Comparison of exhaust gas emissions between autonomous and human operator excavator

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Abstract. The scope of this study was to compare the exhaust gas emissions of an autonomous driving and a human operator excavator under real construction work conditions. The test diesel engine excavator with EPA 2012 emission regulations rules (Tier 4final/Stage IIIB) has an engine power of 44.3 kW at an engine speed of 2100 rpm. In addition, it has various devices, such as exhaust gas recirculation (EGR) and diesel particle filter (DPF), to reduce the engine-out emissions. The exhaust gas emissions, including carbon dioxides (CO_2) and nitrous oxides (NO_x), were measured with a portable Gasmet DX4000 FTIR gas analyzer and analyzed with Calcmet software. Pressure transmitter with digital output by G2 6DOF IMU by Novatron was used to check the pressure and angular variations, respectively. In addition, FLIR E60 IR Camera was used to visualize the exhaust gas during the chilly winter experiment conditions.

The exhaust gas tests were carried out in a simple move of bucket with autonomous driving and repeated with a human operator. For both tests, the movement of the bucket was done in 0%, 50% and 100% engine speed positions. In autonomous driving, autonomous trajectories were generated in the Rhino Grasshopper environment. Based on the emission analysis results, the CO_2 emission was lower during autonomous driving than during human operation. The same trend was also seen in the case of NO_x emissions. The human operator used a higher movement speed and a slightly different movement compared with autonomous driving, which may explain the difference in emissions.

Keywords: Autonomous excavator, Exhaust gas emissions, Sustainability.

1 Introduction

In Finland, the content of greenhouse gases (GHGs) such as carbon dioxide (CO_2) was 48.1 mln. tons of CO_2-eq, of which working machines contributed 2.4 mln. tons of CO_2-eq. Even though the total GHGs have decreased by 23 % in seven years (from 2013 to 2020), the content of GHGs in the case of working machines has not changed. [1] Although Finland's GHG emissions represent 0.1 % of the world's GHG emissions, concern about global climate change and global warming have pushed the construction sites to act more to decrease the GHG values. The emissions of working machines or non-road mobile machines (NRMM), such as nitrous oxides (NO_x), carbon monoxide (CO), hydrocarbons (CHs) and particulate matter (PM), have been regulated by the European Union (EU) since 1997 and the emission limits are tightening [2]. However, the formation of CO_2, which is currently a major concern, is not yet regulated. Therefore, optional EU Green Deal–agreement has been reached between the Finnish government and some construction companies to have fossil-free construction sites so that by the end of 2030, 50 % of working machines would run on electricity, hydrogen or biogas [3]. In addition, many infrastructures companies have carried out environmental assessments and adopted rating schemes such as CEEQUAL [4] as part of their sustainability strategy.

Nowadays, life cycle assessment (LCA) methodology is used as a calculation tool to estimate GHG emissions. To harmonize the LCA calculation results between projects, a specific guideline has been done to infra sector, for instance, by the NordFoU organization [5]. To calculate the GHG emissions of machines used for the mass transfer process, the data presented in the Technical Research Centre of Finland (VTT) LIPASTO TYKO 2017 database [6], and the machine power, the working hours and fuel consumption for working machines are needed. Since 90% of the NRMM are still running on diesel, research work is still needed in different working or engine scenarios. Therefore, NRMM emissions have been studied in many ways. For example, engine laboratory studies have been conducted with different bio-based fuels and/or after-treatment systems, such as selective catalytic reduction (SCR) unit [7–11] real-world tailpipe emissions of NMMM have been analyzed using portable emission measurements (PEMS) equipment [12–15] in chilly weather conditions (2–12 °C) [16]. A mobile laboratory van “sniffer” has also been used [11]. There are also studies in which calculation models, such as EPA NONROAD2008 [17], are used to estimate and compared to the PEMS results of the machine. Since calculation methods have some uncertainties, the discrete-event simulation [18] even an artificial neural network [19] are also used to assess emissions from the construction process.

The automation of working machines to help human operators has been studied for many years. To integrate machines as an integral part of intelligent systems, an autonomous excavator has been equipped with different sensor systems [20]. In addition, a soil surface shape and a large-scale construction site can be monitored from an excavator by using a solid-state 2D pulsed time-of-flight (TOF) laser profilometer and commercial mechanically spinning pulsed time-of-flight multi-echo Lidar [21, 22]. A part of this system is emission monitoring, which plays a significant role in sustainable development in construction sites. However, there is still a high potential to study how automation and robotic technologies can promote sustainability in infrastructure projects as Hoeft *et al.* (2021) pointed out their literature review article [23].

