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# An Application of Morphometry to Artificial Systems: The Evolutionary Study of Farm Tractors

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Morphometry is a method for describing and analysing statistically the shape variations within and among samples of organisms as a result of growth, experimental treatments or evolution. Morphometric methods are needed whenever there is the necessity to describe and compare shapes of organisms or of particular structures of living beings as a macroscopic result of genetic effects (i.e., as an internal response) induced by a set of external stimuli (e.g., environmental variations, geographic migrations of populations).
An artificial system (movable or not) is the result of the realization of an idea aimed at solving a problem or a need that, at a certain point, has emerged in human daily-life. Hence, the very concept of a system and the proposition of possible variations or improvements concerns the idea of evolutionary adaptation. The driver of this process is, once again, external (fulfilment of a need and/or a constraint); differently from biological systems, the response arrives also from the outside of the system (designers), because, at present, no technical system is capable of self-evolving (except some particular types of computer programs). Therefore, the same morphometric methods usually adopted for living beings can also be used to study the evolution of a given artificial system over a long period, by quantifying the same technical characteristics on a set of specimens/models from different years.
Regarding the agricultural machinery and tractors in particular, the need to replace animal and human labour-force and, therefore, to increase the total working-capacity, led initially to the concept of the first agricultural machines. Subsequently, over the years, a number of opportunities (new technologies, new materials) and constraints (legislative, environmental) acted on the designers as stimuli to change and improve their projects. Focussing the attention on tractors, these stimuli had as a consequence the evolution of some technical characteristics, which can be investigated, for example, by extracting homologous technical data from tractors' official documents (e.g., the test reports for OECD - Organization for Economic Co-operation and Development), as done in the study presented here. The final purpose of this investigation is tracing a series of temporal trends regarding some technical features of interest, eventually highlighting the effects of the new laws on them and investigating the achievement or not of stable values.
With the present document the Authors wants to illustrate the approach, showing also, as example, a possible application of it to one technical parameter concerning the relative positioning of the centre of gravity.

## 1. Introduction

Geometric morphometry (or, simply, "morphometry") is the statistical analysis of shapes aimed at performing comparisons or evidencing differences. It is based on the study of the two- or three-dimensional Cartesian coordinates of landmark points in objects or living beings belonging to a similitude group (James Rohlf & Marcus 1993; Lawing & Polly 2010; Zelditch, Swiderski & Sheets 2012; Mitteroecker & Gunz 2009; Costa et al. 2011). The morphometry is applied mainly in biology, for the rigorous quantitative analysis of variation in organismal size and shape of a population (Klingenberg 2002), the study of the temporal evolution of species but also for the quantification of the differences between isolated populations of individuals of the same species (Antonucci et al. 2012), hence to observe evolutionary convergences/divergences (Antonucci et al.

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2009). In general, when using this method applied to biological entities, the premise is that the shape is the most evident expression of a genome under the evolutionary thrusts of the environment surrounding a population of individuals, and therefore can be a key of investigation for variability and evolution (Darwin 1859). Based on the same idea, but applied to all systems, a “universal” or “generalized” Darwinism has been proposed: it holds that the ontology of all evolutionary systems (natural or artificial) accords to the Darwinist scheme of variation, selection and inheritance. The proposition is that, at a sufficiently-abstract level of analysis, evolutionary processes in different domains are identical in their basic scheme (Hull 1988; Dennett 1995). Concerning technical products (or their subparts), it is necessary to consider that their initial design and their subsequent development is the result of differentiation and similitudes, and hence: on one hand, of the requests from customers and of the product positioning (Gautschi & Sabavala 1995), on the other hand, of the application of the modulus and parametric-design concepts, to create an artefact family (Guzzomi, Maraldi & Molari 2012) maybe using parametric design (Li, Chen & Li 2010) or other design tools (Chandrasegaran et al. 2013). This is particularly evident when considering aesthetic features: for example, the convergence of the shape of European utilitarian cars of the last 60 years toward a more similar fusiform and compact asset was described through morphometry using Darwinian evolution as a metaphor to quantify and interpret changes over time and the societal pressures promoting them (Costa & Aguzzi 2015; Grimson & Murphy 2009). (Kutzbach 2000) focuses the attention on new/upcoming technical systems, which will raise the overall complexity of farm machinery, while (Renius 1994) analyses the trends in tractor design and prefigures a scenario for European tractors, proven effectively to be correct nowadays. (Reece 1970) inquired farm tractors’ shape and its influent factors. The conclusion drawn by (Reece 1970) is that very little real improvement in performance can be obtained without a radical change of form. This experience has caused most manufacturers to adopt a policy of slow, steady development of both tractor design and manufacturing facilities. (Guzzomi & Rondelli 2013) investigated the physical parameters of 326 modern narrow-track tractors, measured according to OECD Code 6; they used morphometry to inquiry the suitability of protective structures (energy absorption) over 16 years. In all these works, morphometry demonstrates to be an excellent instrument to quantify some aspects related to aesthetics and shape in general, letting the analyst visualize the historical development of a product also considering that shape is often functional to obtain a related performance. However, with the aim of giving a complete overview of the eventual changes occurred to a product over the time, morphometry is usually put beside the temporal trends of other technical quantities, e.g. related to motor and tractor performances as done on the tractors tested at the Nebraska Tractor Test Laboratory from 1959 through 2002 (Kim, Bashford & Sampson 2005). This is the approach adopted also in this study.

