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Controlling idling : a ready-made solution for reducing exhaust emissions from agricultural tractors

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Abstract

Mechanised agriculture accounts for nearly 70 million tonnes of CO_2 emissions annually. To mitigate these CO_2 emissions, powertrains running on alternative fuels and hybrid powertrains are under development. However, such solutions have not yet reached the technical maturity required for the marketplace. To make significant progress, considering the pressure imposed by the European Commission and others, ready-made solutions must be deployed to achieve rapid and large-scale reductions of greenhouse gas emissions. One such solution is to reduce unnecessary engine idling. This paper presents an investigation of the duration of idling stops, the energy required for starting the engine, and the time at which the engine should be turned off to avoid higher emissions from continued idling. Four tractors with different engine displacements were used in experiments. For the tractors, the energy required for engine start-up was measured and real-world data were collected over several months. From data analysis, it was found that shutting off the engines for idling stops longer than 4.4 s resulted in lower emissions. The four tractors showed different idling patterns; turning off the engine during unnecessary idling stops led to fuel savings of 1.1% to 5.1%. Based on these results, 770,000 tonnes of CO_2 annually could be saved by equipping tractors with the proper technology for turning off the engine during unnecessary idling stops.

KEYWORDS: idling, greenhouse gas emissions, CANBUS, climate change, real-world data

Nomenclature		
c_{CO}	Carbon monoxide (CO) concentration	(ppm)
c_{CO_2}	Carbon dioxide (CO_2) concentration	(%)
c_{NO}	NO concentration	(ppm)
c_{NO_2}	NO_2 concentration	(ppm)
$\dot{f}$	Engine fuel rate	($l\ h^{-1}$)
$f_{el,st}$	Mass of burned fuel necessary for restoring $E_{el,st}$ in the Battery when the engine is running	(kg)
$f_{eq,st}$	Equivalent fuel used for starting the engine	(l)
$\dot{f}_{idle}$	Engine fuel rate during idling	($l\ h^{-1}$)
$f_{inj,st}$	Fuel injected to accelerate the engine up to the minimum self-sustaining engine rotational speed	(kg)
f_{save}	potential fuel savings by avoiding unnecessary idling	(l)
$m_{CO_2,st}$	Mass of CO_2 generated for a single start-up	(g)
$\dot{m}_{CO,idle}$	Mass flow rate of CO during idle	($g\ h^{-1}$)
$\dot{m}_{CO_2,idle}$	Mass flow rate of CO_2 during idle	($kg\ h^{-1}$)
$\dot{m}_{NO,idle}$	Mass flow rate of NO	($g\ h^{-1}$)
$\dot{m}_{NO_2,idle}$	Mass flow rate of NO_2	($g\ h^{-1}$)
n_e	Engine rotational speed	(rpm)
$n_{e,idle}$	Mean value of the engine speed during the idling phase	(rpm)
n_{su}	Number of additional start-up	(-)
t_0	Instant of the engine start-up occurring when P_{batt} started to be greater than 0 kW	(s)
t_c	Instant of the engine start-up occurring when P_{batt} is equal to 0 kW	(s)
t_{cr}	Instant of the engine start-up where $\dot{f}$ started to be greater than 0 $l\ h^{-1}$	(s)
$t_{eq,idle}$	Number of seconds of idling beyond which shutting down the engine could reduce fuel consumption	(s)
t_s	Duration of engine start-up	(s)
v_t	Tractor ground speed	($km\ h^{-1}$)
CANBUS	Controller area network	
DOC	Diesel Oxidation catalyst	
EC	European Commission	
ECU	Electronic control unit	
EGR	Exhaust gas recirculation valve	
$E_{el,st}$	Energy required by starter to run the engine	(J)
EGD	European Green Deal	
GHG	Greenhouse gas	
GNSS	Global navigation satellite system	
I_{batt}	Battery current	(A)
NO_x	Nitrogen oxides	
NRMM	Non-road mobile machinery	
O_p	Presence of the operator on the seat of the vehicle	(-)
P_{batt}	Power delivered by the battery	(W)
P_{tlp}	Position of the three-point linkage	(%)
SCR	Selective catalytic reduction	
T_c	Engine coolant temperature	(°)
$\dot{V}_{fi}$	Flow of oil through the i_th auxiliary valve	(%)

1. Introduction

In 2020, the European Commission (EC) presented the European Green Deal (EGD) which is an ambitious set of measures aimed at making Europe the first climate-neutral continent. According to the European Environment Agency (2021), in 2019 mechanised agriculture accounted for nearly 70 million tonnes of CO_2 (figure retrieved for the sector 1.A.4.c.ii – Off-road Vehicles and Other Machinery of Intergovernmental Panel on Climate Change [IPCC]). To further reduce greenhouse gas (GHG) emissions, in 2019, the European Union introduced the Stage V regulation for Non-Road Mobile Machinery (NRMM) which imposes a reduction of 97% for particulate matter and of 94% for hydrocarbons and nitrogen oxides (NOx) from those imposed by Tier 1. To meet these targets, machinery manufacturers have been working since that time on exhaust after-treatment devices (Michelin et al., 2000; Rudder, 2012). However, these devices are bulky and can reduce tractor visibility and ground clearance, thus limiting tractor driveability. Moreover, considering the progress in exhaust after-treatment devices fitted by manufacturers in the last years, further reductions in exhaust emissions are not expected in the coming years without changes to different fuels. Most of the solutions for decarbonising heavy agricultural equipment that being researched or are under development by manufacturers involve the use of alternative fuels for engines (Bisaglia et al., 2018; Davies & Sulatisky, 1989) or hybrid and electric powertrains (Beligoj et al., 2022; Mattarelli et al., 2019; Mocera & Somà, 2020; Moreda et al., 2016; Scolaro et al., 2021). Most of these studies report theoretical results and analysis, although Varani et al., (2021) tested a hybrid prototype which resulted in a reduction of fuel consumed per hectare by up to 30% compared to a conventional powertrain.

