Fuel consumption and exhaust emissions during on-field tractor activity: a possible improving strategy for the environmental load of agricultural mechanisation

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Abstract

Agricultural machinery plays an important role on the environmental sustainability assessments of the agricultural sector and, in particular, a prominent part of its impact is due to fuel consumption and engine exhaust gases emissions.

In order to adopt trustworthy data on agricultural machinery operations for fulfilling reliable local inventories in Life Cycle Assessment (LCA) studies, field tests were performed. During the trials several operations were monitored (i.e. ploughing, spike harrowing, rotary harrowing, sowing and rolling) and the measured data with CAN-bus (among which the fuel consumption) and with the engine exhaust gases emissions analyser (CO_2, CO and NO_X) were attributed to the field working states of effective work, turns at headlands and stops that were identified thanks to GPS. Moreover, data during the farm-field transfers were also collected.

In addition to data processing from the field trials, a model for predicting fuel consumption and engine exhaust gases emissions was adopted and its reliability was studied for further future uses.

From the results, specific considerations about the tested tractor (Valtra N101, 82 kW maximum power, IIIA emission stage) and the studied working conditions (e.g., engine speed, torque, working speed and depth) can be performed to get information valid for the engine and the operations.

Keywords: Agricultural machinery; CAN-bus; exhaust gas analyser; efficiency improvement; environmental sustainability

1 Introduction

Thanks to the application of recent technology to agricultural machinery, and to tractors in particular, a great potentiality for the enhancement of efficiency and for the monitoring of engine variables has been proven (Pitla et al., 2016; Shadidi et al., 2014). Specifically, the use of CAN-bus (Controller Area Network), data logging software, GPS (Global Positioning System) and exhaust gases emission analysers allows collecting a huge amount of data directly related to in-field activity (Hameed et al., 2012; Yahya et al., 2009). In this context, the interest in quantifying and reducing the environmental load of agricultural productions (Renzulli et al., 2015) must be considered as well, and its reliability can be improved with the adoption of the abovementioned technology for both improving the machinery engineering and knowledge (Bishop et al., 2016) as well as the related environmental sustainability (Lovarelli and Bacenetti, 2017).

Regarding the environmental point of view, agricultural mechanisation is responsible for a substantial share of impacts, mainly due to fuel consumption and engine exhaust gases emissions and to the materials wear. The quantification of these impacts, at least for the mechanical field operations, still shows shortcomings (Lovarelli et al., 2017), but also room for improvement (Gabel et al., 2016). In fact, collecting data and monitoring tractors' activity permits to improve the efficiency of tractors, the machinery fleet and their use. This certainly presents advantages on the construction and management perspectives, but also on the environmental one (Lovarelli et al., 2016). Commonly, one of the most limiting factors to inventory data collection for environmental assessments of agricultural machinery is the unfeasibility to collect or measure some inventory data (i.e. primary source) because they can be time consuming and site and time dependent. Although primary data are the most reliable, collecting difficulties and site-specificity cause the widespread use of secondary data (i.e. databases, scientific literature) that, on the other side, can be simplified and not fully reliable (Sala et al., 2017), especially if uncritically used (Lovarelli and Bacenetti, 2017). Nevertheless, particularly for agricultural productions, the geographical (Perozzi et al., 2016), temporal and managerial characteristics (e.g., soil texture, field shape and slope, climate and seasonality, machinery fleet and management choices) deeply affect most environmental loads (Bacenetti et al., 2015; Lovarelli et al., 2017).

Collecting primary data is getting more possible thanks to the availability on the market of tractors and implements equipped with new technology and of new techniques or management strategies (Marx et al., 2015). In particular, technology such as CAN-bus, GPS, electronic devices and exhaust gases analysers, allow access to a huge amount of data measurable constantly and simultaneously to the work on field (Fellmeth, 2003; Pitla et al., 2016). These data describe how the engine works, the fuel consumed and exhaust gases emitted and the working features and interactions in the tractor (Janulevičius et al., 2016). Thus, it is possible to monitor and map variables (Bietresato et al., 2015), to increase the reliability of analyses on modern machinery, optimise inputs use and management (Larsson and Hansson, 2011; Lindgren and Hansson, 2004) and identify the optimal combination of work conditions to reduce inputs use (Hameed et al., 2013). In particular, primary data give information on the specific working context and the specific variability of the field operation, therefore accurate processing and robust prediction models for engine-related variables are achievable. Manufacturers can use such information to improve the construction and maintenance of tractors as well as to identify failures.

The general aim of the study is to make advances on the data and model availability related to the modern technology present on tractors, which results helpful for several scopes among which the improvement of data reliability for sustainability evaluations completed by means of Life Cycle Assessment (LCA). The possibility of having trustworthy and specific data permits to calculate the environmental load of agricultural machinery operations in a reliable way, allowing playing a management role for the environmental sustainability and for introducing effective sustainability measures in the manufacturing field and in the farmers' perspective. For reaching this goal, the specific aims of this study are to:

(i) identify the most important data for the filling of reliable inventories of agricultural machinery field operations, thus showing what happens along the different working states of a single operation,

(ii) design and execute experimental field trials, carried out to collect primary data on field operations for cereal crops cultivation, as well as the methodology that was adopted for the data processing and its possible future repeatability,

(iii) apply a reliable quantification model for the prevision of fuel consumption and exhaust gases emissions that takes into account the engine behaviour during the field operations,

(iv) show the discrepancies that can emerge in terms of description of field activities among measured data on field, data related to single working states respect to the whole field work as such and data from test benches, these last with regard mainly to engine exhaust emissions. Lastly, all these differences affect the environmental sustainability of the field operations which is highlighted by several impact categories (e.g., Climate Change, Ozone Depletion, Acidification, Particulate Matter Formation, Photochemical Oxidant Formation and Fossil Depletion; Wolf et al., 2012) (Lovarelli and Bacenetti, 2017).

2 Materials and methods

2.1 Goal of the field trials

The aim of the field experiments is to collect data from CAN-bus and gases analyser in order to have information about the engine working features, fuel consumption and exhausts emissions while directly working on field in order to realise detailed and reliable Life Cycle Assessment (LCA) studies on agricultural machinery operations. In fact, the final goal is the inventory fulfilment for LCA studies on agricultural machines aggregated with this tractor.

LCA is an internationally recognised method that permits to quantify the environmental impact of processes (ISO Series 14040), for which inventory data concerning fuel consumption, engine exhaust gases emissions and the consumption of materials composing machinery represent essential information.

Thanks to the GPS present on the tractor used for the field trials were built maps of the fields. Maps were built on a Microsoft Office Excel spreadsheet using the GPS coordinates and translating them into X-axis and Y-axis data. Every map was characterised by CAN-bus and exhaust gases emissions data grouped in the following working states:

(i) effective work: condition in which the tractor is driving on the stretch effectively carrying out the operation;

(ii) turn at headland: condition in which the driver is manoeuvring at the headlands, including when the implement is lifted/lowered and/or turned before or after the turn;

(iii) stop: when the tractor is not moving, therefore its GPS position along time does not change. In this condition, often, the engine is idling, but this is not a compulsory condition;

(iv) transfer: the whole condition of transport from the farm to the field and vice versa.

To better study the role of the working states, the trials can be distinguished in two main parts:

(i) completion of field operations (such as ploughing, sowing) with defined engine and field working features to study the behaviour of the tractor in those conditions;

(ii) comparison of turning strategies at the headlands during an operation to study the behaviour of the engine within different conditions during the turns at the headlands.

In both cases the aim is to identify the most relevant differences in terms of fuel consumed and exhaust gases released, what working conditions show the best outcomes on the environmental perspective and how can vary the fuel consumption and engine exhaust gases emissions by changing only few work conditions.

