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Research Paper

Nitrogen-oxide emissions from diesel-engine farm tractors during real-life cycles and their correlation with the not-to-exceed operating zones

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A methodology is introduced to help provide a better understanding of how real-life factors influence emissions from tractors by determining: engine speed vs. load for modes in which tractors most often operate in farms; the operating time for tractor engines in load vs. speed modes that fall into the range of exhaust gas not-to-exceed (NTE) control zones; NO_x emissions during tractor real-life cycles, and the quantities emitted by engines when operating in NTE zone. Real-life operating times were calculated and broken down by engine operating modes and NO_x emissions by referring to load profile databases accumulated in the control processors of tractor engines. Tests showed that for the ten farm tractors studied (Massey Ferguson 6499), they operated with engine operating modes that fell into the NTE zone for only about 51% of their total real-life operating times and in that mode emitted 60.1% of the total NO_x gases emitted during the whole of their operation. Most of the tractors (~76%) emitted NO_x during engine loads above 50% of the maximum torque (T_{max}), 21.6% at loads between 30 and 50% of T_{max}, and only 2.3% in loads up to 30% of the T_{max}. The most significant amount of NO_x emitted during the real-life cycles occurred when the tested engines operated in a cyclic fuel injection mode with 10–20 mg cycle^{-1} and engine speeds of 700–1100 rpm. The data acquired using this method could help farmers operate tractors in a more rational and environmental modes.

1. Introduction

Tractors play an important role in agriculture as the main motive power for operating various add-on implements. The modern trend in agricultural development is to use automated technologies and often to use more powerful and efficient equipment (Cavallo, Ferrari, & Coccia, 2015). All this creates the preconditions for reducing production costs and increasing its competitiveness. However, use of more powerful agricultural machinery has related negative consequences, in particular, higher fuel consumption and harmful impacts on the environment. In agriculture, tractors are the most fuel-consuming machines that are used and emit significant amounts of nitrogen oxides to the environment. Because of today's production conditions and environmental

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Nomenclature

Symbols

B_m	Total fuel consumption engine operating mode, kg
b_c	Cyclic fuel injection quantity, mg cycle^{-1}
$b_{c\ m}$	Cyclic fuel injection quantity engine operating mode, mg cycle^{-1}
c	Number of engine operating cycles per revolution
$E_{e\ m\ (x)}$	Specific emission of exhaust gas components (x is NO or NO_2) engine operating mode, g kW^{-1} h^{-1}
$E_{m\ (x)}$	Emission of exhaust gas x engine operating mode, during the operational time (x is NO or NO_2), g (1000 h)$^{-1}$
$E_{ppm\ m\ (x)}$	Concentrations of nitrogen oxides (NO or NO_2) in the exhaust gas for the engine operating mode, % or ppm
i_c	Number of the engine cylinders
M	Operating mode of the engine
n	Engine speed, min^{-1}
n_m	Engine speed at operating mode, min^{-1}
P_m	Power at engine operating mode, kW
t	Operational time, h
t_m	Operational time at engine operating mode, h
T	Torque, N m
T_m	Torque at engine operating mode, N m
T_{max}	Maximum torque of the engine, N m
W_m	Work at engine operating mode, J
Θ_E	Exhaust gases temperature, F
ε	Transient adjustment factor for assessing changes in engine load
$\sigma_{E\ m}$	Volumetric gas flow engine operating mode, m^3 h^{-1}
$\sigma_{O\ m}$	Volumetric air flow engine operating mode, m^3 h^{-1}
η_{σ_O}	Volumetric efficiency coefficient of air flow
ρ_E	Molar gas density, kg kmol^{-1}
υ_e	Displacement of the engine, cm^3

Abbreviations

ECU	Electronic control unit
EEM	Electronic engine management
EU	European union
NTE	Not-to-exceed zone
NRTC	Non-road transient cycle
O_2	Oxygen
N_2	Nitrogen
CO	Carbon monoxide
CO_2	Carbon dioxide
NO_x	Nitrogen oxides
NO	Nitric oxide
NO_2	Nitrogen dioxide
HC	Hydrocarbons
PM	Particulate matter
EGR	Exhaust gas recirculation
DOC	Diesel oxidation catalyst
SCR	Selective catalytic reduction
DPF	Diesel particulate filter

requirements, machinery manufacturers are obliged to produce increasingly cost-efficient and more environmentally-friendly tractors. Reductions in fuel consumption and emissions of noxiousness of exhaust gases, as well the search for a rational connection between them, is a global scientific problem (Gonzalez-de-Soto, Emmi, Benavides, Garcia, & Gonzalez-de-Santos, 2016; Imdadul et al., 2017; Lovarelli, Bacenetti, & Fiala, 2017; Palash et al., 2013; Yang et al., 2016). New technical innovations to reduce fuel consumption and the emission of noxious exhaust gases are being installed in new tractors, yet increases in the power and the quantity of tractors used has overshadowed this economy (Cavallo, Ferrari, Bollani, & Coccia, 2014a; Cavallo, Ferrari, Bollani, & Coccia, 2014b; Gonzalez-de-Soto et al., 2016; Walmsley et al., 2015). Sophisticated, cost-efficient and environmentally-friendly tractors are replacing older models; however, producers often do not have sufficient feedback concerning the use of their innovations operating under real-life situations. Insufficient information is available about real-life operating modes, fuel consumption, and oxide emissions from particular tractors during longer or shorter phases of operation. With the absence of such data, it is difficult to assess impact of innovations and comparing the economic and environmental indicators of tractors during field operation is complex. It is also a challenge to assess how farmers operate their tractors on different farms, to explore where possibilities exist to reduce fuel consumption and determine adverse environmental impacts during operation, particularly in the field. These problems require exploration.

1.1. *Fuel consumption and oxide emission during tractors real-life cycle*

Fuel consumption during field operation of tractors heavily depends on engine speed and load. Indicators of engine performance are considered to be good only when engine revolutions are <80% of nominal maximum while the power supplied by the engine >80% of nominal engine power (Janulevičius, Juostas, & Pupinis, 2013; Lee, Kim, & Kim, 2016). However, it appears that under real-life cycles most operate with engine loads that are between 50 and 70% of nominal power (Juostas & Janulevičius, 2009; Lovarelli, Bacenetti, & Fiala, 2016). In order to save fuel, proper machine adjustment, and the selection of suitable engine speeds and load, may serve as simple and efficient methods. Auxiliary operations, such as turning at the headland, driving without a load, engine idling, etc. can significantly increase fuel consumption per working unit (Lovarelli et al., 2016; Pitla, Luck, Werner, Lin, & Shearer, 2016). Research (Lovarelli et al., 2016; Perozzi, Mattetti, Molari, & Sereni, 2016) has indicated that during tractor field operations engines idle for significant amounts of time, i.e. between 20–30%. Similar prolonged running in idle mode has been observed when analysing real-life cycles of road cargo transport vehicles (Shancita et al., 2014). When in