INTRODUCTION

In 2016, approximately 91 percent of the urban population worldwide was reported to take in air breath that is below the World Health Organization (WHO) air quality requirements of particulate matter ($PM_{2.5}$). Close to more than half of that were exposed to air pollution, 2.5 times greater than the safety standards. Approximately, 4.2 million people are said to be dying due to pollution levels of ambient air and premature lives of 0.8 million lost annually due to approximately $PM_{2.5}$ in the earth's atmosphere. In 2018, WHO reported that the effects of exposure to air pollution resulted to death of 7 million people, with the worst hit nations being developing countries.

While particulate matter was reported as the most severe in cities around the world, other ambient air pollution sources discovered included CO, NOx, and HC. Uganda has not been spared by these problems due to its average annual urbanization growth rate of 2.0%. About 16% urbanization in 2014 was reported and is predicted to reach 32% urbanization by the year 2050 (World Urbanization Trends, 2014). This urbanization is said to keep pace with an increase in construction activities. As a result, there is more utilization of construction machinery, resulting into increase d demand for petroleum products (diesel) (UBOS, 2015), which increases the air pollution emissions. This is why Matagi (2002), reported that due to increased motorized diesel consumption and resurgence of economic activities, there was increased noise pollution and dust emissions resulting in nasal and bronchial discomfort. In 2014, a survey on the air quality in Uganda's city Kampala for both particulate matter $PM_{2.5}$ and coarse particles, concentrations were obtained way above 100 µg/m^3. Carbonaceous aerosol was between 35 – 55% (Schwander *et al.,* 2014). An analysis of ambient air pollution levels and their effects on the lung function of children in Kampala city and Bwenge sub-county a low developed area, revealed that children in high ambient sites exhibited lower lung function. This was attributed to the high $PM_{2.5}$ levels in Kampala of 177.5 µg/m^3. These children suffered underweight and cough which were associated with low lung function (Kirenga *et al.,* 2018). Much as studies have been conducted worldwide to indicate this air pollution in many cities around the world, Sub-Saharan Africa has had the least studies attempting to contribute to the data needed to monitoring and regulating of ambient pollution (Schwela, 2012). In addition, Agricultural lands and human-built environment constitute the majority of changes and are increasing continuously (Azizi *et al.,* 2016). In Uganda, some attempts have been made to characterize the ambient air pollution, however, hardly any studies can be reported focusing on analyzing the likely causes of this air pollution. Worldwide, the construction industry is the third-highest pollution emission contributor after oil and gas and chemical manufacturing sectors. This equipment pollution of CO_2 makes it the third emitter per unit of energy used just after cement and steel production industries (Avetisyan *et al.,* 2011). Greenhouse gases mainly are emitted during the construction materials' production (Balasbaneh *et al.,* 2017; Akan *et al.,* 2017). The other air emission pollutants also coming from the construction equipment include CO, NOx, and PM, constituting the most common exhaust pollutants as categorized by the Environmental Protection Agency (EPA, 2017). Greenhouse gases originating from the construction industry due to diesel consumption by the construction equipment (Moretti *et al.* 2018) are seen in a multitude of studies like Marzouk *et al.,* 2017; Alzard *et al.*, 2019; Fan 2017; Zhang *et al.,* 2017. The construction equipment accounted for 29% of diesel exhaust emissions only second to on-road vehicles in Oregon State in USA (DEQ, 2017). Montadka (2017), also identified dust plus emissions from diesel exhaust of construction equipment as part of the long run harmful emissions affecting the health of workers. Particle pollution was identified by Giunta *et al.* (2019) and Giunta (2020) to be emitted by this equipment. This pollution was said to produce the highest perceived and undesired effects from the construction industry to the surrounding communities. The impact of the construction equipment has even gone a long way to account for numerous disputes, like legal disputes from noise pollution (Kwon *et al.,* 2017). The equipment on the other hand has been reported to produce other harmful effects from vibrations. These result in damage to infrastructures like buildings, affect humans by causing whole body or vibration white finger, and become a nuisance for the local population in the surrounding areas (Svinkin, 2004). However, much as studies have been reported worldwide on ambient air pollution, noise and vibration effects, in Uganda, there is a lack of clear information about the sources of the high ambient air pollution levels reported in its urban centers. This is evidenced by a paucity of literature on the same, yet there is continuous high urbanization infrastructure developments ongoing. This leaves a gap for studies which can assess and establish whether the high ambient air pollution reported in its cities and towns could be from the high construction developments. This is in line with what has been recommended by other studies on the need for increased research in towns of developing nations in Sub-Saharan Africa so as to serve as useful data. This will also inform the environmental protection agencies on which sectors to focus on, while regulating and monitoring air pollution. This will quantify and predict air emissions at the scale of individual equipment, hence covering up on the limited database (Heidari *et al.,* 2015). A road infrastructure project taking place in Kampala city was taken a case study. Kampala was selected because it’s characterized by a rapidly growing population and a stable growing economy with many infrastructure developments taking place. This has seen a rapid increase in vehicular traffic, which has necessitated the expansion of its road infrastructure. Kampala has a population of approximately 1.52 million, with a population density of about 7,715 persons per square kilometer. About 0.79 million live within the central business district of this city, where the case study road construction project was selected. The city has been ranked among the top fifteen fastest growing cities in the world with an annual average growth rate of 4.03% as per City Mayors Statistics (CMS, 2018). Illnesses noted as a result of exposure to high concentrations of diesel exhaust include dizziness, irritation of the eyes, nose, throat; headache; respiratory disease like asthma, and lung cancer (OSHA, 2017). These health problems are experienced by both the road construction workers and the people within the surrounding areas where this equipment is being used. Therefore, the aim of this study is to analyze the impact of road infrastructure equipment on the surroundings in terms of air pollutant emissions, noise, and vibrations on a selected road infrastructure project in Kampala city, Uganda in 2019.

