Energy consumption evaluation of soil tillage operation using non-linear multibody tractor and plough models implemented in real-time simulator for different soils and speeds

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Abstract

The integration of advanced technologies in agriculture, known as Agriculture 4.0, aims to optimize practices, enhance productivity, and improve sustainability. Despite significant advancements in precision agriculture, ploughing operations have seen limited technological growth, even though they are among the most power-demanding and widely used soil preparation methods. Traditional on-field ploughing tests are irreversible, time-consuming, and costly, highlighting the need for a comprehensive virtual model of ploughing operations within a simulated environment. This study presents the development of a high-fidelity analytical model for ploughing, implemented in a real-time multibody simulation platform, both in software and Human-In-The-Loop (Hu-IL) configurations. The simulation environment incorporates a tractor model rigidly connected to the plough model, receiving contact forces from the field model. The model outputs vehicle dynamics information and ploughing operation data, allowing for operator inputs or simulated inputs. The model is used to perform a sensitivity analysis on ploughing parameters, including tractor speed, soil hardness, ploughing depth, and the number of furrows, to evaluate their impact on energy consumption and operational efficiency. In literature each component (tractor, plough, soil, etc.) is generally analyzed separately form the other; this paper aims to combine all the key factors that contribute to overall fuel consumption instead, considering the non-linearities of each subsystem.

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Introduction

Agriculture faced an extraordinary evolution in last years pushed by mechatronics, and information technology with the capability of measuring, storing, and elaborating a huge amount of data and deploy working operations with a very high special resolution. It is the agriculture 4.0 also known as Precision Agriculture (Lal and Stewart *et al*., 2015; Pallottino *et al*., 2018).

An important brick of agriculture 4.0 are the virtual simulation platforms and digital twins that are widely used to create a digital farm environment to perform rapid and reversible tests of farming operations, and training of the operators. Simulators can be found in desktop, static, and dynamic configuration.

Ploughing is the oldest and most widespread primary tillage operation used for soil inversion to redistribute nutrients before crops planting. Ploughing is a high energy and time demanding operation which can be optimized to reach the target of today agriculture of reducing the environmental impact. Many studies in literature focus on the plough geometry, also adopting simulation tools, like in Jeshvaghani *et al*. (2013) and Saunders (2002).

The shape of the moldboard plough, as depicted in Figure 1, is governed by the three angles required to cut, lift, and turn the slice of soil. Moldboard ploughs are often reversible and can be rotated depending on the ploughing side, they are typically mounted on the tractor *via* the three-point linkage creating a rigid body connection in case of number of furrows between 1 and 4, otherwise they are equipped with one depth wheel or more that make them semi-mounted or trailed ploughs.

When the plough dives and travels at a relative speed with the ground, an inclined force is generated on its body (pull force). For simplicity, according to Figure 2, it can be divided into its components: D (stands for draft) is the horizontal largest component of pull that acts as a resistance force. S is the lateral force and V the vertical one in z direction.

To design a simulator a proper model is required to catch the relevant aspect that want to be reproduced. The standard ASABE D497.7 MAR2011 proposes data and fitting functions to estimate many implement power and force requirements including ploughing.

Nazemosadat *et al*. (2022) propose a finite element simulation model to study the plough-soil interaction. This model is very sophisticated and allows for precise calculation of draft force, but it is not suitable for a real-time simulation.

Works by Godwin *et al*. (2007) and Saunders *et al*. (2000) propose and analytical model for calculating the ploughing forces based on physical modeling of the plough. The model considered friction, cutting, and inertial forces arising on the plough body from the interaction with soil providing a set of equations depending on the plough geometry and soil texture. The model considers the draft drag force having a quadratic relationship with respect to both speed and depth. Figure 3 represents ploughing draft force as a function of tractor speed and ploughing depth according to Godwin model for three soil hardnesses.