In this article, the goal of the research work is to determine, whether automation can help to decrease harmful emissions formation compared with the human operated excavator. For this purpose, the emissions of a smart excavator system were measured and analyzed in real-time conditions using a simple bucket move.

2 Experimental

2.1 Smart (autonomous) excavator system

In this study, the Bobcat E85 commercial excavator (8.5 tons) was used, which was modified for autonomous excavation purposes [21, 22, 24]. The excavator has a diesel engine with EPA 2012 emission regulations rules (Tier 4final/Stage IIIB) and an engine power of 44.3 kW at an engine speed of 2100 rpm. In addition, it has various devices, such as exhaust gas recirculation (EGR) and diesel particle filters (DPF) to reduce the engine-out emissions.

Figure 1 illustrates the configuration of the excavator system used in the test. The exhaust pipe of the excavator was connected to the emission measuring equipment using a heated probe. The smart excavator was equipped with GNSS (Global Navigation Satellite System), CAN bus 6 DOF IMUs and rotary encoder, 4 IP cameras and stereo cameras for the VR remote control. The basis of the sensor system is the Novatron IMU G2 sensor. The excavator is equipped with Novatron Xsite machine control system (MCS), which uses GNSS localization and the IMU sensors from boom, arm and bucket (red line in Fig.1) to guide the operator in reference to machine control models (MCM). The orientation of the machine, its position and GNSS data with the MCM can be seen from the machine control interface displayed on the tablet size monitor in the cabin. IMU and GNSS data was used as feedback on automation control. The excavator has engine control unit (ECU) that controls the excavator's electrical systems including the electro-hydraulics (blue line in Fig. 1.). The control signals of remote control and automation are routed from control the PC to the ECU via the automation unit. The excavator was equipped with both a radio receiver and a wireless data connection, so, depending on the worksite, both methods of receiving a Real-Time Kinematic (RTK) correction were enabled. The RTK-corrected GNSS positioning data should reach close to centimetre accuracy.

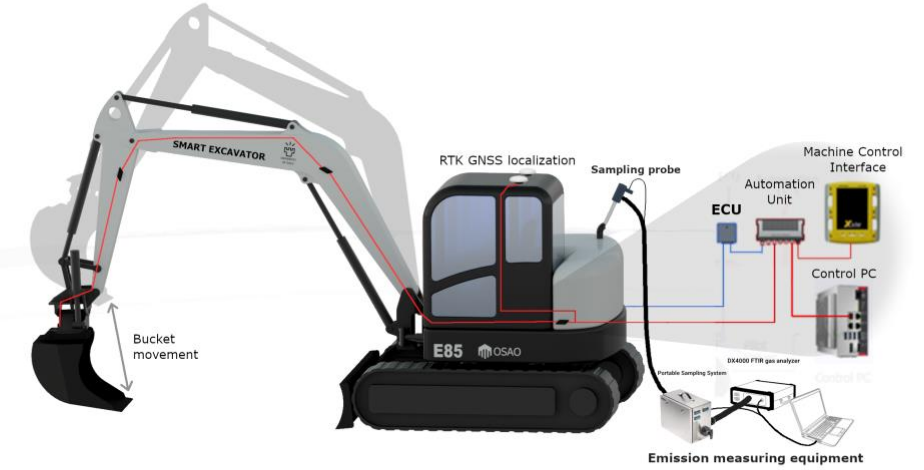

Fig. 2. Smart Bobcat E85 excavator equipped with machine control system as well as emission measurement equipment. In addition, the bucket movement is presented.

2.2 Bucket movement during the autonomous and human operator experiments

Several different trajectories for the emissions between autonomous and human operated excavator were compared. This article focuses on the trajectory in which only the boom was raised up and lowered down. Figure 1 presents the simple bucket movement used in the experiments, as well. The operations of the examined trajectory were as follows: 5 min with 0% engine speed, 5 min with 50% engine speed, and 5 min with 100% engine speed. A 0% engine speed is equal to an idle speed. The task of the human operator was to mimic the automatic trajectory joint angles and speed as much as possible.

In autonomous driving, automatic trajectories were generated in the Rhino Grasshopper environment, and the generated trajectories were then fed into the excavator control system. The automatic control system was created in a MATLAB Simulink environment. In Rhino Grasshopper, the digital twin of the smart excavator was created, and the desired trajectories were tested before the trajectory data were fed to the excavator control system. Pressure transmitters with digital output and G2 6DOF IMU by Novatron were used to check the pressure and angular variations on each link, respectively.