The shift towards these technical solutions requires dedicated infrastructure to support the adoption of new powertrains. In particular, the infrastructure should also enable the clean production of energy (e.g., biodiesel, natural gas, electricity) from agricultural wastes, but several gaps and barriers still hinder their development (Kapoor et al., 2020). Therefore, such solutions still require time to reach the technological maturity required for the marketplace. Considering the pressure imposed by the EC, ready-made solutions must be deployed to achieve rapid and large-scale reductions of GHG emissions; on such solution is reducing unnecessary engine idling. However, for agricultural tractors engine idling has not been fully investigated despite it being an application with significant opportunity to reduce GHG emissions, particularly since tractors often operate at low fuel efficiency (Brodrick et al., 2002). Agricultural tractors often have prolonged idling periods (from 10% up to 43% of their operational time) (Perozzi et al., 2016); of these idling periods, the majority, at least on medium row-crop tractors, are not necessary for farming operations (Molari et al., 2019). The amount of idling time depends on the specific operation being carried out, ranging from 20% for ploughing up to 47% for harrowing (Lovarelli et al., 2018). Therefore, reducing idling time could be an effective method of reducing fuel consumption and CO_2 emissions (Janulevičius et al., 2016).

These studies provided the motivation for us to study engine idling on agricultural tractors and to determine if turning off the engine reduces CO_2 emissions in comparison with keeping it idling. By doing so, the opportunity may be created to add a start-and-stop system to agricultural tractors; a proven solution for passenger cars (Whittal, 2012), but one that has not yet been adopted for agricultural tractors. The potential benefits of start-and-stop systems are highly reliant on the pattern of idling stops in terms of frequency and duration (Mattetti, Beltramin, et al., 2022), which are both are dependent on the type of tractor, farm, and tractor mission profile (Mattetti et al., 2012, 2021). To evaluate the potential benefits of in turning off the engine when it is not needed, it is important to fully characterise engine idling and start-up behaviours for different types of tractors to educate farmers on the advantages and disadvantages of avoiding unnecessary engine idling. This also involves the proposal of novel tractor solutions. However, few studies have been dedicated to engine idling and start-up for agricultural tractors. These aspects of engine performance have been investigated primarily for heavy duty trucks (Canova et al., 2009; DeBruin, 2013; Gaines et al., 2013), but with insufficient depth of analysis. Moreover, heavy duty vehicles have different engine designs and different duty-cycles than agricultural tractors. Therefore, the results from those studies are not directly relevant for agricultural tractors and farmers. This study reports the pattern of idling stops, the energy required to turn on the engine, and the extent to which idling the engine is convenient for different tractor classes to fully evaluate the potential fuel and emission savings by avoiding unnecessary idling. To this end, the authors utilised a large real-world dataset to estimate the potential benefits for farmers.

2. Materials and methods

This study was performed using four different tractors. Their specifications are provided in Table 1.

Table 1 – Main specifications of the tractors used for the tests. PF = particulate filter, DOC = diesel oxidation catalyst, EGR = exhaust gas recirculation valve, SCR = selective catalytic reduction.

Tractor model	Steyr 4095 Kompact	CASE IH Maxxum 115	New Holland T7.260 PowerCommand	New Holland T8.435
Tractor denotation	Steyr	CASE	NH T7	NH T8
Engine type	Turbo Diesel			
Number of cylinders	4	4	6	6
Engine displacement [l]	3.400	4.485	6.700	8.700
Compression ratio	17.0:1	18.0:1	17.0:1	15.9:1
Nominal power [kW]	74	86	162	279
Battery capacity [Ah]	132	110	176	200
Battery cold cranking ability [CCA]	962	960	1300	1900
Transmission type	Partial powershift	Partial powershift	Full powershift	Continuously variable transmission
Gas cleaning system	PF and EGR	DOC and SCR	SCR	DOC and SCR
Complaint emissions stage	IV-A	IV-B	IV-A	V

All the tractors were equipped with engines manufactured by the same vendor (FPT Industrial, Turin, Italy) and with new batteries, except for the NH T8. Before performing the test, the batteries were fully recharged with a dedicated charger. For this study, the testing procedure developed by Mattetti et al. (2022) was adopted. A brief outline of that procedure is provided to give readers the necessary background to understand the results; for further information related to the methodology, the authors suggest that readers refer to that study. Two types of tests were adopted, hereafter referred to as "engine-start test" and "real-world test." The former was performed by measuring the input energy required to start the engine, whilst the latter was performed to evaluate the potential fuel and emissions savings by avoiding unnecessary idling. The raw data of NH T7 were the same as those analysed by Mattetti et al. (2022), but the presentation of the results was modified to make valid comparisons between the results of the different types of tractors.

4.1 *Engine-start test*

For the engine start test, the following parameters were recorded:

- Battery voltage (V_{batt});
- Current flow to the battery (I_{batt});
- Engine speed (n_e) from the CANBUS;
- Engine fuel rate ($\dot{f}$) from the CANBUS;
- Engine coolant temperature (T_c) from the CANBUS;
- Temperature of the fuel gases at the exhaust with a gas analyser;
- Concentration of CO_2 (c_{CO_2}) with a gas analyser;
- Concentration of CO (c_{CO}) with a gas analyser;
- Concentration of NO (c_{NO}) with a gas analyser;
- Concentration of NO_2 (c_{NO_2}) with a gas analyser.

c_{NO} and c_{NO_2}were not recorded for the NH T7 since in the first instance they were not considered significant, but to compare tractors with different exhaust after-treatment devices, c_{NO} and c_{NO_2} were measured for the other tractors. The procedure for the engine start tests consisted of 10 cycles, each of which included engine start-up, 60 s of engine idling, and 30 s of engine off. The idling duration was chosen to restore V_{batt} to the level prior to starting the engine. The tests were performed with the auxiliar loads ON and OFF. In the following, they are denoted as AUX ON and AUX OFF, respectively. The auxiliary loads that were considered were the lights (front and rear headlights, work lamps, warning beacon); cab radio; heating, ventilation, and air conditioning (HVAC); compressor; and the blower fan (set at maximum speed). Since the start-up behaviour of engines is also dependent on the environmental temperature, thus the engine start-up tests were performed at the same ambient temperature (~ 14 °C) for all the tractors.