In particular, the analyses performed here had the principal aim of tracking the trend of different technical parameters of farm tractors in the last 50-60 years, with the secondary aim of having a tool at the disposal to understand, for each parameter, if it is likely, on the basis of the observed trends, that a further evolution (increase, decrease) will take place or, rather, that the value will remain constant in the next future.

## 2. Materials and Methods

### 2.1 Performed activities: overview

The performed activities can be divided into *three phases*:

1. *Preliminary Phase*: identification of a set of data that are consistent, continuous in time from an established date and sufficiently numerous; acquisition of all of the documentation (in paper or digital format) containing these data (in our case: OECD test reports); eventual digitization of paper test report to have a uniformity of the supports of the documentation; drawing up a list of keywords in the official languages (English, French) of the test reports regarding the technical parameters of interest; performing of a computer-aided search of the numerical values of the technical parameters of interest; homogenization of the measurement units (in particular, conversion to SI units); transcription of the data into a specifically-created spreadsheet/database;
2. *Processing Phase*: writing in the spreadsheet/database of the mathematical formulas for the calculation of a set of derived parameters; provision of Cartesian graphs on quantities to be studied;
3. *Study Phase*: querying of the spreadsheet/database based on the basis of some filters applied on the tractors’ characteristics; regeneration of graphs with the filters activated; observation of points’ dispersions and trends; calculation of regression curves.

With the aim of giving an operative methodology, after the very first time, the described activities should be repeated every time a database update (addition of new entries) is possible/requested (e.g., once per year).

### 2.2 Preliminary Phase: choice of the OECD test reports as source of data for the study

A key point for the validity of studies on temporal trends, like the present one, is the choice of the suitable source for the data to be elaborated/plotted. Indeed, within the observation period (stated by analysts on the basis of their needs) data should be as continuous-in-time as possible and sufficiently numerous, to have a clearly-defined trend, representative of what happened in reality. But, above of all, as previously underlined, data must be consistent, i.e. taken from the same source or, at least, with the same methods, to be sure they can be effectively consistent and comparable. All the data used in this study were obtained from OECD test reports directly or indirectly, i.e. by reading data on these test reports or by calculating other parameters from them (see following paragraphs). OECD test reports have been chosen as they are a source of technical data measured on the basis of standard tests, hence performed in authorized OECD test centres according to harmonized procedures. The relevant test reports have the aim of making comparable the technical characteristics of tractors produced in different areas and periods of the world.

### 2.3 The database

A total of 1418 test reports were consulted and the related data (up to 49 entries per test report) were saved on a specifically-created spreadsheet. The covered period ranges from 1961 to now, with a distribution of the tractors over the years, in different classes of engine power or displacement as shown in Figure 1. Other classification keys, used for categorizing the tractors in the analyses, are, for example: the tractors' general type (universal/special-purpose i.e. for vineyards and orchards), the tractors' chassis type (conventional/articulated), the fuelling system type (with/without turbocharger, with/without common rail).