About the estimation of lateral and vertical forces, they are commonly considered proportional to the draft force according to the following coefficients (Eq. 1):

$$V \approx \frac{D}{5} \qquad S \approx \frac{D}{3} \qquad \text{(Eq. 1)}$$

The vertical force provides inclination in the vertical plane of the pull force, increasing the load on the rear tire, the lateral force (Eq. 1) gives more stability in the case of in-furrow ploughing and points in the direction opposite to the side of soil turning by the plough, it changes direction according to the side the plough is turned.

The three-point hitch system (3PH, ASAE S217.12 DEC01, 1994) is a crucial improvement in modern agriculture, improving efficiency in operations like ploughing. It is composed by two lower arms connected to hydraulic lifters and an upper central linkage that affects the forces redistribution on the vehicle during ploughing. The change in wheel vertical forces induced by the implement forces (Bauer, 2017) affects the tire slip condition thus the fuel consumption of the tractor. 3PH can work in floating connection, when no force is applied on the lifting arms, or by rigid connection, as it is modeled in this work.

Implement's draft power, W_{plough} is the main contribution to fuel consumption; however, other quantities from the tractor side influence the fuel consumption as well. Among those, the most relevant are the tires' rolling resistance (W_{rol}) and slip condition (W_{slip}), and the internal combustion engine (ICE) dissipated power, $W_{diss,m}$. The total dissipated power can thus be written as:

$$W_{diss} = W_{ploug} + W_{rol} + W_{slip} + W_{diss,m} \qquad \text{(Eq. 2)}$$

Rolling resistance power W_{ro} is related to the tire deformation and sinkage within the soil thus a correct modeling of the tire soil interaction is important. The rolling resistance dissipate power is:

$$W_{rol} = \sum_{i=1}^{n} M_{yi}\omega_i \qquad \text{(Eq. 3)}$$

where M_{yi} is the rolling resistance moment of the -th wheel and is the wheel hub angular velocity.

The tire slip power dissipation W_{slip} is also relevant since, considering F_{xi} the longitudinal force developed by the -th tire, the dissipated power by the tire contact forces is:

$$W_{rol} = \sum_{i=1}^{n} M_{yi}\omega_i \qquad \text{(Eq. 4)}$$

where v_{sxi} is the sliding velocity in the contact patch which is the difference between the wheel peripheral speed and the tractor forward speed.

Finally, the ICE efficiency which depends on motor delivered torque T_m and motor speed w_m makes the motor to consume more or less power depending on the operating point in the motor efficiency map. The dissipated power of the ICE is then equal to:

$$W_{diss,m} = \left(1 - \eta(T_m, \omega_m)\right) W_m \qquad \text{(Eq. 5)}$$

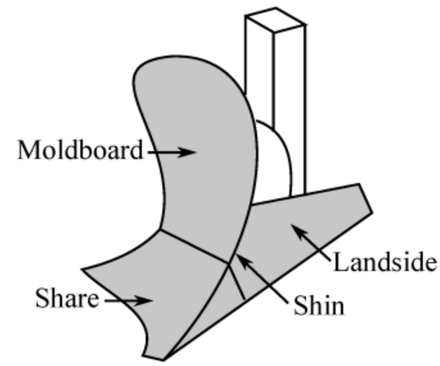

Figure 1. Example of a plough highlighting its main parts.

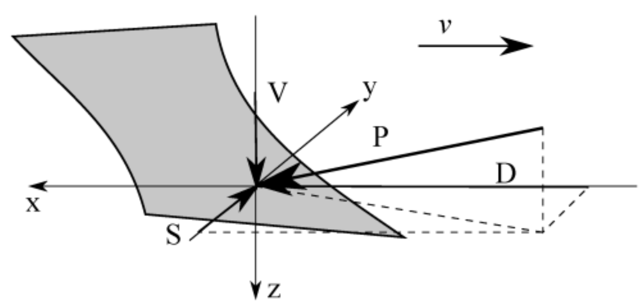

Figure 2. Ploughing field forces, total force and draft D, side S, and vertical V components.

