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Start and stop systems on agricultural tractors as solution for saving fuel and emissions

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1 Start and stop systems on agricultural tractors as solution for saving fuel

2 and emissions

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11
 12 **KEYWORDS:** idling, green-house emissions, CANBUS, climate change, real-world data

13

η_{alt}	alternator efficiency	(-)
η_{eng}	diesel engine efficiency	(-)
η_{cha}	battery charging efficiency	(-)
η_{disc}	battery discharging efficiency	(-)
ρ_{CO}	density of CO at the exhaust	($kg\ m^{-3}$)
ρ_{CO_2}	density of CO_2 at the exhaust	($kg\ m^{-3}$)
ρ_{fuel}	fuel density	($kg\ m^{-3}$)
c_{CO}	Carbon monoxide (CO) concentration	(ppm)
c_{CO_2}	Carbon dioxide (CO_2) concentration	(%)
h_{fuel}	fuel lower heating value	($MJ\ kg^{-1}$)
\dot{f}	Engine fuel rate	($L\ h^{-1}$)
\dot{f}_{idle}	Engine fuel rate during idling	($L\ h^{-1}$)
$f_{el,st}$	amount of burned fuel necessary for restoring $E_{el,st}$ in the battery when the engine is running	(kg)
$f_{inj,st}$	fuel injected to accelerate the engine up to the minimum self-sustaining engine rotational speed	(kg)
f_{save}	potential fuel savings	(L)
\dot{m}_{CO}	mass flow of CO	($kg\ h^{-1}$)
\dot{m}_{CO_2}	mass flow of CO_2	($kg\ h^{-1}$)
$m_{CO,el\ st}$	CO emissions for starting the engine	(kg)
$m_{CO_2,el\ st}$	CO_2 emissions for starting the engine	(kg)
$\dot{m}_{CO,idle}$	CO mass flow rate during idling	($kg\ h^{-1}$)
$\dot{m}_{CO_2,idle}$	CO_2 mass flow rate during idling	($kg\ h^{-1}$)
$m_{CO,inj,st}$	CO emissions generated for accelerating the engine up to the minimum self-sustaining engine rotational speed	(kg)
$m_{CO_2,inj,st}$	CO_2 emissions generated for accelerating the engine up to the minimum self-sustaining engine rotational speed	(kg)
$m_{CO,save}$	potential CO savings	(kg)

$m_{CO_2,save}$	potential CO_2 savings	(kg)
n	Engine rotational speed	(rpm)
n_{ign}	number of additional engine restarts	(-)
n_{PTO}	Rear PTO rotational speed	(rpm)
p	Exhaust gas pressure, equal to the ambient pressure	(Pa)
$t_{eq,idle,f}$	equivalent idling seconds of fuel	(s)
$t_{eq,idle,CO}$	equivalent idling seconds of CO	(s)
t_s	duration of the engine start-up	(s)
t_{unn}	Duration of unnecessary idling	(s)
v_t	Tractor ground speed	(km h ⁻¹)
$E_{el,st}$	energy required by the starter to run the engine	(J)
E_{ICE}	energy that must be given by the engine to recharge the energy delivered by the battery during the electric start-up	(J)
I_{batt}	Battery Current	(A)
I_{un}	unnecessary idling logical variable	(-)
K_{CO}	CO emission factor assumed to be the maximum allowable according to the limits established in the European emission standards for non-road mobile machinery specified in Stage V regulation	(g kW ⁻¹ h ⁻¹)
M_*	molecular weight	(g mol ⁻¹)
O_p	Presence of the operator on the seat of the vehicle	(-)
P_{batt}	power delivered by the battery	(W)
R	gas constant	(J K ⁻¹ mol ⁻¹)
RHP	Position of the rear three-point hitch	(%)
T_c	Engine coolant temperature	(°)
T_{exh}	temperature of the gases at the exhaust	(K)
V_{batt}	Battery Voltage	(V)
\dot{V}_{CO}	volume rate of CO	(m ³ h ⁻¹)
\dot{V}_{CO_2}	volume rate of CO_2	(m ³ h ⁻¹)
\dot{V}_f	Volume rate of fuel gasses	(m ³ h ⁻¹)
\dot{V}_{fi}	Oil flow through the auxiliary valve in percentage with respect to the maximum flow. i stands for the number of the auxiliary valves (i.e., 0, 1, 2, and 3)	(L min ⁻¹)

14

15

Abstract

16 Agricultural tractors may idle from 10 to 43% of their entire operating life and this
17 inoperative time must be minimised because it is detrimental to the environment, public
18 health, fuel economy, and engine lifespan (Perozzi et al., 2016). On passenger cars, start and
19 stop (SS) systems have been extensively used, but they are not currently installed in any

20 commercial tractor. Studies show that for very short idling stops SS systems might be
21 ineffective for the additional energy required for re-starting the engine. This study aims to
22 investigate the potential advantages of SS systems on agricultural tractors. To this aim, the
23 energy required for engine start-up and the subsequent emissions were measured and then
24 compared with the energy and the emissions during idling. Moreover, a predefined control
25 strategy of the SS system was developed, and its potential fuel and emission savings were
26 estimated using real-world data. In terms of fuel consumption and CO emission, turning off
27 the engine is recommended for stops longer than 4 s and 134 s, respectively. From the
28 collected real-world data, the tractor was run on idle for 21.7% of the entire operating
29 duration. The results obtained with the SS control strategy developed in this paper applied to
30 the US area, where there are 1.2 million tractors of the same power level of the tractor used in
31 this study with a yearly usage up to 850 h, would permit to save 285.6 million litres of fuel,
32 and, respectively of 16.5 and 754 tons of CO and CO₂.

33

34

Introduction

The agricultural sector is responsible for about 21% of the world's greenhouse gas emissions, mainly due to the use of fossil-based fertilisers, the combustion of biomass and the polluting gas emissions of agricultural machinery (Qiao et al., 2019). Most of the self-propelled agricultural machinery are powered by endothermic engines, where fossil fuels still represent 95% of the forms of energy used for their propulsion (IPPC, 2014). Nearly all modern agricultural tractors are propelled by diesel engines, so during fuel combustion process, polluting gases such as carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), and hydrocarbons (HC) are emitted together with greenhouse gases, like CO₂. These gases are strictly regulated by emission Stages (or Tiers) introduced by European and US legislators. To comply with these emission limits, present-day tractors are equipped with several emission reduction technologies such as Diesel Particulate Filter (DPF), Exhaust Gases Recirculation (EGR), Diesel Oxidation Catalyst (DOC) and Selective Catalytic Reduction (SCR) (Rudder, 2012). A further solution to reduce the emission of polluting gases is to reduce the time spent by the tractor in idle condition. Vehicles idling time could be classified in two main categories: necessary or unnecessary (Brodrick, Lipman, et al., 2002). While the former cannot be eliminated since it is needed for the vehicle operation (e.g., engine heating during start-up), the latter may occur for the negligence of drivers. Unnecessary idling is frequent for road trucks due to driver mandatory rest periods, where drivers keep the engine idling to maintain the battery voltage and the cab temperature at their optimal levels. In the USA, on average, long-haul trucks idle for about 1800 hours per year consuming more than 5500 litres of diesel (Argonne National Laboratory, 2015). Even agricultural tractors are exposed to prolonged idling periods; indeed, an extended field campaign on a fleet of tractors showed that tractors idle for a period that ranges from 10% to 43% of the time (Perozzi et al., 2016). Molari et al. (2019) investigated the reasons for idling