2.2 Instrumentation used

Among the instrumentation developed to map, understand and study the activity of the tractor engine and of the related devices employable during on-field activity, the most widely used system is the CAN-bus. It is a serial high-speed wired data network connection that permits to electronic devices to communicate with each other and that, coupled with storing instrumentation, permits to collect huge amounts of data with high frequency (Speckmann and Jahns, 1999). CAN-bus is normed with SAE J1939 for the connections of electronic devices on agricultural machinery and with the standard protocol ISO 11898 (ISO, 2003). It is commonly available on modern medium-high power tractors and has permitted to use and take advantage of electronics on agricultural machinery, in particular with the improvement in data monitoring and collection and in sustainability evaluations. The data logger that was used for the acquisition and storage of CAN-bus data is Dewesoft® software that is equipped with the translation key from CAN-bus and uses more than 100 communication channels to be selected. Already on-board it was possible to check how variables were changing over time, by means of the interface available with an on-board-mounted laptop that allowed selecting the variables to be shown. The data collection and saving in Microsoft Office Excel format was performed for the subsequent processing phase.

The portable instrument for the measurement of engine exhaust gases is Testo® 350; it analyses the flux of gases from the exhaust pipe of the tractor and results the values in ppm (or in % for CO_2). The measured gases are NO_X, NO, NO_2, CO and O_2; CO_2 (%vol) is obtained from calculations deriving from O_2 concentration. In addition, the sample exhaust gas temperature (°C), the sample flow of exhaust gas (L min^{-1}; maintained as constant as possible by a pump) and the instrument temperature (°C) are also measured. Gas emissions (g h^{-1}) were calculated based on measured flow rates and concentrations with the methods described in Directive 97/68/EC.

It includes a stainless-steel gas sampling probe equipped with integrated thermocouples located close to the exhaust pipe. From the probe, gases reach Testo® 350 on-board of the tractor, equipped with up to 6 electrochemical (for NO_X – obtained as sum of NO and NO_2) and infrared (for CO) sensors that analyse the gas concentration, and values are shown on a display and data are stored in an on-board memory (up to 250,000 values). Digital sensors for calibration history and interference filter with electronic lifespan indicator are available as well as temperature monitoring and diagnostics are guaranteed by the instrument. The retention time ranges between 20 s and 40 s depending on exhaust gases. The instrument accuracy is high: for CO_2 is equal to ± 0.2% vol O_2; for CO ±5 ppm within a CO concentration value between 0-199 ppm and ± 5% mass for higher concentration (200-2000 ppm); for NO and NO_2, the accuracy is ±5 ppm within a NO and NO_2 concentration value between 0-99 ppm and ± 5% mass for a concentration of 100-2000 ppm and 100-500 ppm, respectively for NO and NO_2. A thermoelectric chiller removes moisture and every 30 minutes, for approximately 7 minutes, the analyser rinses from moisture the sensors and the analysis chamber. During this period, therefore, no emission measurement took place and the tractor was left on, in idling stationary conditions.

With the GPS (Global Positioning System), the position on field was identified to build a map in which the phases of working activity could be classified. The instrument's precision is characterised by less than 100 mm error. CAN-bus and the exhaust gases emission analyser detected engine and tractor data and, thanks to the GPS, all of them were attributed to a position on field.

2.3 Field trials

Data collection was performed directly during field trials in order to evaluate the real field working conditions and not the standardised bench testing ones.

The experiments were performed in Umeå (Sweden) in October 2016 at the Swedish Machinery Testing Institute. The same driver carried out the operations with the tractor Valtra N101, made available by the contractor company. **Table 1** reports the tractor characteristics.

Table 1. Tractor Valtra N101 characteristics.

Characteristic	Unit	Value
Rated power	P_{MAX}	82 kW
Rated engine speed	s	2200 min^{-1}
Maximum torque	M_{MAX}	490 Nm
Mass	m	4850 kg
Driving wheels	4 WD	
Emissive Stage	IIIA	
Exhaust treatment technology	EGR (Exhaust Gas Recirculation)	

Valtra N101 was equipped with CAN-bus (Controller Area Network), GPS (Global Positioning System), a laptop with installed the Dewesoft® software for CAN-bus data collection and storage, and guidance control. Additionally, to measure the exhaust gases released during the field operations, Testo® 350 portable emissions gas analyser was used.

The CAN-bus data related to torque (M; Nm), engine speed (s; min^{-1}), fuel consumption (FC; L h^{-1}), engine power (P; kW), engine load (L; %), and the Testo® 350 data on exhaust gases emissions (EM of CO_2, CO and NO_X; g h^{-1}), O_2 (ppm) and instrument and gas temperatures (°C) could be attributed to each of the studied working states.

2.4 Description of the field trials

The following operations were analysed: (i) ploughing, (ii) rotary harrowing, (iii) spike harrowing, (iv) sowing, and (v) rolling. The choice of studying multiple operations was aimed to have a wide view on the mechanical features of the tractor and to avoid having data focused only on distinct work conditions that characterise a field operation but may not be descriptive of another. Similarly, different headland strategies were compared in order to show how the strategy affects the engine variables, fuel consumption and exhaust gases emissions and, consequently, its environmental impact.

The trials were carried out on two sandy-loamy fields.

2.4.1 Headland strategies

In the first field (area = 1.7 ha), rotary harrowing was carried out with the aim of comparing alternative strategies for completing the turns at the headlands. In more details, to perform these turns different driving schemes were used in accordance with practical farm working schemes. Every strategy was characterised by different engine running features.

Five headland strategies were identified as shown in **Figure 1**; analysing all of them allowed comparing the engine use during the strategies and identifying the most beneficial on the environmental point of view and the improvable driving conditions that permit to reach lower fuel consumption and lower exhaust gases emission. Hence, the field was split in five areas; the dimension of each of them was defined in order to have a minimum number of turns (at least 10 for all operations) for repeatability in the statistical analysis.

Figure 1 around here

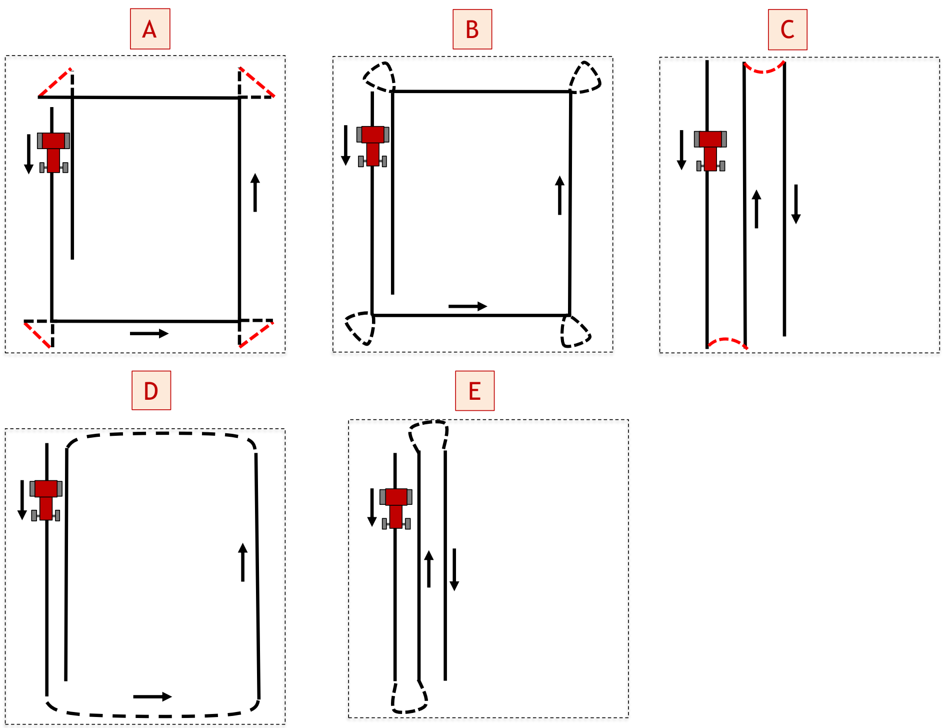


Figure 1. Studied headland strategies, namely A, B, C, D and E. The spotted lines identify the turn on the headlands, with the black-coloured line for the forward direction and the red-coloured line for the reversing.