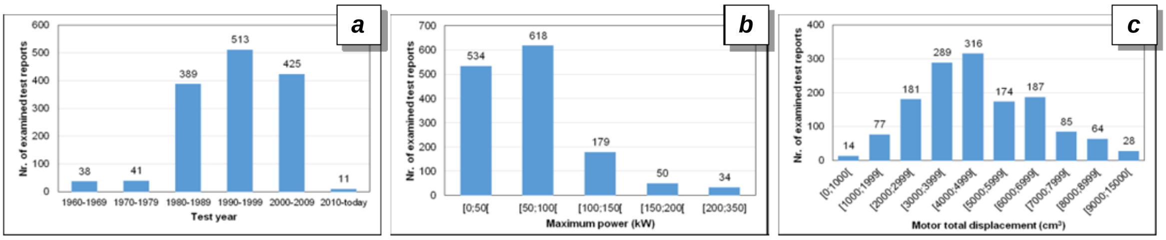


*Figure 1: Classification of the tractors analysed in the consulted test reports (tot. 1418) on the basis of the test year (6 classes; graph a), of the maximum motor power (5 classes; graph b) referred to the normed test conditions (OECD codes 1 and 2), or of the motor total displacement (10 classes; graph c).*

The reference codes for the testing of tractors considered in this paper were two: the OECD code 1 and 2 (respectively 52% and 48% of the examined test reports). Despite having the same purposes, they differ in the total number of mandatory tests. In particular, the code 2 (OECD 1984), subsequent to the code 1 (OECD 1959), is configured as a restricted version of the code 1 and hence has less data to be reported in the database. For example, the calculation of the position of the centre of gravity (COG) is always present in the tests prescribed by the code 1, while in the code 2 it is an optional test and often it is not performed. This is why the complete spatial position of the COG (on term of: absolute height, distance from the rear axle, left shift from the tractors' longitudinal plane) is not always available for all tractors of the database.

### 2.4 Studied quantities

The studied variables can be divided in *two main groups* (Table 1):

- "*primary*" quantities, i.e. those quantities whose values have been directly read on the test reports and reported as they are within the spreadsheet used to organize the data;
- "*secondary*" or "*derived*" quantities, i.e. those technical parameters whose value has been mathematically calculated from one or more primary quantity, by applying formulas specifically written or taken from the literature, implemented in the spreadsheet with its proprietary syntax.
- It should be observed that what done in this study is a *modified morphometric analysis*, i.e. a shape-analysis inspired by the above-enunciated principles of morphometric approach (in particular, concerning the main sizes of the tractor shape and the COG's coordinates, where available; Figure 2) with a special focus also on other not-geometrical parameters (e.g., the mass) but very interesting from a technical point of view.
- A properly-said morphometric analysis (i.e., with more markers/points on the tractors' outline) is practically impossible in the present case, because it would have implied the acquisition of the blueprints of all the tractors, property of their own manufacturers and maybe related to very old models (hence no more available).

*Table 1: Primary/secondary morphometric quantities (related only to outline dimensions and COG position).*

| Ref. Category | Primary quantities | Secondary quantities |
|---|---|---|
| *Wheel support polygon* | • Wheelbase (mm)<br>• Minimum front track (mm)<br>• Minimum rear track (mm) | • Ratio between front track and wheelbase (-)<br>• Ratio between rear track and wheelbase (-)<br>• Ratio between front and rear track (-) |
| *Outline dimensions* | • Length without ballast (mm)<br>• Minimum width (mm)<br>• Maximum width (mm)<br>• Height at the highest point of the safety cab (mm) | • Ratio between minimum width and length without ballast (-)<br>• Ratio between height at the highest point of the safety cab and length without ballast (-)<br>• Ratio between height at the highest point of the safety cab and minimum width (-) |
| *COG position* | • Absolute height (mm)<br>• Distance from the rear axle (mm)<br>• Left shift from the tractors' longitudinal plane (mm) | • Ratio between height at the highest point of the safety cab and mass (mm $kg^{-1}$)<br>• Ratio between COG height and height at the highest point of the safety cab (-)<br>• Ratio between rear axle distance and wheelbase (-)<br>• Ratio between left shift from the tractors' longitudinal plane and minimum rear track (-)<br>• Ratio between COG height and distance from the rear axle (-)<br>• Theoretical angle of longitudinal static stability (°)<br>• Theoretical angle of lateral static stability (°) |
| *Mass* | • Front and rear mass without ballast and driver (kg)<br>• Total tractor mass without ballast and driver (kg) | • Front/rear mass distribution (-)<br>• Ratio between front and total mass (-)<br>• Ratio between rear and total mass (-)<br>• Ratio between wheelbase and mass (mm $kg^{-1}$) |