60 by monitoring the activity of an agricultural tractor through a dashcam and a CANBUS data
61 logger. Results show that about 67% of the idling stops were mainly due to the driver's
62 behaviour (i.e., talk among drivers, use of the mobile phone, etc.) while the remaining 33% of
63 time required the use of any subsystem of the tractor, such as the hydraulic pump necessary
64 for implement hitching and servicing. During idling, the fuel efficiency of internal
65 combustion engines drops of 20% with respect to nominal operating conditions (Brodrick et
66 al., 2002a) and in this condition, the fuel is mostly used to run accessories and auxiliaries that,
67 on heavy duty vehicles (i.e., trucks, and agricultural tractors), are mechanically driven leading
68 to parasitic loadings (Saetti et al., 2021). The necessary idling could be reduced with tractor
69 subsystems electrification, however the high investment costs to develop this technology still
70 hinder its use (Scolaro et al., Submitted). On the other hand, unnecessary idling could be
71 simply reduced with the adoption of start-stop (SS) systems, which represents a low-cost
72 hybridisation technology widely spread among modern automotive vehicles (Salmasi, 2007).
73 These devices are controlled by the engine control unit (ECU) and its duty is to automatically
74 shut-off the engine when it starts idling. Bench tests performed on different cars and with
75 different test cycles demonstrated that improvement in fuel efficiency thanks to SS could vary
76 from 1% to 14.4 % (Wishart et al., 2012). In real world conditions, the improvement in the
77 fuel efficiency due to SS is even more variable for the several intercorrelated variables (i.e.,
78 itineraries, traffic loads, weather conditions, and driver behaviour) that affect the duration and
79 the number of idling stops (Abas et al., 2017; Thitipatanapong et al., 2013). A key factor for
80 an efficient SS system is a well-designed and smart control algorithm that is able to avoid the
81 engine shut-off for very short idling periods. Indeed, the engine restarts require additional
82 energy and, to obtain an overall positive effect, this energy must be lower than the energy
83 consumed by the engine idling. Tests performed on a medium size car demonstrated that SS
84 systems are convenient only when idling stops are longer than 10 s (Gaines et al., 2013). At

85 present, to the authors' knowledge, no significant studies on the implementation of SS
 86 systems specifically designed for agricultural tractors are available in literature. The aim of
 87 this work is to evaluate the energy demand and the pollutant gas emissions of a tractor diesel
 88 engine during the start-up and idling phase in order to evaluate the potential benefits of an SS
 89 system in this type of tractors. In addition, the proper timings and strategies to adopt SS are
 90 discussed in order to achieve advantages in terms of **reducing** fuel consumption, carbon
 91 dioxide and carbon monoxide emissions.

92 **Materials and methods**

93 *Data acquisition*

94 The tractor used for the test was a New Holland T7.260 PowerCommand™ (CNH
 95 Industrial N.V., Amsterdam, Netherlands) whose specifications are reported in Table 1. This
 96 type of tractor was chosen since tractors of this class are rich in embedded sensors allowing
 97 comprehensive monitoring of the activity of the different embedded subsystems.

<i>Table 1 – Specifications of the tractor used for the test</i>	
Engine type	Turbo Diesel
Number of cylinders	6
Engine displacement [cm ³]	6700
Engine tier (emission reduction technologies)	4A (DOC, DPF, SCR)
Nominal power [kW]	162 at 2200 rpm
Torque [Nm]	1000 at 1500 rpm
Unladen mass [kg]	8140
12V alternator [A]	150
Battery capacity [Ah]	176
Battery cold cranking ability [CCA]	1300

98

99 Two types of tests were carried out:

- 100 ● **Engine start test:** for measuring the energy necessary for starting the engine and the
 101 correlated emissions;

102 ● **Real world test:** for evaluating the potential fuel and emissions savings in using a SS
103 system with a specified control strategy.

104 **Engine start test**

105 *Test description*

106 For this test, the NI CompactDAQ 9178 (National Instruments, Austin, TX, USA)
107 equipped with a NI 9215 (National Instruments, Austin, TX, USA) as analogue input and a NI
108 9861 (National Instruments, Austin, TX, USA) as CANBUS input was used. The NI 9215
109 was connected with:

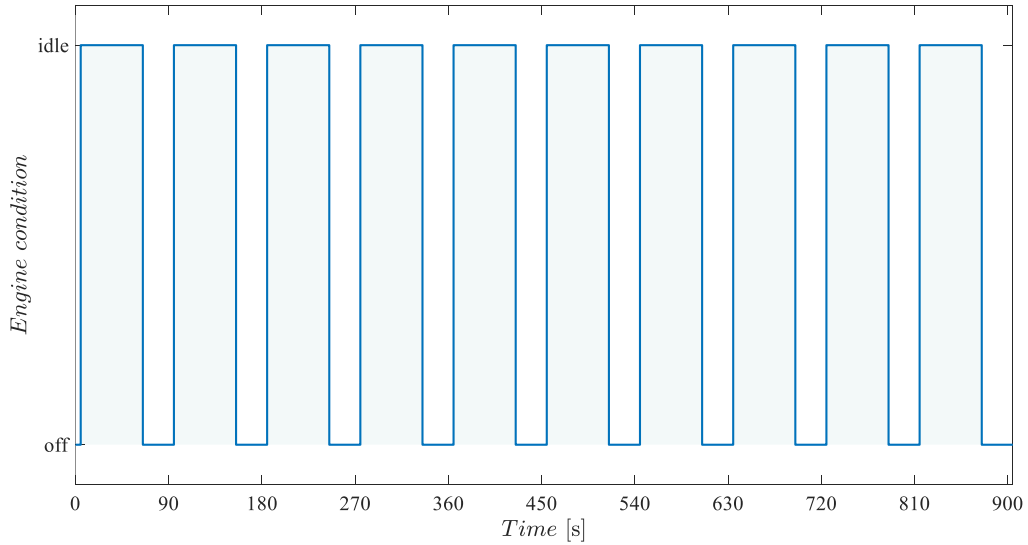
- 110 ● battery poles for measuring the voltage at the battery (V_{batt}).
- 111 ● current transducer HAT 500-S (LEM Holding, Plan-les-Ouates, Switzerland) installed
112 on the negative pole of the battery, to record the current flow towards the battery
113 (I_{batt}). This value was positive in case the current flows to the battery and negative
114 otherwise.

115 The NI 9215 was set up to sample data at 1000 Hz, **this frequency was chosen after**
116 **preliminary tests, where it was demonstrated to be fast enough to properly record current and**
117 **voltage peaks during the ignition process.** The NI 9861 was set up to record the CANBUS
118 signals with the following specified Suspect Parameter Numbers (SPNs) and Parameter
119 Group Numbers (PGNs):

- 120 ● SPN 190 and PGN 61444, “*Engine speed*” reporting the revolution speed of the
121 engine crankshaft, denoted as “ n ” in the following. **Sampling rate = 10 Hz.**
- 122 ● SPN 183 and PGN 65266, “*Engine fuel rate*” reporting the litres of fuel consumed by
123 the engine per hour of running. This value is denoted as “ \dot{f} ” in the following.
124 **Sampling rate = 10 Hz.**

125 • SPN 110 and PGN 65262, “*Engine coolant temperature*” reporting the temperature of
126 the liquid found in the engine cooling system. The value is denoted as “ T_c ” in the
127 following. **Sampling rate = 1 Hz.**

