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THE POWER DELIVERY EFFICIENCY OF A MECHANICAL FRONT WHEEL DRIVE TRACTOR. A COMPUTATIONAL AND EXPERIMENTAL STUDY

Dissertation presented to University of Bologna, Viale Giuseppe Fanin 50, Bologna, Italy

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1 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.

Above is possible to see a comparison between different tractor's constructive layout. The comprehension of the role of each single constructive parameters on the power delivery efficiency η_T is one of the aims of this PhD thesis.

EQUILIBRIUM EQUATIONS OF THE VEHCILE'S CHASSIS

$$F_{DP} = F_{DPf} + F_{DPr} \quad \text{[Eq.1]}$$

$$G = W_f + W_r \quad \text{[Eq.2]}$$

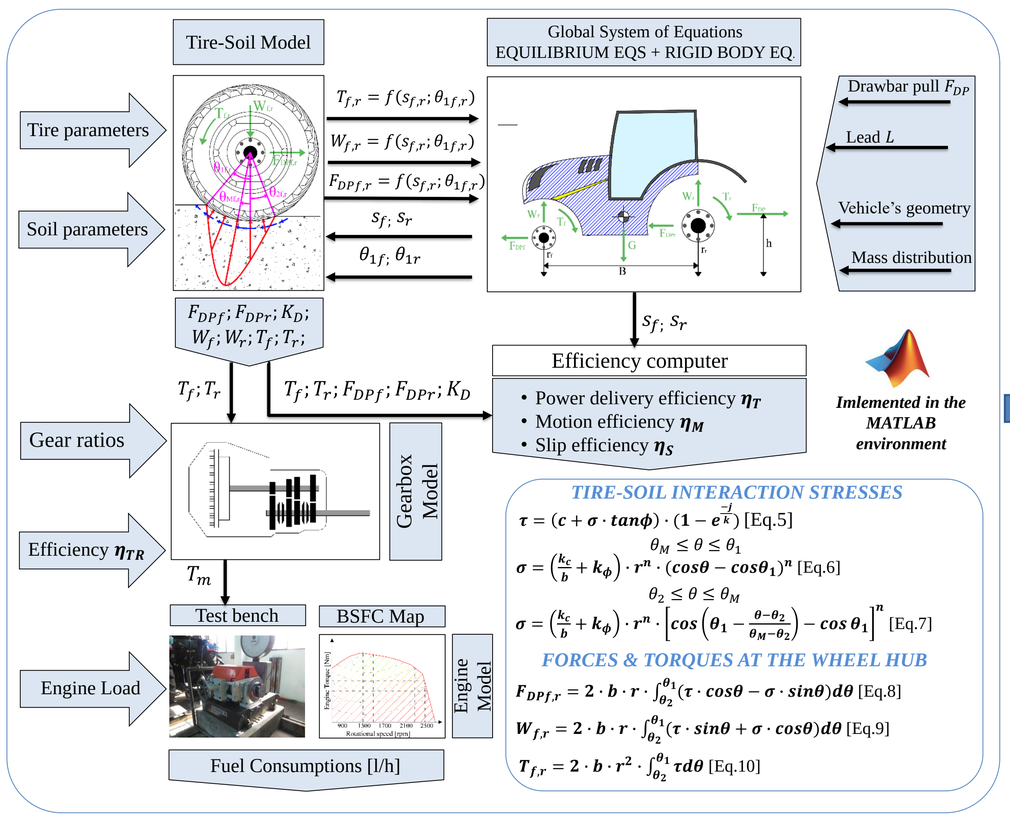
$$W_f \cdot B - G \cdot l_2 + F_{DPf} \cdot (r_r - r_f) + T_f + T_r + F_{DP} \cdot (h - r_r) = 0 \quad \text{[Eq.3]}$$

RIGID BODY EQUATION OF THE VEHICLE

$$s_r = (L + 1) \cdot s_f - L \quad \text{[Eq.4]}$$

2 Implementation and validation of the vehicle model

The implementation of a *MFWD* (Mechanical Front Wheel Drive) tractor model was carried out on the *Matlab*® platform and 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 ***[Eqs. 5,6,7]***. The contact patch is delimited by the entry angle (θ_1) and the route recovery angle (θ_2), then computing the integral of normal (σ) and tangential (τ) stresses between the two contact angles is possible to reconstruct forces ($F_{DPf,r}$, $W_{f,r}$) and torques ($T_{f,r}$) acting at each single wheel hub ***[Eqs. 8,9,10]***. This formulation of the problem globally relies on four main unknowns: slip and entry angle of the front wheels (s_f, θ_{1f}) and slip and entry angle for the rear wheels (s_r, θ_{1r}), 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 ***[Eqs. 1,2,3]*** and a rigid body equation ***[Eq.4]*** which linearly correlates the slip of the front (s_f) and rear wheels (s_r). Once the unknowns of the system were calculated, they were then used to determine the power delivery efficiency of the tractor (η_T). 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 a validation is highly required; we validated the model in terms of drawbar force (F_{DP}) and power delivery efficiency on different soil conditions and with a vehicle operating with different mass distributions. The correlation between simulated and experimental data was very satisfactory highlighting the capability of the model in the description of tractive performances.