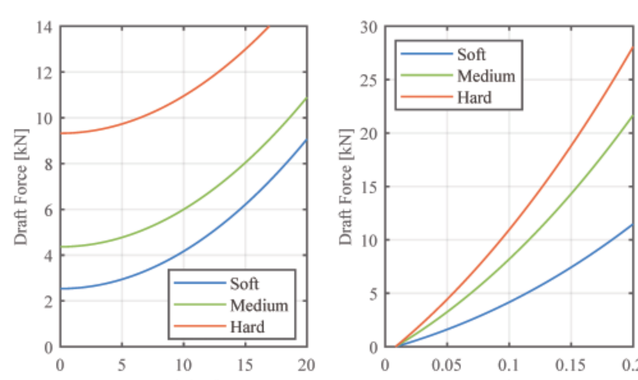

Figure 3. Representation of ploughing draft force as a function of tractor speed and ploughing depth according to Godwin model for three soil hardnesses.

All the contributions have a non-linear expression; thus, it is not easy to infer the effect of one parameter on the fuel consumption.

Most paper in literature focus only on the plough without analyzing the overall system tractor plus implement. Natsis *et al.* (1999) propose in fact an analysis of the plough power consumption for different soil and other parameters without including the tractor model. Jensen *et al.* (2025) analyze the overall consumption when ploughing based on experiments but is not proposing a complete model of the tractor plus plough. A similar study is in Karem (2019) where an experimental campaign is proposed to evaluate overall fuel consumption when ploughing; again, a complete model is missing. Zhang (2023) proposes a model of the tractor and the powertrain to optimize fuel consumption in tillage operations; this model is not accounting for all the non-linearities described in a multibody model.

If a proper and realistic model of ploughing forces is coupled with a sophisticated tractor and soil model this simulation environment can be used to drown sensitivity analysis on different plough and tractors to minimize relevant quantities for today precision agriculture, like the ploughing time, the fuel consumption, the soil compaction, *etc*.

This paper shows some relevant results regarding energy and power consumption while ploughing considering two ploughers, three soil hardness, two ploughing depths, and several running speeds based on a sophisticated non-linear model of the tractor powertrain and tire-soil contact forces. Results are obtained thanks to a real-time simulation which accounts for both the implement and the tractor including detailed tire-soil model to compute tire losses.

The paper is organized as follows: in the next section the simulation environment is presented. In the following one, simulation results of the performed maneuvers are reported. Finally, conclusions are drowned.

Materials and Methods

The simulation environment consists in a real-time multibody simulator based on IPG CarMaker and AgriSI©[1] (precision agriculture simulation software) simulation platforms in which the ploughing model is incorporated as Python code of AgriSI©.

As depicted in Figure 4, the simulation environment model includes the tractor model, which is rigidly connected to the plougher model from which it receives contact forces from field model. As output, the model returns the vehicle dynamics information, and the ploughing operation data. It is to point out that the model can take operator inputs (steering wheel angle, throttle or speed request) from the simulator human interface or from simulated inputs.

Tractor tires contact forces are modelled according to the MF-Tyre 5.2 (https://2021.help.altair.com/2021/hwdesktop/mv/topics/motionview/MFTyre-MFSwift_Help.pdf) in which tires have been previously characterized by experimental data. The rolling resistance coefficients were computed according to the ASAE D497.7 and the scaling factors were tailored to model four different tire-soil interactions: non deformable (asphalt), hard, medium, and soft soil. An example of the traction forces is reported in Figure 5 which reports the longitudinal contact forces as function of wheel slip for soft and hard soil. The tractor model is coupled with plough model to perform on-field tillage by predicting in RT the soil forces and calculating useful information as hectares tilled, operation time, and the energy required for ploughing. The lifted plough maneuvers such as lifting and rotation of the plough implement can be controlled by the user and tested during on-road maneuvers to study the vehicle dynamics with a rigidly mounted cantilever representative of the implement inertia. The plough model consists in a set of equations implementing the Godwin model (Godwin *et al.*, 2007; Sanders *et al.*, 2000) to calculate the soil-plough interaction forces based on a reference geometry which is reported in Figure 6. The ploughing forces are balanced by the connection forces with the tractor at the 3PH that are fed into the tractor model to obtain the motion resistance forces.