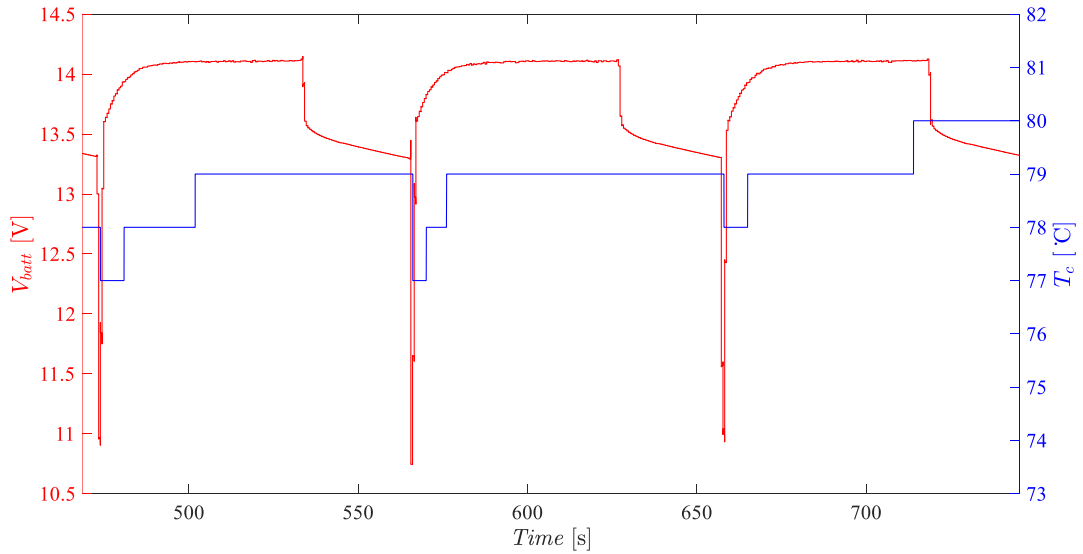
128 Moreover, at the exhaust, the gas analyser MRU Vario Plus Industrial (MRU air fair
129 emission monitoring systems, Humble, TX, USA) was installed in order to measure the
130 concentration of pollutants at the vehicle exhaust pipe. The concentration for carbon dioxide
131 (CO₂) and carbon monoxide (CO) are denoted as c_{CO_2} and c_{CO} , respectively. The instrument
132 also recorded the temperature of the fuel gases at the exhaust (T_{exh}). All the data recorded
133 from the gas analyser were sampled at 0.5 Hz. This instrument complies with US-EPA
134 methods CTM-030 (US EPA, 1997) and CTM-034 (US EPA, 1999) and international ASTM
135 D6522 (ASTM International, 2011); it has been certified according to DIN EN 50379-1 (BSI
136 Standards, 2012a) and DIN EN 50379-2 (BSI Standards, 2012b). The gas analyser is also able
137 to measure the nitrogen oxides (NO_x); however, they were not analysed in detail in this work
138 since this study is focused on the engine idling and in this condition, the combustion
139 temperature is low and so the NO_x concentration. Indeed, Nada et al show the exponential
140 relationship between NO_x and temperature (Nada et al., 2015). The test procedure consisted
141 of 10 cycles composed of 60 s of engine idling, and 30 s of engine off (Fig. 1).



142

143 *Fig. 1- Engine duty-cycle of the engine start tests. Each ignition is followed by 60 seconds of*
 144 *idle and then 30 seconds of stop.*

145 The idling duration was chosen in order to maintain V_{batt} at the voltage level prior engine
 146 starting, as shown in Fig.2. This condition was chosen as SS systems do not work when the
 147 state of charge of the battery is not at the optimal level. The cycles were carried out with the
 148 auxiliaries active (denoted AUX ON in the following) and inactive (denoted AUX OFF in the
 149 following). The considered auxiliaries were the lights (front and rear headlights, work lamps,
 150 warning beacon), the cab radio, the heating, ventilation and air conditioning (HVAC)
 151 compressor, and the blower fan, which was set at its maximum speed. All the auxiliaries
 152 except for the HVAC compressor are powered by the battery leading to an electrical loading.
 153 When the engine was off, the auxiliaries were left on as usually occurs with vehicles equipped
 154 with SS systems. All the tests were conducted at the optimal engine working temperature
 155 condition ($T_c \approx 79\text{ }^\circ\text{C}$ according to the tractor manufacturer recommendation) as SS systems
 156 do not work if the engine temperature is too low due to the greater friction losses and gaseous
 157 emissions when the engine is cold (Hadavi et al., 2013; Lee et al., 2019). Thus, prior to the
 158 test, the engine was left idling until reaching the optimal T_c .



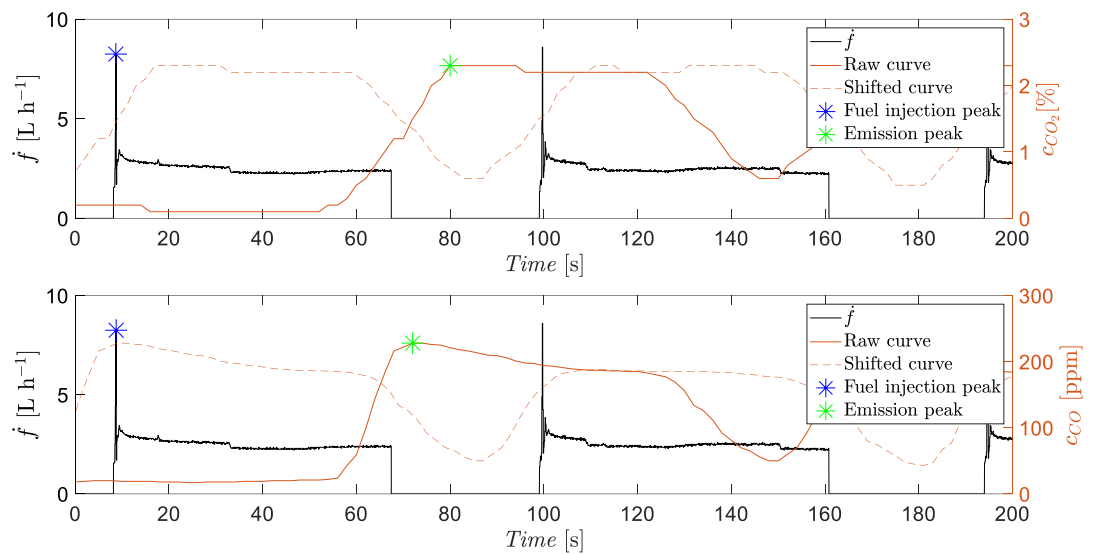
159

160 *Fig. 2 – Portion of battery voltage signal (V_{batt}) (red) and engine coolant temperature (T_c)*
 161 *behaviour (blue) during the test in the AUX OFF condition.*

162 All the **acquired signals** were resampled at 1000 Hz using a cubic spline **interpolation** for a
 163 consistent sampling rate among the recorded signals. From the recorded signals, the electric
 164 power delivered by the battery (P_{batt}) was calculated with equation 1:

$$P_{batt} = V_{batt} I_{batt} \quad (1)$$

165 In order to be able to compare the emissions measurements with the electrical and ICE
 166 measurements, the delay of the emissions measurements was removed by subtracting the
 167 average time difference between the fuel injection peaks (enclosed in the blue **markers** in Fig.
 168 3) and the emissions peaks (enclosed in the green **markers** in Fig. 3). This delay is due to the
 169 time constant of the sensors, the time taken for the combustion process to occur, and the time
 170 taken by the combustion gases to reach the exhaust after fuel injection; the latter two are
 171 considerably smaller than the first one. The c_{CO_2} and c_{CO} delay is shown in Fig. 3, together
 172 with the shifted curves.



174
175
176
177
178

Fig. 3 – Portion of fuel rate (\dot{f}), CO concentration (c_{CO}) and CO₂ concentration (c_{CO_2}) for showing the removal of the delay of the emissions curves. The blue markers corresponds to fuel injection peaks; while the green markers, highlight emissions peaks.

