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[F] PhD Extended Abstract Form

The power delivery efficiency of a mechanical front wheel drive tractor. A computational and experimental study

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Extended Abstract

1. Problem statement and introduction

The increase of the global population, the continuous drying up of raw materials and the environmental problems are the main driving forces that guide the manufacturers towards the production of increasingly efficient vehicles.

The power delivery efficiency η_T of a tractor describes the quality of the process of transforming the power supplied by the engine into useful power, the great importance dedicated to this parameter is related to the fact that a reduction of fuel consumption passes through an improvement of the efficiency of the vehicle. Currently, on the market there are tractors that despite being designed to perform the same tasks show a profoundly different constructive layout. This variety of constructive architectures underlines the fact that there is no clarity on which is the optimal solution. In this framework the development of a vehicle model able to describe the tractive performances of a tractor and using that an optimization study on the design parameters affecting the power delivery efficiency is particularly suitable.

Accurate bibliographic research revealed that tractive performances and power delivery efficiency of agricultural tractors have been already investigated in the past in different manners. In the vast majority of cases the problem was faced experimentally: the influence of tyre size (diameter and width), mass distribution, inflation pressure and type of soil are parameters that have been physically changed to understand how these affect the power delivery efficiency; this kind of approach is simple and provides results under operational conditions but has also important drawbacks: first of all, in many of the studies the influence of mass distribution on the power delivery efficiency is not examined independently, since a mere change in front ballasting also changes the overall mass of the tractor; moreover, changing the tyre inflation pressure does not allow decoupling the effect of lead of the front wheels from that of front-to-rear tyre diameter ratio on the tractive performance; last, the range of variation of mass distribution, lead of the front wheels and tyre rolling radii that can be obtained is narrow.

In the technical literature is also possible to find several theoretical studies following different approaches; the simplest studies are based on a phenomenological approach, which relies on the computation of empirical quantities such as the wheel mobility number and the wheel numeric; these studies use a simple mathematical formulation, they are not demanding from a computational point of view but they are unreliable moving away from the calibration conditions of the coefficients and moreover, they are not very useful in improving tractor designs since they do not describe the underlying physics of the phenomena involved in traction. Other studies have been carried out with a more analytical approach, using a description of the tyre-soil interaction grounded on fundamental mechanics, however this kind of studies were not directly focused on agricultural tractors but generic off-road vehicles. The latter typology of studies although more elegant from a physical point of view do not satisfactorily address the case of agricultural tractors for several reasons: first, agricultural tractors are equipped with a different driveline: the so-called Mechanical Front Wheel Drive (MFWD), consisting of a torque splitting system between the front and the rear axles designed to have the front axle rotating at a different speed than the rear axle (front axle lead); moreover, agricultural tractors typically have a greater mass and can be non-isodiametric.

In this Ph.D. thesis, a whole tractor model is developed which accounts for the special features of a MFWD powertrain overcoming the weaknesses of the past studies. In particular, a MFWD powertrain that uses a locked 4WD transmission system with front axle lead was modeled. The model was then used to investigate the effects of a complete set of design parameters on the power delivery efficiency of a tractor. To this end, the results of the numerical simulations conducted with the tractor model were analyzed using a gradient-based method. This Ph.D. thesis aims to identify the key design parameters affecting the power delivery efficiency and to quantify their effect on the tractive performance to define an optimal tractor layout.

2. Implementation of the vehicle model and experimental validation

The implementation of a MFWD tractor model was carried out on the MATLAB platform and, as usual in the vehicle modeling practice, starts with the definition of the tyre-soil interaction. This kind of interaction occurs through the development of normal and tangential stresses distributed along the contact patch between tyre and soil. The contact patch is delimited by two contact angles: the entry angle and the route recovery angle, then computing the integral of normal and tangential stresses between the two contact angles is possible to reconstruct forces and torques acting at each single wheel hub.

The development of a MFWD tractor model wants to simulate the tractive performances of the vehicle under operational conditions, to accomplish this goal it was assumed that on a straight line trajectory the left and right handsides of the tractor exhibit the same behaviour allowing to halve the total numebr of unknowns.