In the sections of each area where the phase of effective work was carried out, the same working variables were considered, which means that gear, engine speed (min^{-1}), working speed ($km\ h^{-1}$) and working depth (mm) were kept constant. The exception is the effective work on two areas, as reported in **Table 2**, where on 3 areas (i.e. I, II and V) the same engine speed and gear were kept during all the effective work, while in the remaining 2 areas (i.e. III and IV) engine speed or gear changed the way forward from the way back.

Table 2 around here

Table 2. Engine speed and gear used in the 5 areas characterised by different headland turning strategies.

Areas	Engine speed (min^{-1})	Gear (-)
I	s_1 = 1850	g_1 = 2
II	s_1 = 1850	g_1 = 2
III	s_1 = 1700 s_2 = 2000	g_1 = 2
IV	s_1 = 1850	g_1 = 1 g_2 = 3
V	s_1 = 1850	g_1 = 2

2.4.2 Field operations

With regard to the operations of ploughing, spike harrowing, sowing and rolling, a second field characterised by an area = 4.2 ha was used (ploughing and rolling were performed only on one part of the field, with A_{plough} = 1.2 ha and A_{roller} = 2.8 ha). Similarly to rotary harrowing, data were collected during the work on field, taking into account the transfers from farm to field and vice versa and the work on field distinguished in effective work, turns at headlands and stops.

In each operation, engine speed and working speed were changed as reported in **Table 3**. When applicable (i.e. ploughing and spike harrowing) the working depth was also varied. The headland strategy was kept constant along the whole operation, but – when needed - differed in the different operations. To analyse the most common work characteristics on field and to study whether other alternative work conditions have a better environmental outcome than others do, during some operations the working depth, working speed and engine speed were changed.

Table 3 around here

Table 3. Variables adopted in each operation.

Operation*	Headland strategy	Implement working width (b; m)	Implement working depth (H; mm)	Implement mass (m; kg)	Working speed (s; km h^{-1})	Tractor engine speed (s; min^{-1})
Ploughing (1-2)	D	1.47	H_1 = 180 H_2 = 280	1200 kg	s_1 = 5.0 s_2 = 7.0	n_1 = 1400 n_2 = 1800
Harrowing, rotary harrow (A-E)	A-B-C-D-E	3.0	100	890 kg	s_1 = 4.0 s_2 = 5.0 s_3 = 6.0	n_1 = 1700 n_2 = 1850 n_3 = 2000
Harrowing, spike harrow (1-4)	E	3.0	H_1 = 80 H_2 = 120	350 kg	s_1 = 6.0 s_2 = 8.0	n_1 = 1000 n_2 = 1400 n_3 = 1800
Sowing (1-2)	A-E	6.0	--	570 kg	s_1 = 5.0 s_2 = 8.0	n_1 = 1080 n_2 = 1800
Rolling	D	5.4	--	2460 kg	s_1 = 7.0 s_2 = 10.0	1000

* In brackets are shown the codes that identify the operations. More in details:

(i) ploughing 1 = work depth 180 mm; ploughing 2 = work depth 280 mm;
(ii) rotary harrowing A-E = A-E represent the 5 different headland strategies abovementioned;
(iii) spike harrowing 1 = all three engine speeds are studied one after the other on the same stretch; spike harrowing 2 = engine speed 1000 min^{-1}; spike harrowing 3 = engine speed 1400 min^{-1}; spike harrowing 4 = engine speed 1800 min^{-1};
(iv) sowing 1 = external part of the field with headland A; sowing 2 = internal part of the field with headland E.

2.5 Identification of working states

Collected data were processed on Microsoft Office Excel spreadsheet.

A first temporal offsetting of data from CAN-bus and Testo® 350 was made, and the identification of geographical coordinates from GPS followed.

As mentioned above, the working states were identified with the GPS coordinates considering that the worked fields had rectangular shape and, therefore: (i) when the GPS coordinates varied according to a defined angle (based on tests) the tractor was turning at headlands, (ii) when the GPS coordinates varied without exceeding the defined angle the tractor was working on the stretch (effective work), (iii) when the GPS coordinates did not change for a period longer than 5 s, the tractor was stopping, and (iv) when the coordinates were outside a mapped polygon that corresponded to the field border it was transferring to/from the field. An example of ploughing operation is shown in **Figure 2**. Maps such as Figure 2 were used to inspect manually that the identification of working state was correct.

Figure 2 around here

Figure 2. Distinction of work states for the ploughing operation. The working depth in Section 1 (left-bottom) was H_1 = 180 mm and in Section 2 (right-top) H_2 = 280 mm.

In all operations, every stretch of effective work and every turn at headlands were numbered. This made possible to take mean values per stretch or turn and thereby quantify the stretch-to-stretch and turn-to-turn variation. Additionally, the specific values of brake specific fuel consumption (bsfc, g kWh^{-1}) and engine exhaust emissions (g kWh^{-1}) were also quantified in each stretch and turn, in order to be widely comparable among operations and avoid misinterpretations due to temporal effects.

2.6 Predicting model adopted

From a literature analysis emerged that several prediction models for fuel consumption exist, some of which are based on generic equations (Grisso et al., 2004; Janulevičius et al., 2013; Sørensen et al., 2014) and others on engine-specific (Lindgren, 2004, 2005).Whilst generic equations are easier to use and require less data, engine-specific ones allow for better precision.

Among them, the equation proposed by Lindgren (2005) was adopted (Eq. 1). In this model, torque (M; Nm), engine speed (s; min^{-1}) and engine-specific coefficients are needed. Torque and engine speed were directly gathered from the field measurements, while the 9 engine-specific coefficients for equation (Eq. 1) were calculated modelling the semi-static condition (i.e. with no transient effect) as described in Lindgren (2005). For the studied tractor, coefficients were identified with Matlab® using a least square fit for calibration. Fuel consumption (FC; $L\ h^{-1}$) was quantified for all working states and total working time considering the mentioned equation, which is also adopted for the quantification of EM (CO_2, CO and NO_X; $g\ h^{-1}$) with the related 9 engine-specific coefficients quantified for EM. The total FC and EM for the operation is the sum of every value got per record of engine speed and torque.

$$FC = c_1 \cdot s + c_2 \cdot s^2 + c_3 \cdot s^3 + M \cdot (c_4 \cdot s + c_5 \cdot s^2 + c_6 \cdot s^3) + M^2 \cdot (c_7 \cdot s + c_8 \cdot s^2 + c_9 \cdot s^3) \quad [1]$$

where:

- FC = fuel consumption ($L\ h^{-1}$);
- from c_1 to c_9 = engine-specific coefficients;
- s = engine speed (min^{-1});
- M = torque (N m).

As mentioned, the data processing on engine exhaust gases is made with the same equation, but results are less reliable because the production of each gas depends on a wide range of factors such as other gases present, temperatures, oxygen concentration, technologies and after-treatment systems and driving abilities (Larsson and Hansson, 2011; Lindgren and Hansson, 2004). However, Equation 1 responds well to engine exhaust emissions (Lindgren, 2005) and is valid for their quantification adopting adequate coefficients for each of the studied exhaust gases (see Table 7). Lindgren (2005) studied two equations for fuel and exhaust emissions prediction: one assumes steady state conditions and one takes into account transient effects. Steady state occurs when there is no change during the experiments for the measured data, whilst transient effects are changes due to fast variations in torque and/or engine speed. Transients are quantified evaluating the difference (%) from the steady state condition. Equation (1) is valid for the steady state condition, whilst the additional presence of three coefficients for the transients would permit to quantify FC and EM in transient conditions.