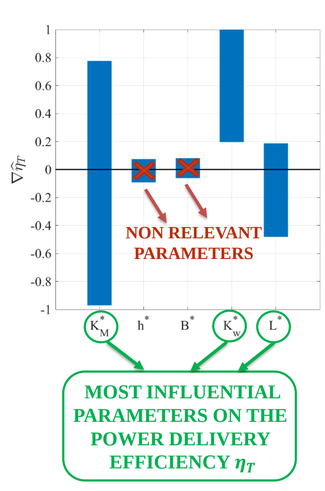


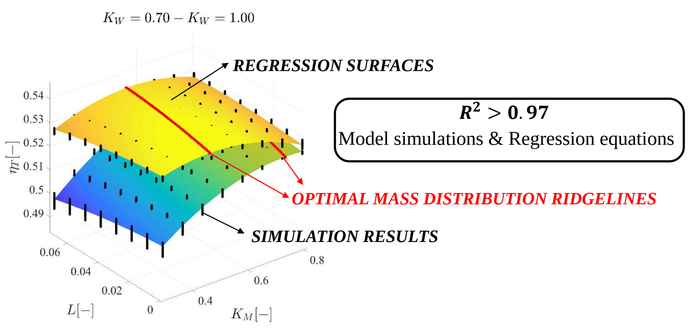
VEHICLE MODEL

MODEL VALIDATION

3 Results and discussion of the simulations

Once the model had been validated we performed a complete set of simulations varying 5 different constructive parameters: mass distribution (K_M), wheelbase (B), front-to-rear ratio of kinetic rolling radii (K_W), drawbar height (h) and front wheels lead (L) on 8 equally spaced steps for a total 32768 simulations, keeping constant drawbar force (F_{DP}=27.5 kN), and soil properties (sandy soil); each simulation corresponds to a different tractor's constructive layout. A gradient method based on the central difference scheme allowed us to compute the direction cosines. Direction cosines have been plotted along the five directions of the gradient to get the most influential parameters. The three most influential parameters are: mass distribution (K_M), front-to-rear ratio of kinetic rolling radii (K_W) and front wheels lead (L). These 3 most influential parameters have been used for the computation of regression surfaces approximating simulation results described by a second order polynomial equation ***[Eq.11]***.





Performing the first partial derivative with respect to the mass distribution and setting it equal to zero is possible to get the formulation for the optimal mass distribution in function of front-to-rear ratio of kinetic rolling radii (K_W) and the front wheels lead (L) as outlined in ***Eq.12*** and depicted by red ridgelines on the regression surfaces.

$$\eta_T = 0,403 + 0,31K_M - 0,164L + 0,172K_W - 0,114K_M^2 - 0,517L^2 - 0,201K_MK_W + 0,28K_ML - 0,02K_WL \quad \text{[Eq.11]}$$

$$\frac{\partial \eta_T}{\partial K_M} = 0$$

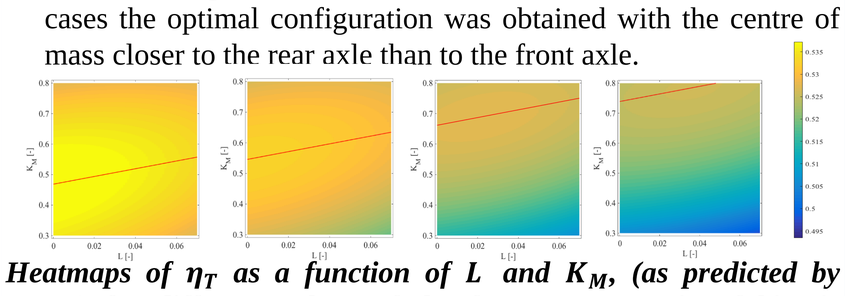
$$K_{M,opt} = \frac{-0.31 + 0.201 \cdot K_W - 0.28 \cdot L}{-0.228} \quad \text{[Eq.12]}$$

OPTIMAL MASS DISTRIBUTION EQUATION

The direction cosines of $\nabla\eta_T$ along h and B remain close to zero for all the simulations performed. This means that changing the value of these parameters does not substantially affect the value of η_T. Moreover, the signs of the direction cosines of $\nabla\eta_T$ indicate that η_T depends monotonically on K_W and non-monotonically on K_M and on L. This means that, within the domain of variation of the design parameters, η_T has a maximum value: this value can be the optimum set of tractor design parameters that maximises the power delivery efficiency of the vehicle.

4 Optimal tractor layout

- Within the range of variation of the design parameters explored in this study, ***the maximum power delivery efficiency was found for a tractor having no lead of the front wheels, equal kinetic rolling radii of the front and rear tyres and the centre of mass shifted towards the front axle (mass distribution: 46% on the rear; 54% on the front).***
- For traditional non-isodiametric tractors ($K_W \approx 0,7$) the optimal mass distribution is markedly shifted on the rear, approximately 75% of the global mass.
- The simulations performed in this study show that if the front-to-rear ratio of kinetic rolling radii decreases (i.e. the front tyre kinetic rolling radius becomes smaller than that of the rear tyre) the power delivery efficiency decreases.
- If the lead of the front wheels increases, in order to restore the maximum power delivery efficiency the tractor centre of mass should be shifted rearwards. This is due to the fact that the presence of lead of the front wheels forces the slip of the front wheels to be greater to that of the rear wheels. As a result, in this cases the optimal configuration was obtained with the centre of mass closer to the rear axle than to the front axle.



Heatmaps of η_T as a function of L and K_M, (as predicted by Eq.11) for different values of the front-to-rear ratio of kinetic rolling radii (K_W=1; K_W=0.91; K_W=0.79; K_W=0.7). The red lines are the maximum efficiency lines for a given value of K_W.

5 Final Remarks

This study presents the following innovations with respect to the current state of the art of the technical literature:

- This study defines 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.
- 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.
- The tractor-model presented in this thesis is versatile 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 in the on-board vehicle electronics allows keeping the vehicle always in the best operation mode producing fuel savings.
- In general, this study 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.