2.3 Exhaust gas emissions from the excavator

The excavator was running motor/heating oil for winter-quality diesel during the emission exhaust gas experiments conducted in winter (December 2021). The weather conditions during the human operator and automation experiments were snowing, the temperature was around +2°C, and ambient pressure was 1004 mbar and 999 mbar.

Thermal imaging of the exhaust gas of the excavator was carried out using the FLIR E60 IR Camera. The sensor is obtained images having a resolution of 320 × 240 pixels and a thermal sensitivity of which was 0.05°C at 30°C. It was equipped with a 15-mm lens supplying a field of view (FOV) of 25° and 29°.

The emission measurement equipment used in the experiments is presented in Figure 1. The emissions of the exhaust gas from the tailpipe of the excavator were measured as a function of time every 20 s using a Gasmet DX4000 FTIR gas analyzer. The volume of oxygen (O_2) was measured by using a Portable Sampling System (PPS) with ZrO_2 sensor. The 50 cm-long unheated stainless-steel tube was insulated with a layer of tin paper to prevent water condensation to the exhaust pipe. This was then connected to the heated probe (180°C), which was used to take undiluted and wet exhaust gas emission from the excavator pipe in where it was pumped to PSS via a 5 m- long heated line (180°C). From the PSS the gases were directed into Gasmet FTIR gas analyzer (180°C) via a 1 m-long heated line (180°C). There was a two-stage particulate filtration (particle size 2 mm): the first one was the sampling probe (PTFE) and the second one was in the PSS (stainless steel, RST). Calcmet software was used to collect, store and visualize the FTIR spectra of wet sample gas and to analyze the concentrations of gas components: NO, N_2O, NO_2, NH_3, CO, CO_2, CH_4, C_2H_4, C_3H_8, benzene (C_6H_{14}), formaldehyde (CHOH), acetic acid (CH_3COOH), dodecane ($C_{12}H_{26}$), SO_2, and water (H_2O).

3 Results and discussion

The exhaust gas emission experiments of the excavator were studied under engine running conditions using thermal IR and photograph images. The visualization of exhaust gas is not very prominent in engine running conditions, as can be seen in Figure 2a). This may be because the exhaust gas temperature rapidly reaches the ambient temperature. However, it seems that the tin layer insulation of the stainless-steel tube between the heated probe and the exhaust pipe was prevented unwanted water condensation (Fig 2b). Therefore, it can be assumed that the analyzed exhaust gas stream was undiluted.

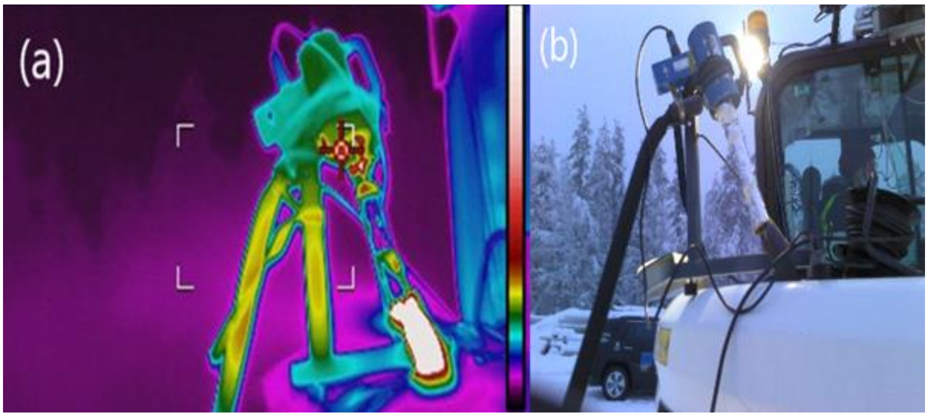

Fig. 3. The thermal IR image (a) and photograph image (b) of excavator exhaust gas during engine running condition.

The measured results of the Gasmet DX4000 FTIR gas analyzer are both qualitative and quantitative. Based on the literature, the results of Gasmet FTIR are suitable for exhaust gas measurement on a laboratory scale [9]. Table 1 shows all measured gases and the maximum concentrations or volumes between autonomous driving and human operator experiments for 0%, 50% and 100% engine speed [rpm], for the boom up experiment, as an example.