From each engine cycle, the following parameters were calculated from the recorded data following the procedure reported by Mattetti et al. (2022):

- Duration of start-up (t_s);
- Electrical power delivered by the battery (P_{batt});
- Electrical energy demanded by the starter to start the engine ($E_{el,st}$);
- Volume of fuel injected to accelerate the engine from 0 rpm to the minimum self-sustaining engine rotational speed ($f_{inj,st}$);
- Volume of fuel needed to restore $E_{el,st}$ in the battery when the engine was running ($f_{el,st}$);
- Equivalent fuel used to start the engine ($f_{eq,st}$), calculated using Eq. (1):

$$f_{eq,st} = f_{el,st} + f_{inj,st} \tag{1}$$

- Mean values of the fuel rate ($\dot{f}_{idle}$), emissions of CO ($\dot{m}_{CO,idle}$), CO_2 ($\dot{m}_{CO_2,idle}$), NO ($\dot{m}_{NO,idle}$), and NO_2 ($\dot{m}_{NO_2,idle}$) during the idling phase using the approach described in Mattetti et al. (2022);
- Number of seconds of idling beyond which shutting down the engine could reduce the amount of consumed fuel (t_{eq}), calculated using Eq. (2):

$$t_{eq} = \frac{f_{eq,st}}{\dot{f}_{idle}} \tag{2}$$

- Mean value of engine speed during the idling phase ($n_{e,idle}$).

4.1 *Real-world test*

In the real-world test, the four tractors remained in use in the experimental farm of the Alma Mater Studiorum – University of Bologna, Cadriano, BO, Italy. The size of the farm is 500 ha, of which 67%, 10%, and 23% of the land is devoted to cereals, orchards, and hay, respectively. The farm consisted of three different units (i.e., areas where tractors are stored overnight) and located in three different towns; the furthest locations of the farm units are 35 km apart. The tractors were used by the same operators, all of whom had more than 20 years of experience. Each tractor was monitored for a certain period and used for specific farming tasks (Table 2).

Table 2 – Details of the real-world data recording.

Tractor denotation	STEYR	CASE	NH T7	NH T8
Period of monitoring (dd/mm/yyyy – dd/mm/yyyy)	01/12/1015 - 17/08/2016	24/06/2020 – 30/10/2020	15/10/2018 – 04/10/2021	14/09/2021 – 22/06/2022
Main tractor tasks	Tasks with front loaders, weed control	Goods transportation, and haymaking	Goods transportation, primary and secondary tillage	Primary, and secondary tillage tasks

For all of the tractors, the following data were recorded using a customised controller area network (CANBUS) data logger previously used by the authors in other studies (Mattetti et al., 2021; Molari et al., 2013):

- Flow of oil through the i_th auxiliary valves ($\dot{V}_{fi}$) from the CANBUS (only for tractors equipped with electronically controlled auxiliary valves);
- Presence of the operator in the cab (O_p) from the CANBUS; equal to 1 when the operator was in the seat and 0 otherwise;
- Position of the three-point linkage (P_{tlp}) from the CANBUS; equal to 0 when the rear three-point hitch is fully down and 100% when it is fully up;
- Speed of the rear PTO shaft and the front PTO shaft from the CANBUS;
- Tractor ground speed (v_t) from the global navigation satellite system (GNSS) receiver embedded into the CANBUS data logger.

Since unnecessary idling is closely linked to the operator behaviour (Molari et al., 2019), the operators were unaware of the recording process and presence of the data logger in the tractor. The CANBUS data logger was configured to record data anytime the tractor engine was turned on in order to collect data under the most realistic conditions (Ludes & Steeples, 1999).

Idling stops were identified any time the engine load was very low, i.e., when the following conditions were met:

- n_e equal to $n_{e,idle}$, calculated from the engine start test of each tractor;
- v_t equal to 0 km h^{-1}.

Idling stops were classified as unnecessary if they could be avoided with no significant impact on productivity. Based on this definition, unnecessary idling stops were classified as unnecessary when all the following conditions were met:

- The operator had not been on the seat for longer than 10 s; thus, very short idling stops which could be part of the standard farming manoeuvres were excluded.
- No use of the three-point linkage or any auxiliary valve, meaning the peak-to-peak value of P_{tlp} or $\dot{V}_{fi}$ in the idling stop had to be 0; based on this condition, the idling stop to implement hitching was not classified as unnecessary idling.
- T_c had to be between a lower and upper bounds, so that idling stops performed for warming engines and those after heavy loads were not considered to be unnecessary. The latter condition was necessary since engines must be properly cooled after being heavily loaded (Keel-Blackmon et al., 2016). The two boundary temperature values were chosen based on the manufacturers' recommendations provided in each tractor user manual.

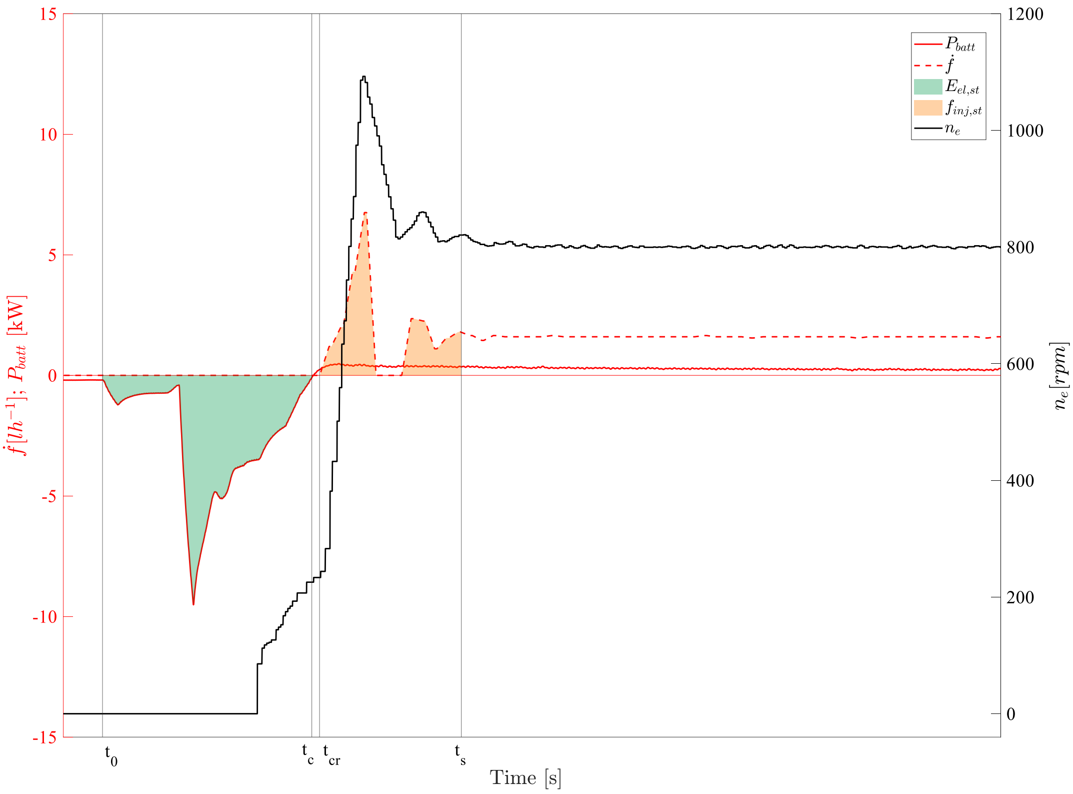
Unnecessary idling was reported with a logical variable; from its falling edges, the number of unnecessary idling stops provided the number of additional engine start-ups (n_{su}). Thus, the potential fuel savings by avoiding unnecessary idling (f_{save}) were calculated using Eq. (1).

