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On the traction tests: how they affect the performances of tractor tyre combination

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Abstract. In the last decades improving efficiency became the predominant theme of tractors and tyre manufacturers. Performed traction tests on the field are the most helpful instrument for evaluating vehicle performances under different load conditions that can rapidly replicate real tractor configuration and usage. This work performed two traction test procedures with a New Holland tractor with continuously variable transmission equipped with Michelin very-high flexion tyres and wheel force transducers. This tractor was connected to another used as a braking unit and tested with two traction test procedures denoted as transient and steady-state procedures. In the former, the braking unit was driven at a fixed velocity and the pulling tractor increased the wheel velocity, progressively increasing the drawbar force. Instead, in the second, the pulling tractor was driven at a fixed velocity and the braking unit reduced its velocity at different levels thus applying a discretely increasing drawbar force. The collected data were analysed to evaluate parameters related to traction capability and efficiencies, such as vehicle traction ratio, traction efficiency and power delivery efficiency. Procedures were compared in terms of reproducibility, variability, and repeatability. Both test methods have pros and cons, but the steady-state procedure provided better accuracy in the results, an easier way to impose and control different test parameters, and the best test-to-test repeatability. The results of this work help understand how data collected by traction tests performed with the latest generation tractors could be affected by the testing procedures.

Keywords: Drawbar tests, Wheel Force Transducers, Tractive performance, Traction tests, Data variability.

1 Introduction

The efficiency of the operations is usually quantified as the pulling power available at the drawbar compared to that provided by the engine, this parameter is denoted as power delivery efficiency (η_{PDE}) in literature [1]. Generally, traction tests are conducted by tractor and tyre manufacturers focusing on the performance of the tractors and the tyres independently. However, it is widely known that these two factors are closely interrelated. To assess tractor drawbar performance, traction tests are carried out by varying drawbar loads causing a tractor slip variation. Several testing methods are reported in the literature [2], but almost all of them were performed on concrete or applied only to tractors with mechanical transmissions or standard tyres [3], [4], [5]. In the recent past, tractors have been equipped with continuously variable transmissions (CVTs), increased flexion tyres (IF), and very high flexion tyres (VF) [6], respectively affecting the transmission efficiency and tyre-soil interaction. This work aims to evaluate, in terms of reproducibility, variability [7], and test-to-test repeatability, the impact of different traction test procedures on the results of traction tests performed over the newest generation tractor equipped with the latest tyre technology.

2 Materials and Methods

Tests were performed with a New Holland T7.315 HD tractor (CNH Industrial SpA, Basildon, UK), with CVT transmission. The tractor characteristics are given in Table 1. The tractor was equipped with VF tyres Michelin AxioBib2 (Michelin S.C.A., Valladolid, ES, and Troyes, FR) and wheel force transducers sensors (WFTs) (LW-2T-100K, Michigan Scientific Corporation, Charlevoix, US) on the four wheels. WFTs measure forces and torques on the three spatial axes and the wheel's angular velocity. A right-handed axis reference system is assumed throughout this work. X and Z axes are respectively parallel and perpendicular to the ground and positively oriented, correspondingly, in the direction of vehicle motion and downward.

Table 1: Technical specifications of the tractor used for the tests.

Engine maximum power [kW]	230
Ballasted static mass [kg]	19370
Rear – Front ballast [kg]	4700 - 3100
Rear – Front axle static mass [%]	60-40
Rear – Front tyres	VF 710/70 R42 – VF 600/70 R30
Rear – Front pressure [bar]	1 – 1
Rear – Front rolling radius [m]	0.971 – 0.736

The tractor was equipped with a Global Navigation Satellite System (GNSS) receiver (xProGPS_nano, Suchy Data Systems, GmbH, Erdweg, DE) to acquire the tractor ground velocity (V_t), a CAN-Bus data logger (Kvaser Memorator Pro 5xHS, KVASER, Molndal, SE) to acquire engine speed (ω_e) and engine torque (T_e). At the same time, a load cell (NBC Elettronica, Sondrio, IT) was used to acquire the drawbar force (F_d). From the WFTs signals of forces in the motion direction (F_{xj}^{WFT}), forces perpendicular to the ground (F_{zj}^{WFT}), wheel torques (T_{w_j}), and wheel angular velocities (ω_{w_j}) were acquired. The subscript j = left front, right front, left rear and right rear, indicate the different wheels. In this study, the tractor and tyres were tested with two testing procedures denoted as transient procedure (TP) and steady-state procedure (SSP). In both the vehicle was connected to a breaking unit (Fendt 942 Vario, Marktoberdorf, DE), ballasted with a 3460 kg ripper on the rear (Alpego Mega Craker KX 410-9, Alpego S.p.A., Lonigo, IT) and a front ballast of 1800 kg. In the TP, a secondary braking unit (John Deere 8R410 AutoPow^{TM}, Waterloo, US) was used to keep the velocity of the convoy constant (Fig. 1).