3 Results

Results are reported in two sections; first, on the processing of the measured data on field and then on the application of modelling.

3.1 Results on the measured data

For each operation, the working time was measured distinguishing in effective work, turns at the headlands, stops and the transfer from farm to field and vice versa. Results about the working time are reported in **Table 4** for all operations. In most cases, the effective work ranges between 60% and 70% of the total work time on the field (i.e. effective work, turns and stops without transfers), with a lower value for sowing (where stops are responsible for 29% of the total working time on field due to the filling of the hopper) and a higher value for rolling (which is a quite straight-forward operation). The turns at the headlands show a higher variability, ranging between 8% for rolling and 28% for rotary harrowing where the 5 headland strategies for the turns have been studied. For the stops, the result is affected by the rinsing of Testo® instrumentation that was performed with the tractor in a stationary idling position, as well as by the hopper filling during sowing. When considering the effective field work capacity, thus taking into account the transfers, the share of the total working time of the operation is affected by the distance from the field and influences the results; in particular, the contribution of transfers ranges between 17% and 56% for all the evaluated operations. Of course, considering the transfers (total working time of the operation = 100%), the work capacity on field decreases (i.e. effective work plus turns plus stops in a range between 44% and 83% of the total working time, due to transfers effect).

Table 4 around here

Table 4. Working time distribution (h) in the studied operations.

Operation	Effective work	Turns at headlands	Stops	Transfers	Total working time
Ploughing	1.93 h	0.62 h	0.39 h	1.46 h	4.40 h
Harrowing, rotary	1.77 h	0.82 h	0.36 h	1.40 h	4.35 h
Harrowing, spike	2.10 h	0.31 h	1.00 h [a]	0.70 h [b]	4.11 h
Sowing	0.69 h	0.16 h	0.35 h [c]	1.19 h	2.39 h
Rolling	0.29 h	0.03 h	0.09 h	0.53 h [b]	0.94 h

[a] This includes the time to couple tractor-implement on field (implement already on field) and to change the work layout of the implement (i.e. change of working depth between two field parts).
[b] The spike harrow and roller were already on the headlands of the field, therefore only the way back was measured. Thus, the total time (including way forward and way back) has been estimated.
[c] This includes the time to refill the hopper with seed.

The trend along time of the measured variables can be retrieved from the processing. **Figure 3** illustrates an example for this by focusing on two sections of rotary harrowing (i.e. headland turning strategies A and D) in which is also shown the distinction of collected data among effective work, turns at headlands and stops. In particular, when the headland strategy included changes in direction (e.g., strategy A), the trend in fuel consumption is widely variable (5-17 L h^{-1}), whereas when the turn is performed in a homogeneous driving scheme (e.g., strategy D) the fuel consumption is homogeneous and with a reduced variation level (5-8 L h^{-1} for most data). The variation in fuel consumption due to the effective work during the case of “headland strategy D” is consistent along the field in accordance with the change in gear (see Table 2, area IV).

Figure 3 around here

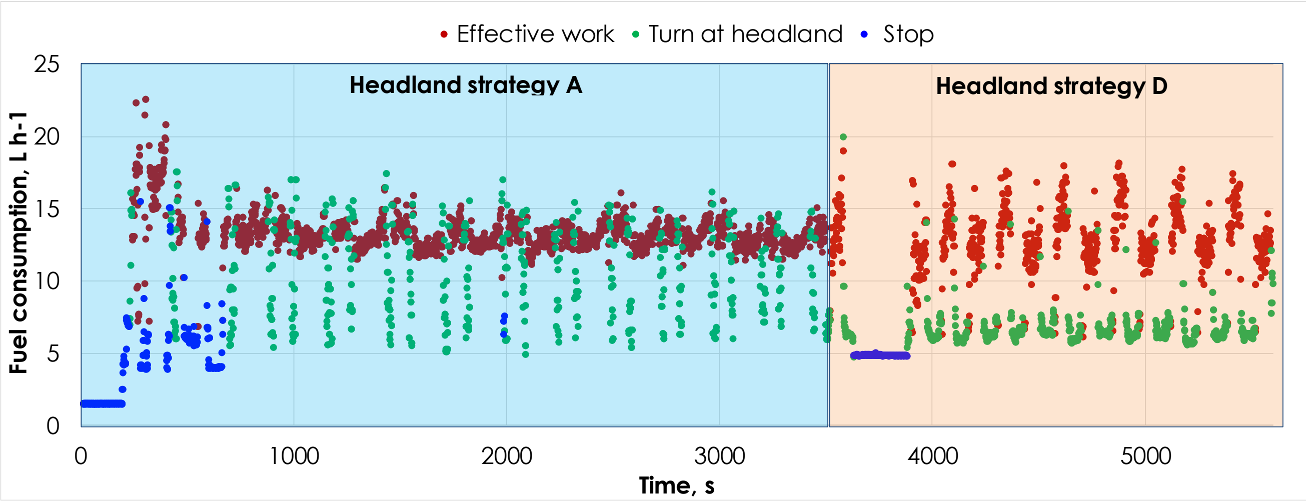


Figure 3. Trend along time of the measured fuel consumption for the rotary harrowing with the strategies for the headlands named "A" and "D".

To get a value per stretch of effective work and per turn, every stretch and turn was numbered and statistics was calculated on them. In particular, **Figure 4** shows an example for ploughing, where every stretch and every turn are identified and report the average brake specific fuel consumption (bsfc; g kWh^{-1}) and CO_2 specific emission (EM_{CO2}; g kWh^{-1}). The specific values for bsfc and CO_2 were calculated considering the fuel consumed (L h^{-1}), CO_2 emitted (g h^{-1}) and absorbed engine power (kW) and averaging them per section of work state (i.e. per stretch and per turn). During the effective work, the values go up and down due to the field gradient that affected the tractor's developed engine power, which caused changes in brake specific fuel consumption and specific exhaust gases emissions between the way forward and the way back.

Figure 4 around here

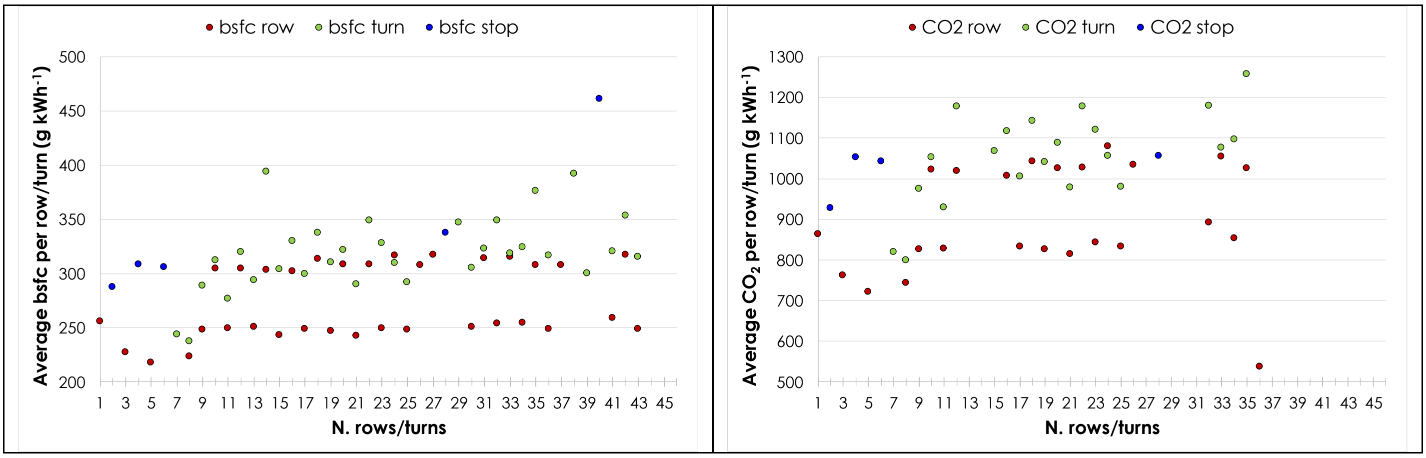


Figure 4. Average values for each work state of effective work, turn at headlands and stop for the ploughing operation (specific for Section 2 of ploughing). On the left, brake specific fuel consumption (g kWh^{-1}). On the right: specific values for CO_2 emission (g kWh^{-1}).