Fuel-based hydrocarbons (HCs), in other words, methane (CH_4), ethylene (C_2H_4), propane (C_3H_8), hexane (C_6H_{14}), formaldehyde (CHOH), acetic acid (CH_3COOH), and dodecane ($C_{12}H_{26}$) were measured to determine the content of carcinogenic compounds. The concentrations of the HC components were analysed to be all under 10 ppm. In addition, the formation of CO was low, under 2 ppm. This means that diesel was almost completely combusted in the cylinder to CO_2 and H_2O, as was expected. In addition, the concentrations of ammonium (NH_3) and sulphur dioxide (SO_2) are under 3 ppm. The reason NH_3 was analysed, is that the role of NH_3 emission is to be the precursor of PM and sulphate (SO_4^{2-}) formation [25]. In our experiments the particulates were not measured since the excavator has DPF. The emitted SO_2 is originated from used diesel fuel with a maximum value of 10 mg/kg (or 10 ppm) of sulphur. Therefore, in this article, the formation of CO_2 and H_2O emissions, the consumption of oxygen, and the formation of NO_x, which is a sum of the N_2O, NO_2 and NO emissions from the fuel combustion process are studied in more detail.

Table 1. The comparison of Gasmet DX4000 FTIR gas analyzer results for autonomous and human operator experiments. Analyzed gas components in wet flow and their maximum concentration [ppm] or volume [vol-%] values are presented during boom up experiment with engine speed of 0%, 50%, and 100%.

Analysed compound [volume or concentration unit]	Autonomous driving [rpm]			Human operator [rpm]		
	0%	50%	100%	0%	50%	100%
H_2O [vol-%]	4.0	3.9	3.8	4.3	4.9	5.0
CO_2 [vol-%]	3.8	3.6	3.5	4.1	4.7	4.8
O_2 [vol-%]	5.7	5.8	5.8	5.3	5.5	5,4
CO [ppm]	<1	<2	<2	<2.5	<2	<2
N_2O [ppm]	<4	<4	<3	<4	<2	1
NO [ppm]	160	133	133	153	105	100
NO_2 [ppm]	<20	20	20	43	68	83
SO_2 [ppm]	<2.5	<2.5	<2.5	<2	<2	<2
NH_3 [ppm]	<1.5	<1.5	<1.5	<1	<1	<1
CH_4 [ppm]	<3	<3	<3	<3	<3	<3
C_2H_4 [ppm]	<4	<4	<3	<4	<4	<4
C_3H_8 [ppm]	0	0	0	0	0	0
C_6H_{14} [ppm]	<7	<7	<7	<8	<7	<7
CHOH [ppm]	<4	<4	<4	<4	<4	<4
CH_3COOH [ppm]	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
$C_{12}H_{26}$ [ppm]	<3	<3	<3	<3	<3	<3

Van der Horst and Mourik (2010) showed in their research work that the automation of the excavator has been proven to maintain safety and accuracy better than human operators for specific long-lasting operation processes [26]. Based on the preliminary results presented in this article, automation has a positive effect on emissions, since the formation of CO_2 and H_2O emissions during the autonomous excavator tests were lower than during human operator regardless of the engine speed. At the same time, oxygen consumption had the opposite effect, as can be seen in Figure 3. It is well known that the formation of CO_2 is related to the consumption of diesel. For instance, during the idling period, the engine is not run-in high efficiency, which has an increasing effect on the formation of CO_2 emission [27]. In addition, the emission factors have been found to differ between working models and to depend on operation conditions [17].