179 With the aim of better analysing the emissions, the relative measurements of volumetric
180 concentration obtained with the gas analyser have been converted to absolute quantities using
181 the fuel consumption registered by the CANBUS. The procedure used for this conversion is
182 reported below. Diesel fuel is a mixture of hydrocarbons, mainly paraffins, but its exact
183 composition varies depending on the supplier, the final application and the period of the year.
184 In this case, it was hypothesised that the average chemical composition of the used fuel was
185 $C_{12}H_{23}$. Using the oxidation reaction and assuming complete combustion, which is a good
186 approximation for this type of calculation in diesel engines where the amount of air is
187 considerably higher than the stoichiometric one, it can be found that for each litre of fuel
188 burned approximately 2.624 kg of CO_2 are produced (Geerlings & van Duin, 2011). Thus, the
189 mass flow of CO_2 emissions was calculated using equation 2:

$$\dot{m}_{CO_2} = 2.624 \dot{f} \quad (2)$$

190 To estimate the mass flow of CO , the following procedure was adopted:

191 a) The volume rate of CO_2 (\dot{V}_{CO_2}) was calculated using equation 3. The density of CO_2 at
192 the exhaust (ρ_{CO_2}), for each time step, was estimated using the ideal gas equation
193 (equation 4).

$$\dot{V}_{CO_2} = \frac{\dot{m}_{CO_2}}{\rho_{CO_2}} \quad (3)$$

$$\rho_* = \frac{p M_*}{R T_{exh}} \quad (4)$$

194 where:

- 195 ○ ρ_* is the density of CO and CO_2 (namely, ρ_{CO} and ρ_{CO_2});
- 196 ○ p is the gas pressure equal to the ambient pressure (i.e., 101.325 kPa);
- 197 ○ M_* is the molecular weight, equal to 44 g mol⁻¹ for CO_2 and 28 g mol⁻¹ for CO ;
- 198 ○ R is the gas constant, equal to 8.314 J K⁻¹ mol⁻¹.

199

200 b) The volume rate of fuel gases (\dot{V}_f) and CO (\dot{V}_{CO}) were estimated using c_{CO_2} and c_{CO}
201 with equations 5 and 6, respectively.

$$\dot{V}_f = \dot{V}_{CO_2} / c_{CO_2} \quad (5)$$

$$\dot{V}_{CO} = \dot{V}_f c_{CO} 10^{-6} \quad (6)$$

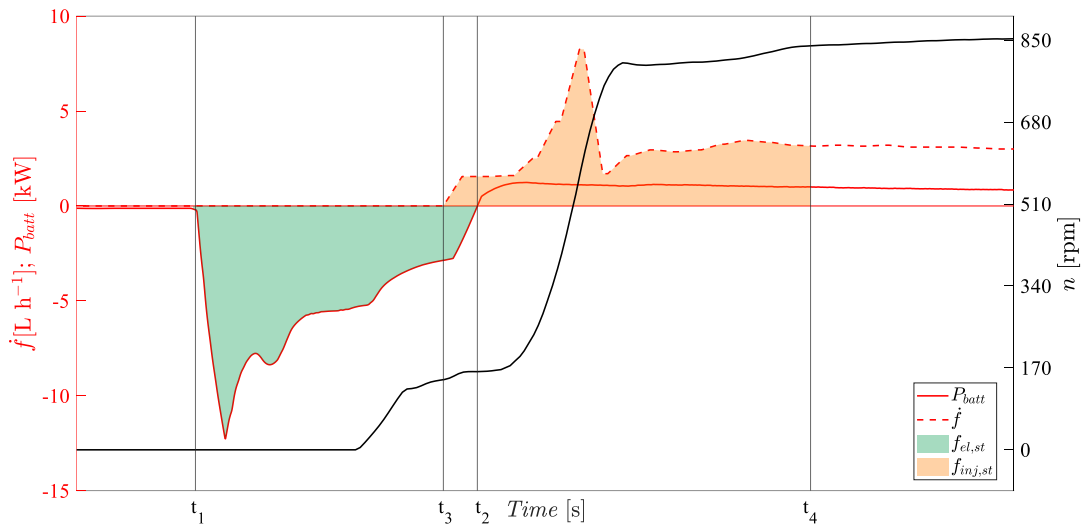
202 c) The mass flow of CO (\dot{m}_{CO}) was calculated with equation 7, while the density of CO
203 at the exhaust (ρ_{CO}) was calculated using the ideal gas law reported in equation 4.

$$\dot{m}_{CO} = \rho_{CO} \dot{V}_{CO} \quad (7)$$

204

205 For each starting cycle, signals were divided into two parts, one related to the engine start-
206 up and the other related to the engine idling. This allowed to quantify the fuel and the
207 pollutant masses required for both parts. The first part can in turns be subdivided in two:

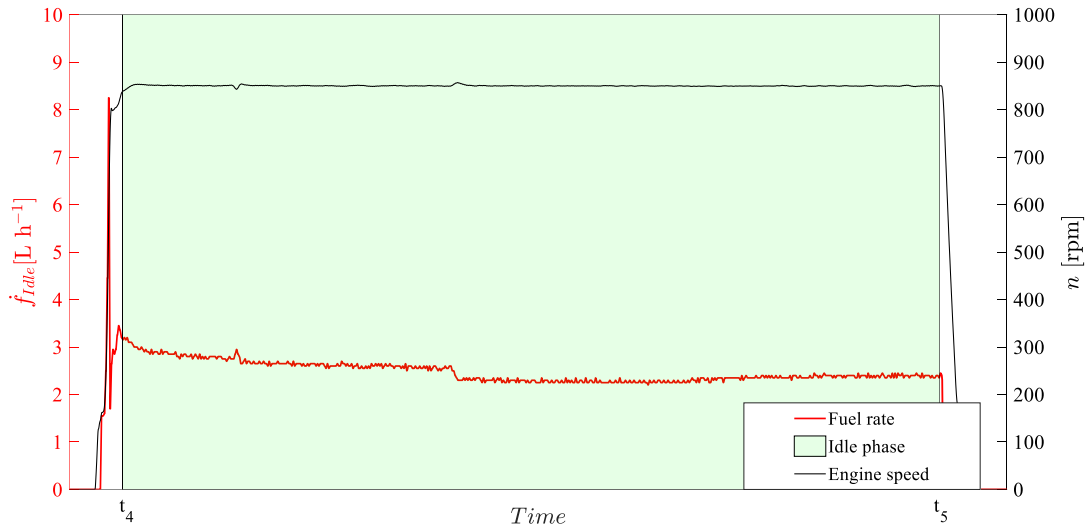
- 208 - **electric start:** corresponding to the electrical energy demanded by the starter to run
209 the engine. This was absorbed by the starter from the battery in the time frame
210 between the instants t_1 and t_2 . This time frame was detected by selecting the portions
211 of the signals where the P_{batt} was greater than a given threshold (i.e., -0.9 kW and -0.1
212 kW for AUX ON and AUX OFF, respectively) defined by observing the value of
213 P_{batt} when the engine was off (Fig. 4).
- 214 - **fuel injection:** corresponding to the period in which fuel is injected for accelerating
215 the engine from 0 rpm up to the minimum self-sustaining engine rotational speed (i.e.,
216 840 rpm). It is delimited by the instants t_3 and t_4 (Fig. 4). The former was defined by
217 observing when \dot{f} started to be greater than 0 L h^{-1} , while the latter when n started to
218 be greater than 840 rpm.



220

221 *Fig. 4 – Portion of fuel rate (\dot{f}), battery power (P_{batt}), and engine speed (n) during a single*
 222 *ignition (AUX OFF). The green area reports the energy required by the starter to run*
 223 *the engine ($E_{el,st}$), while in orange the amount of fuel injected to bring the engine to*
 224 *the self-sustaining speed ($f_{inj,st}$).*

225 The **idling** part was identified as the portion in which the n was between 840 rpm and 860
 226 rpm and its portion is delimited by the instants t_4 and t_5 (Fig. 5). In this period, the fuel was
 227 used to sustain the engine and eventually the auxiliaries.



229

230 Fig. 5- Portion of fuel rate (\dot{f}) and engine speed (n) during a cycle. The portion highlighted
231 in green underlines the idling part of the cycle.