$$f_{save} = t_{unn}\dot{f}_{idle} - n_{su}f_{eq,st} \tag{1}$$

3. Results and discussion

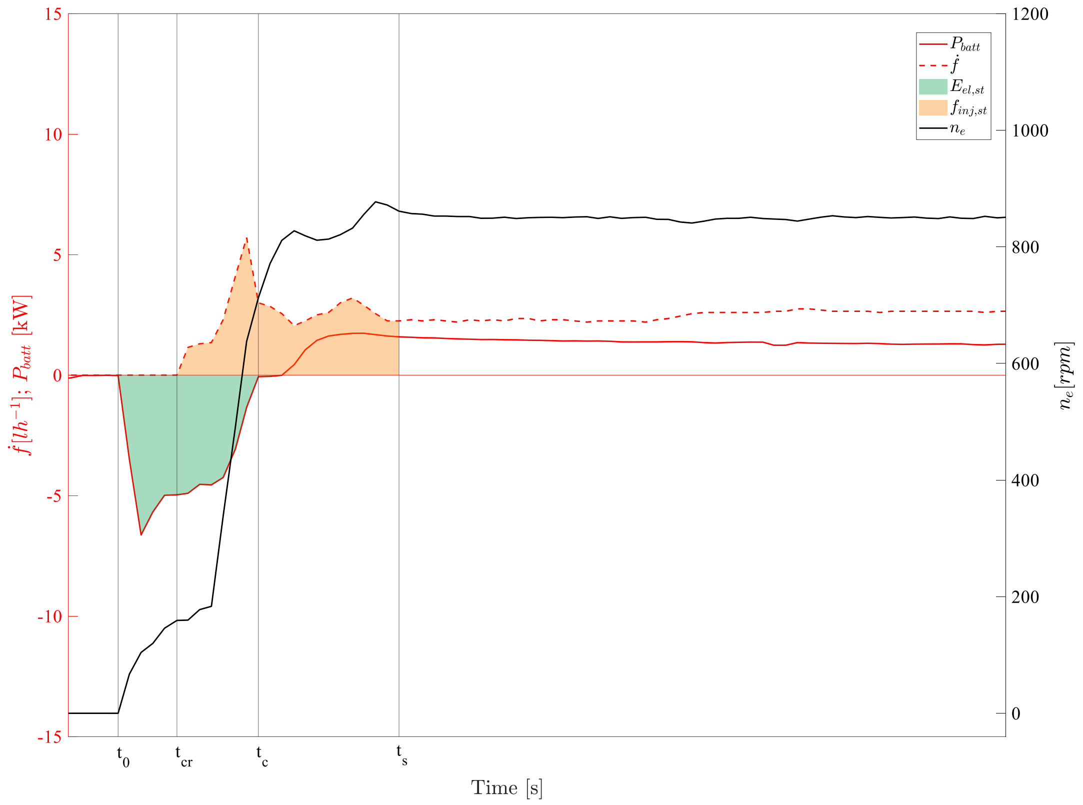
3.1 Engine-start test

In Fig. 1, the behaviours of the engine during start-up are reported for all the tractors during the AUX ON test, since it is the operating condition that most closely represents real-world conditions. No significant differences in the trends with AUX OFF tests were observed.



15
10
5
0
-5
-10
-15
1200
1000
800
600
400
200
0
P_{batt}
$\dot{f}$
$E_{el,st}$
$f_{inj,st}$
n_e
$\dot{f}[lh^{-1}]$; P_{batt} [kW]
$n_e[rpm]$
t_0
t_c
t_{cr}
t_s
Time [s]

a)


