also increase, with a consequent increase in the price of the considered tractor. Results from the linear regression model tested for price *versus* weight for every type of tractor are reported in Table 8. The high R^2 value (0.91) and the low RSR value (0.28) highlight the excellent correlation and agreement between measured and estimated prices for 4WD standard tractors when the linear regression model is built using the whole dataset. On the contrary, when segmenting 4WD tractors by power range (<60, 61-120, 121-200 and >200 kW) lower R^2 values and higher RSR values were found, indicating a less accurate price prediction based on their weight. For crawler tractors (R^2=0.82, RSR=0.39) and isodiametric 4WD tractors (R^2=0.76, RSR=0.43), a good estimate of their price can be done using their weight, while for the remaining tractor typologies, the weight can be considered a satisfactory but not optimal predictor of price, as suggested by the lower R^2 and RSR values. In high-tech narrow tractors, no relationship was found between price and weight (R^2=0.02), probably due to their high price list, as already observed by analyzing the price to power ratio, and the limited weight range typical of this category of tractors.

Lift capacity to weight ratio

As mentioned, the lift capacity to weight ratio can be a useful index to evaluate the lift capacity of the 3-point hitch for a specific category of tractors. Regardless of its actual mechanical meaning (in Table 4, lift capacity greater than the total weight of tractors is reported for some categories, which does not have any practical significance), this ratio allows us to choose the type of coupling capable of optimizing tractor performance. In any case, the higher lift capacity to weight ratio has been obtained for 2WD and 4WD standard tractors, respectively, with a value of 1.2 and 1.1 kg of lift capacity for 1 kg of weight. Obviously, it is an index, taking into account only the maximum force provided by the 3-point hitch without considering the longitudinal stability of the tractor. Low-tech and high-tech narrow tractors and isodiametric 4WD tractors present a very similar ratio, ranging from 0.9 to 1.1, with no statistical differences. Instead, crawler tractors and rubber-tracked tractors (equal from a statistical point of view) show interesting behavior; indeed, the lift capacity to weight ratio resulted in values equal to 0.6 and 0.5, respectively. This means that these particular categories of tractors, despite their weight and rated engine power, are particularly designed to provide high drawbar power for driven operating machines at the expense of mounted implements.

Table 8. Results from the linear regression model tested price *versus* weight.

Tractor typology	Price/power (€/kw) equation	p	R^2	S	RMSE	RSR
4WD standard tractors	Pr=26.2·W-27,566	0.00	0.91	0.29	24,740	0.28
30-60 kW	Pr=11.3·W+15,586	0.00	0.59	0.88	4953	0.49
61-120 kW	Pr=19.3·W+4191	0.00	0.68	0.64	15,696	0.47
121-200 kW	Pr=32.5·W-81,114	0.00	0.73	1.61	19,567	0.45
>200 kW	Pr=19.3·W+84,003	0.00	0.64	1.67	35,069	0.48
2WD standard tractors	Pr=23.9·W-18,946	0.00	0.51	4.16	4697	0.51
Low-tech narrow tractors	Pr=26.2·W-8024	0.00	0.65	1.16	6908	0.48
High-tech narrow tractors	-	-	0.02	-	-	-
Isodiametric 4WD tractors	Pr=27.8·W-12,740	0.00	0.76	1.50	5913	0.43
Crawler tractors	Pr=10.5·W+20,100	0.00	0.82	0.99	2914	0.39
Rubber tracked tractors	Pr=20.5·W+86,247	0.00	0.60	3.32	47,594	0.50

4WD, four wheel-drive; 2WD, two wheel-drive; Pr, price (€); P, power (kW); R^2, coefficient of determination; S, standard error of regression; RMSE, root mean squared error RSR, RMSE-observations standard deviation ratio.

Results from the linear regression model tested for lift capacity *versus* weight for every type of tractor are reported in Table 9.

The high R^2 value (0.91) and the reasonably low RSR value (0.31) indicate a very good correlation and agreement between measured and estimated lift capacity for isodiametric 4WD tractors. The weight can also be considered a good predictor of lift capacity in 4WD tractors when the linear regression model is built using the whole dataset. On the contrary, when segmenting 4WD tractors by power range (<60, 61-120, 121-200 and >200 kW), only in tractors up to 120 kW power can their lift capacity be estimated from their weight with good accuracy. The same can be highlighted for high-tech narrow tractors (R^2=0.76, RSR=0.50).

In rubber-tracked tractors and in 4WD standard tractors with rated engine power >200 kW, weight is not a predictor of lift capacity, as the R^2 values are equal, respectively, to 0.13 and 0.12. It deals with tractors characterized by similar mechanical structures; indeed, many of the considered rubber-tracked tractors are also available in wheeled versions. Being machines designed to provide high traction force for the implements, the various models are characterized by increasing weight and rated engine power but with the same lift capacity, which happens to be practically independent of the size of the tractor. For the other tractor typologies, R^2 values between 0.53-0.64 and RSR values above 0.60 suggest that the rated engine power is a satisfactory but not optimal predictor of weight.

