

Computing time and fuel requirements to assess efficiency of a field work from conventional laboratory tests : application to a plowing operation

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The development of large-scale agricultural mechanization required to sustain food production, combined with limited conventional fuel resources, spurs on to better assess the time and energy investments required for commodities production. The proposed analysis is based on the description of field working dynamics collected on an experimental tractor during a plowing operation. The energy needs can there be characterized as having a dual alternating profile, depending on the tractor working phase within the field. As a result, two field oriented performance indicators consisting in time efficiency [$\text{h}\cdot\text{ha}^{-1}$] and area specific consumption [$\text{l}\cdot\text{ha}^{-1}$] are defined out of the profile characteristics. A model converting the draft of an implement into an engine running point is then developed to compute these indicators. The model is fitted on data collected over conventional bench tests, and is validated by an application to a plowing operation. Lastly, a sensitivity analysis on the operational parameters is conducted.

Key words: tractor, field operation, working dynamics, operational efficiency indicators, fuel consumption

Introduction

Agricultural tractors are operated all along the year, using various pieces of machinery to cover different field operations. The powertrain is therefore subjected to highly variable demands in terms of speed and load (Smith 1993), thus requiring different levels of fuel consumption. This complicates the definition of robust efficiency indicators assessing the energy inputs in relation with agricultural production. Thereby, the frame of analysis is limited when evaluating the environmental impact of a product through Life Cycle Assessment methods (Pradel, Rousselet et al. 2010).

The energy efficiency of agricultural tractors is currently assessed according to the OECD standard (OECD 2012), the procedure consisting in tests run over laboratory steady-state modes. Either for the engine or for the transmission, each test is based on a set of different running points defined by associating engine speed and torque, -respectively- tractor speed and draft. These points are considered to represent one or a group of different field operations, but in fact they do not always reflect actual operating conditions.

Energy efficiency of agricultural tractors is conventionally quantified through a specific fuel consumption expressed in [$\text{g}\cdot\text{kWh}^{-1}$] (Ortiz, Canavate et al. 2007; Ortiz-Canavate, Gil-Sierra et al. 2008). The most common way for defining the power requirements is given by the US-EPA, consisting in multiplying a weighting coefficient by the nominal engine power (Harvey 2003).

Using this approach, it is very difficult to separately express the time saving and fuel reduction associated to an increasing engine power. Many field data acquisition campaigns have already been organized to describe the energy requirements for operating different implements (Kim, Kim et al. 2000; Alsuhaibani, Al-Janobi et al. 2010) and to characterize the related efficiency (Adamcuk, Grisso et al. 2004). To build up a comprehensive energy balance, operational efficiency indicators should be introduced.

This paper presents a new approach for the evaluation of agricultural machinery (e.g. tractor+implement) performance, consisting in describing the energy requirements set by an implement during field applications and in expressing the related operational efficiency. A long term data acquisition campaign based on analog and digital recorded signals which monitored the different power flows was organized to better understand the related working dynamics. Depending on the tractor working phase within the field (i.e. crop line or headland turning),

we consider the mechanical energy needs as having a dual alternating profile. The experimental setup consisting in a tooled-up tractor providing the descriptive signals used for the identification of the working phases is presented. Statistical analysis was conducted for the definition of the corresponding magnitudes and frequency. A parametric model computing the operational efficiency was defined according these alternating phases. Its computation requires a set of parameters that were determined from results of conventional bench test operations.

From a steady state laboratory condition approach, we show how to convert conventional bench test results into operational efficiency assessment and thereby how to propose a field oriented diagnostic. The result relies on two indicators: time efficiency TE [$\text{h}\cdot\text{ha}^{-1}$] and area specific consumption C_{ha} [$\text{l}\cdot\text{ha}^{-2}$].

For application purposes, the method is specifically applied to a plowing operation. In the last section, we assess the model validity by comparing the predicted results to the measured ones. Finally, a sensitivity analysis is conducted to evaluate the impact of the different field parameters capable of affecting the operational efficiency.

Material and methods

Experimental tool layout

The indicators are based on input data defined by the operational working conditions. In order to identify the different possible profiles depending on the implement type, we monitored the working dynamics of a tractor used over diverse agricultural operations. A data acquisition campaign was organized, consisting in monitoring a fully instrumented Massey Ferguson 6475 tractor. This tractor is equipped with a 90kW engine (Perkins Tier III, 6 cylinders, 6.6L, rated speed of 2200 RPM), corresponding in France to a mid-size popularly sold tractor (Agreste 2005; Axema 2012). It is mounted with a manual 4-gear x 6-powershift transmission. The principle of the campaign was to lend the tractor to a farmer who used with the different implements for tillage, seeding, fertilizing and for transport operations. Total recorded data represents 570 hours of operation, including farm to field transit and transport operations.

The experimental setup consisted in combining two sets of measuring devices. The measurements of the on-board standard built-in sensors providing information through the embedded CAN and ISOBUS buses were extended by additional sensors. Decoding CAN signals according to the standard (SAEJ1939 2006) provided access to engine speed N_e [RPM], engine percentage of load L_e [%], and fuel consumption C_h [$\text{l}\cdot\text{h}^{-1}$]. Global vehicle operational parameters were given by the ISOBUS messages, with information on vehicle speed, selected gear and hitch position. Signals were monitored and sampled at actual emission rates by a dedicated recording device (EFFIBOX) connected to the buses via the J1939 diagnostic plug located behind the seat. This system also recorded GPS position and speed, enabling to measure the tractor ground speed (accuracy of +/- 4%).

Additional sensors were installed to evaluate power flows delivered by the three main power outputs dedicated to the wheels, PTO and the hydraulics. Torquemeters using telemetry transmission (MANNER 1-channel PCM) were designed and mounted on both rear axles in order to measure the corresponding torques. Front axle power is assumed to be given by measuring torque and rotational speed of the 4-wheel drive shaft. Individual rear axles rotating speeds are measured with incremental encoders. The 4-WD shaft rotating speed is given by knowing the rear final drive speed and the corresponding transmission ratio read from the transmission schematics. Commercially available PTO torque- and speed-meter (DATUM 420 PTO-type) was used to monitor the power delivered at the rear shaft in case of PTO driven implements. Further, the main pump line before the rear hydraulic block was instrumented with a flow turbine (HYDROTECHNIK RE6) and a pressure transducer in order to measure the hydraulic power generated. Considering the fan as a significant power-absorbing auxiliary, fan speed was recorded as well. All the signals of the specially added sensors were recorded by a CAMPBELL CR-3000 data acquisition board fitted with a serially connected CR-1000 for extension. The recording equipment ran as an autonomous black box, enabling a non influencing observation of the different activities throughout the year.

Preliminary laboratory measurements

Before launching the field campaign, the tractor was run on the IRSTEA tractor testing platform. PTO dynamometer and traction tests were conducted following the OECD code 2 testing procedure (OECD 2012). Engine and traction power characteristics were determined. Conventional procedures were extended to analyze and calibrate the signals available on the CAN-bus. We also proceeded to GPS tests and found +/- 4% of gap between the GOS speed and the truck speed.

Engine test and sensor calibration

The engine test consisted in 52 successive points evenly distributed across the engine map. We also included low speed and low load points which are not considered by the conventional procedure. We verified the consistency of the information provided by the CAN-bus by making a comparison to test-bench data which served as a benchmark. Whereas engine speed N_E and fuel consumption C_n are directly given in engineering units ([RPM], respectively [l/h]), the engine torque is expressed in engine load L_E [%]. The indicated percentage of load expresses the total delivered engine torque i.e. including the energizing of engine accessories (like cooling fan and pumps) and the engine internal friction. Modern tractors are fitted with a viscous coupling unit to propel the cooling fan, consequently, there is no fixed ratio between the engine speed and the fan speed. For a given effective torque measured at the PTO, the total engine load can vary due solely to the varying fan speed. The calibration giving the engine effective torque T_E [Nm] as a function of the engine load L_E has therefore to take into account the fan absorbed torque as a function of its rotational speed. This is defined by the technical specifications of the fan. The engine total torque $T_{E,T}$ is then assumed to be a linear function of the engine load (L_E), where α and β to be determined after calibration.