232

233 After having classified the signal portions in the start-up event, the following metrics were

234 calculated:

- 235 • the duration of the start-up (t_s) with equation 8.

$$t_s = t_4 - t_1 \quad (8)$$

- 236 • energy demanded by the starter to start the engine ($E_{el,st}$) with equation 9:

$$E_{el,st} = \int_{t_1}^{t_2} P_{batt} dt \quad (9)$$

- 237 • amount of burned fuel necessary for restoring $E_{el,st}$ in the battery when the engine is
238 running ($f_{el,st}$) using equation 10:

$$f_{el,st} = \frac{E_{el,st}}{(\eta_{disc}\eta_{cha}\eta_{eng}\eta_{alt}) * (h_{fuel}\rho_{fuel})} \quad (10)$$

239 where:

- 240 ○ η_{disc} , battery discharging efficiency set to 0.85 (Ganesan & Sundaram, 2012);

- 241 ○ η_{cha} , battery charging efficiency set to 0.85 (Kulikov & Karpukhin, 2018);
- 242 ○ η_{eng} , diesel engine efficiency set to 0.45 (Patton & Bennett, 2011);
- 243 ○ η_{alt} , alternator efficiency set to 0.6 according to Saetti et al. (2021);
- 244 ○ ρ_{fuel} , fuel density, set to 827 kg m^{-3} (Parravicini et al., 2020);
- 245 ○ h_{fuel} , fuel lower heating value, set to 43.51 MJ kg^{-1} (Parravicini et al., 2020).
- 246 • greenhouse emissions for starting the engine ($m_{CO_2,st}$) using equation (11).

$$m_{CO_2,st} = 2.624 f_{el,st} \quad (11)$$

- 247 • CO emissions for starting the engine ($m_{CO,el st}$) using equations 12 and 13:

$$E_{ICE} = \frac{E_{el,st}}{(\eta_{disc}\eta_{cha}\eta_{alt})} \quad (12)$$

$$m_{CO,el st} = K_{CO}E_{ICE} \quad (13)$$

248 where:

- 249 ○ E_{ICE} : energy that must be given by the engine to recharge the energy delivered
- 250 by the battery during the electric start-up.
- 251 ○ K_{CO} : CO emission factor assumed to be the maximum allowable according to
- 252 the limits established in the European emission standards for non-road mobile
- 253 machinery specified in Stage V regulation ($3.5 \text{ g kW}^{-1} \text{ h}^{-1}$) (International
- 254 Council on Clean Transportation, 2016). This was carried out in order to
- 255 establish a general condition for CO emissions during the battery charging
- 256 process. In reality, this value changes depending on the use of the tractor after
- 257 ignition that determines the engine load. The value might be lower than that
- 258 reported here leading to conservative results.

- 259 • the fuel injected to accelerate the engine up to the minimum self-sustaining engine
 260 rotational speed ($f_{inj,st}$) using equation 14.

$$f_{inj,st} = \int_{t_3}^{t_4} \dot{f} dt \quad (14)$$

- 261 • CO₂ and CO emissions generated for accelerating the engine up to the minimum self-
 262 sustaining engine rotational speed (respectively, $m_{CO_2,inj,st}$ and $m_{CO,inj,st}$) using
 263 equations 15 and 16, respectively:

$$m_{CO_2,inj,st} = 2.624 f_{inj,st} \quad (15)$$

$$m_{CO,inj,st} = \int_{t_3}^{t_4} \dot{m}_{CO} dt \quad (16)$$

- 264 • idling fuel consumption (\dot{f}_{idle}) corresponding to the average value of \dot{f} during the time
 265 frame t_4 and t_5 .
 266 • The CO₂ mass flow rate during idling ($\dot{m}_{CO_2,idle}$) was calculated using equation 17,
 267 which is derived from equation 2 with \dot{f}_{idle} instead of \dot{f} :

$$\dot{m}_{CO_2,idle} = 2.624 \dot{f}_{idle} \quad (17)$$

- 268 • The CO in idling conditions ($\dot{m}_{CO,idle}$) was estimated with eq. 6 as the average of \dot{m}_{CO}
 269 during the corresponding period; specifically, from t_4 to t_5 .

270 The sum between $f_{el,st}$ and $f_{ign,st}$, and the sum between $m_{CO,el st}$ and $m_{CO,inj st}$ are the
 271 total fuel consumed and the total CO pollutant emission for an engine restart, respectively.
 272 Both permit to calculate the duration of idling that lead to the same energy expenditure
 273 ($t_{eq,idle,f}$) and CO emission ($t_{eq,idle,CO}$) of an engine restart and they were calculated with
 274 equations 18 and 19, respectively:

$$t_{eq,idle,f} = \frac{(f_{el,st} + f_{inj,st})}{\dot{f}_{idle}} \quad (18)$$

$$t_{eq,idle,CO} = \frac{(m_{CO,inj,st} + m_{CO,el,st})}{\dot{m}_{CO,idle}} \quad (19)$$

275 In other words, $t_{eq,idle,*}$ provides the number of seconds of idling beyond which shutting
 276 down the engine could bring benefits in terms of consumed fuel or in terms of CO emissions.

277

278 **Real world test**

279 The tractor used for the engine start test was monitored for three years and it accumulated
 280 1314 hours of use. In particular, a CANBUS data logger was installed on the tractor, as
 281 already discussed by the Authors in other studies (Mattetti et al., 2021; Molari et al., 2013).
 282 For the analysis, in addition to the CANBUS signals recorded during the engine start tests, the
 283 CANBUS signals with the following SPNs and PGNs were considered:

- 284 ● SPNs: 1907, 1919, 1931, 1943 and PGNs 65072, 65073, 65074, 65075, “Auxiliary
 285 valve number port flow” reporting the flow through the valve in percentage with
 286 respect to the maximum flow. These signals are denoted as \dot{V}_{fi} in the following, where
 287 i stands for the number of the auxiliary valves (i.e., 0, 1, 2, and 3). **Sampling rate = 10**
 288 **Hz**
- 289 ● SPN 9711 and PGN 64388, “Operator Presence State” reporting the presence of the
 290 operator on the seat of the vehicle. The signal is denoted as O_p in the following, which
 291 is equal to 0 when the operator was not on the seat and 1 otherwise. **Sampling rate =**
 292 **10 Hz**
- 293 ● SPN 1873 and PGN 65093, “Rear hitch position” reporting the position of the rear
 294 three-point hitch in percentage. The signal is 0 when the rear three-point hitch is fully

295 down and 100% when it is fully up. The signal is denoted as RHP in the following.

296 **Sampling rate = 10 Hz**

- 297 • SPN 1883 and PGN 65090, “Rear PTO Output Shaft Speed” reporting the speed of
298 the rear PTO output shaft. The signal is denoted as n_{PTO} in the following. **Sampling**
299 **rate = 10 Hz**