Fig. 1: Tractor under testing followed by the two braking units connected through ropes during a repetition of the transient procedure.

In TP, the braking units were driven at a fixed V_t equal to 1 $m\ s^{-1}$, and then the pulling tractor increased its wheel peripheral velocity (V_w) until 50% of slippage, progressively increase the F_d, and then returned to decrease the V_w until 0% slippage (Fig. 2 – left). Thus, during each TP test increasing and decreasing ramps of pulling tractor V_w were performed. In SSP, the engine speed of the pulling tractor was set at 1900 rpm by the manual throttle, the tests were performed using two different V_w, 0.85 and 1.4 m s^{-1}, maintained fixed during the test. In SSP, when the convoy of tractors reached the target velocity, the braking unit reduced the ground velocity of the convoy with steps of 10% of the target velocity up to reach 50% of slippage of the pulling tractor (Fig. 2 – right), with a consequently stepped increased of F_d. In both procedures, differentials were locked, and the four-wheel drive mode was engaged.

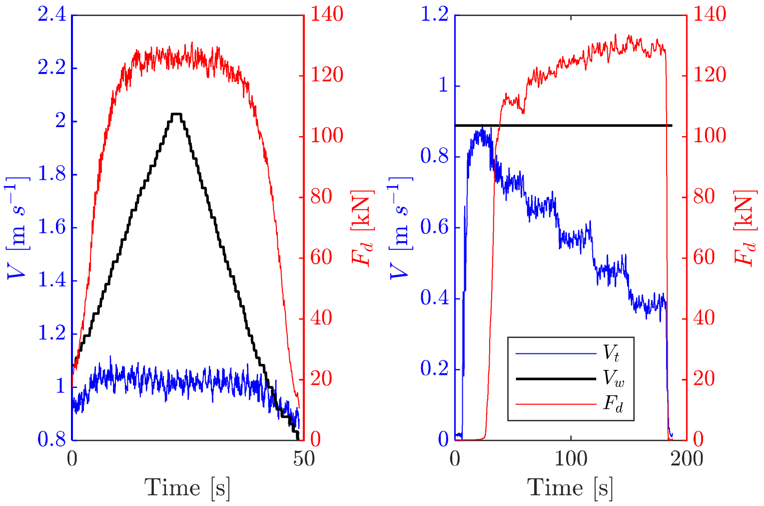

Fig. 2: Tractor ground velocity (**V_t**), requested wheel velocity (**V_w**) and drawbar force (**F_d**) trends for Transient Procedure (TP) (left) and Steady-State Procedure (SSP) (right).

Four repetitions of each test, alternated between TP, SSP at 0.85 $\mathrm{m\,s^{-1}}$ and SSP at 1.4 $\mathrm{m\,s^{-1}}$, were performed on the same field in the north of Italy, Dovera (CR), (45°21′28.3″ N, 9° 32′ 24.1″ E) the field humidity measured according to the ASTM standard [8] was 18.5%, and the average Cone Index (CI) [9] of 60 penetrations, measured by a penetrologger with a cone tip dimension of 12.7 mm (Fieldscout SC 900, Spectrum Technologies Inc., Aurora (IL), USA), in the depth between 0 and 150 mm was 0.795 MPa. Based on the Brixius [3] classification, the soil at the field site was identified as 'medium or tilled soil' according to the CI values recorded on the day of testing. The soil is classified as sandy loam textural class [10].