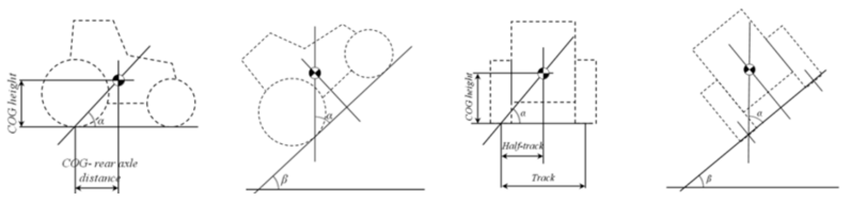


*Figure 2: geometrical parameters related to the position of the COG and significance of the theoretical angles of longitudinal static stability (left) and of lateral static stability (right), indicated with β in both the pictures.*

## 3. Results and discussion

Among all the examined parameters, as an example of what can be done, it is reported hereinafter a first study on the parameter "*ratio between the COG (orthogonal) distance from the rear axle and the wheelbase*" (COGDR/WB). Indeed, the study of this ratio is very useful because it allows formulating considerations independent of the absolute dimensions of tractors, but rather, related to the position of the COG within the tractor's shape. To have a comprehensive understanding of the evidenced trends, this study has been accompanied by an analysis of the trends of the primary quantities used in the calculations of the analysed secondary quantity of interest (Figure 3, graphs a-d-g-l and b-e-h-m). This short study is also completed by a differentiation of trends made on the number of tractors' driving wheels (2, 4), due to the important architectural implications on the powertrain and, hence, on the front-rear mass distribution. Indeed, even if further preliminary classifications of data (e.g., on the maximum engine power) are surely possible before plotting some characteristic of interest, according to a preliminary analysis the number of driving wheels is most influent characteristic on the COGDR/WB general trend. Looking at the graph that plot the ratio under study for the whole population of studied tractors (Figure 3, c), it can be seen that the trend line is almost-perfectly horizontal and at a value of about 0.4 (especially from 1980 on). The dispersion of points around this value is quite consistent in a fairly-uniform band of points between 0.3 and 0.5 with outliers around 0.6. A categorization of tractors on the basis of the number of driving wheels (2, 4) allows highlighting substantially-constant trends but differently-positioned in the graphs. In particular, the 2WD tractors have the ratio around 0.35 (Figure 3, f), due to the absence of a transmission line to the front wheels, while the 4WD a ratio slightly greater than 0.4 (Figure 3, i), hence more aligned with the graph of all tractors because of the greater number of 4WD tractors on the total. The points placed at values of the ratio higher than 0.5 (around 0.6) are due to the articulated tractors (Figure 3, n), often having the motor overhanging the front axle (especially small articulated tractors). Finally, looking at the graphs of the COG distance from the rear axle and the wheelbase referred to all the tractors (Figure 3, a-b), we can observe that both these quantities have grown since 1960, due to the general increase of dimensions experimented by tractors in these last years. However, independently from the value, the constancy of the ratio indicates that COG distance from the rear axle and the wheelbase have grown accordingly, i.e. the COG relative position has remained unchanged.