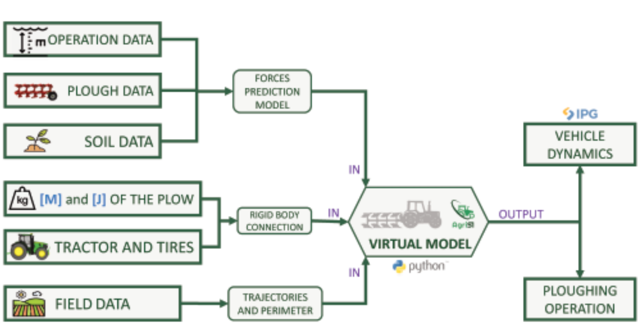

Figure 4. Real-time simulation environment developed for power and energy evaluation of ploughing operations.

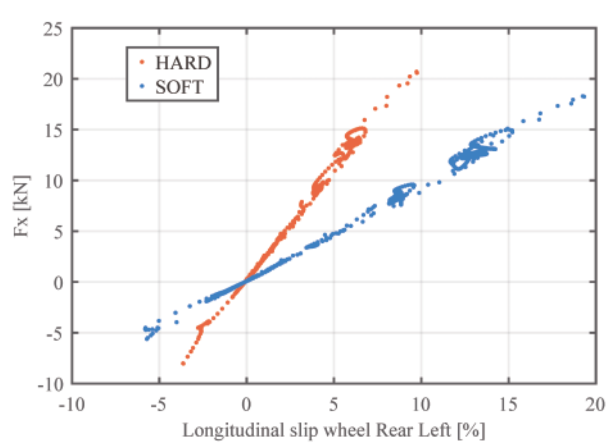

Figure 5. Tractor tires longitudinal forces as function of wheel slip for two soil hardnesses.

[1] *AgriSI© is an agriculture native simulation platform developed by Soluzioni Ingegneria srl (www.si-ita.it), born in 2020 in collaboration with CREA (Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria).*

Regarding soil properties, three different soil hardnesses were simulated. Table 1 reports the soil parameters adopted to compute the ploughing draft force according to Godwin model. To represent different soils, the cohesion and shear stress coefficient were changed. Values are taken from literature (Das, 2002).

The model also considers the tractor attitude when in-furrow ploughing as depicted in Figure 7. In this condition, the tractor has two wheels inside the furrow, i.e., on the previously tilled soil, and the wheel on the other side on non-tilled soil. This makes the tractor to drive straight with a significant roll angle and consequent camber angles on the tires. This camber angles produce lateral contact forces on the tire which requires the operator to steer to maintain a straight trajectory. Figure 8 reports the screenshot of a simulated ploughing operation performed with the real-time simulator showing the amount of steering wheel angle required to the operator to maintain a straight trajectory.

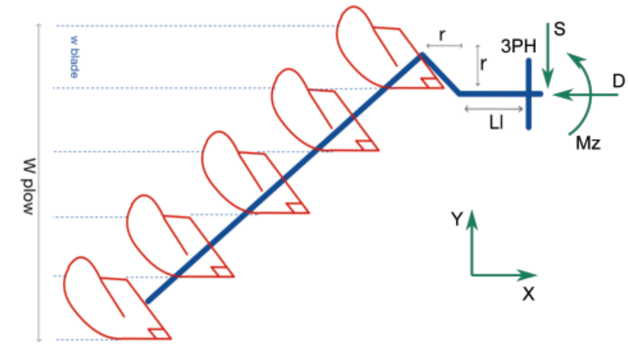

Figure 6. Geometrical representation of plough model implemented in the real-time simulator. Highlighted are the forces and moment exchanged with the tractor.