The tractor slippage (s), referred to the rear axle wheels, was calculated as reported by Wong [12] in Eq.(1).

$$s = 1 - \frac{V_t}{r_{rr} * \omega_{w_{RR}}}$$

Eq.(1)

where r_{rr} is the rolling radius of one of the rear wheels calculated such as reported in Eq.(2), where $\omega_{w_{RR}}$ is the angular velocity of the right rear wheel measured by the WFTs, proceeding with the tractor self-propelled on concrete, without any load applied to the drawbar.

$$r_{rr} = \frac{V_t}{\omega_{w_{RR}}}$$

Eq.(2)

The vehicle traction ratio (VTR), traction efficiency (η_{TE}) and η_{PDE} were calculated as the following Eq.(3), Eq.(4) and Eq.(5).

$$VTR = \frac{F_d}{\sum_j F_{z_j}}$$ Eq.(3)

$$\eta_{TE} = \frac{F_d * V_t}{\sum_j T_{w_j} * \omega_{w_j}}$$ Eq.(4)

$$\eta_{PDE} = \frac{F_d * V_t}{T_e * \omega_e}$$ Eq.(5)

where the vertical net force of the j-th wheel (F_{z_j}) is defined in Eq.(6), as well as the horizontal net force (F_{x_j}). Indeed, WFT's forces must be corrected since their axes were not vertically aligned with the vehicle reference system. Measured forces were projected on the absolute vehicle reference system through the rotational matrix [11]. Moreover, unsuspended masses force (F_{zj}^{wheel}), including tyre and rim weight previously measured by lifting the tractor, must be added to the vertical forces to account for the soil reaction.

$$\begin{cases} F_{x_j} = F_{xj}^{WFT} * cos(\theta_j) - F_{zj}^{WFT} * sin(\theta_j) \\ F_{z_j} = F_{zj}^{WFT} * cos(\theta_j) + F_{xj}^{WFT} * sin(\theta_j) + F_{zj}^{wheel} \end{cases}$$ Eq.(6)

In the last formula, θ_j is the static transducer angle misalignment measured by a digital protractor (Pro 360, Mitutoyo Italiana S.r.l., Lainate (MI), IT). θ_j changed for each wheel and was defined as positive if the transducer was forward-oriented with respect to the vertical axis of the vehicle reference system. In the TP, the mean values were separately calculated for increasing and decreasing ramps every 2% of s values. For SSP, tests performed at 0.85 and 1.4 m s^{-1} were considered together in the analysis and a mean value for each steady-state step was calculated. Fitting curves used to fit the VTR, the η_{TE} and the η_{PDE} (with respect to s) are bi-exponential as reported in Eq.(7), Eq.(8) and Eq.(9), where A, B, C, D, E, F, G, H, J, K, L and M are the fitting coefficients. The latter were selected to automatically ensure the maximisation of the coefficient of determination (R^2) at least at a value above 0.9.

$$VTR = A * e^{B*s} + C * e^{D*s}$$ Eq.(7)

$$\eta_{TE} = J * e^{K*s} + L * e^{M*s}$$ Eq.(8)

$$\eta_{PDE} = E * e^{F*s} + G * e^{H*s}$$ Eq.(9)

3 Results and Discussions

Trends of VTR, η_{TE}, and η_{PDE} obtained from both procedures are coherent with those reported in previous similar studies [1], [13]. However, TP tests returned some trend discrepancies between data collected during increasing and decreasing ramps as shown for VTR in Fig. 3 – left. Specifically, during the increasing ramps of the tests, traction parameters resulted in a lower trend with respect to the subsequent decreasing phase. This difference could be referred to as hysteresis. It is caused by different engine responses and the CVT transmission, which introduced uncontrolled variable gear ratios during the test due to the transmission variator. In SSP the data collected in terms of VTR and η_{TE} are not influenced by the two velocities at which the tests were performed. This is clear in Fig. 3– right since VTR data points from the two tests overlap. Fig. 3 show also the 90% prediction bounds for VTR with respect to s for TP and SSP procedures. For both procedures, data points are included in the prediction bounds. On the other hand, TP returns a wider prediction bound due to the hysteresis. For the TP test, the wider prediction bound and the variability between increasing and decreasing ramps were observed also for η_{TE} and η_{PDE} with respect to s, although, they are not shown here for results conciseness.