Determining transmission efficiency

Following the OECD procedure, transmission performance evaluation consisted in using a dynamometric truck to apply given drafts at the drawbar at different speeds, running on a concrete track. The test was done with 3 different gears (2D, 2E and 3A), corresponding to frequently selected gears for field operations. The slip taking place on the track was also recorded for each test point. Measurements were conducted over a [5-9] km.h⁻¹ speed range with draft forces of 8 to 48 kN. Usually, the conventional procedure aims to test the global powertrain performances, measuring the engine fuel consumption for a given draft power. Here, the equipment was used to singly evaluate the traction performances, the diagnostic being not affected by the losses occurring at the [tire + soil] interface. To these purposes, the torquemeters installed on the transmission output axles enabled a precise evaluation of the transmission efficiency. This is given by the ratio of the output power delivered at the axles over the power delivered by the engine. By taking into account the torque lost for the fan propulsion, it was defined by :

$$\eta_{trans} = \frac{P_{axles}}{P_E} = \frac{T_R N_R + T_L N_L + T_{4WD} N_{4WD}}{\left[(\alpha L_E + \beta) - 5800 \left[\frac{N_{Fan}}{2000} \right]^3 \frac{75}{2\pi N_{Fan}} \right] N_E} [-] \quad \text{Eq. 1}$$

where $N_{R/L}$ and $T_{R/L}$ represent the speeds and torques respectively measured at the rear right and left axles. 4WD refers to the measurement of the power communicated from transmission to the front axle via the cardan shaft. P_E represents the effective power delivered by the engine (with fan torque subtracted from engine load percentage), using the speed and crankshaft torques given by the CAN-bus.

Field experiment and working dynamics analysis

The work presented here is oriented to a plowing operation, carried out on a rectangular field, using a 5-share plow, with a 14-20" variable share-width. For the experiment, it was set into a constant 16" configuration (width $l_{imp} = 2.03$ m, depth $d_{imp} = 0.25$ m), working on a clay-loam soil (15-25% humidity, cone index $CI = 1.2$ Mpa). The acreage was measured through GPS data mapping, enabling to determine the field length $L_{line} = 680$ m. Assuming zero overlap, the field width was determined by counting $n_{line} = 32$ paths multiplied by the implement width, where $l_{field} = n_{line} \cdot l_{imp} = 65$ m, covering a surface $S = 4.42$ ha in a duration of $D_o = 4$ h 07 min. The total amount of fuel needed for the operation was obtained by integrating instantaneous consumption over time, totalizing $C_T = 77.83$ l. Abnormal idling periods dedicated to plow setting or related technical issues were removed from the data before statistical analysis.

Procedure to analyze tractor and implement working dynamics

Tractor working dynamics is very specific compared to that of other vehicle types. General field work is usually based on two modes of functioning, considering the tractor either working in a crop line or turning at field borders. As a consequence, depending on the operation type, several vehicle-state descriptive variables (engine speed, vehicle speed, engine load, hitch position, hydraulic pressure...) follow a two level-alternation repeated along the field. Regarding the implement application following a continuous pattern on a rectangular field, we assume that the working dynamics (e.g. engine speed N_E) can be idealized and considered as having a square profile (Fig. 1) of particular characteristics.

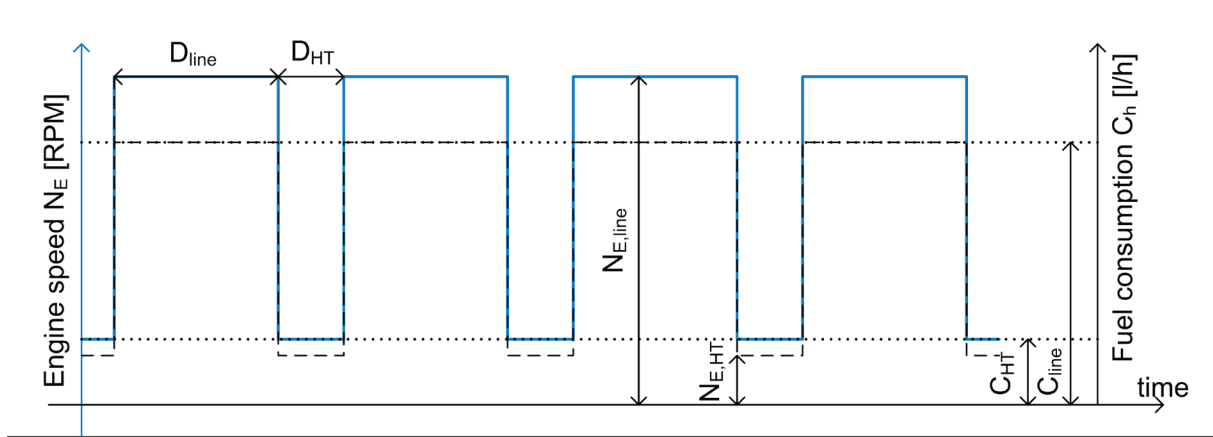


Fig. 1. Idealized square profile for dual stage operation

The high level duration D_{line} is the time defining the mean time needed to operate a crop line. This value depends on both the field length and the speed. The amplitude $N_{E,line}$ is the dependant on the speed chosen for the operation. The low level duration D_{HT} corresponds to the time needed to turn the tractor at the end of the crop line. $N_{E,HT}$ is the amplitude of the mean engine speed during the headland turning phase. The profile characteristics (D_{line} , D_{HT} , $N_{E,line}$, $N_{E,HT}$) are determined by statistical analyses of field measurements after having distinguished crop line sequences from maneuver sequences. One or several of the previously listed variables can be used to designate the working phase. For the farmer equipped with this tractor, the usage of the speed regulation feature along crop lines makes the engine speed very constant during this working phase. Figure 2 shows for instance the distribution of the engine speed recorded during the operation.