This formulation of the problem globally relies on four main unknowns: slip and entry angle of the front wheels and slip and entry angle for the rear wheels, hence to evaluate these quantities a system of four equations is required. The proposed system of equations consists of three equilibrium equations of the chassis and a rigid body equation which linearly correlates the slip of the front and rear wheels. Once the unknowns of the system were calculated, they were then used to determine the power delivery efficiency of the tractor. In the vehicle model have been also implemented the gearbox model and the Diesel engine model to define fuel consumptions while is operating.

To ensure the reliability of the model an experimental validation is highly required ***(Fig. 1a)***; we validated the implemented model in terms of drawbar pull and power delivery efficiency on three different soil conditions and with a vehicle operating with three different mass distributions; the equipment used to measure the experimental power delivery efficiency consisted of: a GPS receiver to measure the speed of the tractor, a load cell ***(Fig. 1c)*** to measure the drawbar force exerted, a CAN-BUS data logger to evaluate the power supplied by the engine and finally a moving ballast to change the mass distribution ***(Fig. 1b)***. The correlation between measurements and simulations was very satisfactory ***(Fig. 2a)***, highlighting the fact that the model can truly describe the behaviour of a commercial tractor.

Once the model had been validated a complete set of simulations was performed keeping constant the soil properties and the drawbar force applied but varying 5 different constructive parameters: mass distributions (K_M), wheelbase (B), front-to-rear ratio of the rolling radii (K_W), drawbar height (h) and front wheels lead (L) on 8 equally spaced steps for a total of 8^5 simulations, acquiring for each simulation the value of the power delivery efficiency, is important to remark that each simulation corresponds to a different tractor layout.

Afterwards the gradient of the power delivery efficiency was computed using the approximated method of the central difference scheme, the direction cosines of the gradient vector had been used to understand which the most influential parameters are.

Fig.1a: *Drawbar tests for the validation of the vehicle model under operational conditions. The rear tractor is used to exert a drawbar force on the front tractor, which is the one under test.*

Fig.1b: *Image of one of the tractors used in the validation tests. On the front of the vehicle is possible to see the device used to vary the mass distribution (K_M).*

Fig.1c: *Detail of the load cell used for the measurements of the drawbar force (F_{DP}) exerted by the tractor.*

3. Results and discussion

The computation of the gradient of the power delivery efficiency and consequently of the direction cosines ***(Fig. 2b)*** allowed determining that the most influential parameters are: the mass distribution (K_M), the front-to-rear ratio of rolling radii (K_W) and the lead of the front wheels (L), indeed wheelbase (B) and the drawbar height (h) can be assumed as negligible. The analysis of the direction cosines made also possible to bring out other two features : the power delivery efficiency depends in a non-monotonic way on the lead of the front wheels and mass distribution while in a monotonic way on the front-to-rear ratio of kinetic rolling radii. Using the three most influential parameters as independent variables of a second-order polynomial equation ***(Eq. 1)*** approximating the model simulations ($R^2 > 0.97$) was possible to define a series of regression surfaces. Afterwards the first partial derivative of the polynomial equation, computed respect the mass distribution and then set it equal to zero allowed to define a simple equation to compute the optimal mass distribution $K_{M,opt}$ given the lead of the front wheels and the front-to-rear ratio of rolling radii ***(Eq. 2).***

$$\eta_T = 0{,}40 + 0{,}31K_M - 0{,}16L + 0{,}17K_W - 0{,}11K_M^2 - 0{,}52L^2 - 0{,}20K_M K_W + 0{,}28K_M L - 0{,}02K_W L \quad \textbf{(Eq. 1)}$$

$$K_{M,opt} = \frac{0{,}31 - 0{,}20K_W + 0{,}28L}{0{,}22} \quad \textbf{(Eq. 2)}$$