Rated engine power to displacement ratio

For 4WD and 2WD standard tractors, high-tech narrow tractors, isodiametric 4WD tractors, and crawler tractors, the power to displacement ratio is very similar, ranging from 19.2 to 21.3 kW/dm^3, although some statistical differences can be highlighted (Table 4). Low-tech narrow tractors present a lower value (16.4 kW/dm^3), while rubber-tracked tractors show a higher value (28.8 kW/dm^3). Concerning the subcategories of 4WD standard tractors, the power to displacement ratio increases significantly, by about 64%, from 17.6 kW/ dm^3 for low-power machines (30-60 kW) to 28.9 kW/ dm^3 for tractors with rated engine power >200 kW.

Results from the linear regression model of power *versus* displacement for every type of tractor are reported in Table 10.

Linear regression models defined for 4WD standard tractors with 121-200 kW rated engine power, 2WD standard tractors, and low-tech, and high-tech narrow tractors show R^2<0.5, indicating that displacement is a bad predictor of power for these tractor typologies. In these categories of tractors, a wide range of engine power can be obtained with the same displacement by acting on the injection system and the engine mapping, allowing a not negligible economic saving for manufacturers.

The best results were found for 4WD standard tractors, considering the whole dataset, and isodiametric 4WD tractors. With R^2 values of 0.84 and 0.81 and RSR values of 0.42 and 0.43, the power of these tractors can be estimated accurately knowing their

Table 9. Results from the linear regression model tested lift capacity *versus* weight.

Tractor typology	Lift capacity/weight (-) equation	p	R^2	S	RMSE	RSR
4WD standard tractors	LC=1.0·W+694	0.00	0.84	0.02	1203.0	0.40
30-60 kW	LC=1.3·W-871	0.00	0.74	0.07	568.2	0.51
61-120 kW	LC=1.3·W-771	0.00	0.78	0.03	931.0	0.47
121-200 kW	LC=0.8·W+2865	0.00	0.56	0.06	837.1	0.67
>200 kW	-	-	0.12	-	-	-
2WD standard tractors	LC=1.5·W-712	0.00	0.58	0.22	347.2	0.66
Low-tech narrow tractors	LC=0.8·W+339	0.00	0.60	0.04	279.7	0.64
High-tech narrow tractors	LC=2.2·W-4051	0.00	0.76	0.16	289.9	0.50
Isodiametric 4WD tractors	LC=1.1·W-245	0.00	0.91	0.03	167.1	0.31
Crawler tractors	LC=0.4·W+1178	0.00	0.64	0.06	187.1	0.61
Rubber-tracked tractors	-	-	0.13	-	-	-

4WD, four wheel-drive; 2WD, two wheel-drive; LC, lift capacity (kg); W, weight (kg); R^2, coefficient of determination; S, standard error of regression; RMSE, root mean squared error RSR, RMSE-observations standard deviation ratio.

Table 10. Results from the linear regression model tested power *versus* displacement.

Tractor typology	Power/displacement (kW/dm^3) equation	p	R^2	S	RMSE	RSR
4WD standard tractors	P=27.2·D-26	0.00	0.84	0.40	23.4	0.42
30-60 kW	P=11.7·D+16	0.00	0.60	0.88	6.1	0.64
61-120 kW	P=11.9·D+35	0.00	0.57	0.46	11.1	0.66
121-200 kW	-	-	0.17	-	-	-
>200 kW	P=23.7·D+46	0.00	0.71	1.94	29.6	0.68
2WD standard tractors	-	-	0.31	-	-	-
Low-tech narrow tractors	-	-	0.47	-	-	-
High-tech narrow tractors	-	-	0.25	-	-	-
Isodiametric 4WD tractors	P=19.6·D-0.7	0.00	0.81	0.69	7.4	0.43
Crawler tractors	P=15.1·D+18	0.00	0.61	2.46	5.3	0.64
Rubber tracked tractors	P=21.3·D+87	0.00	0.66	3.11	42.4	0.59

4WD, four wheel-drive; 2WD, two wheel-drive; P, power (kW); D, displacement (dm^3); R^2, coefficient of determination; S, standard error of regression; RMSE, root mean squared error RSR, RMSE-observations standard deviation ratio.

displacement. Nevertheless, as observed for the other parameters, when segmenting 4WD tractors by power range (<60, 61-120, 121-200 and >200 kW), lower R^2 values and higher RSR values were found, indicating a less accurate rated engine power prediction from their displacement.

Conclusions

In this study, the technical parameters of several typologies of agricultural tractors were analyzed, and linear regression models were implemented to estimate the following parameters: weight to rated engine power ratio, price to rated engine power ratio, price to weight ratio, lift capacity to weight ratio, and rated engine power to displacement ratio.

For each typology of tractors, linear equations allow for the estimation of some parameters useful to carry out technical-economic analysis.

The proposed simplified solutions can reduce the complexity of the estimation process, leading to the correct implementation of the resources, contributing to the sustainable management of the economic resources, and helping farmers, advisors, contractors, and farm machinery experts in the selection of the most appropriate tractors for the specific production realities.

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