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Research Paper

Estimation of carbon-oxide emissions of tractors during operation and correlation with the not-to-exceed zone

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The continuing rise in fossil fuel use significantly aggravates global warming problems because of carbon dioxide (CO_2) emissions. This article shows a procedure to indirectly obtain data concerning the environmental pollution of a tractor by starting from direct data. The research confirms that qualitative indicators of a tractor's work for an operational period could be identified from a database compiled from engine processors. The average work rate of tractors measured under field conditions, together with the operating time in an engine's work mode, fuel consumption, and CO_2 and CO emissions, have been measured. Correlations between CO_2 and CO emissions and the NTE (not-to-exceed) zones during a tractor's operational period have also been determined. The study showed that the tractors worked, on average, 51% of the operational period with the engine working modes within the NTE zone. While working in these modes, the tractors consumed approximately 73.4% of the fuel used for the whole operational period, and emitted into the environment approximately 76% of the CO_2 and 9.7% of the CO of the emissions of the whole operational period. It was found that there are possibilities to reduce fuel consumption and CO_2 and CO emissions during tractor operational periods by improving the tractor's operation by choosing engine work modes in a more rational way.

1. Introduction

One of the biggest current environmental problems is linked to growing ambient air pollution and global warming occurring because of increased greenhouse gas (GHG) emissions. The most common GHG is carbon dioxide (CO_2), and approximately 96% of all CO_2 emissions are the result of burning fossil fuels (Pao, Chen, & Li, 2015).

The general trend of global agricultural development is toward automated technologies and more powerful and productive agricultural machinery (Bochtis, Sørensen, & Busato, 2015; Osinenko, Geissler, & Herlitzius, 2015). This trend creates a reduction in the cost of agricultural production and increases competitiveness in the global market. Nonetheless, use of more powerful tractors and agricultural machines has several negative consequences primarily related to the damaging impact of the machines on the environment (Cavallo, Ferrari, & Coccia, 2015). Current production

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Nomenclature

Symbols

B_h	hourly fuel consumption, kg h^{-1}
$B_{h\ m}$	hourly fuel consumption in particular mode, kg h^{-1}
B_m	total fuel consumption in particular mode, kg
b_c	cyclic fuel injection quantity, mg cycle^{-1}
$b_{c\ m}$	cyclic fuel injection quantity in particular mode, mg cycle^{-1}
$b_{e\ m}$	specific fuel consumption for operating mode, g kW^{-1} h^{-1}
c	number of engine operating cycles per revolution
$E_{e\ m(x)}$	specific emission of engine exhaust gas components (x is CO_2 or CO) in particular mode, g kW^{-1} h^{-1}
$E_{m(x)}$	emission of engine exhaust gas x in particular mode, during the operational time (x is CO_2 or CO), g (1000 h)$^{-1}$
$E_{ppm\ m(x)}$	concentrations of carbon-oxides (CO_2 or CO) in the exhaust gas for the engine operating mode, % or ppm
i_c	number of the engine cylinders
m	engine operating mode
n	engine rotations, min^{-1}
n_m	engine rotations at particular mode, min^{-1}
P_m	engine power for operating mode, kW
P_{max}	engine maximum power, kW
t	engine operational time, h
t_m	engine operational time at particular mode, h
T_m	engine torque for operating mode, N m
T_{max}	engine maximum torque, N m
W_m	work for operating mode, J
Θ_E	temperature of exhaust gases, F
ε	transient adjustment factor for assessing changes in engine load at operating mode
$\sigma_{E\ m}$	volumetric gas flow in particular mode, m^3 h^{-1}
$\sigma_{O\ m}$	volumetric air flow in particular mode, m^3 h^{-1}
η_{σ_O}	volumetric efficiency coefficient of supplied air flow
ρ_E	molar gas density, kg kmol^{-1}
υ_e	engine displacement, cm^3

Abbreviations

BSFC	brake specific fuel consumption, g kW-1 h-1
GHG	greenhouse gas
ECU	Electronic control unit
EEM	Electronic engine management
EU	European Union
LHV	lower heating value
MFWD	mechanical front-wheel drive provides four-by-four capabilities to tractors with different-sized front and rear wheels
NTE	not-to-exceed (emission limits and testing requirements as an additional instrument to make sure that heavy-duty engine emissions are controlled over the full range of speed and load combinations commonly experienced in use)
O_2	oxygen
CO	carbon monoxide (engine exhaust gas component)
CO_2	carbon dioxide (engine exhaust gas component)
NO_x	nitrogen oxides (engine exhaust gas components)
HC	hydrocarbons (engine exhaust gas components)
PM	particulate matter (engine exhaust gas components)

conditions and environmental requirements force manufacturers to seek techniques to reduce fuel consumption and emissions of harmful exhaust gases. Despite global achievements in reducing fuel consumption and noxious exhaust gases in new vehicles and tractors, the quantity of these machines has increased more rapidly, which negates this benefit (Bietresato, Calcante, & Mazzetto, 2015; Hao, Liu, Zhao, Li, & Hang, 2015; Lee, Kim, & Kim, 2016; Lei et al., 2016; Walmsley et al., 2015). The problem of using agricultural tractors effectively has become crucial (Juostas & Janulevičius, 2009).

1.1. *Fuel consumption and exhaust gas emissions*

Indicators of fuel consumption and CO_2 emissions are strongly interdependent. The results from research (Nabi et al., 2015; Tse, Leung, & Cheung, 2015; Wu et al., 2015) have shown that in all cases CO_2 emissions directly depend on fuel consumption. As the fuel consumption increases, the CO_2 emissions increase proportionally. Studies have shown that the fuel consumption, thermal efficiency and CO_2 emissions can be attributed to differences in the lower heating value (LHV) of various fuels (Lei et al., 2016; Mofijur, Atabani, Masjuki, Kalam, & Masum, 2013; Yilmaz, 2012). The CO_2 emission per kWh is thought to be equal to the inverse thermal efficiency divided by the energy supplied per carbon atom (i.e., LHV/carbon fraction of a fuel) and assuming that all of the carbon in the fuel becomes CO_2 (Lindgren, Larsson, & Hansson, 2010). If fuels in the engine burn completely, the exhaust gas will contain carbon dioxide (CO_2), water vapour (H_2O) and nitrogen (N_2). However, in real conditions within an internal combustion engine, the fuel partially burns; therefore, the exhaust gas contains carbon monoxide (CO), nitrogen oxide (NO_x), hydrocarbons (HC) and particulate matter (PM) (Mofijur et al., 2013; Pali, Kumar, & Alhassan, 2015; Yilmaz, 2012). After a partial combustion of organic compound fuels, CO gas is formed. In the ambient air, CO relatively quickly turns into CO_2. When adequate O_2 is accessible, the hydroxyl radical OH is one of the principal oxidising agents that converts CO into CO_2 (Imdadul et al., 2016).

Currently, the significant global warming problems caused by CO_2 have been magnified by the continued and increasing use of fossil fuels in internal combustion engines. Reducing CO_2 emissions has become an explicit goal of policy measures to support the production and use of biofuels. The European Union (EU) mandates a 10% share of biofuels in the EU's total energy mix by 2020 (EC, 2009; EU, 2013). Vegetable oil-based fuels applied as diesel fuel extenders could reduce