Results

Many tests were performed to perform a sensitivity analysis on the ploughing relevant parameters (speed, soil, depth, trim loads, and number of furrow) giving a complete overview of the tillage operation. The most relevant maneuvers, here discussed, are described by the parameters contained in Table 2. Tests were held with the SIL2 version simulator with a John Deere 6250R tractor (4WD – 210 kW) equipped with a Kverneland LS mounted reversible moldboard plough with adjustable number of furrows from 3 to 6 (default 5).

The sensitivity analysis is run by changing one at the time the following parameters:

- Tractor forward speed from 5 to 10 km/h
- Soil hardness: soft, medium, and hard
- Ploughing depth 200 and 400 mm
- Furrow number 3 and 6 while 5 is default.

The considered outputs are the worked area, the time required to complete the operation, the energy consumption, and others.

The total energy is the integral over the time of engine power (the product between engine torque and engine speed), the tillage energy is the integral over the time of the draft force multiplied by the ploughing speed, tire losses account for the rolling resistances, longitudinal and lateral losses due to slips.

The use of the model allows to separate the single contributions to the total energy, computed at the engine shaft. In the results reported in Tables 2 to 4 the total energy is split into its main contribution showing the effect of ploughing parameters on the energy dissipated in ploughing forces, and in tire contact forces which are affected by ploughing forces.

In particular, Table 2 shows simulation result for tillage operation at two different ploughing speeds (5 and 10 km/h) on soft soil with a five furrows plough. The total working time per hectare is of course directly dependent on the speed. At higher speeds, also

Table 1. Soil parameter adopted in simulation to represent three different soil resistance to plough operation.

	Soft soil	Medium soil	Hard soil
Bulk unit weight (kN/m^3)	15	15	15
Cohesion (kN/m^2)	8	20	32
Shearing resistance angle (deg)	12	16	20
Soil-metal friction angle (deg)	24	24	24

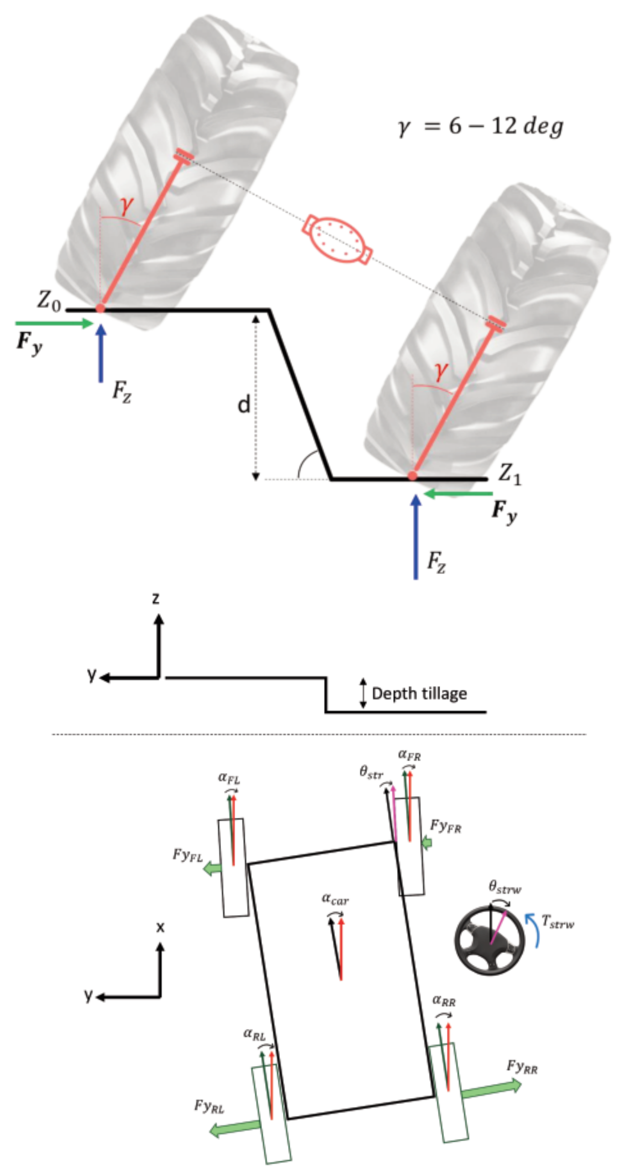

Figure 7. Tractor attitude when in-furrow ploughing. On the left, the back view of the tractor; on the right, the top view. Highlighted are the tire contact forces, the slip angles, and the steering wheel angle required to maintain a straight trajectory.