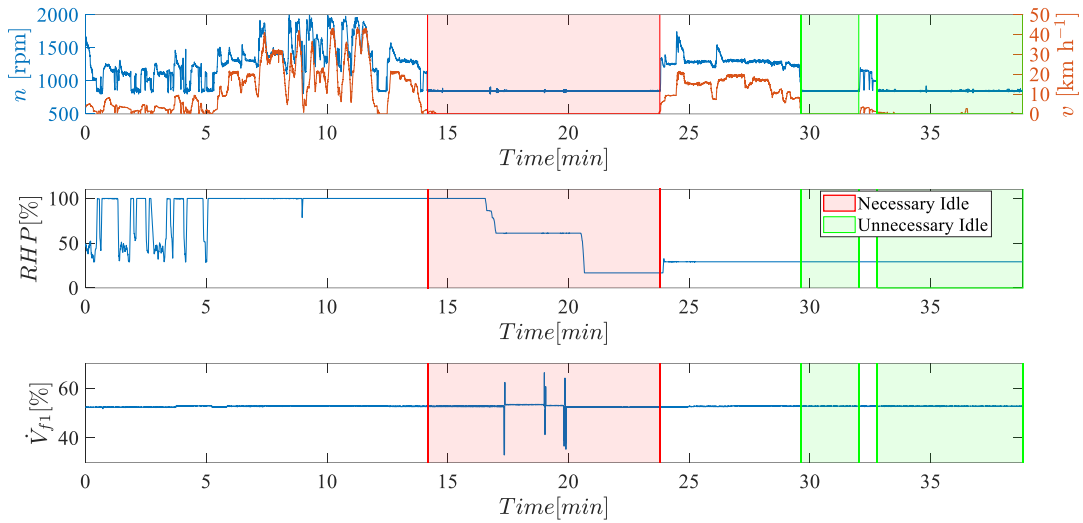
300 In addition to these signals, the machine position and its ground speed (v_t) were measured
301 through the GNSS (Global Navigation Satellite System) receiver embedded into the
302 CANBUS data logger. Through MathWorks MATLAB (Natick, MA, USA), all the signals
303 were imported and interpolated at 10 Hz using a cubic spline so that the sampling rate of all
304 the signals was the same. Idling stops were identified when:

- 305 • n lower than 850 rpm;
306 • v_t equal to 0 km h⁻¹;
307 • n_{PTO} equal to 0 rpm;

308 Idling stops were classified as unnecessary if they can be avoided with no significant
309 impact on productivity and as necessary otherwise. According to this definition, unnecessary
310 idling occurred anytime the operator did not use the three-point linkage and any auxiliary
311 valves. Thus, an idling stop was classified as unnecessary according to the following rule:

- 312 • O_p was 0 for longer than 10 s, chosen on the basis of the results of the engine start test
313 and because very short idling may occur for inadvertent driver manoeuvres;
314 • the peak-to-peak value of RHP and \dot{V}_{fi} in the idling stop was 0;
315 • T_c was above 78 °C.

316 The unnecessary idling was reported with a logical variable denoted as I_{un} , which was 1
317 when unnecessary idling occurred and 0 otherwise. In Fig.6, an example of classification of
318 both types of idling stops are reported.



320

321 *Fig. 6– Example of the idling classification. On top, engine speed (n) and vehicle ground*
 322 *speed (v_t); on the middle, rear hitch position (RHP); on bottom, flow rate of auxiliary*
 323 *valve n. 1 (\dot{V}_{f1}). Areas of unnecessary idle are shaded in green, while the area of*
 324 *necessary idling are shaded in red. In the necessary idling stops, the tractor was an*
 325 *idle condition and neither the three-point linkage nor the hydraulic distributors were*
 326 *in use. The $\dot{V}_{f2}, \dot{V}_{f3}, \dot{V}_{f4}$ were 0 %, thus they were not plot for sake of clarity*

327 A SS system would permit to save the fuel waste caused by unnecessary idling, but additional
 328 fuel would be used for the greater number of engine restarts. The potential savings of fuel,
 329 CO_2 , and CO due to the introduction of an SS system are, respectively, denoted as f_{save} ,
 330 $m_{\text{CO}_2,save}$, and $m_{\text{CO},save}$ and they were calculated using equations 20, 21 and 22, respectively.

$$f_{save} = t_{unn} \dot{f}_{idle} - n_{ign} (f_{el,st} + f_{inj,st}) \quad (20)$$

$$m_{\text{CO}_2,save} = 2.624 f_{save} \quad (21)$$

$$m_{\text{CO},save} = t_{unn} \dot{m}_{\text{CO},idle} - n_{ign} (m_{\text{CO},elst} + m_{\text{CO},injst}) \quad (22)$$

331 Where:

- 332 • t_{unn} is the duration of unnecessary idling;

333 • n_{ign} is the number of additional engine restarts counting the number of falling edges of
334 I_{un} ;
335 \dot{f}_{idle} , $f_{el,st}$, $f_{inj,st}$, $m_{el,st}$, $m_{inj,st}$, and $\dot{m}_{CO,idle}$ used in equation 20 are the average value
336 of the data calculated in the engine start test with AUX ON since it provides the more
337 conservative results.

338 **Results and discussion**

339 *Start-ups tests*

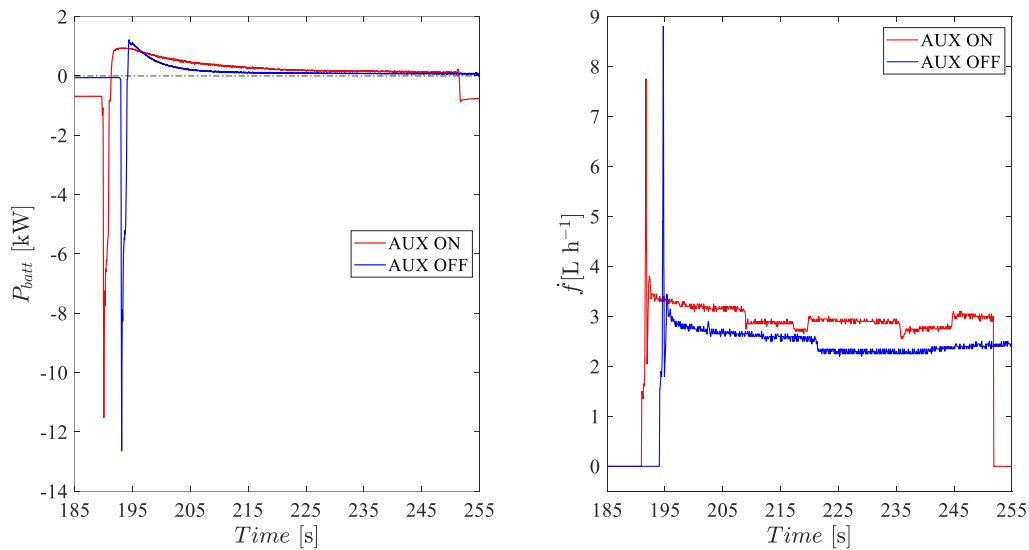
340 The typical behaviour of \dot{f} and P_{batt} during an idling cycle are reported in Fig. 7 for AUX
341 ON and OFF tests. For both tests, the signals are characterised by a certain amount of
342 irregularity caused by a few auxiliaries that occasionally demand energy from the engine.
343 Those auxiliaries may be the HVAC (its influence can be observed only for the AUX ON
344 tests), and the brake air compressor (its influence can be observed for both tests and it is
345 automatically engaged when the pressure in the circuit reservoir is below a certain value; thus
346 it could not be controlled during the test) due to their cyclic ON-OFF control logic (Saetti et
347 al., 2021). When the engine is off, P_{batt} is negative since the lights and the cab radio
348 demanded energy from the battery. During the idling phase, \dot{f} decays with a similar trend of
349 the P_{batt} due to the fact that the power demand of the alternator depends on the voltage
350 difference between the alternator and the battery, which decreases with the increase of the
351 battery state of charge (Saetti et al., 2021). Moreover, for the AUX OFF, the decay of P_{batt}
352 during charging is more pronounced than with the AUX ON due to the lower electrical
353 loading.

354 In other words, with the AUX OFF there is lower energy consumption and most of the
355 power generated by the alternator can be given almost exclusively to the battery. Thus, the

356 battery state of charge deprived before the start-up is restored in a quicker way than the AUX
357 OFF case.