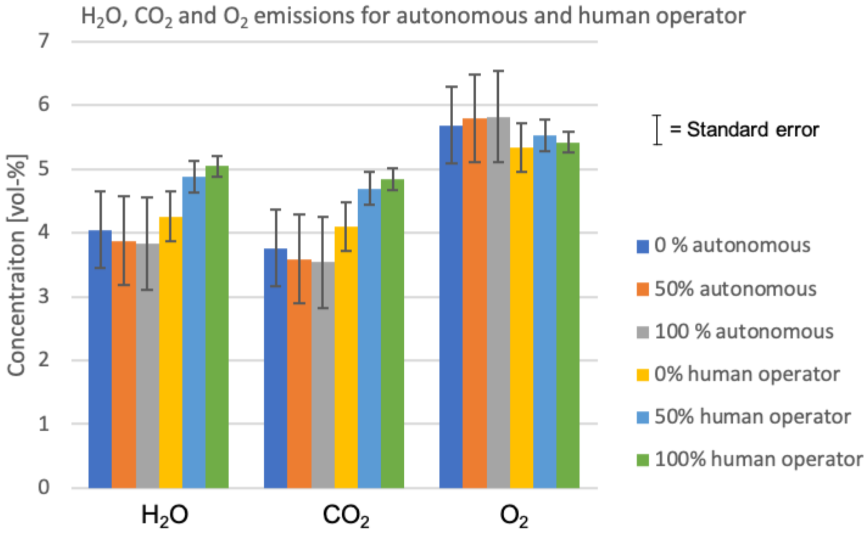

Fig. 4. Comparison of H_2O, CO_2 and O_2 for autonomous and human operator, when engine speed was 0%, 50% or 100%. Error bars are presenting the standard deviation.

The so-called fuel-NO_x compounds are produced during the fuel combustion in cylinders in oxygen-rich and high-temperature conditions. NO_x emissions cause both human and environmental problems. Besides of using NO-free fuels and electric or hybrid engines, one way to reduce NO_x emissions is to guide human operators to improving the efficiency and optimization of the use of machines. Therefore, avoiding for example unnecessary idling time during the construction work is important. Fan et al. (2022) showed in their emission inventory of construction machine study that idling, moving and working modes have differences between NO_x and hydrocarbon contents in exhaust gas [28]. The formation of N_2O, NO, NO_2 and calculated NO_x emissions during the autonomous and human operator tests are presented in Figure 4. When the engine was running at a low engine speed the formation of NO_x emissions was higher than when it was running at full speed. The reason for this phenomenon is that the ratio of fuel oxygen (or air) is low; in other words, there is more oxygen than fuel for the low-engine -speed period. During the high-engine-speed period, the formation of NO_2 was higher compared with the low-engine-speed period. This is an interesting phenomenon, and according to Lu et al. (2019), NO_2 formation mechanism depends on the temperature and concentration of NO and HO_2 radicals in the flame zone [29]. As in the case of CO_2, the formation of NO_x was lower for autonomous driving than for human operator, but that depended more depending on engine speed.

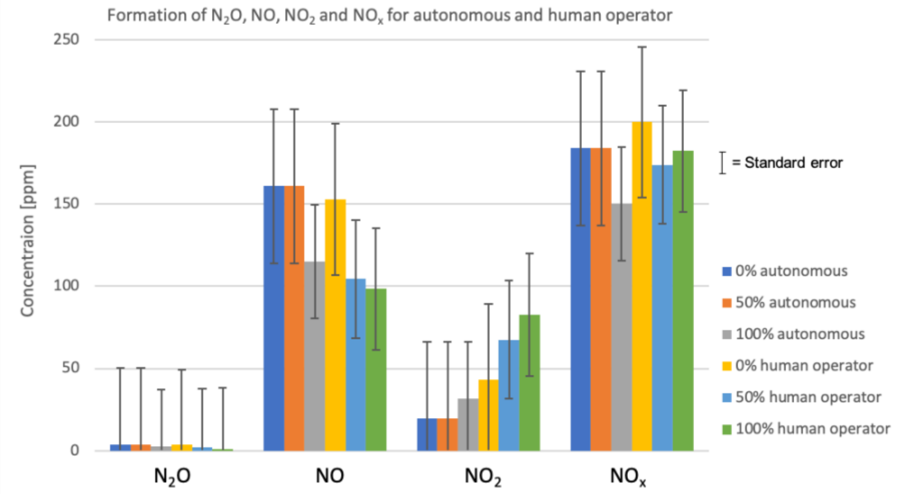

Fig. 5. Formation of N_2O, NO, NO_2 and NO_x for autonomous and human operator experiments when engine speed was 0%, 50% or 100%. Error bars are presenting the standard deviation.

Conclusion

The primary task of this study was to evaluate how automation can influence to the exhaust gas emissions of the excavator. Three different engine speeds were investigated with simple bucket moves with or without a human operator. In both cases it was found that engine speed affects unwanted emissions. Thus, to keep the construction site as sustainable as possible, unnecessary working operations, such as idling, should be as low as possible. It was found that the CO_2 and NO_x emissions during the automation tests were lower than during the human operator tests. The successful demonstration of gas emissions tests increases confidence in autonomous trajectories. Using autonomous trajectories will probably be the answer in the future to help human operators decrease emissions even more. From a sustainability point of view, the automation of working machines would probably help construction sites run more efficiently and therefore decrease greenhouse gas emissions.

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