the energy consumption is higher, as expected. What is nontrivial is that also the total energy per hectare is dependent on the speed but in a non-linear fashion: time halves when doubling the speed while the total energy grows of only about 50% Furthermore, looking at the tire and tillage contributions, the percentage of consumed energy spent for tillage is higher at higher speed while the energy dissipated in the tire is smaller. Also soil texture plays a significant role on the outcome of a ploughing operation since it affects both the tire losses and the tillage energy. Table 3 reports the simulation results for tillage operation at 5 km/h ploughing speed and three

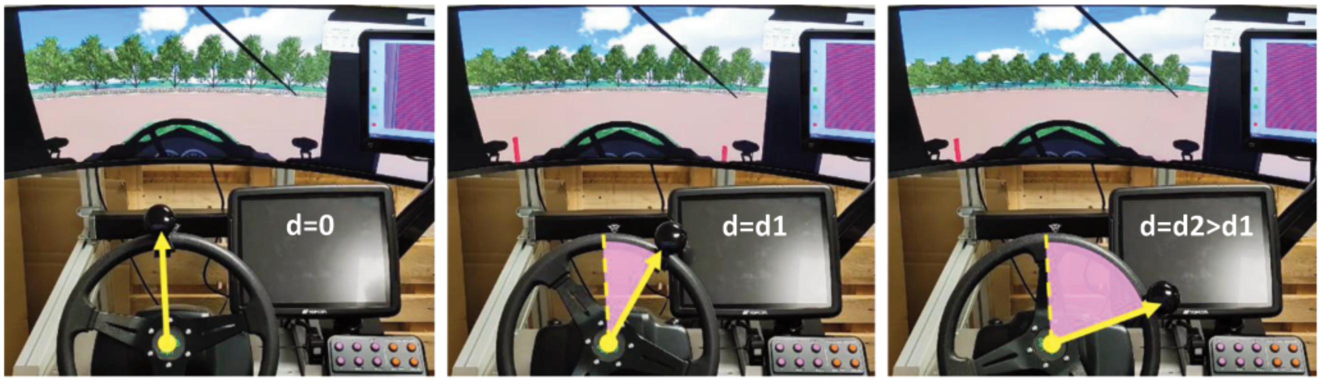

Figure 8. Real-time AgriSI© simulator human interface representing an in-furrow ploughing operation which requires the operator to steer to maintain a straight trajectory.

Table 2. Parameters and results of all the simulated operations.

#	Operation	Operation data Speed (km/h)	Depth (mm)	Furrows	Time (min/ha)	Tot. energy (kWh/ha)	Tillage energy (kWh/ha)	Tire energy (kWh/ha)	Till/tot energy (%)
1	Low speed	5	0.2	5	40	25.73	11.06	15.51	60.28
2	High speed	10	0.2	5	20	38.95	15.39	25.28	64.92
3	Soft soil	5	0.2	5	-	25.57	13.46	12.77	49.93
4	Medium soil	5	0.2	5	-	35.03	15.05	21.12	60.31
5	Hard soil	5	0.2	5	-	44.28	16.70	29.25	66.07
6	Low depth	8	0.2	3	-	18.10	8.12	10.25	56.67
7	High depth	8	0.4	3	-	40.17	17.2	25.02	62.29
8	Less furrows	7	0.2	3	57.28	45.80	19.95	26.84	57.28
9	More furrows	7	0.2	6	29.01	41.38	16.15	27.04	29.01

Table 3. Simulation result for tillage operation at two different ploughing speeds for soft soil, 200 mm depth, and 5 furrow plough.