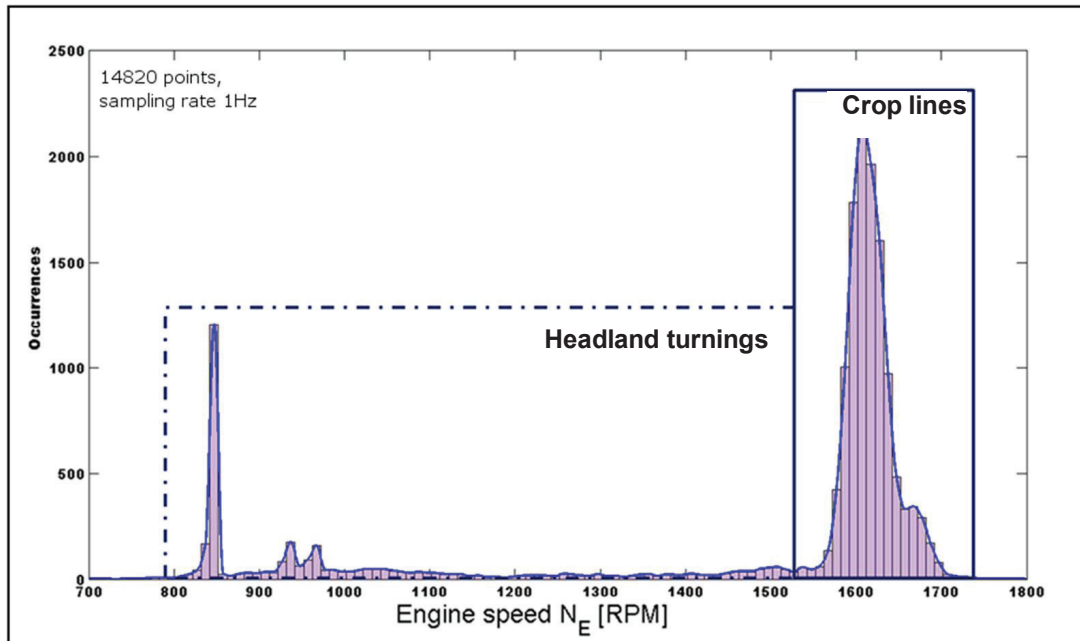


Fig. 2. Distribution of the engine speed over the plowing operation

Two modes of functioning can so be considered for the engine speed distribution, with a quite obvious Gaussian-like pattern for the peak around 1600 RPM and secondary spread-out multi-modal distribution. In order to propose an algorithm usable for any implement, including the ones used at the drawbar, a specific algorithm based on the engine speed distribution plot is proposed to distinguish crop line from headland turning data:

- Plot the distribution of the instantaneous engine speed signal $N_E(t)$
- Read graphically the distribution to determine a mean value for the high level peak $\mu_{NE,line}$.
- Estimate the width of the curve at its base to determine the standard deviation $\sigma_{NE,line}$.
- Sort out crop line data from gross data when following criterion is met :

$$|N_E(t) - \mu_{NE,line}| < 2\sigma_{NE,line}$$

Eq. 2

Any point meeting this criterion and whose direct neighbors also respect it is assigned to a class of data G_{line} corresponding to the crop line phase. All the other points corresponding to unstable sequences are attributed to headland turnings which will also include temporary idling phases. These points are therefore assigned to another class G_{HT} . In both G_{line} and G_{HT} classes, index discontinuities correspond to time breaks and mark a switch to another phase. This finally enables the signal to be broken down into several sequences of lines and headland turnings.

For any variable I describing the operation (engine speed, engine load, vehicle speed...), mean values are calculated. Considering the two classes of activities G_{line} and G_{HT} , Equation 3 is used to define the respective amplitudes of the two states of operations, crop line and headland turnings :

$$I_{line/HT} = \overline{I_{j,j \in G_{line/HT}}} \quad \text{for line and respectively headland turning descriptive variables} \quad \text{Eq. 3}$$

Modeling operational efficiency

Operational efficiency indicators

Operational efficiency is expressed in terms of area specific fuel consumption C_{ha} [$l \cdot ha^{-1}$] and time efficiency TE [$h \cdot ha^{-1}$], both highly correlated to the corresponding working profile characteristics (Fig. 1). Time efficiency represents the time required to cover a considered field surface, and is computed out of:

$$TE_p = \frac{25}{9} \frac{\frac{3.6L_{line} + D_{HT}}{V_{line}}}{l_{imp}L_{line}} [h \cdot ha^{-1}] \quad \text{where } L_{line} \text{ representing the field length} \quad \text{Eq.4}$$

The area being handled is defined by setting the path width given by the implement width l_{imp} [m] while assuming zero overlap. The speed V_{line} [$km \cdot h^{-1}$] corresponds to the ground speed over crop lines. Depending on the field length, V_{line} defines the productive time needed per line. As a productivity reducing parameter, headland turning time D_{HT} has also to be defined, here by statistical analysis. The area specific consumption corresponds to the total amount of fuel required to complete the surface, obtained by weighting the hourly consumption C_h [$l \cdot h^{-1}$] over line and headland turning time:

$$C_{ha,p} = \frac{25}{9} \frac{C_{h,line} \frac{3.6L_{line} + C_{h,HT}D_{HT}}{V_{line}}}{l_{imp}L_{line}} [L \cdot ha^{-1}] \quad \text{Eq. 5}$$

Both indicators are defined by the operation type and the working conditions but also by the field geometry. After reconstructing the working profile by setting the operational parameters V_{line} , D_{HT} , l_{imp} , L_{line} and running the low and high descriptive engine running points on the test bench, laboratory operation can finally be used to assess time efficiency and area specific consumption indicators.

Computing operational efficiency from operational parameters

Considering a given field application, the operational parameters chosen by the farmer include working speed, implement width and working depth, field length and headland turning time. Each of these affects directly the operational efficiency defined with time and consumption indicators, as previously mentioned. Time efficiency is affected by three groups of parameters related to agronomic, technical, and human issues (Steinkampf 1983). The engine running point depends on the operational parameters, thereby also on the hourly consumption. A flowchart (Fig. 3) presents a layout of a model converting the farmer's operational parameters into two operational efficiency indicators.

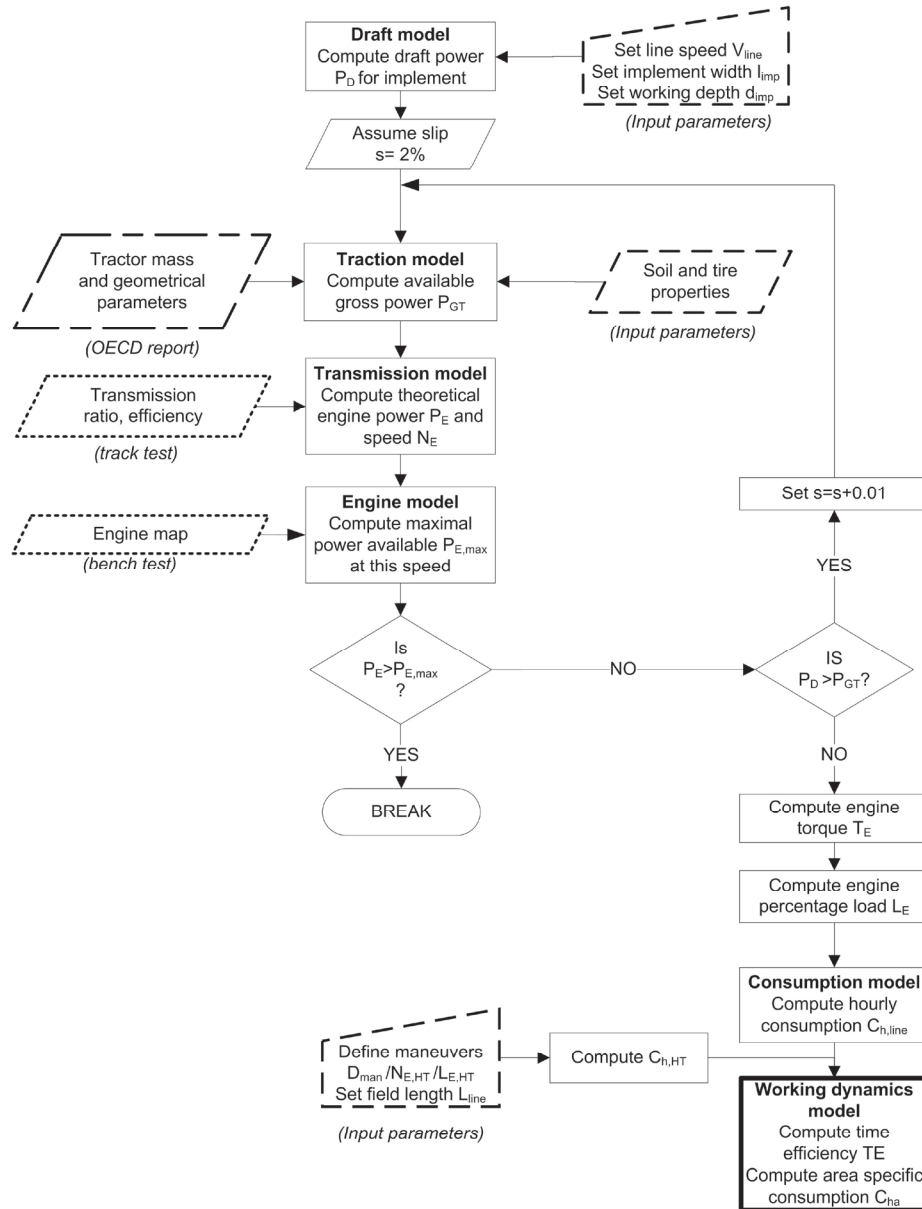


Fig. 3. Algorithm of the model computing the operational efficiency indicators

Engine actual power is distributed along transmission losses, slip, tire deflection and soil compaction, and finally draft power. We use those different subsystems to define backwards an engine running point regarding the operational parameters. For the achievement of a model including traction and transmission, as well as for the realization of an engine model and a consumption model, several sub-blocks are needed to execute the global model, following the steps below:

1. Compute draft power considering a draft force F_D (Kheiralla et al. 2004):

$$F_D(V_{line}, l_{imp}, d_{imp}) = [f_1 + f_2 d_{imp} + f_3 d_{imp}^2 + f_4 V_{line} + f_5 V_{line}^2 + f_6 V_{line} d_{imp}] l_{imp} [kN] \quad \text{Eq. 6}$$

2. Compute coefficient of traction and motion resistance (ASAE 1999) adapted to a 4WD tractor.
3. Compute axles dynamic weights, considering load transfer between both axles to determine the gross traction power P_{GT} (Sahu 2008) corresponding to the transmission output power.
4. Compute corresponding engine power P_E , considering transmission efficiency from own tests done on the track.
5. Compute engine speed N_E by considering vehicle ground speed, slip and tire radii.

6. Compute engine effective torque T_E needed to develop the power at the previously computed engine speed.
7. Convert the effective torque T_E into a corresponding engine load L_E .
8. Once the engine running point being determined, the original model from (Souza 1990) giving the brake thermal efficiency as a function of the engine speed and torque is adapted to predict the hourly fuel consumption as a function of engine speed N_E and load L_E :

$$C_h(N_E, T_E) = c_1 + c_2 L_E + c_3 N_E + c_4 L_E^2 + c_5 L_E^3 + c_6 L_E^4 + c_7 N_E^2 + c_8 N_E L_E \text{ [l.h}^{-1}\text{]} \quad \text{Eq. 7}$$

This model is fitted on the results of fuel consumption read out of the CAN-Bus, and compared to the test bench measurements operated prior to the field campaign.

The global model takes into account adherence and engine power limitation issues. After having converted the draft requirements into transmission power, if the engine power is overrun, the tractor stops. Adherence issues are treated with an iterative loop comparing draft power and gross traction available at the wheels. Slip is increased by a 1% step as long as the draft power exceeds the tractor draft capability. Headland turning time is considered statistically as a fixed value when a rectangular field is assumed. The hourly consumption during headland turning is also computed from Equation 3, after having determined the average engine speed and load occurring on the field for this phase. Finally, after setting a field length, operational efficiency is computed by using Equations 4 and 5.

Results

Test bench results

Engine test

On the basis of the information provided by the tractor manufacturer, we added the fan torque to the effective torque measured at the PTO so as to calibrate the total engine torque $T_{E,T}$ [Nm] as a function of the percentage of load. The results of the calibration are plotted in Figure 4.

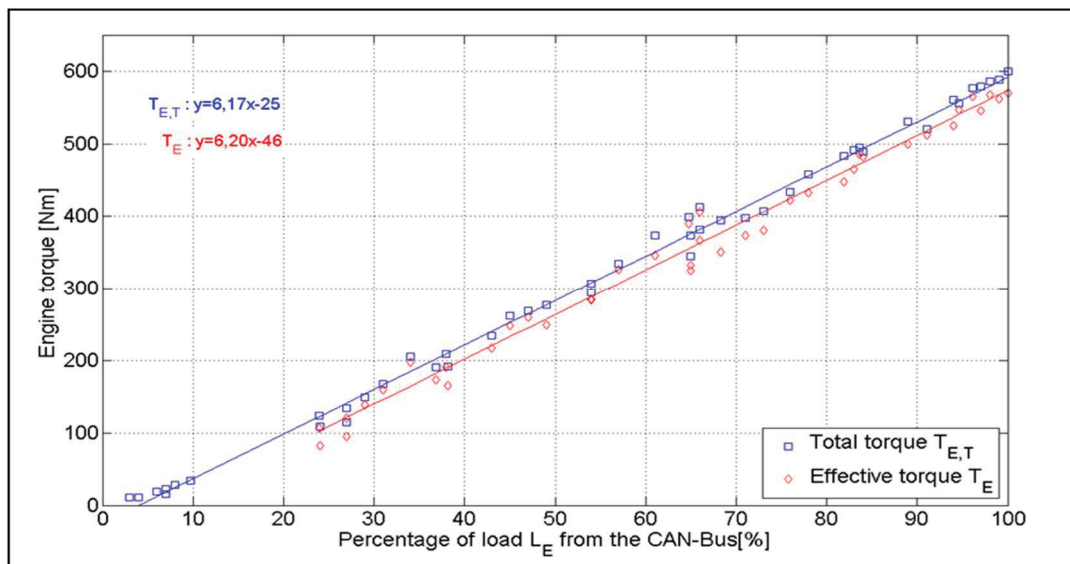


Fig. 4. Calibration of engine percentage of load L_E got via the CAN-bus

The linear regression (in blue) shows acceptable results regarding linearity and correlation ($R^2=0.9978$). The offset of -25 Nm is guessed to be due to the propulsion of the other accessories (i.e. water and lubrication pumps, alternator...) and also to engine internal friction. This regression is used to fit the parameters of Equation 1, where $\alpha=6.17$ [Nm/%] and $\beta=-25$ Nm.

For loads above 20%, when the fan torque can be neglected compared to the engine effective torque, a second regression gives the effective torque directly as a function of the load percentage. It also shows good correlation ($R^2=0.9954$) but with more discrepancy ($\sigma= 17.6$ Nm). For further purposes, and assuming the fan behavior between test bench operation and field operation remaining homogeneous, we integrate the fan torque directly into the load percentage by using the second regression formulated through:

$$T_E = 6.2 L_E - 46 \text{ [Nm]} \tag{Eq. 8}$$

For the engine speed and fuel consumption signals, good correlations between test bench measurements and CAN-based values confirmed the overall consistency of the information provided by the CAN network during the steady-state operations conducted during the calibration.

Besides, the data analysis enabled to fit the model of hourly consumption, as given by (Eq. 7).

The model coefficients are given in Table 1. The Figure 5 shows the result of the fit, where $R^2=0.9986$.

Table 1. Coefficients for the fuel consumption predicting model

$c_1=1.445496296$	$c_5=-0.000156655$
$c_2=-0.231913244$	$c_6= 0.000000755$
$c_3= -0.001105875$	$c_7= 0.000001327$
$c_4=0.010390967$	$c_8=0.000160999$

The fit using De Souza’s model permits an acceptable fuel consumption prediction once knowing the engine running point, and can then be used in the algorithm to compute the operational efficiency.