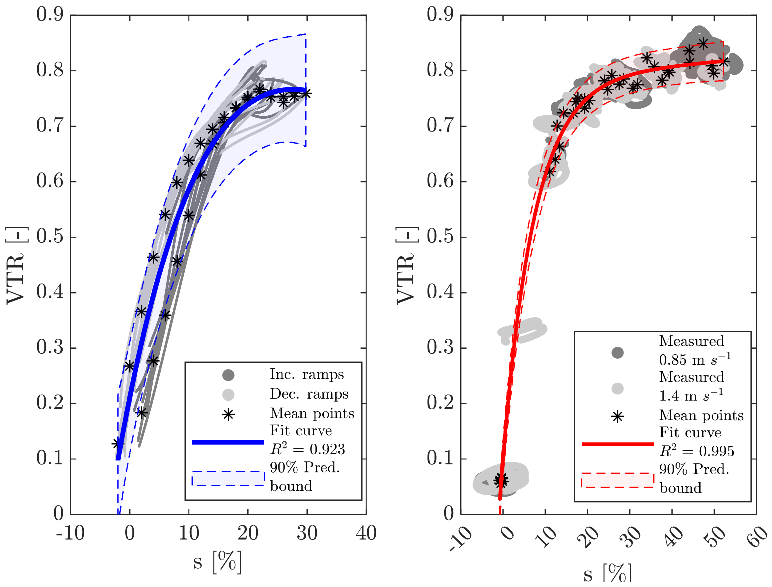

Fig. 3: Fitting curves of Vehicle Traction Ratio (VTR) with respect to tractor slippage (s) and 90% prediction bounds with respect to measured points for Transient Procedure (TP) (left) and Steady-State Procedure (SSP) (right).

Fig. 4 shows that for VTR the fitting curve return by the two procedures are very close, however, the maximum s values reached for TP tests are lower with respect to SSP′s ones. Indeed, this was due to the high tractor mass and the high tyre traction which caused the engine to reach its operational limit. This meant the tractor was not able to sufficiently increase the V_w to reach 50% of s. For η_{TE} and η_{PDE}, the curves have a common trend with respect to s, as they rapidly grow at low s values (reaching their maximum) and then decrease for higher s values. This was also observed in previous studies [1], [13]. However, for SSP, the maximum values and the peak positions are in accordance with tests on similar fields in the literature [14].

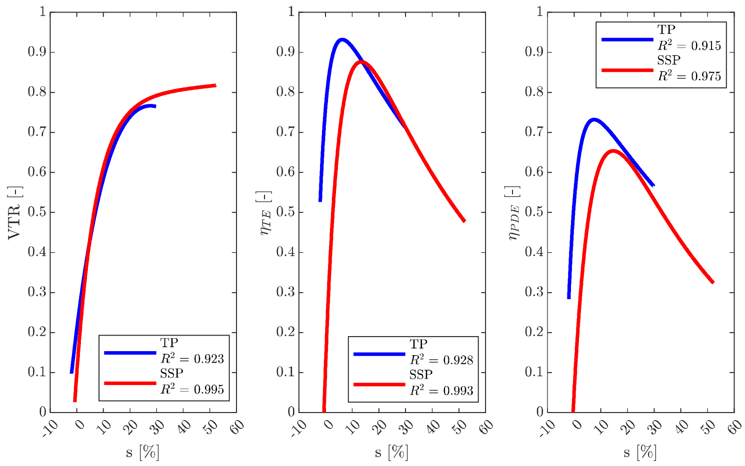

Fig. 4: Fitting curves of Vehicle Traction Ratio (VTR) (left), Traction Efficiency ($\boldsymbol{\eta_{TE}}$) (centre), and Power Delivery Efficiency ($\boldsymbol{\eta_{PDE}}$) (right) with respect to tractor slippage (s) for Transient Procedure (TP) and Steady-State Procedure (SSP).

4 Conclusion

Traction tests for agricultural tractors are an important instrument to rapidly investigate the vehicle under different drawbar loads and tractor slippages. In this article, two different testing procedures were applied to a vehicle equipped with CVT transmission and VF technology tyres. Data analysis focused on VTR, η_{TE}, and η_{PDE} to evaluate traction capability and vehicle and tyre efficiencies. Data collected with the TP procedure showed trends affected by increasing and decreasing ramps. On the other hand, the two velocities of SSP tests returned overlapping data evidencing the possibility to reduce the number of tests. Based on the observed results, we assert that the SSP outperforms the TP, particularly in the assessment of efficiencies in tractors equipped with CVTs. This study highlights how testing procedures affect vehicle behaviour and the data collected. The SSP procedure returns stable data that can be mediated and interpolated by fitting curves, at the same time remaining representative of the collected data to evaluate tractor and tyre efficiency. Finally, the study has examined a single operational condition. As a next step, it might be advisable to analyse the tractive performance of different vehicle configurations and operating conditions.

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