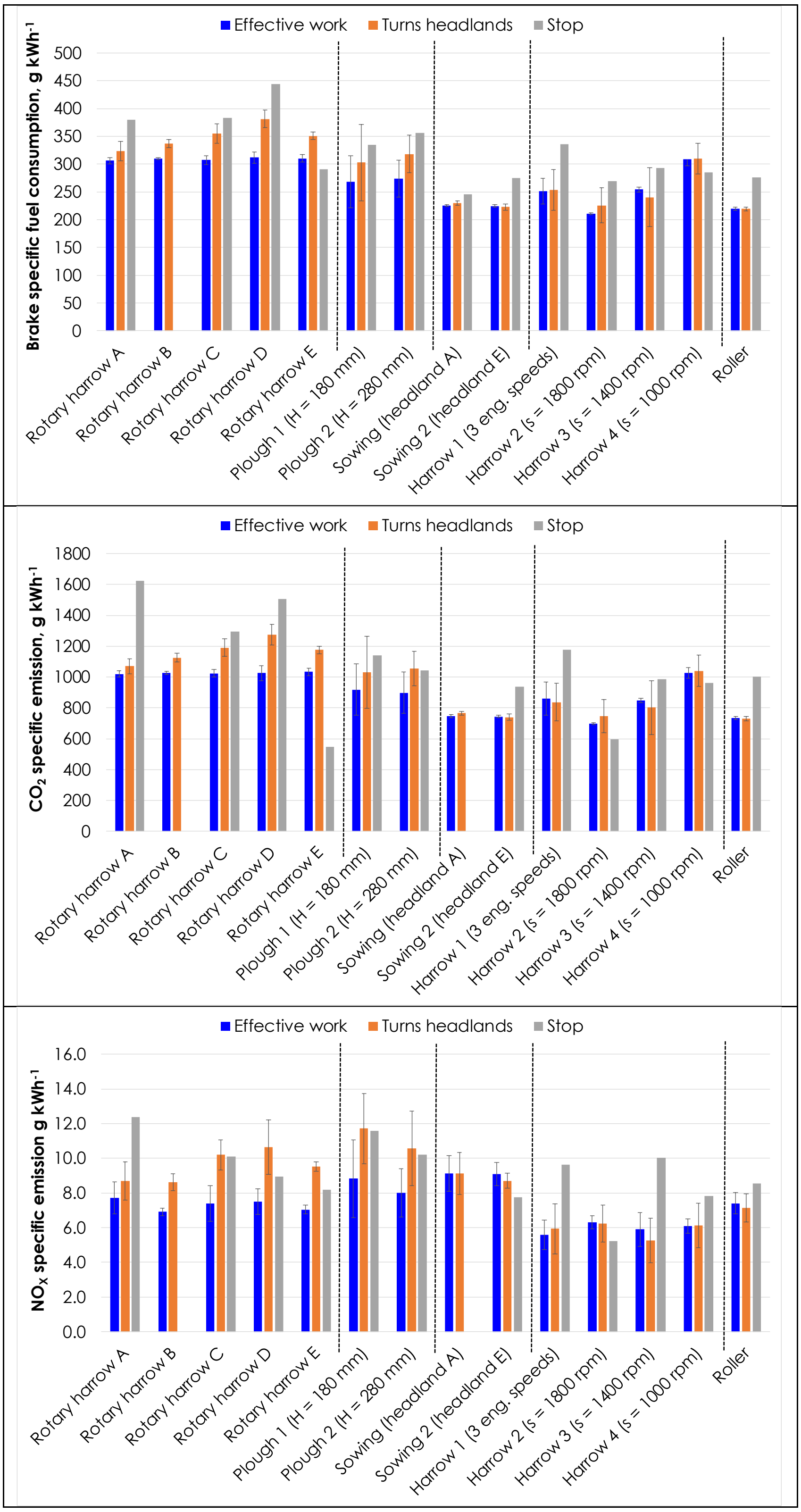
From the figure, it emerges that the specific values referred to the turns are higher respect to those during the effective work; thus, the efficiency of fuel (kWh g^{-1}) and the related one of CO_2 are better for the effective work state. It can also be seen that the stops play a role in regard of specific consumption and emission. In particular, although the stops are short in time, the bsfc and specific emission of CO_2 show values higher (340.3 g kWh^{-1} and 1020.7 g kWh^{-1} for bsfc and specific CO_2, respectively) than the average of turns (318.3 g kWh^{-1} and 1054.9 g kWh^{-1} for bsfc and specific CO_2, respectively) and, mainly, of effective work (274.2 g kWh^{-1} and 897.0 g kWh^{-1} for bsfc and specific CO_2, respectively), especially in the second part of the field.

Similarly, all results on the assessed operations that refer to the average bsfc (g kWh^{-1}), CO_2, NO_X and CO (g kWh^{-1}) per effective work, turn and stop are reported in **Figure 5**. Each operation was distinguished in different parts[1] when different variables were considered (e.g., rotary harrow A-E for the 5 headland strategies, ploughing 1-2 for the two different working depths).

As expected, the specific values for fuel and exhaust gases emissions are almost always higher during turns at headland and stops rather than during the effective work on field due to the tougher working conditions, engine load and impact of transients. In particular, bsfc and CO_2 have a similar trend, due to their dependence on fuel use; instead, NO_X and CO show higher variability, mainly due to the EGR system, oxygen concentration and catalyst temperature.

[1] See notes to Table 3 for the details on each operation.

Figure 5 around here



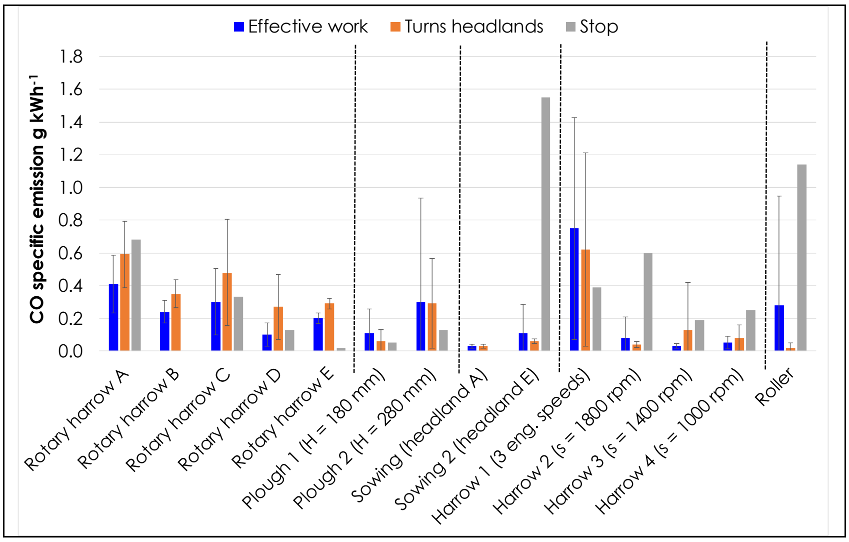


Figure 5. Brake specific fuel consumption (bsfc; g kWh^{-1}), CO_2 (g kWh^{-1}), NO_X (g kWh^{-1}) and CO (g kWh^{-1}) average values per work state gathered from the data from field measurements. Standard deviation is also reported for effective work and turns at headlands, while it was not calculated for stops due the low number of stops in the operation.