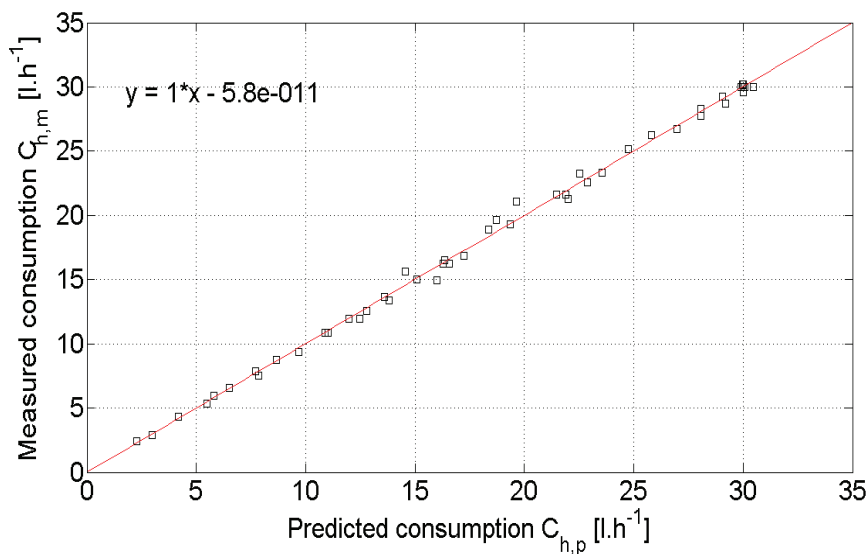


Fig. 5. Resulting fit of the hourly fuel consumption model

Transmission efficiency measurements

Figure 6 plots the efficiency results obtained during the conventional OECD transmission test as described in (OECD(2010)).

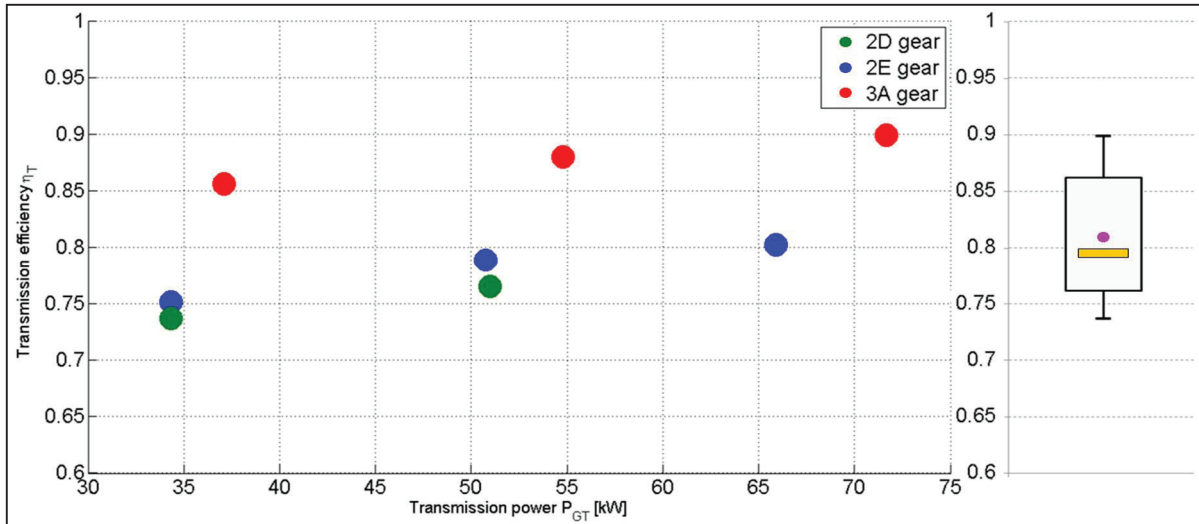


Fig. 6. Transmission efficiency for different gears at different power levels

The attached box plot gives the efficiency distribution, showing the different behavior depending on the chosen gear. Ortiz (Ortiz-Canavate, Gil-Sierra et al. 2008) considers that the efficiency ratio varies only slightly when operating under 8 km.h^{-1} . For the tractor tested here, gears 3A and 2E have similar transmission ratios ($q_{T3A} = 81.48$, $q_{T2E} = 82.87$), offering comparable driving speeds and vehicle behavior. As tillage operations are generally run within a limited low speed range, the effect of the speed on the transmission range can be neglected. We therefore consider for the transmission efficiency a mean value given by $\eta_T = 0.81$. This is the parameter set for the 4th step of the algorithm.

Field experiments: Characterization of the plowing activity

The gross data sequence was processed so as to distinguish crop lines from headland turning with the sorting algorithm based on the engine speed as defined in Section 2.3.1. Figure 7 illustrates the results for one hour of operation by representing the engine speed with alternating high-low level profile.

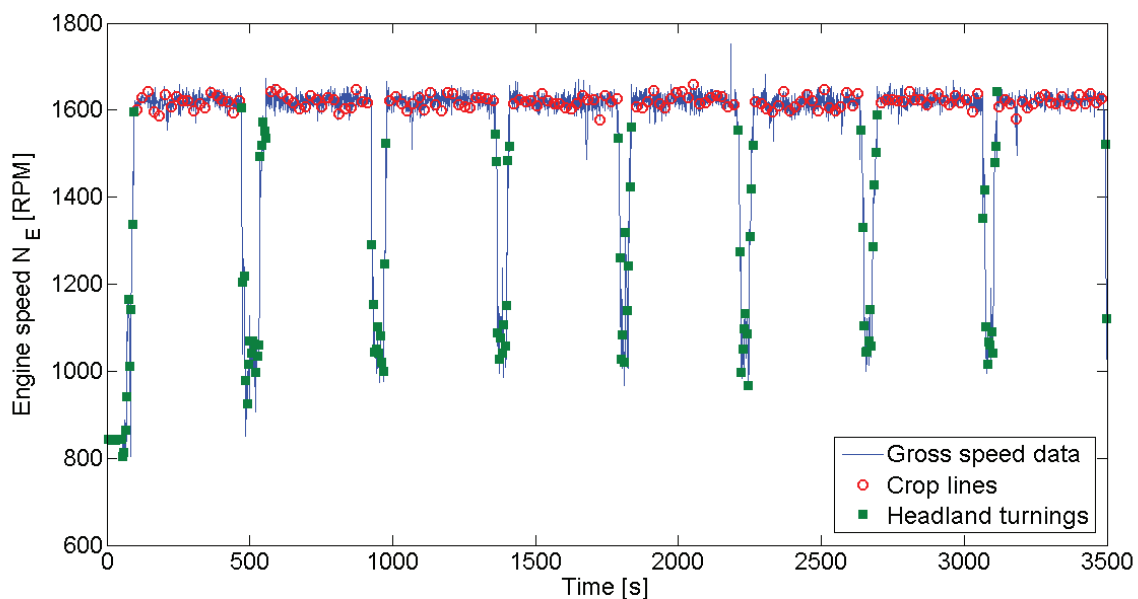


Fig. 7. Engine speed evolution, distinguishing crop lines and headland turning operations

The evolution corresponds to the idealized square profile. For each phases constituting the two groups of data G_{line} and G_{HT} , Figure 8 illustrates the corresponding normalized distributions of engine speed and torque, vehicle speed, and hourly fuel consumption.