15
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1200
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200
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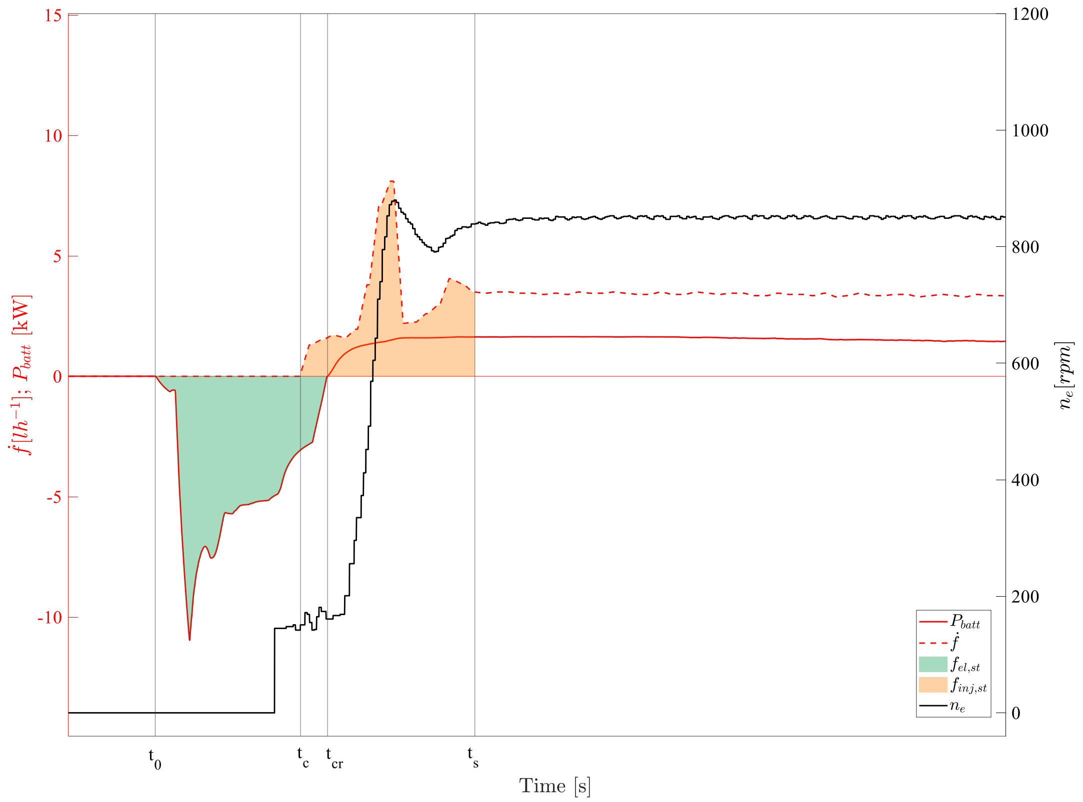
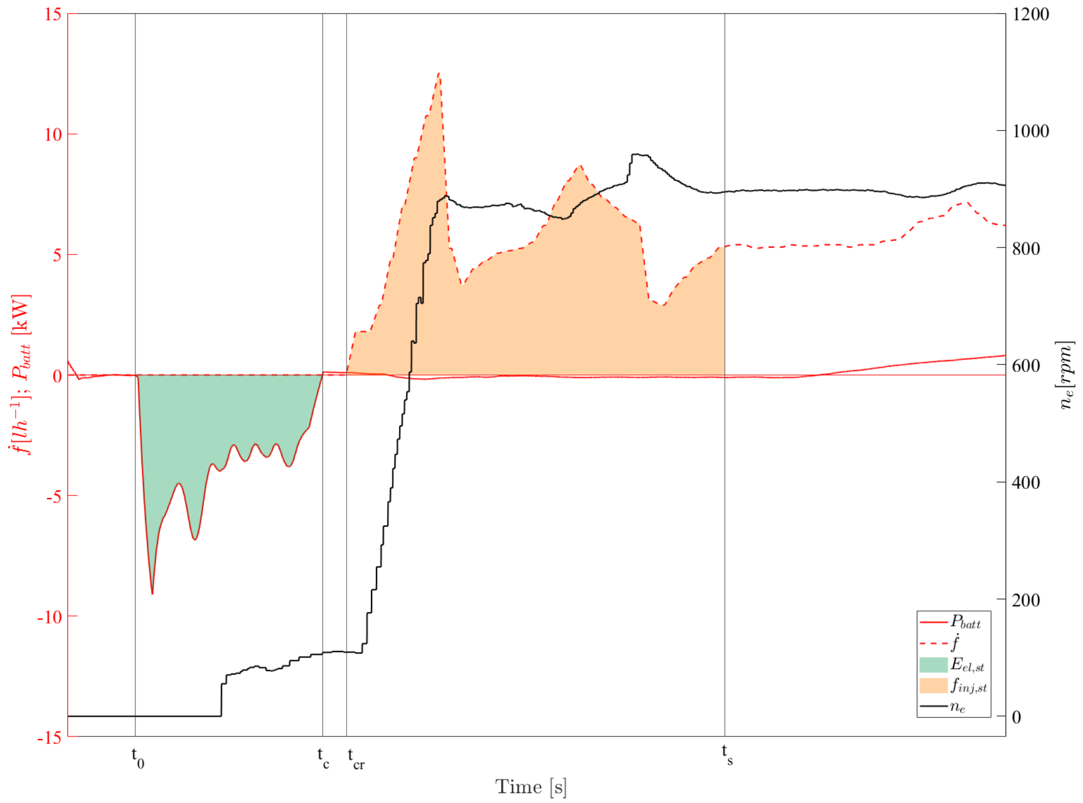
P_{batt}
$\dot{f}$
$E_{el,st}$
$f_{inj,st}$
n_e
$\dot{f}[lh^{-1}]$; P_{batt} [kW]
$n_e[rpm]$
t_0
t_{cr}
t_c
t_s
Time [s]

b)



15
10
5
0
-5
-10
$\dot{f}[lh^{-1}]$; P_{batt} [kW]
1200
1000
800
600
400
200
0
$n_e[rpm]$
t_0
t_c
t_{cr}
t_s
Time [s]
P_{batt}
$\dot{f}$
$f_{el,st}$
$f_{inj,st}$
n_e

c)



d)

Fig. 1: Portion of fuel rate ($\dot{f}$), battery power (P_{batt}), and engine speed (n_e) during start-up with the auxiliaries running (AUX ON test). The green area indicates the energy required by the starter to run the engine ($E_{el,st}$), while the orange area indicates the amount of fuel injected to bring the engine to the self-sustaining idling speed ($f_{inj,st}$). a) STEYR, b) CASE, c) NH T7, d) NH T8. t_0 occurred at the initial change of P_{batt}, t_c occurred when P_{batt} was equal to 0 kW, t_{cr} occurred at the initial change of $\dot{f}$, and t_s occurred when n_e was equal to $n_{e,idle}$. The temporal scale of all the figures is the same.

The general behaviour of the signals during the start-up event was similar for all the tractors. In particular, the start-up event consists of three phases:

- **Cranking:** where the energy necessary to speed up the engine crankshaft is supplied only by the starter motor (DeBruin, 2013), occurring in the time elapsed between t_0 and the minimum value between t_c and t_{cr} in Fig. 1;

- **Crank-to-run transition:** where the energy is supplied both by the starter and the fuel occurring in the time between t_c and t_{cr} in Fig. 1. This phase was not present in all the tractors (i.e., NH T8 (Fig. 1 d));
- **Crank-to-run:** where the energy to speed up the engine is supplied only by the fuel, and the fuel injection is controlled by the electronic controlled unit (ECU) to minimise the self-sustaining engine speed (DeBruin, 2013; Humbert & Kibler, 1977). This phase occurred in the time between the maximum value between t_c and t_{cr}, and t_s.

During the cranking phase, n_e reached the starter speed (ranging from 110 rpm for the NH T8 up to 210 rpm for the STEYR), and from the crank-to-run transition phase, an abrupt change in n_e was observed. An important aspect during start-up is the increase in n_e, which should be brief but also regular in order to not induce any driver discomfort (Srinivasan et al., 2015). This was observed for all the tractors except for the STEYR, which showed a large overshoot flare (i.e., the overshoot difference between the peak engine speed and the idle speed). For new batteries, a major single peak of the P_{batt} signal at the beginning of the start-up event should be observed (Kerley et al., 2015); this was the case for most of the tractors. For the NH T8 tractor, a second major peak could be observed which is an indication of minimum battery ageing, as shown in a previous study (Kerley et al., 2015). The major differences in the start-up events of the tractors were the duration of the start-up event and the distribution of the three start-up phases. The mean value of t_s for all the tractors and the time contribution of the three phases are reported in Table 3.