From the figure, a comparison among headland strategies can be performed within the rotary harrowing operation (i.e. headland strategies A-E). The results show that the highest values for bsfc, CO_2 and NO_X specific emissions are gathered during headland strategy D, followed by strategy C (-6.8% respect to turns in D) and strategy E (-7.9% respect to turns in D). For CO, instead, the opposite trend emerges, being strategy A the worst (followed by strategy C: -18% respect to A). Regarding the effective work, instead, the values are much closer to each other, as expected, due to the choice of adopting the same work conditions; however, higher values for bsfc and NO_X specific emission are shown in headland strategy D, where the turn strategy affected the effective work values as well. Another comparable operation is ploughing, where, however, not relevant differences emerge between the ploughing performed at 280 mm or at 180 mm depth (all values range within 89% and 100%, except for CO where lower results were highlighted during the first case).
The last comparable operation is the spike harrowing with options 2-4 (the variable is engine speed, with s_2 = 1000 min^{-1}, s_3 = 1400 min^{-1}and s_4 = 1800 min^{-1}, respectively), from which it emerges that at lower engine speed the bsfc and the CO_2 specific emission were higher for all the three evaluated working states (other harrowing cases range for both variables between -16% and -32% of option 2). For NO_X as well as for CO, the best condition resulted the one in which harrowing was performed at

s_3 = 1400 min^{-1} (effective work and turns at headlands) (-6% and -16% for NO_X during effective work and turns, respectively and even more for CO, for which, however, high variability is encountered) while the emissions during the stops were lower when the engine speed was s_4 = 1800 min^{-1} (range between 42% and 85% respect to the worst case). In particular, the results obtained during the stops were affected by the fact that, when stops were shorter than 20 s, the engine speed was not idling but remained set at the work conditions.

For each variable is also reported the standard deviation of the operation and working state in order to understand how repeatable are the results. In most cases, standard deviation values are restrained, except for CO emission for which quite high values can be identified. Moreover, in some operations such as ploughing 2 (H = 280 mm) and spike harrowing 1 (with the combination of 3 engine speeds one after the other on the same stretch; the field length was b = 420 m) show high standard deviations for torque and engine speed. Differences in these values can also be found from stretch to stretch and from turn to turn, mainly due to the specific fieldwork conditions.

In order to understand in which working conditions, the Valtra N101 engine performs the best in terms of bsfc and specific emission, as shown in **Table 5**, the median values for bsfc, CO_2, NO_X and CO specific emissions (g kWh^{-1}) have been grouped according to engine speed and torque combinations. In more details,

- engine speed is split in 3 groups: (A) s < 1100 min^{-1}; (B) 1100 ≤ s < 1600 min^{-1}; (C) s ≥ 1600 min^{-1};
- torque is split in 3 groups: (a) M < 100 Nm; (b) 100 ≤ M < 200 Nm; (c) M ≥ 200 Nm.

In this case, median was chosen since it resulted being a better indicator than mean and mode. The groups of engine speed and torque were selected in order to group them in low, medium and high values.

Table 5 around here

Table 5. Median value of brake specific fuel consumption (g kWh^{-1}) and of specific emissions of CO_2, NO_X and CO (g kWh^{-1}) for each combination of engine speed and torque.

Variables	**Combination of engine speed and torque**								
	A-a	**A-b**	**A-c**	**B-a**	**B-b**	**B-c**	**C-a**	**C-b**	**C-c**
BSFC g kWh^{-1}	312.5	394.5	421.4	239.6	278.8	263.4	219.8	252.1	288.5

CO_2 g kWh^{-1}	907.9	1265.6	1338.2	760.1	884.3	1027.5	710.1	810.0	927.2
NO_X g kWh^{-1}	7.5	9.1	10.2	7.1	8.4	7.2	6.6	5.8	5.5
CO g kWh^{-1}	0.0	0.0	0.2	0.0	0.0	0.1	0.0	0.0	0.1

Notes: (A) s < 1100 min^{-1}; (B) 1100 ≤ s < 1600 min^{-1}; (C) s ≥ 1600 min^{-1}; (a) M < 100 Nm; (b) 100 ≤ M < 200 Nm; (c) M ≥ 200 Nm.

In more details, the combined groups that include low engine speed values (i.e. A-a, A-b and A-c) are the less desirable solutions, since they show the highest values. High values mean that a worse efficiency is linked to this condition, characterised by the engine running slowly (idling or almost idling). The same trend is confirmed for CO_2 and NO_X. For nitrogen oxides, however, the trend involves also that at low torque (i.e. A-a, B-a and C-a) emissions are bigger than at high torque and, similarly to previous variables, they are the highest at low engine speed (s < 1100 min^{-1}) followed by the intermediate step with medium-high torque and engine speed (B-b).

Regarding CO, the results are again more complicated to evaluate, although it emerges that CO specific emissions are higher with low engine speed (s < 1100 min^{-1}) and high torque (≥ 200 Nm) (i.e. case A-c).

3.1.1 Data processing of the transfer working phases

The transfer phases were studied considering the complete transfer from farm to field and vice versa. This phase involves a wide range of variation in fuel consumption (1.5-24.9 L h^{-1}) due to the transferring on the paved road that involves fast travel speed changes. For this reason, they are analysed separately.

In **Table 6** are reported the values of bsfc (g kWh^{-1}) and of the specific emission of exhaust gases (g kWh^{-1}) (when available) during each of the transfers studied for the field operations. Besides, also torque (Nm), engine speed (min^{-1}) and engine power (kW) are given as mean value of the transfer. Once more, these values are to be adopted in the inventory of LCA studies, since transfers represent a phase of the whole operation.

Table 6 around here

Table 6. Brake specific fuel consumption (bsfc, g kWh^{-1}), specific emission of CO_2, NO_X and CO (g kWh^{-1}), torque (Nm), engine speed (min^{-1}) and power (kW) for the transfer phases. During part of the transfers, no information was collected on exhaust gases emission.

Work phases	bsfc g kWh^{-1}	CO_2 g kWh^{-1}	NO_X g kWh^{-1}	CO g kWh^{-1}	Torque Nm	Eng. speed min^{-1}	Eng. power kW
Transfer 1	371.79	0.32	27.50	4.17	134.0	1650.7	23.2
Transfer 2	412.53	--	--	--	93.49	1408.30	13.8
Transfer 3	429.86	0.58	51.55	0.64	63.06	1094.95	7.3
Transfer 4	452.18	0.00	0.02	0.00	84.0	1220.8	10.7
Transfer 5	268.01	--	--	--	116.5	1019.7	12.4

3.2 Results on the modelled data

The 9 coefficients needed for modelling fuel consumption and engine emissions for the engine of tractor Valtra N101, in accordance with the model described in Section 2.6, are shown in **Table 7**. For both fuel consumption and emissions, they were calibrated with the measured values.

Table 7 around here

Table 7. Model engine-specific coefficients calculated for tractor Valtra N101.