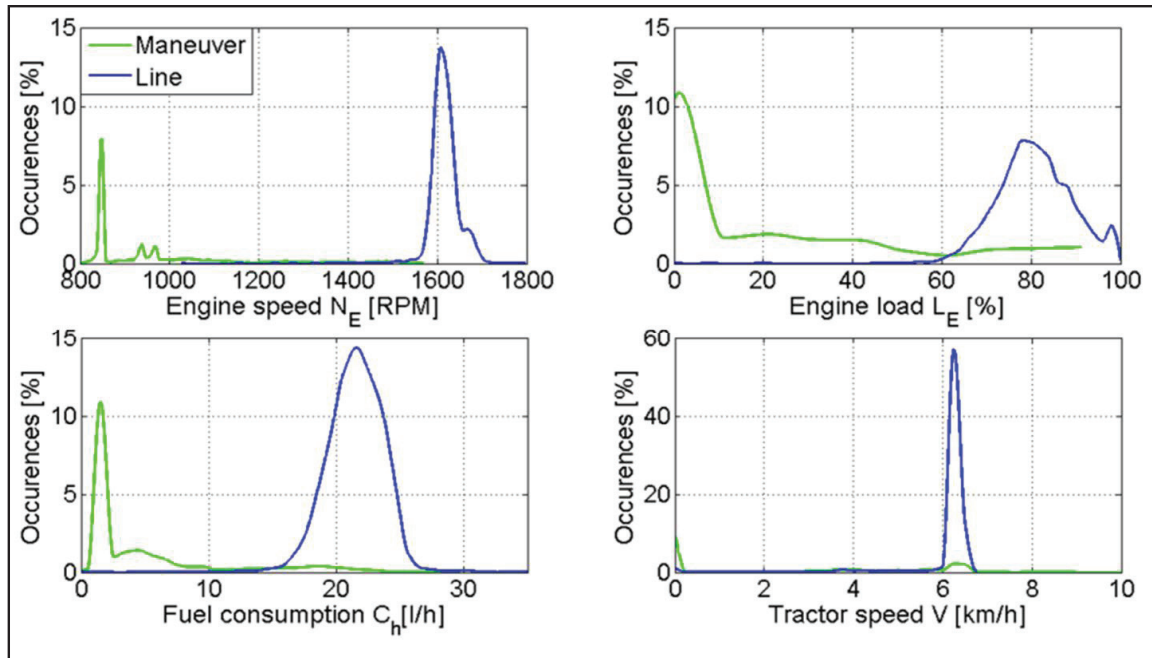


Fig. 8. Distribution of the tractor operating parameters as a function of the working phase for plowing

Identifying the field operational variables describing the working profile characteristics is made by reading the distributions. Over the crop lines, the engine speed was very constant around $N_{E, line} = 1616$ RPM. The percentage of load was $L_{E, line} = 79.7\%$ (equivalent to $T_{E, line} = 448$ Nm), showing more discrepancy for a speed $V_{line} = 6.3$ km.h⁻¹. For headland turnings, we determined $N_{E, HT} = 981$ RPM for a percentage of load $L_{E, HT} = 24\%$ (equivalent to $T_{E, HT} = 100$ Nm).

From the measured values ($N_{E, line, m}$ & $L_{E, line, m}$) and ($N_{E, HT, m}$ & $L_{E, HT, m}$), the hourly consumptions were computed by using Equation 7, leading to the predicted consumptions $C_{h, line, p} = 22.57$ l.h⁻¹ and $C_{h, HT, p} = 3.93$ l.h⁻¹. The line speed of $V_{line, m}$ measured in the experiment was 6.3 km.h⁻¹ over a length $L_{field, m} = 680$ m and a headland turning time $D_{HT, m}$ of 75 s. Table 2 compares the operational efficiency observed on the field and the one computed after reconstruction of the working dynamics obtained by using Equations 3 and 4.

Table 2. Field operational efficiencies measured and computed from square profile characteristics

	Field measurement	Computed efficiency
Time efficiency [h.ha ⁻¹]	$TE_m = S/D = 0.93$	$TE_p = 0.93$ according Eq.4
Surface consumption [l.ha ⁻¹]	$C_{ha, m} = C_t/S = 17.61$	$C_{ha, p} = 17.48$ according Eq.5

Whereas time efficiency shows good matching, surface consumption shows more discrepancy. This is due both to the +/- 0.5 l.h⁻¹ of error induced by computing consumption from De Souza’s model, and to the initial total acreage determination. However a good correspondence is found between field measurements and the results computed from the idealized square profile, showing a difference as low as 3.2%. It validates the ability to propose an operational efficiency from an idealized profile of the working dynamics. By setting field length, headland turning time and implement width, the hourly consumption of two steady-state points can be used to generate operational efficiency.

Modeling results

The previous identification method can be used all along the year to recognize typical engine running points that can later be run in laboratory operations. However, using a tractor is very subjective, so that it is reasonably not possible to set absolute values for any application. We conducted a sensitivity analysis to study the influence of the plowing parameters on efficiency indicators: tractor speed, working width and working depth. Their effects on time efficiency and area specific consumption are discussed hereafter.

Effect of tractor speed and implement width on the engine running point

Increasing the speed requires the powertrain to overcome the increase of both draft and motion resistance. The farmer’s choices regarding speed and plow width directly impact the engine operation. The effect of speed and plow width is discussed in Figure 9. It represents the running point across the engine map giving the maximum effective power available as a function of speed. Background contouring represents the corresponding hourly fuel consumption C_h , here limited to 12-30 l.h⁻¹. The working depth is $d_{imp} = 0.25$ m. The blue dots are a 100 points randomly taken from the G_{line} class representing the engine speed data corresponding to crop line operation.

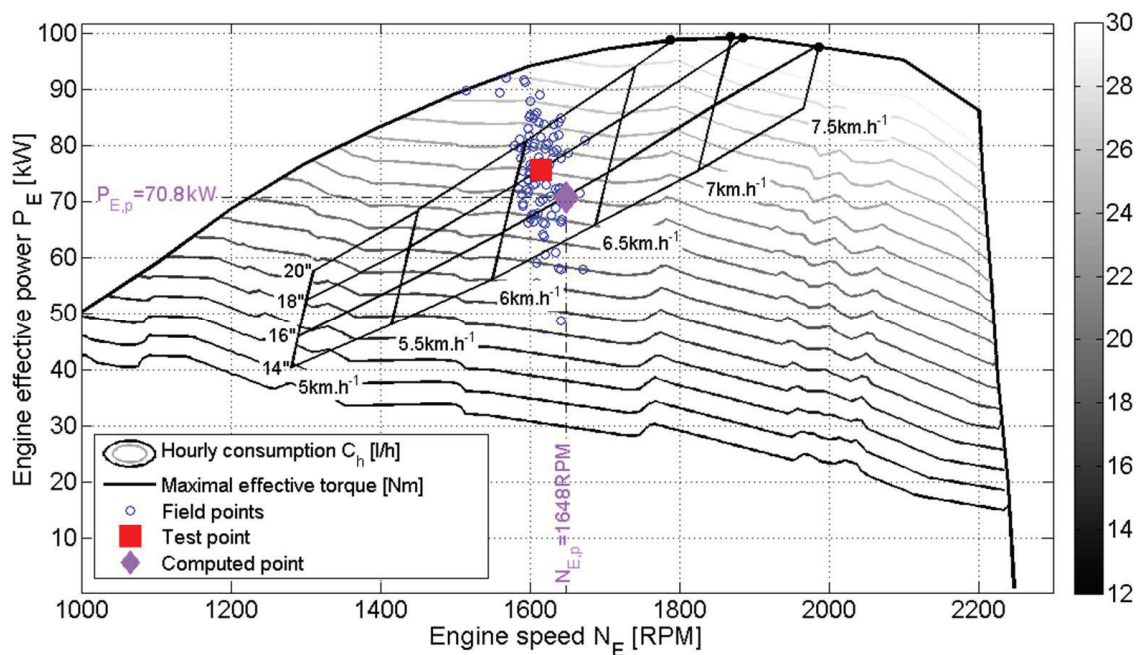


Fig. 9. Effect of tractor speed and implement width on the engine running point, related consumption C_h [l.h⁻¹]

In comparing the average values of power and speed to the instantaneous points, we observe that engine speed remains tightly centered around the mean value, whereas engine instantaneous power shows more discrepancy. The poorer consistency of the CAN-bus information in dynamic mode and the effects of hitch automatic leveling with respect to slip and inhomogeneous soil properties require further investigations. The difference between the modeled and measured points (with a 16” configuration of the plow moved at 6.3 km.h⁻¹) is due to a higher computed slip. Consequently the engine runs at higher speed to reach the given line speed. This error is thought to be due to tire and soil characteristics which are considered as constant in the model but which can in fact vary depending on the inflation pressure or the type of soil. The effective power developed by the engine increases with the tractor speed. In this configuration, increasing the speed by 0.5 km.h⁻¹ requires the engine to accelerate by 130 RPM and to increase the power by 10 kW. Also, at a given tractor speed, a larger plow requires more power but also a higher engine speed. This is due to the cumulative effect of higher draft requirements and higher slip.