358

359

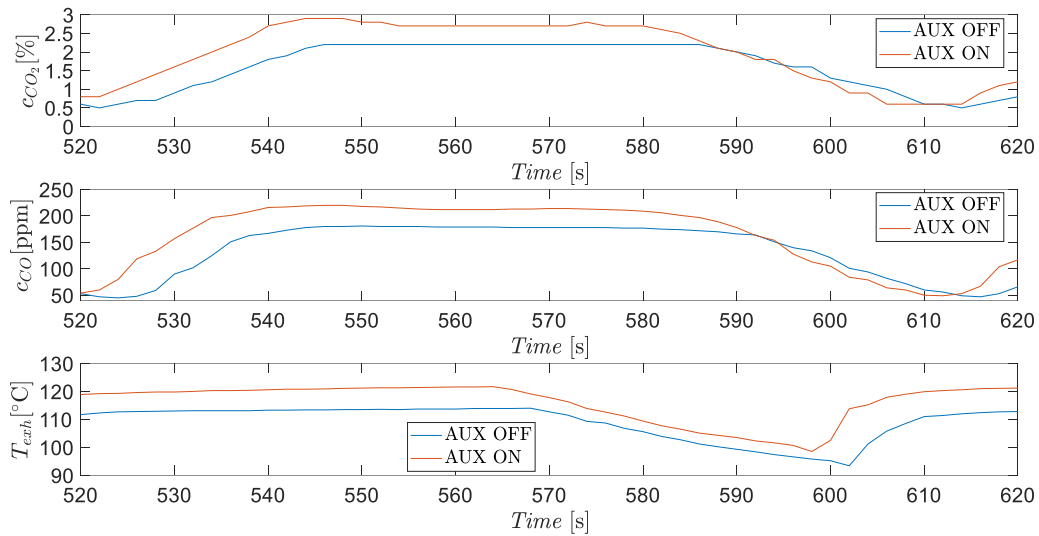


360

361 *Fig. 7 – Portion of battery power (P_{batt}) and fuel rate (\dot{f}) during a cycle for AUX ON and*
362 *AUX OFF tests. The AUX OFF electric power signals decay to zero faster than the*
363 *AUX ON signal.*

364 The CO₂ and CO volumetric concentrations in the exhaust registered during the tests are
365 shown in Fig. 8. As expected, the emissions are higher for the AUX ON case, since the
366 electric power demand of the auxiliaries has to be provided by the ICE through the alternator;
367 so, the air fuel mixture should be richer to guarantee the higher required engine power (the
368 idling rotational speed is the same).

369



370

371 *Fig. 8 – Portion of CO₂ concentration (c_{CO_2}), CO concentration (c_{CO}), and exhaust*
 372 *temperature (T_{exh}) during a cycle for AUX ON and AUX OFF tests.*

373

374 The t_s registered with the AUX ON was 3.10 s (standard deviation= $2.90 \cdot 10^{-1}$ s), while the
 375 one registered with the AUX OFF was 2.89 s (standard deviation= $2.22 \cdot 10^{-1}$ s). t_s is slightly
 376 longer with AUX ON because of the engagement of the HVAC compressor leading to greater
 377 mechanical loading.

378 *Start-ups tests – fuel consumption metrics*

379 In Table 2, the average values of **fuel consumption metrics** calculated from the engine start
 380 test are reported:

Table 2 - Idle influence on fuel consumption. In the brackets, the standard deviation of each parameter is reported

	AUX OFF	AUX ON
\dot{f}_{idle} [L h ⁻¹]	2.40 ($6.15 \cdot 10^{-2}$)	2.98 ($2.69 \cdot 10^{-2}$)
$f_{el,st}$ [L]	$9.17 \cdot 10^{-4}$ ($5.87 \cdot 10^{-5}$)	$1.06 \cdot 10^{-3}$ ($8.27 \cdot 10^{-5}$)
$f_{inj,st}$ [L]	$1.39 \cdot 10^{-3}$ ($5.87 \cdot 10^{-5}$)	$1.56 \cdot 10^{-3}$ ($8.54 \cdot 10^{-5}$)
$t_{eq,idle,f}$ [s]	3.48 ($1.34 \cdot 10^{-1}$)	3.16 ($1.36 \cdot 10^{-1}$)

381

382 \dot{f}_{idle} with AUX ON is 24% greater than that with AUX OFF due to the richer air-fuel mixture.
383 This value is significantly lower than that of the heavy duty trucks, probably due to the
384 smaller auxiliaries in tractors than in heavy duty truck (Brodrick, Dwyer, et al., 2002). The
385 greater \dot{f}_{idle} with AUX ON is caused by the greater mechanical and electrical loading caused
386 by the auxiliaries, quantified in the amount of 650 W (standard deviation: 2.44 W). Moreover,
387 for AUX ON, a greater standard deviation value than that with AUX OFF was observed,
388 caused by the higher variability in \dot{f} due to the occasional engagement of some auxiliaries. On
389 average, $t_{eq,idle,f}$ is below 3.5 s in both testing conditions but the greatest calculated value
390 was 3.73 s. Instead, in another study on passenger cars, this quantity was about 10 s (Gaines
391 et al., 2013). This means that for agricultural tractors, the proportion between the energy spent
392 for engine start-up and the idling fuel consumption is different from that for passenger cars.
393 This can be explained by the fact that the tractor used for the tests is equipped with a different
394 engine type (diesel rather than gasoline) and a greater engine size, 6700 cm³ with respect to
395 the less than 2500 cm³ of those of the cars used in the above-mentioned study, which leads to
396 a much greater idling fuel consumption (Rakha et al., 2011).

397

398 *Start-ups tests – emissions metrics*

399 In Table 3, the average values of emission metrics calculated from the engine start test are
 400 reported:

401

<i>Table 3 - Idle influence on emissions. In the brackets, the standard deviation of each parameter is reported</i>		
	AUX OFF	AUX ON
$\dot{m}_{CO_2, idle} [kg\ h^{-1}]$	6.29 (6.15 10^{-2})	7.83 (2.69 10^{-2})
$\dot{m}_{CO, idle} [g\ h^{-1}]$	3.42 10^{-1} (2.25 10^{-2})	3.86 10^{-1} (6.09 10^{-3})
$m_{CO_2, el, st} [g]$	2.4 (1.55 10^{-1})	2.80 (2.18 10^{-1})
$m_{CO_2, inj, st} [g]$	3.67 (1.21 10^{-1})	4.11 (2.26 10^{-1})
$m_{CO, el, st} [g]$	1.12 10^{-2} (1.00 10^{-3})	1.40 10^{-2} (1.71 10^{-3})
$m_{CO, inj, st} [g]$	2.78 10^{-4} (4.34 10^{-5})	2.19 10^{-4} (1.15 10^{-5})
$t_{eq, idle, CO} [s]$	120 (13.3)	134 (15.1)