Engine-specific coefficients	**Variable**			
	Fuel consumption	**CO_2 emission**	**CO emission**	**NO_X emission**
c_1	$-2.29\cdot10^{-3}$	$-5.57\cdot10^{0}$	$4.33\cdot10^{-2}$	$-3.95\cdot10^{-1}$
c_2	$4.35\cdot10^{-6}$	$1.12\cdot10^{-2}$	$-6.77\cdot10^{-5}$	$6.27\cdot10^{-4}$
c_3	$-1.10\cdot10^{-9}$	$-2.90\cdot10^{-6}$	$2.67\cdot10^{-8}$	$-2.14\cdot10^{-7}$
c_4	$5.92\cdot10^{-5}$	$1.49\cdot10^{-1}$	$-1.52\cdot10^{-4}$	$5.74\cdot10^{-3}$
c_5	$-5.15\cdot10^{-8}$	$-1.26\cdot10^{-4}$	$2.80\cdot10^{-7}$	$-7.04\cdot10^{-6}$
c_6	$1.91\cdot10^{-11}$	$4.81\cdot10^{-8}$	$-1.46\cdot10^{-10}$	$2.38\cdot10^{-9}$
c_7	$-1.18\cdot10^{-7}$	$-3.04\cdot10^{-4}$	$2.66\cdot10^{-7}$	$-1.19\cdot10^{-5}$
c_8	$1.64\cdot10^{-10}$	$4.27\cdot10^{-7}$	$-5.97\cdot10^{-10}$	$1.64\cdot10^{-8}$
c_9	$-5.35\cdot10^{-14}$	$-1.42\cdot10^{-10}$	$4.31\cdot10^{-13}$	$-5.85\cdot10^{-12}$

As stated in Lindgren (2005), adopting the equation that evaluates transient effects permits to reduce the model error. Nevertheless, for these field experiments, the equation (Eq. 1) in steady state conditions was selected. The reason is related to the analysis performed on transients (i.e. the rate of change in engine speed per second over the maximum engine speed of the engine): their effect on all studied operations is reduced, as shown in **Figure 6**. The difference in the colours is related to the couple Engine Speed-Torque, which was made in order to identify the possible differences in transient due to the relation between engine speed and torque; the adopted couples "engine speed-torque" were built splitting engine speed in three groups (s < 800 min^{-1}; 800 ≤ s <1200 min^{-1}; s ≥1200 min^{-1}) and torque in three groups (M < 50 Nm; 50 ≤ M <150 Nm; M ≥ 150 Nm) and matching the combinations. The values that constitute the grouping differ from the former ones because, in this case, it was more important to focus on the phases in which transients can play a prominent role, thus splitting with bigger detail the sections with low engine speed and torque. The graph is aimed to show the impact of the transient respect to fuel consumption modelling with the steady-state condition (Y-axis, left) at different transient presence, both negative and positive transients (X-axis). It can be seen with the triangular dots in the figure (Y-axis, right) that most data (96.0%) are enclosed in the range ±5% of transient effect; instead, in the range ±10% are included 99.3% of all data. Considering the range ±5%, the impact of the transient is very restrained, which explains why the steady state modelling equation was adopted.

Figure 6 around here

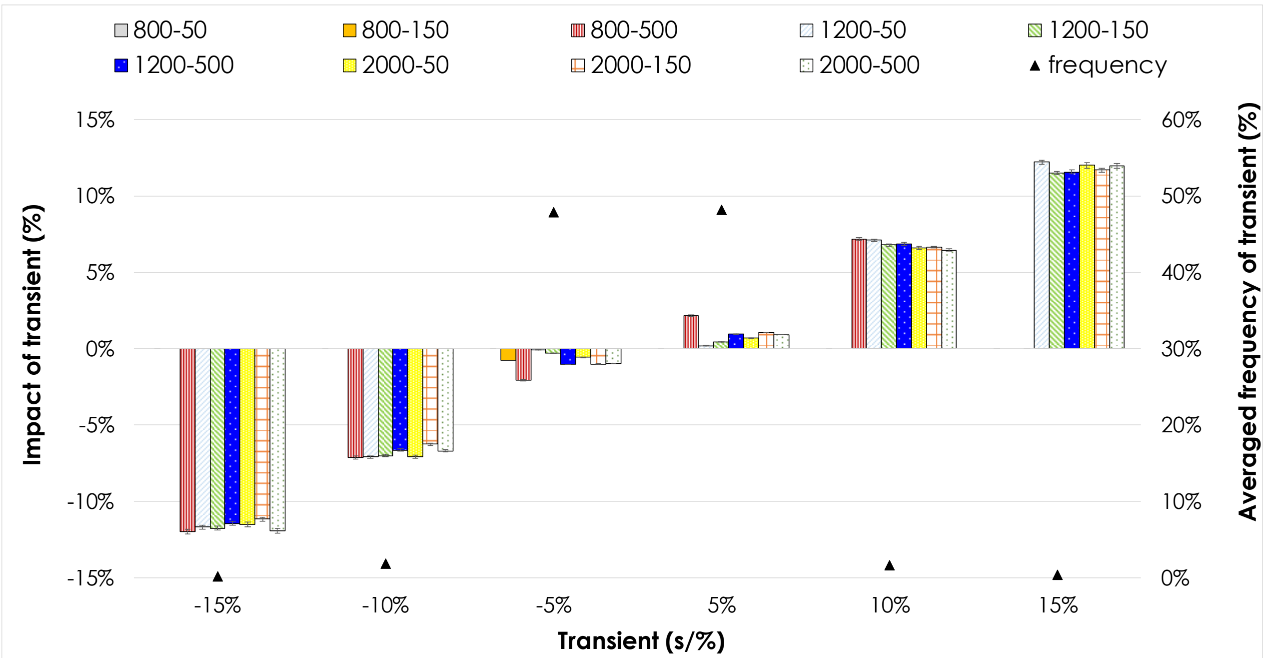


Figure 6. Transients effect during all the studied operations. The legend reports the combination of values of engine speed (s < 800 min^{-1}; 800 ≤ s < 1200 min^{-1}; s ≥ 1200 min^{-1}) and torque (M <50 Nm; 50 ≤ M < 150 Nm; M ≥ 150 Nm) per series. The triangle-dots show the averaged frequency of transients.

The model described very well the engine, and mostly the fuel consumption and CO_2 emissions; for NO_X and, mainly, for CO more variability must be considered and therefore the model outcomes are less performing. Carbon monoxide (CO) was subject to excessive unrepresentativeness from the steady state model and usually depends on unregular conditions. In fact, CO is affected by several variables (Lindgren, 2005), among which air supply and the abilities of the driver, motivating the not sufficient response to the model. **Table 8** reports the R^2 resulting from the use of Eq. 1 to all analysed field operations referring to both fuel consumption and exhaust gases emissions. R^2 was quantified as the covariance of calculated and measured variables (i.e. fuel and each exhaust gas) divided by the product of their standard deviations, in accordance with Pearson equation for the correlation coefficient.

Table 8 around here

Table 8. Values of R^2 for the model used in predicting fuel consumption and engine exhaust gases emissions.

Work state	R^2			
	Fuel consumption	CO_2 emission	NO_X emission	CO emission
Effective work	0.97	0.90	0.22	0.19
Turns at headland	0.92	0.77	0.38	0.32
Stops	0.95	0.65	0.42	0.05

Nitrogen oxides (NO_X) depend on the internal engine temperature and the higher the temperature the higher is the NO_X emission. In this case, the tractor is equipped with the EGR, which involves that when the exhaust gases reach a defined threshold for temperature, the EGR system starts and brings to NO_X reduction. This works mostly during the effective work; instead, during turns the temperature in the exhaust pipe varies more in accordance with the working conditions, therefore higher variation can be identified. For what regards the stops, the engine is commonly idling and the EGR does not start working, at least until the threshold temperature is reached. Due to the lower temperature, NO_X emission values are lower. The main problems in this case are, however, that: first, some measured data reach very high values, probably due to the working conditions and sensibility of the instrument and, second, the temperature fast variation cannot be correctly identified with the model.