Effect of field length and tractor speed on the operational efficiency

Higher tractor speeds affect the hourly consumption, but simultaneously reduce the time required to operate a crop line. This effect is shown in Figure 10 expressing the operational efficiencies. The abacus is built to consider various ground speeds and field lengths. It is given for a plow set in a 16” configuration, a working depth of $d_{imp} = 0.25$ m and a headland turning time of $D_{HT} = 75$ s.

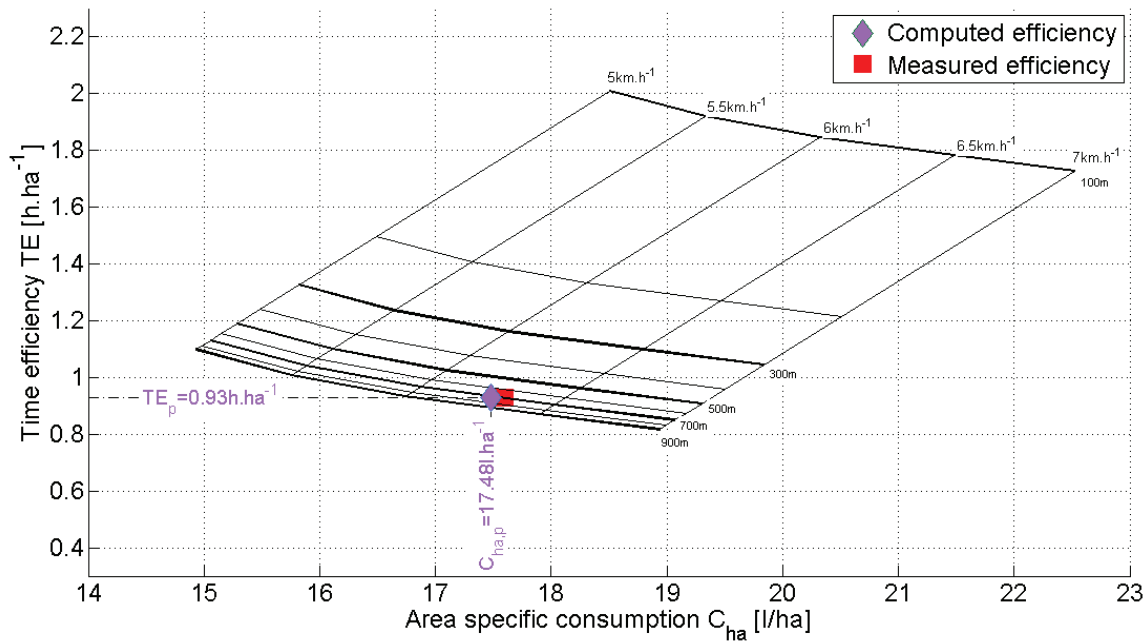


Fig. 10. Effect of field length and tractor speed on the operational efficiency indicators

Validation. It can be seen that there is quite no difference between the measured and the computed time efficiencies, but the area specific consumption is slightly underrated in its prediction. The area specific consumption is biased by the consumption model used for the computation. The bias simultaneously combines a misplacement of the computed engine running point and the potential lack of precision of the fuel consumption predicting model ($\pm 0.5 \text{ l.h}^{-1}$).

Effect of speed. Increasing the speed reduces the time needed to operate a line. At a given field length, increasing speed from 5 to 7 km.h^{-1} reduces the operation duration by 0.25 h.ha^{-1} . However, it also requires more energy to operate, thus increasing the area specific consumption by 4 l.ha^{-1}

Effect of field length. Field patterns depend on the field boundaries and the maneuverability of the tractor plow combination. Some common patterns are reported by (Hunt 1995), the ideal being the one with the minimum of so-called « unproductive turns ». Long, rectangular fields reduce the turning times and decrease their impact with respect to the productive time over crop line. At a fixed speed, still filling the agronomical requirements for a given quality of the work executed, area specific consumption decreases roughly with field length. Going from a 150 m long field to a 900 m one reduces the area specific consumption by 3.5 l.ha^{-1} . Field length also strongly impacts the time efficiency, which can be almost doubled for the longest fields. Higher speed increases both time efficiency and area specific consumption. At a given speed, it is shown that the longer the field, the better the time efficiency. This is due to the incompressible headland turning time at the field borders which has a quite significant weight with respect to the productive line time, regardless of the speed. It is also shown that area specific consumption is better for long fields than for shorter ones. These indicators allow a direct assessment of labor and fuel costs in relation with ground speed and field shape.

Effect of plowing width and tractor speed on the operational efficiency

With the same headland turning time and working depth, we now use a fixed field length of $L_{\text{line}} = 680 \text{ m}$, as defined for the validation case. Figure 11 shows the effect of changing the plow width on the operational efficiency indicators.

Going from a 14" to a 20" plow setting increases the working width by 76 cm. This parameter can be defined by the farmer from the tractor cabin by commanding the hydraulic cylinder setting the plow geometry. At a given speed, a larger plow enhances the time efficiency by 0.35 h.ha^{-1} . At the same time, the wider the plow, the lower the area specific consumption C_{ha} . Compared to a 14" one, a plow in a 20" configuration saves 2 l of fuel per hectare. Enlarging the plow slightly increases the hourly consumption, but also reduces the number of paths required

to cover the field surface. Even if the hourly consumption $C_{h, line}$ is increased, it is largely compensated by the reduced time required to operate. To increase the operational efficiency, choosing a large plow is therefore more suitable than operating at higher speeds. This is possible as long as the tractor can sustain the required draft power.

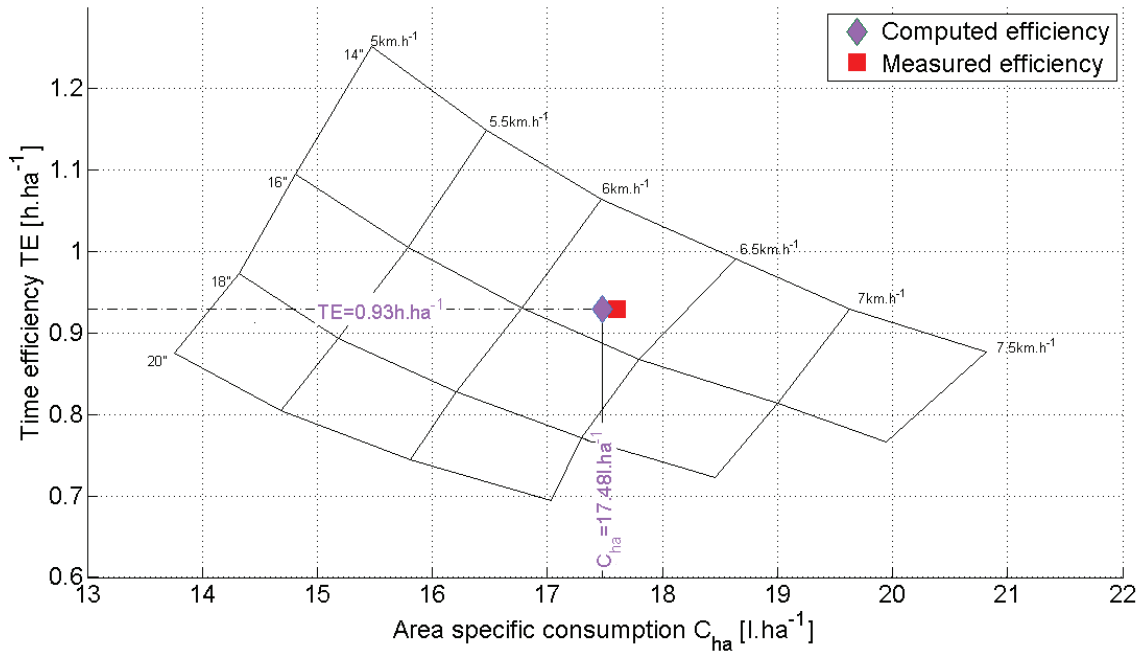


Fig. 11. Effect of plowing width and tractor speed on the operational efficiency indicators