402

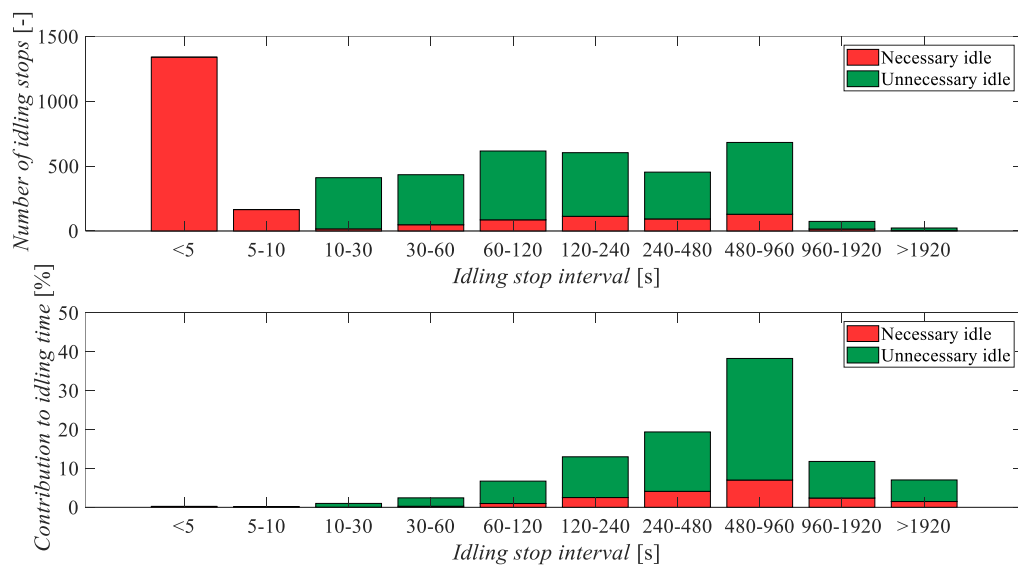
403 Since \dot{m}_{CO_2} is proportional to \dot{f} (see equation 2), the same conclusions derived for the metrics
 404 related to the fuel flow rate can also be used for the CO₂ related metrics. $m_{CO_2, el, st}$ is
 405 considerably higher than $m_{CO_2, inj, st}$; this could be due to the conversion factor used in this
 406 study during the battery charging in the electric start calculation. Specifically, CO emissions
 407 were assumed to be the maximum permissible threshold given by the Tier V regulations (3.5
 408 g kW⁻¹ h⁻¹). This value might be high but it leads to conservative numbers on the benefits of
 409 SS system. $t_{eq, idle, CO}$ is much greater than $t_{eq, idle, f}$ in both testing conditions; thus turning off
 410 the engine using a fuel based logic only leads to fuel savings, but might not lead to a
 411 reduction of CO emissions, but rather to their increase if the off period is not long enough. On
 412 the other hand, a SS configured with a logic based on $t_{eq, idle, CO}$ will have reduced fuel
 413 savings as compared to the actual reduction potential. This is due to the high CO emissions of

414 diesel engines at low loads and the lower efficiency of the oxidiser converter at low
 415 temperatures.

416

417 *Real-World tests*

418 The tractor was run on idle 21.7% of the entire operating duration, this value is aligned
 419 with the average value reported in previous studies (Perozzi et al., 2016). Unnecessary idling
 420 accounts for 45% of the total idling **time**, highlighting the potential advantages of adopting SS
 421 systems in agricultural tractors. Idling stops were binned into time intervals as some of the
 422 authors carried out in a previous study (Perozzi et al., 2016) and its distribution and their
 423 contribution to the idling duration are reported in **Figure 9 (top)**.



424

425 *Fig. 9 – In the graph at the top the number of stops at each idling stop time interval. In the*
 426 *graph at the bottom is presented the definition of the percentage of influence of the*
 427 *unnecessary idle and necessary idle over the total idle time.*

428 By definition of the unnecessary idling, all the idling stops shorter than 10 s were classified
 429 as necessary. Most of the idling stops are shorter than 10 s (equivalent to 31% of the total
 430 idling stops), however their contribution to the total idling **time** is negligible (less than 0.4%).
 431 For idling stops longer than 10 s, unnecessary idling stops dominate necessary idling stops for

432 any time interval. For unnecessary idling, most of the contribution to the total idling time (i.e.
 433 31.3%) and most of the idling stops (i.e. 554 stops) lies into the interval 480-960 s.
 434 Additionally, there are also a great number of idling stops in the time intervals 120-240 s (i.e.
 435 531 stops) and 240-480s (i.e. 491 stops) but they respectively influence the total idling time
 436 by only 10.5% and 15.3% of the entire unnecessary idling (Fig 9, bottom).

437

438 In Table 4, the theoretical impact of the adoption of the SS system is reported.

f_{save} [l]	367.86
N° of engine start-ups imposed by the driver	1155
N° of additional engine start-ups caused by the SS system	2435
$m_{CO_2,save}$ [kg]	956.44
$m_{CO,save}$ [g]	21.26

439 For necessary and unnecessary idling statuses, the tractor consumed 449 L and 367.9 L of
 440 fuel, respectively. These are nearly 2% and 1.65% of the entire fuel consumption during the
 441 period of use of the tractor. The number of engine start-ups imposed by the driver during the
 442 period of use is 1155 (i.e., on average 4 engine start-ups per day). Adopting the SS system
 443 with the defined strategy, the number of engine start-ups will increase by 67%, leading to a
 444 much greater load on the starter and the battery, affecting their durability. Considering the
 445 additional engine start-ups (from tests results the average fuel consumption of a complete
 446 ignition is around 0.003 l) induced by the SS system, the potential fuel saving is 1.62% of the
 447 entire consumed fuel of the tractor. In contrast to the results obtained in (Whittal, 2012),
 448 where CO emissions increased for a diesel powered vehicle (BMW 118d) equipped with a SS
 449 system, this study indicates that CO emissions could be reduced with the use of a SS system
 450 in a tractor. Specifically, a 21.26 g CO reduction was calculated; unfortunately, a comparison
 451 with the total CO emissions cannot be done, as emissions were not monitored during the real

452 tests campaign due to the fact, the gas analyser could not be installed for a prolonged field
453 experimentation. This could be explained by the fact that the idling stop distribution of on-
454 road vehicles is different from the one of tractors, and in particular, tractors tend to be stopped
455 for idling for longer than on-road vehicles.

456

457

4. Conclusions

458 Engine idling is a frequent operating status of agricultural tractors and it is mostly not
459 necessary since the operator does not request any use of the three-point linkage or hydraulic
460 remotes. Thus, the corresponding fuel and green-house emissions could be avoided and
461 tractor manufacturers should address novel solutions to limit the engine idling. This paper
462 reports the results of a feasibility study on the introduction of SS systems in agricultural
463 tractors. To this goal, the energy required for engine start-up and the subsequent emissions
464 were measured. In terms of fuel consumption and CO₂ emission, turning off the engine is
465 recommended for stops longer than 4 s; while for CO emission, turning off the engine is
466 recommended for stops longer than 134 s. Additional research is needed to evaluate the
467 impact of different engines architectures (i.e., engine size, number of cylinders, etc.) on these
468 figures. The potential fuel and emission savings reported in this study seem limited, but
469 considering that only in the US there are 1.2 million tractors of the same power level of the
470 tractor used in this study (USDA, 2019) and that these tractors can be used up to 850 hours
471 per year (Mattetti et al., 2019), yearly reductions of 285.6million litres of fuel, and,
472 respectively of 16.5 and 754 tons of CO and CO₂ emissions could be attained every year with
473 tractors equipped with SS systems. These figures should be considered as first estimation of
474 the impact of idling reduction on emission of agriculture mechanisation. The implementation
475 of a SS dedicated to agricultural tractors requires some rework on the powertrain architecture.

476 In particular, more powerful and durable alternators are required for quickly recharging the
477 battery in order to restore the energy required for start-ups and for enduring the much greater
478 number of ignitions than those exposed by conventional tractors with no SS system (Ohmae et
479 al., 2006). The ongoing electrification process of agricultural tractors will be an enabling
480 technology for the introduction of SS systems in agricultural tractors. Moreover, with the
481 electrification of the auxiliaries and hydraulic subsystem, there would be the possibility to run
482 the auxiliaries also when the engine is off and this will permit to achieve greater savings than
483 those reported in this study. Especially, since also the fuel and emissions for necessary idling
484 could be eliminated, although they are lower than those of unnecessary idling. The advantage
485 of SS systems is also in terms of comfort since farmers may carry out standing operations
486 around the tractor with no engine noise and harmful gas emissions.

487 However, tractors with a sort of electrified devices are still under study and a few solutions
488 have been proposed (Hahn, 2008; Troncon et al., 2019; Varani et al., 2021). Despite the
489 potential benefits, these solutions will not reach the market within several years. In the
490 meantime, researchers and disseminators must raise the farmers' awareness about the harmful
491 effects and economic losses of unnecessary idling through proper dissemination activities.

492

493

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497

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