Quantity	Unit	Tillage speed (km/h) 5	10
Ploughed area	ha (10^4 m^2)	0.157	0.157
Time per hectare	min/ha	40	20
Total energy per hectare	kWh/ha	25.73	38.95
Tillage energy per hectare	kWh/ha	15.51	25.28
Tire energy per hectare	kWh/ha	11.06	15.39
Tillage/total energy	%	60.28	64.92

Table 4. Simulation result for tillage operation at three different soil hardness at a ploughing speed of 5 km/h, 200 mm ploughing depth, and 5 furrow plough.

Quantity	Unit	Soft soil	Medium soil	Hard soil
Ploughed area	ha (104 m^2)	0.122	0.122	0.122
Draft force	kN	≈10	≈20	≈30
Total energy per hectare	kWh/ha	25.73	35.03	44.28
Tillage energy per hectare	kWh/ha	12.77	21.12	29.25
Tire energy per hectare	kWh/ha	13.46	15.05	16.70
Tillage/total energy	%	49.93	60.31	66.07

different soil hardnesses with a five-furrow plough. Draft force approximated value is also reported to show the difference in tillage resistance for the three considered soils. For the soft soil, the energy wasted in tire losses is greater than the energy required for tillage, while for harder soils the tire losses are almost half of the tillage ones. Depth of ploughing sensitivity analysis is performed considering a three furrows plough mounted on the tractor working in-furrow. Table 2 resumes all the performed simulations with running parameters and obtained results in terms of energy consumption total, and tillage and tires contributions.

Focusing on operations 6 and 7, where the difference between the two operations is the ploughing depth, it can be noticed the increase in total consumed energy due to the doubling of the ploughing depth. Energy is exploited better for tillage in percentage with the deeper furrow because the tire losses get doubled with the depth while the tillage energy grows faster (draft force quadratically increases from 10 kN to 30 kN).

The most practical way of reducing the total tillage time, if the speed can't be increased, is to increase the width of worked soil by mounting more furrows on the plough body. Operations 8 and 9 in Table 4 reports the results of a comparison test between 3 and 6 furrows ploughing on medium soil at 7 km/h. The working time becomes two times shorter in the case of 6 furrows plough with respect to 3 furrows because of the doubled working width. The total energy of the larger plough is less showing how the time affects this variable. Tillage energy instead, is bigger in the case of 6 furrows due to the higher draft force involved. Conversely, the tire losses are more relevant in case of the 3 furrows plough because the tractor has to spend more time rolling on the soil. Finally, the percentage of energy used for tillage suggests the 6 furrows implement is working more efficiently than the 3 furrows one.

Discussion

With the growing interest in precision agriculture, a tool that can model the ploughing operations managing all the complex variables for the field forces generation and the impact on tractor dynamics is needed. This allows to predict operation time and energy required for tillage operation thus improving the farming efficiency.

For this purpose, this paper shows the developed real-time simulation environment that couples a sophisticated model of the tractor with a ploughing model to be run in a Human-In-The-Loop simulator. The model was widely tested showing its capabilities to be adapted to most of the needs of farmers. This tool is able to perform repeatable, fast, and reliable tests becoming the game changer for ploughing decision-making.

The modeled allowed to obtain relevant information related to the energy consumption derived from tillage operation. In particular, a sensitivity analysis was performed considering the tractor speed, the soil hardness, the ploughing dept, and the number of furrows. For each operation the working time and the consumed energy was computed highlighting the energetic contribution due to tillage and due to tire losses. In particular, the proposed model highlighted how the different parameters can affect the fuel consumption in a non-linear way. This means that, when optimization is needed, a correct representation of the systems is necessary which can be provided by the proposed model.

Further developments would be the overall validation of the tool with a dedicated experimental campaign since in the proposed work each single component was validated singularly.

Furthermore, the models allow to design dedicated optimization package that depending on the constraints provided by the farmer will output the optimal ploughing speed, dept, number of furrows to minimize one or more objective.

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