Table 3 – Mean values of the start-up duration and contribution to the three phases for the AUX OFF / AUX ON test

	STEYR	CASE	NH T7	NH T8
Duration of start-up (t_s) [s]	2.2 / 3.0	2.1 / 2.4	2.6 / 2.7	4.2 / 5.0
Contribution of cranking phase [%] (with respect to t_s)	50 / 58	24 / 21	40 / 45	41 / 32
Contribution of crank-to-run transition phase [%] (with respect to t_s)	0 / 2	38 / 29	6 / 8	0 / 0
Contribution of crank-to-run phase [%] (with respect to t_s)	48 / 40	38 / 50	54 / 46	51 / 64

For all tractors, t_s ranged between 2 and 5 s and increased with the engine displacement, without considering the STEYR. For the STEYR, the t_s value was similar to that found by DeBruin (2013) for a passenger car equipped with an engine of similar displacement. Despite the STEYR having the smallest engine displacement of the tractors selected, it does not have the smallest t_s. This was likely caused by the start-up strategy of the engine during which a large overshoot flare could be observed. After the overshoot, the ECU automatically stopped the fuel injection to decelerate the engine to bring it to $n_{e,idle}$. Thus, STEYR required a longer time to achieve a steady n_e value (Fig. 1a). Longer start-up events were observed for AUX ON tests than AUX OFF tests; indeed, the t_s values for the AUX ON tests were as much as 40% greater than those of the AUX OFF tests. This is likely caused also by the greater load required to run the engine when the auxiliary equipment was activated. For most of the tractors, the cranking and the crank-to-run phases were the longest, except for the CASE IH where a much longer crank-to-run transition was observed. Indeed, the crank-to-run transition phase accounted for approximately 0.8 s for the CASE IH. For the NH T8 and STEYR for the AUX

OFF test, there was no crank-to-run transition phase (Fig. 1 – d); as can be seen in Table 3, the sum of the phase percentages is not 100%. The cranking phase ranged from 0.5 s for the CASE to 1.8 s for the STEYR. The latter values are much greater than those observed for passenger cars, for which they are up to 0.8 s (Canova et al., 2009; DeBruin, 2013).

Considering that all the engines were manufactured by the same vendor, they will likely share the same design principles. Also, it can be assumed that the mechanical losses and auxiliary loads should be mostly proportional with engine displacement (Lee et al., 1999; Sorrentino et al., 2015). This assumption is confirmed by the fact that $f_{eq,st}$ and $\dot{f}_{idle}$ increase monotonically with the engine displacement (Table 4). In the AUX ON tests, $f_{eq,st}$ values were up to 40% greater than those in AUX OFF tests. For the NH T8, this increase was negligible, likely due to the fact that, in this tractor, auxiliary equipment was disconnected during the start-up to reduce the starter load. This type of design architecture is common in vehicles equipped with a similar engine displacement to that of NH T8. For all the tractors, most of the fuel used during start-up was injected during the start-up phase (ranging from 50% to 85%) and not during idling period to recharge the battery. This contribution increased with the activation of the auxiliary equipment for all the tractors except for the NH T8.

Table 4 – Mean values of the fuel metrics calculated from the engine start test. AUX OFF / AUX ON test. In the parentheses, the standard deviation values are reported. Means with the same letter on the same row do not differ statistically (p>0.05) by the ANOVA test. Standard deviations are reported in brackets.

	STEYR	CASE	NH T7	NH T8
$f_{eq,st}$ [ml]	1.29 (6.55 10^{-2})^{A} / 1.54 (7.98 10^{-2})^{A}	1.44 (5.38 10^{-2})^{B} / 2.04 (7.81 10^{-2})^{B}	2.30 (8.91 10^{-2})^{C} / 2.62 (1.11 10^{-1})^{C}	7.57 (2.77 10^{-1})^{D} / 7.57 (8.53 10^{-2})^{D}
$m_{CO_2,st}$ [g]	3.4 (1.7 10^{-1}) ^{A} / 4.0 (2.1 10^{-1}) ^{A}	3.8 (1.4 10^{-1}) ^{B} / 5.4 (1.4 10^{-1}) ^{B}	6.1 (2.3 10^{-1}) ^{C} / 6.9 (3.0 10^{-1}) ^{C}	19.9 (7.3 10^{-1}) ^{D} / 19.9 (2.2 10^{-1}) ^{D}
$f_{el,st}$ [%]	50 (2.3)^{A} / 42 (2.5)^{A}	31 (1.3)^{B} / 24 (1.1)^{A}	40 (1.4)^{C} / 40 /2.4)^{B}	15 (1.4)^{D} / 23 (1.2)^{B}
$f_{inj,st}$ [%]	50 (2.3)^{A} / 58 (2.5) ^{A}	69 (1.3)^{B} / 76 (1.1)^{B}	60 (1.4)^{C} / 60 (2.4)^{A}	85 (1.4)^{D} / 77 (1.2)^{B}
$\dot{f}_{idle}$ [l h^{-1}]	1.3 (9.5 10^{-3})^{A} / 1.6 (1.1 10^{-2})^{A}	2.1 (9.6 10^{-3})^{B} / 2.7 (5.7 10^{-2})^{B}	2.4 (6.2 10^{-2})^{C} / 3.0 (2.7 10^{-2})^{C}	6.2 (1.2 10^{-2})^{D} / 6.6 (4.6 10^{-2})^{D}
$\dot{m}_{CO_2,idle}$ [kg h^{-1}]	3.4 (3.8 10^{-2}) ^{A} / 4.0 (1.4 10^{-1}) ^{A}	5.3 (5.9 10^{-2}) ^{B} / 7.0 (3.2 10^{-1}) ^{B}	6.29 (1.6 10^{-1}) ^{C} / 7.83 (7.1 10^{-2}) ^{C}	16.3 (1.1 10^{-1}) ^{D} / 17.1 (2.4 10^{-1}) ^{D}
t_{eq} [s]	3.6 (1.9 10^{-1})^{A} / 3.5 (1.7 10^{-1})^{A}	2.5 (9.5 10^{-2})^{B} / 2.7 (7.5 10^{-2})^{B}	3.5 (1.6 10^{-1})^{A} / 3.1 (1.4 10^{-1})^{C}	4.4 (1.4 10^{-1})^{C} / 4.1 (5.0 10^{-2})^{D}