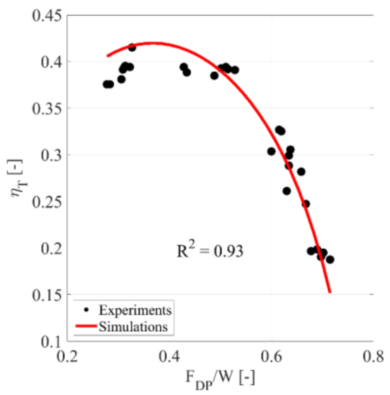

Fig.2a: *Comparison plot between simulations (red line) and measured data (black dots) for one of the six validation tests carried out. This plot is reffered to an untilled loam soil.*

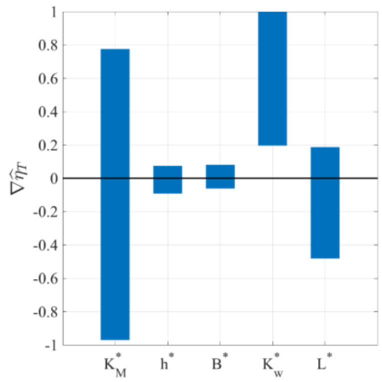

Fig.2b: *Direction cosines of the gradient of the power delivery efficiency. Each bar refers to a tractor design parameter, the bigger the bar the more influential is the parameter.*

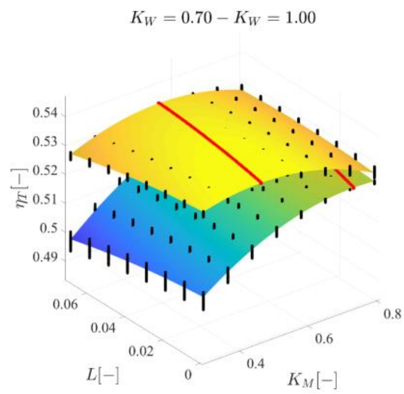

Fig.2c: *Regression surfaces fitting model simulations (black dots) concerning an isodiametric tractor ($K_w = 1.0$ – yellow surface) a standard non-isodiametric tractor ($K_w = 0.7$ – blue/green surface). The red line represents the optimal mass distribution ($K_{M,opt}$).*

4. Definition of the optimal tractor layout

This thesis highlights that a theoretical vehicle model can be a useful tool since all the relevant parameters affecting power delivery efficiency can be analysed in a systematic and coherent manner. Observing the regression surfaces ***(Fig. 2c)*** produced through ***Eq.1*** is possible to infer that the maximum power delivery efficiency was found for an isodiametric tractor having no lead of the front wheels and the mass distribution shifted towards the front axle (54% front, 46% rear), from an efficiency perspective isodiametric tractors are in general between to 2 and 4% more efficient than non-isodiametric vehicles, furthermore isodiametric vehicle have an optimal mass distribution slightly shifted towards the front axle while non-isodiametric tractor markedly shifted towards the rear axle. However, the optimal mass distribution may change considerably if the front to rear ratio of rolling radii and lead of the front wheels are different from their optimal values. Other important considerations arisen from the simulations performed in this thesis are that if the front-to-rear ratio of rolling radii decreases the power delivery efficiency decreases and that if the lead of the front wheels increases, to restore the maximum power delivery efficiency the tractor centre of mass should be shifted rearwards.

Final remarks concerning the competition benchmarks and strength points

The development of this Ph.D. thesis led to the publication of several congress proceedings, scientific paper and conference presentations. The main strength points are reported below:

- The tractor-model presented in this thesis is versatile, scalable and can be easily implemented in the on-board vehicle electronics and used as driver support software for the set-up management of the tractor.
- The tractor-model implemented allows keeping the vehicle always in the best operation mode producing fuel savings.
- The tractor model described so far can be easily extended and coupled with different implement models to predict fuel consumption while the vehicle is performing different tasks or tillage operations.
- Definition of a simple equation for the computation of the optimal mass distribution that can help the manufacturers during the early stage of the design of a new tractor.
- In general, this Ph.D. thesis highlights that the key design parameters cannot be considered unrelated from one another, because their interplay is crucial to the determination of the power delivery efficiency.