Effect of plowing depth and tractor speed on the operational efficiency

With the same headland turning time and plow configuration of 16" per share, for a fixed field length $L_{line}=680$ m, Figure 12 shows the effect of the working depth, ranging from 10 to 25 cm (1 cm=10⁻² m).

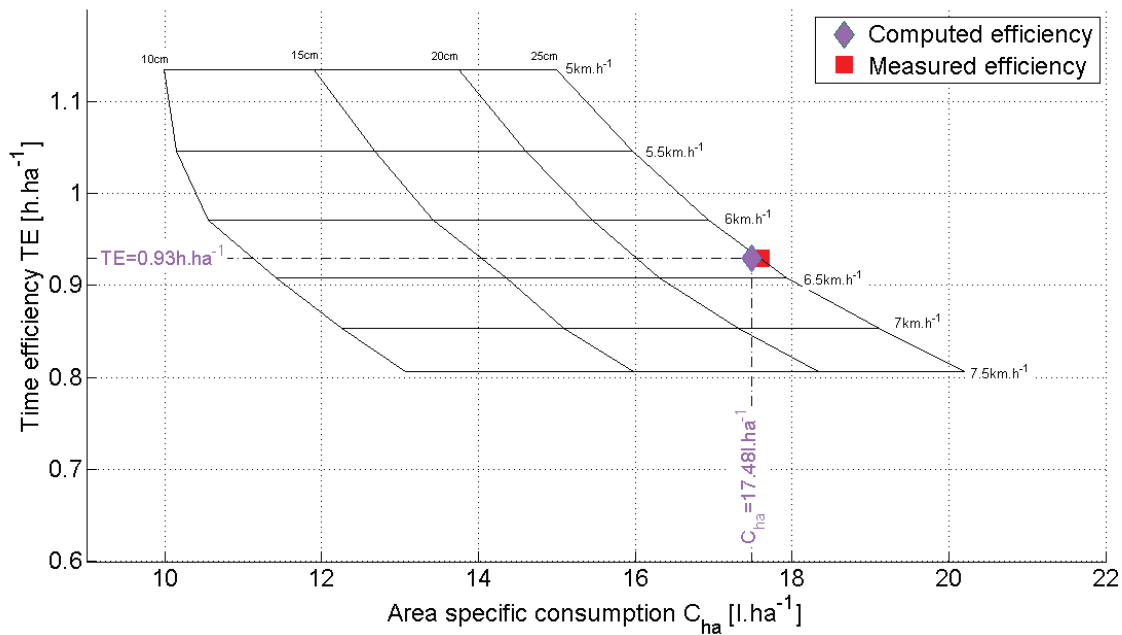


Fig. 12. Effect of plowing depth and tractor speed on the operational efficiency indicators

The time efficiency is not affected by the working depth as long as the tractor is not overloaded. The tractor ability to increase the time efficiency by increasing its ground speed is limited by the engine power. The area specific consumption is directly impacted by the working depth. At a medium speed of $V_{line} = 6 \text{ km.h}^{-1}$, going from 10 to 25 cm of plowing depth drastically increases the area specific consumption by more than 5 l.ha^{-1} . The working depth is chosen by the farmer according to the quality of plowing he wants to achieve. It is therefore recommended for tillage operations not to exceed the working depth defined by the agronomical requirements. Moreover, this encourages the farmer to use the hitch self-leveling system. This feature is available on modern tractors and enables the hitch to automatically lift the plow when a slip limit is reached. When available, the regulated hitch compensates inhomogeneous soil properties by limiting the tractor load, and thereby the consumption.

Discussion

This model is used to predict operational efficiency by converting the draft power required by an implement into an hourly consumption of a tractor engine. For each tractor to be studied, the parameters can be easily fitted by conventional static laboratory tests. Considering idealized working profiles, running the model evaluates the efficiency of a tractor and implement combination. This approach enables to take into account the diversity of possible combinations and operational parameters to provide an objective comparison basis enabling to rank several tractors. So far, the model can be applied to any tractor, but the transmission block considers a fixed gear ratio needed to convert wheel speed into engine speed. Relying on the track tests, we considered a constant transmission efficiency, simplifying hereby reasonably the approach for limited speeds. This assumption is expected to be more dubious for higher speeds, requiring investigating the sensitivity of the transmission efficiency with speed and so strengthening the global model. Tractor efficiency is expressed by considering a homogeneous generic soil type inviting to consider a fixed mobility number. Additional modeling work should be done to extend the model capacities, especially regarding the mobility number to investigate the effect of tire characteristics and soil parameters. The model offers flexible usage of other traction implement by singly changing the traction model coefficients as needed (Kheiralla, Yahya et al. 2004). In addition to plowing, other implement applications available from the database can be studied (specifically PTO-driven implements). The global efficiency predicting model can be completed with additional models describing the energy needs at the PTO and at the hydraulic. This will later permit to compute operational efficiency for wider implement applications

Conclusion

We have presented here a new approach to define the operational efficiency of a field operation on the basis of conventional tractor test-bench diagnostics. Field experiments based on CAN signals monitoring and additional sensors were conducted during plowing. Modeling the two efficiency indicators from the idealized working profile, the algorithm was developed to set engine running points gained from the operational parameters, where quantizing energy conversion assigned to slip, tires, transmission and finally to the engine. Whether for the field efficiency or the area specific consumption, an independent validation with a field experiment showed a high accuracy of the model.

Agricultural operations are characterized by several operational parameters, whether defined by the farmer (speed, implement width, dept, etc.) or required by the environment like soil, field length, turning time, etc. The sensitivity analysis showed that the way of operating impacts the engine running point, and thereby the hourly consumption. Increasing the tractor speed increases the hourly fuel consumption but also reduces the time to operate, especially for long fields which are the most profitable ones. By studying the effect of working width, we observed that wide implements enhance the time efficiency and simultaneously reduce the area specific consumption. In order to reach higher efficiency, using a wider implement is a better choice than increasing the speed because this latter option worsens the area specific consumption. Finally, the influence of the working depth on the area specific consumption makes it important to better adapt the depth to the agronomic requirements and to the quality of work the farmer wants to achieve.

For further purposes, this model can therefore serve farmers and farm managers to investigate different scenarios to optimize their fuel efficiency and working time. Following this method, apart of plowing, other field operations (i.e. cultivator, seedbed preparation, etc.) will need to be implemented. As a complement to other research focusing on matching tractor and implement, it enables a machinery energy assessment on the basis of real functional units. The results given through illustrative abacuses can be further adapted for LCA assessment of agricultural commodities where the energy needs of the tractor as a production tool can be considered.

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