It can be seen from Table 4 that most of the study parameters are significantly influenced by the engine characteristics, as shown by the results of the multi comparison ANOVA test. $\dot{f}_{idle}$ monotonically increases with engine power; this occurs because the larger engines require more fuel due to the higher mechanical losses (Bartolomei, 2021; Sorrentino et al., 2015), and also because during idling, approximately 38% of the fuel is used to run the auxiliaries (Saetti et al., 2021). The higher the engine power, the higher the accessory power demands since they are typically sized as a function of engine rated power (Campbell et al., 2012). However, it was not possible to define a clear relationship between engine displacement and typology since the ECU fuel injection logic and the amount of fuel injected for each tractor plays a crucial role in fuel and emissions generated during start-ups. The recorded mean values of t_{eq} varied significantly between the tractors; however, it has a very low test-to-test variability on the same tractor. Indeed, for all the tests, t_{eq} ranged from 2.5 s up to 4.4 s, meaning that $f_{eq,st}$ and $\dot{f}_{idle}$ increased at a similar rate to the increase in engine displacement. The only exception to this trend is the t_{eq} value for STEYR which was greater than those of the CASE and NH T7, which are equipped with larger engines. This result can be caused by the irregular start-up of the STEYR (Fig. 1 - a), which may decrease the fuel efficiency during start-up. Indeed, for the STEYR, the peak value of $\dot{f}$ was approximately 4 times higher than $\dot{f}_{idle}$, while for the other engines $\dot{f}$ was less than 2.7 times higher than $\dot{f}_{idle}$. The values of t_{eq} found in this study are shorter than the minimum duration requirement of unnecessary idling (i.e., 10 s) and are also well below those reported in another study on passenger cars; in that study, t_{eq} was found to be around 10 s (Gaines et al., 2013). The one-way ANOVA test performed on $f_{eq,st}$, $f_{el,st}$, $f_{inj,st}$, $\dot{f}_{idle}$ and t_{eq} for every tractor between AUX ON and AUX OFF showed a significant difference between the two configurations in the majority of tractors, with the exception of STEYR where no significant difference between the two AUX test were observed for any start-up parameter.

In Table 5, GHG and pollutant emissions metrics calculated from the engine start-up test are reported. Differences in the values between tractors were due to the different after-treatment systems, engine displacement, and design (Table 1).

Table 5 – Mean values of emission metrics calculated from the engine start test. AUX OFF / AUX ON test. NH T7 $\dot{m}_{NO,idle}$ and $\dot{m}_{NO_2,idle}$ are not reported since they were not available in Mattetti et al (2022). Means with the same letter on the same row do not differ statistically (p>0.05) by ANOVA test. Standard deviations are reported in the parentheses.

	STEYR	CASE	NH T7	NH T8
$\dot{m}_{CO,idle}$ $[g\ h^{-1}]$	$1.5\ 10^{-2}\ (1.1\ 10^{-2})^{A}$ / $8.3\ 10^{-4}\ (1.3\ 10^{-3})^{A}$	$0.0\ (0.0)^{B}$ / $0.0\ (0.0)^{B}$	$3.4\ 10^{-1}\ (2.2\ 10^{-2})^{C}$ / $3.9\ 10^{-1}\ (6.1\ 10^{-3})^{C}$	$0.0\ (0.0)^{B}$ / $0.0\ (0.0)^{B}$
$\dot{m}_{NO,idle}$ $[g\ h^{-1}]$	$2.9\ 10^{-1}\ (1.1\ 10^{-2})^{A}$ / $3.5\ 10^{-1}\ (2.8\ 10^{-2})^{A}$	$2.3\ 10^{-1}\ (1.5\ 10^{-1})^{A}$ / $1.6\ 10^{-1}\ (1.3\ 10^{-1})^{B}$	- / -	$1.6\ 10^{-1}\ (1.3\ 10^{-1})^{A}$ / $6.4\ 10^{-2}\ (5.1\ 10^{-2})^{B}$
$\dot{m}_{NO_2,idle}$ $[g\ h^{-1}]$	$1.3\ 10^{-2}\ (1.3\ 10^{-2})^{A}$ / $2.8\ 10^{-2}\ (1.3\ 10^{-2})^{A}$	$2.0\ 10^{-2}\ (2.2\ 10^{-2})^{A}$ / $1.0\ 10^{-2}\ (1.9\ 10^{-2})^{A}$	- / -	$4.1\ 10^{-1}\ (1.3\ 10^{-1})^{B}$ / $2.8\ 10^{-1}\ (2.5\ 10^{-1})^{B}$

For STEYR and NH T7, which are not equipped with a DOC system, CO emissions were measured during idling due to incomplete fuel oxidation; this likely could have been caused by low turbulence in the idling conditions and the low temperature in the combustion chamber. In contrast, for the NH T8 and CASE tractors, no emissions of CO were observed due to the presence of the DOC system which effectively oxidises CO and unburned hydrocarbons from the engine exhaust (Lakkireddy et al., 2006). This means that for tractors equipped with DOC, turning off the engine when it is not needed had no advantage in terms of CO emissions. The mean value of NO emissions decreases with the engine displacement; however, there was no significant difference between the tractors in the AUX OFF configuration. In contrast, the NO_2 emissions show the opposite trend, although the values observed for the STEYR and the CASE are not significantly different. This behaviour is primarily influenced by the aftertreatment systems as opposed to the engine displacement, as previously discussed. $\dot{m}_{NO,idle}$ was considerably higher than $\dot{m}_{NO_2,idle}$, which is expected for naturally aspirated engines not equipped with an SCR catalyst. For these systems, the $\dot{m}_{NO,idle}/(\dot{m}_{NO,idle} + \dot{m}_{NO_2,,idle})$ ratio can be as high as 0.95 (Ko et al., 2019); in more recent turbocharged engines with SCR catalysts, this ratio can be higher (Wild et al., 2017). For tractors equipped with SCR systems, $\dot{m}_{NO_2,idle}$ was considerably higher than $\dot{m}_{NO,idle}$ due to the injection strategy of the ammonia/water mix. The relatively low operating temperature of the exhaust, which was in the range of 180 °C for these tests, decreased the overall effectiveness of the SCR; in the presence of a reheat of ammonium nitrate, a partial conversion of NO into NO_2 can occur (Koebel et al., 2002). The mean total NO_x emissions during idling for this tractor were 0.03 g kWh^{-1}, which is significantly less than the limit of 0.40 g kWh^{-1} imposed by STAGE V emission standards for nonroad engines (International Council on Clean Transportation, 2016). Thus, turning off the engine did not significantly affect NO_x emissions generated by the tractor during use. Moreover, comparing these results with those reported in a previous study (Brodrick et al., 2002), the emissions were reduced by three orders of magnitude, indicating a strong quantitative impact of the emission regulations imposed by policy makers.