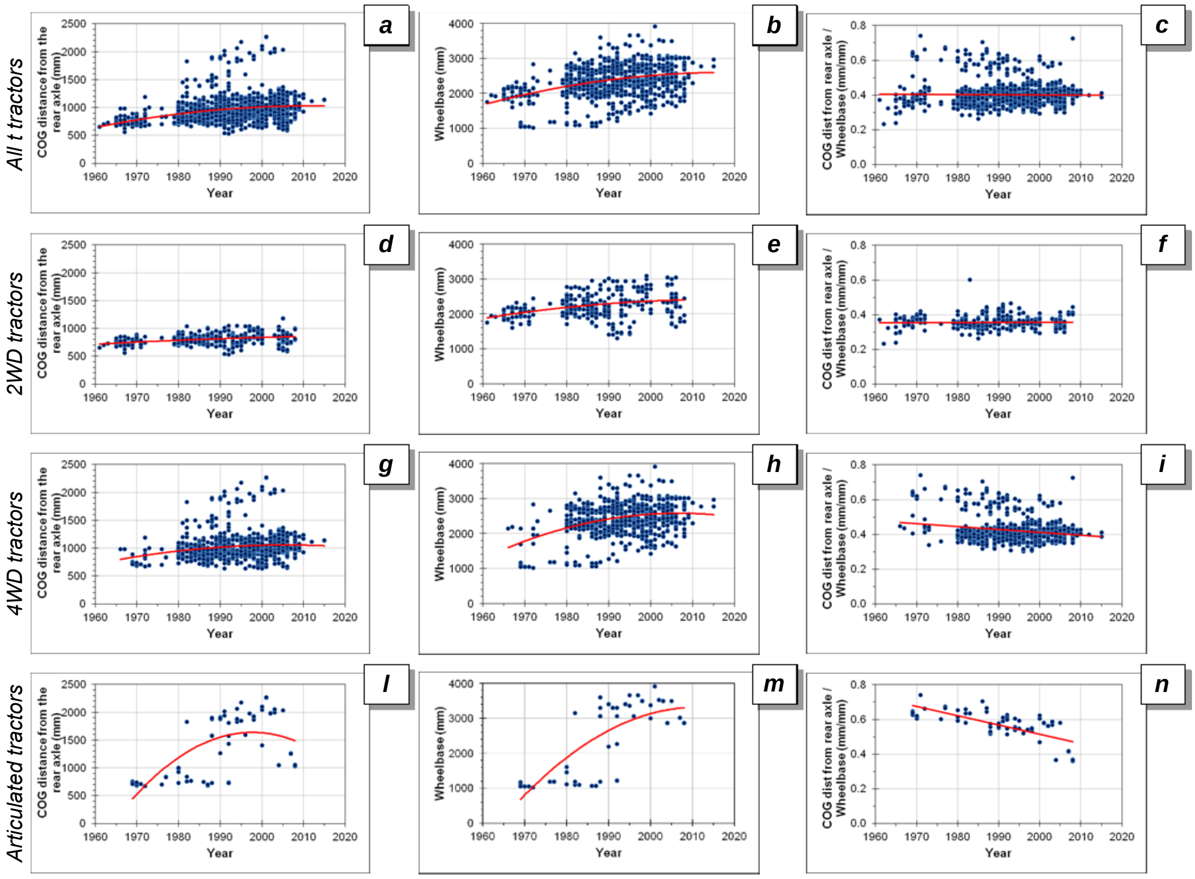


*Figure 3: temporal trends regarding the COG distance from the rear axle (graphs a-d-g-l), the wheelbase (graphs b-e-h-m), the ratio between these two quantities (graphs c-f-i-n). From top to bottom, all the studied tractors (1st row), only 2WD tractors (2nd r.), only 4WD tractors (3rd r.), only (4WD) articulated tractors (4th r.).*

## 4. Conclusions

Over the last 60-70 years, a number of requests, opportunities and constraints acted on the tractors' designers as stimuli to change and improve their projects and, within a generalized Darwinian approach, we can affirm that tractors underwent a real evolution driven by the need to improve overall performances. When dealing with geometrical parameters, morphometry can be used to investigate the evolution of some quantities of interest even for these artificial systems. The three-step approach illustrated here has used, as source of data, a total of 1418 OECD test reports, thanks to their characteristic to be sufficiently numerous, consistent and referred to the same test methods (comparability of the data). The studied variables, plotted in several temporal graphs, can be divided in primary or secondary quantities, if they were read directly on the test reports (up to 49 parameters) or, rather, calculated from one or more primary quantity. For example, the trends emerging from the points distribution of (1) the COG distance from the rear axle and (2) the wheelbase shown that both these quantities have grown (600→1000 mm, 1750→2600 mm) but the ratio between them has remained substantially constant around 0.4 (0.35 for 2WD tractors only), meaning that the COG relative position has remained mostly unchanged. Therefore, it is possible to state that the front-rear distribution of the masses (due to engine, transmission and axles) had shown no substantial changes. The architecture of the powertrain is basically unchanged from its appearance and, unless future introduction of components currently not envisaged (but, for example, necessary for a hybridization of the power unit: battery pack, electric motors), it will remain reasonably stable also in the years to come. The potential emerging from this approach can give a key to understand the degree of technical maturity of this machine, and hence, if the value of each parameter is likely that will change or, rather, will remain constant.

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