Considering the model's response with all data processed and considering effective work, turns and stops, the model calculated values were, on average: (i) +4% respect to the measured bsfc (coefficient of variance = 0.09), (ii) -1% respect to the measured CO_2 (coefficient of variance = 0.39), (iii) +4% respect to the measured NO_X (coefficient of variance = 0.39), and (iv) +2% respect to the measured CO (coefficient of variance = 0.60). It can be observed that most differences are related to bsfc and NO_X, for which, however, the reasons are connected to the higher data availability for bsfc, since differently from emissions there is no rinsing. Moreover, most discrepancies from the measured values are related to the turns and stops where the impact of the transients, although restrained, plays a more important role respect to the effective work phase. In support of this, if the model was not used for the stops, the outcomes would be included within ±2% respect to the measured values for all the 4 variables (bsfc, CO_2, NO_X and CO specific emission). The coefficient of variance for the measured and calculated values is close to 0 for most data, except for the section characterising the stops of two field operations (i.e. section of rotary harrowing and section of ploughing). The good response in this case is also motivated by the fact that, being a mean value for all data, variability is averaged along the whole dataset.

4 Discussion

In this study are reported the results of field experiments carried out with one tractor coupled with several implements realised in order to measure the variables that affect tractor engine, fuel consumption and engine exhaust gases emissions, and to use a model that could satisfactorily describe the system.

From the results, it emerges that a high-level modelling can be reached by monitoring field operations through the electronic instrumentation, which is a very useful step forward to efficiency increase, inputs use and agricultural sustainability assessment. In particular, an interesting finding was the possibility of showing that working states highlight strong differences respect to each other and that studying what working states compose the operation is important.

Collected data on field only describe the specific tractor's engine tested, built to match the IIIA Emissive Stage restrictions; therefore, it was equipped with the EGR system for the reduction of NO_X emissions. Older engines as well as newer ones that must respect the legislation with Stage IIIB (presence of Selective Catalytic Reduction - SCR - with urea) are likely to have a different dynamic. Thus, the results of this study are not applicable to other tractors/engines in their specific terms of the resulting values, but they are widely applicable in general terms when focusing on the engine's behaviour and on the methodology in building a model.

An additional plus is given by the fact that, usually, studies refer to test bench measurements and to the operating points defined by the ISO 8178-C1 Standard (ISO, 1996), whilst in this study the measurements were done directly on field, involving that higher variability due to the effective field work conditions should be taken into account, especially with regard to engine exhaust gases emissions (Larsson and Hansson, 2011; Lindvall et al., 2015). Other studies are available in literature in which analyses were performed directly on field. For example, Lindgren (2004) studied several different field operations to evaluate the effect of transients and to get a model for fuel consumption and emissions release. Janulevičius et al. (2013), instead, studied a ploughing operation and collected data about exhaust emissions using the same gas analyser. In this case, they averaged the results on emissions in three groups of engine load and three of engine speed in order to get an average value for the tractors they used. Although the results were reported as specific values (g kWh^{-1}), in none of them the operations were distinguished in effective work, turns and stops. Conversely, Pitla et al. (2016) analysed field operations within this framework of work states and got results describing the US working context. However, due to assumptions and different operations evaluated, the outcomes are not comparable to this study. Additionally, Merkisz et al. (2015) also studied fuel consumption and CO_2 emissions for a cultivator operation. Nevertheless, they used a different methodology: fuel consumption was gathered through the carbon balance method and emissions were quantified with a portable emission measurement system (PEMS) that also permits to quantify emissions during the fieldwork. Having data directly measured on field makes values not comparable with other operations and other studies but permits to describe accurately the effective work conditions under assessment, without underestimates of variables due to the test bench. Test bench measurements can be still efficaciously used to produce the coefficients for the steady state modelling, which permits to gather coefficients without specifically performing tests on field and, thus, to fasten data collection for subsequent environmental assessments.

Studying the different headland strategies was aimed to show to what extent the headlands strategies affect fuel and exhaust gases emissions (Janulevičius et al., 2013). Headland strategies with a higher degree of manoeuvring involved, in fact, higher specific fuel consumption and higher specific engine emissions. In addition, the field distinction in effective work, turns and stops permitted to understand if and how the fast variation in engine features such as engine speed and torque causes specific increases in consumption and emission. As expected, the specific values gathered during the stops involve an increase in brake specific fuel consumption and specific exhaust gases emissions, causing higher costs for fuel and higher environmental air pollution. The best efficiency of fuel is related to the effective work for almost all studied operations.

The studied operations highlighted a low impact of transients; therefore, extending the model for steady state to transient effects was not expected to give important benefits on the modelling. However, the extension (Lindgren, 2004) can be useful when transients are more present respect to these trials (e.g., during front-loading operations).

The adopted model gave a very good response to fuel consumption and CO_2 emission. However, it underestimated the real emission of NO_X and CO, probably due to the transient effects and accessory variables playing a greater role on these emissions rather than on fuel and CO_2. Moreover, CO is affected by air supply and incomplete combustion (Lindgren and Hansson, 2004) and has resulted being subject to hikes and unregular trends also in other studies. With positive transients, CO emissions increased because of the incomplete combustion, whereas during negative ones emissions were close to the steady state condition. Considering NO_X emissions, instead, what occurs commonly is that at high temperatures in the engine the NO_X emissions increase (Janulevičius et al., 2013); in this case, on the contrary, when the threshold temperature was reached, the EGR started working and the NO_X did not follow the trend. Consequently, with the EGR, NO_X emissions reduced (condition that usually occurs during the effective fieldwork - medium-high torque and medium-high engine load - while increased during the accessory working time). Given this wide variability in the modes to reduce exhausts, a trade-off among them must be found, mainly for environmental pollution issues.

For what concerns the transport phases, the transient effects had higher importance than those on field and, in fact, the steady state model worked less well. In particular, considering that farms are becoming fewer but bigger and that farmers need to drive longer distances to reach fields from farm, especially on an environmental perspective the transfer distances, engine features during transfers as well as fuel consumption and exhaust gases emissions of these accessory work phases are becoming increasingly important.

The results can be widely applicable, both to estimate variables to be adopted in other models and to fill in the inventories for Life Cycle Assessment (LCA) studies to quantify appropriately the environmental impact of agricultural field operations (Larsson and Hansson, 2011; Lovarelli and Bacenetti, 2017), providing reliable results on specific studied cases. Different working conditions and implements as well as exhaust gases emissions from tractors equipped with different emission control strategies can be consistently evaluated, and adequate mitigation strategies can be proposed (Renzulli et al., 2015). Considering the effect of fuel and exhaust gases, the environmental assessment through LCA is very important, since fuel consumption, CO_2 and NO_X are important sources of environmental impact. Fossil resources affect several environmental impact categories, such as Climate Change, Ozone Depletion, Terrestrial Acidification, Marine and Freshwater Eutrophication, and Mineral, Fossil and Renewable Resources Depletion (Wolf et al., 2012). On the other hand, CO plays an important role on human health, although it is commonly less important from an agricultural perspective due to the lower population density that lives in the countryside where most agricultural activities occur.

5 Conclusions

The study was aimed to report the results of measurements deriving from trials on field with different field operations and to apply a model that could describe the tractor's fuel consumption and exhaust gases emissions with reliable results. Every data was related to a work state on field to show what occurs during each state within different work conditions (e.g., working speed, working depth, engine speed, engine load). This permitted also to make statistics on the most frequent work conditions and engine features that characterise agricultural machinery field operations. However, it is fundamental to underline that the results only refer to the tested engine.

The use of such values in the completion of the inventory for environmental sustainability studies permits to improve the reliability of LCA results about agricultural machinery processes and, therefore, to make valid assessments that allow suggesting effective environmental mitigation strategies. In more details, focusing on the effective working conditions on field permits to: (i) avoid underestimations or overestimations as due to bench tests, (ii) quantify the difference between the most sustainable operative solution and the other alternatives for the farmer, (iii) understand where improvements can be introduced along the work stages on field and, finally, (iv) make farmers conscious of their role on the environmental sustainability of agricultural productions.

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Authors contributions

DL planned the field trials, DL and GL planned the study, processed the data and wrote the paper. All authors revised the paper.

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