3.2 Real-world test

The results of the real-world test are reported in Table 6. As can be seen, the idling durations of the NH T7 and STEYR are near the mean value reported in other studies (i.e., ∼22%) (Jenkins, 1960; Perozzi et al., 2016). However, the idling durations for the NH T8 and the CASE differed significantly from the mean value found by Perozzi et al., (2016). Indeed, the idling duration of the NH T8 was even lower than the minimum value observed by Perozzi et al (2016), while the idling duration for the CASE tractor was near the 97.5th percentile observed by Perozzi et al (2016) in the group of tractors denoted EU in that paper. The low idling duration of the NH T8 could be due to the tractor being used primarily for heavy tillage operations on very large fields, which likely involves very few deadtimes resulting from activities such as implementing hitching (Mattetti, Medici, et al., 2022). This was validated by the mean number of daily working hours which was significantly higher than the other tractors. By contrast, the long idling duration of the CASE could be explained by the prolonged use of the tractor for supporting combines during harvesting which involved long idling stops also for keeping the cab in the desired thermal comfort zone. Under such operating conditions, tractors run on idle while the farmers wait for the combines to be fully loaded. For all the tractors, the unnecessary idling durations ranged from 45% of the entire idling for the NH T7 up to 72% for the CASE; these engine idling durations resulted in fuel consumed for idling between 1.9% and 6.8% of the entire used fuel, for the NH T8 and CASE, respectively. Considering that the standard deviation of $\dot{f}_{idle}$ is relatively small as shown in Table 3, in absolute terms, the fuel used for idling can be considered to be almost linearly dependent on the amount of time spent by the tractor in idling. However, in relative terms, the fuel used for idling is affected by the power delivered by the engine in non-idling operations (Jenkins, 1960; Mattetti et al., 2019). Indeed, the amount of fuel consumed in 100 h by the CASE was only 9% higher than that of the STEYR, despite the fact that the nominal power of the CASE is 16% higher than that of the STEYR. This result leads to the conclusion that the STEYR operated at greater engine load than that of the CASE. The tractor with the lowest f_{save} was the NH T8, while the tractor with the highest f_{save} was the CASE. For all tractors, the percentage of idling stops classified as unnecessary ranged from 51 to 73%; the number of idling stops classified as unnecessary in 100 h is associated with additional start-ups required by the starters (n_{su}) and the additional load of each starter. This load ranged from 2.6 to 7.5 times the number of start-ups experienced by the tractor during its monitored usage. This additional load is high, but batteries are designed to withstand a high number of charge/discharge cycles (Yonezu & Ando, 1983). However, if tractors are to be equipped with a start-stop system, it would be beneficial to equip them with enhanced flooded batteries which are designed specifically for vehicles equipped with start-stop systems (Horie et al., 2007).

For all tractors, the mean duration of unnecessary idling stops was much shorter than that of necessary idling stops (Table 6). For all tractors, the mean duration of all idling stops ranged from 28 to 197 s which are well above t_{eq} resulting from the engine start-up tests (Table 4). This result leads to the conclusion that turning off the engine conserves fuel in most cases. The values for the NH T7 changed slightly due to the updated classification for unnecessary idling used in this study in relation to that adopted in Mattetti et al. (2022).

Table 6 – Fuel and emission metrics calculated from the engine start test.

	STEYR	CASE	NH T7	NH T8
Number of working days	205	66	290	57
Accumulated hours [h]	999	371	1314	493
Mean daily operation [hh:mm]	4:52	5:37	4:31	8:39
Total idling [% with respect to accumulated hours]	16.5	31.5	25.0	10.0
t_{unn} [% with respect to accumulated hours]	12.3	23.9	12.4	5.9
Total used fuel [l 100 h^{-1}]	749	815	1672	2761
Fuel used for idling [% with respect to the total used fuel]	2.7	6.8	3.4	1.9
f_{save} [% of the total consumed fuel]	1.9	5.1	1.7	1.1
Number of idling stops in 100 h	527	639	415	460
n_{su} in 100 h	375	438	227	229
Mean duration of necessary idling stops [s]	28	42	108	33
Mean duration of unnecessary idling stops [s]	118	196	197	87

6. Conclusions

The agricultural machinery industry must develop powertrains with higher fuel efficiencies and farmers must use fuel more efficiently for agricultural machinery to minimise GHG emissions and maintain profit margins. The industry has been pushing towards hybrid powertrains as well as powertrains with alternative fuels, but such solutions are not yet widely available. An immediate and ready-made solution is to address the issue of engine idling. This report presents the first comprehensive study investigating engine idling and the start-up process for agricultural tractors. In this study, four types of tractors were tested; the results showed that, in the worst case, turning off the engine conserves fuel for idling stops longer than 4.4 s. This result was consistent for the different engine architectures likely to be used because the engines with larger displacement showed proportional fuel requirements for starting the engine and maintaining idling. In this analysis, most of the engine idling was classified as unnecessary, which could therefore be avoided. In terms of emissions, CO and NO_x levels were not shown to be of concern during idling, especially in tractors equipped with DOC and SCR systems. Reducing idling time is also important in reducing particulate matter emissions since high temperatures during idling can be developed inside the particulate filter which reduces the filter durability. Unnecessary idling accounted for at least 1.2% of annual fuel consumption. Applying that rate of fuel savings to the nearly 70 million tonnes of CO_2 emissions annually that are attributed to agricultural mechanisation, if operators turn off the tractor engine for unnecessary idling stops, CO_2 emissions could be reduced by 770 thousand tonnes, equivalent to 29 thousand of litres of fuel. These are meaningful reductions that can be achieved immediately with no significant effort. It is acknowledged that these figures are optimistic, since operators do not always know beforehand that an idling stop is necessary. Therefore, an automatic system, such as a start-stop system, should be implemented. To support this goal, the emerging trend of electrification in agricultural machinery may enable the required automation to avoid discomfort to farmers caused in turning off the engine during unnecessary idling stops.

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