MATERIALS AND METHODS

The study was a case study approach which employed a purposive sampling technique to come up with the case study project selected, following Battaglia *et al.* (2008) guide. The selected project was considered to best represent the many projects ongoing in various urban centers in Uganda. It consisted most of the non-road construction equipment that had been identified by other studies to contribute to air pollutant emissions. All the equipment taken as the sample because of the small equipment population (Israel, 1992). The hypothesis of the study was that most equipment produced high emissions above the acceptable standards. Also, it hypothesized that the noise and vibration levels produce are above the permissible levels. The data on emissions, noise, and vibration levels for the six road transportation construction equipment were obtained. Particularly this was collected from the road construction project on Namirembe road, central division, Kampala city area (Fig. 1). The project consisted activities like excavation, soil grading, loading, offloading, and compaction at the time of data collection. The construction equipment considered in the study included an excavator, grader, concrete mixer, roller, tamper, and wheel loader as indicated in Fig. 2a. Their extensive use in the ongoing projects makes them well suited to represent the construction equipment generally used in the urban centers.

Overview of the study area

Uganda’s geographical location is on the coordinates of latitude $4^0$12’N and $1^0$29’S and longitude $29^0$34’E and $35^0$0’E. The population stands at 34.9 million, with 6.4 million staying in urban centers as per the 2014 population census. The road infrastructure network in the country of paved roads was reported to have risen from 3,489 km to 3,795 km between 2013 and 2014. Kampala is its capital city and is located in the central region of the country. Its geographical coordinates are $0^0$15’N and 32^0 30’E, and is about 45 km in the northern part of the equator and about 8 Km above Lake Victoria. It is 1300 m above the sea level.

Project descriptions for the case study

Namirembe road-works was the selected project, one of the many infrastructure developments taking place in the central business district of Kampala city. The project was to be built a non-motorized one-way 3.5 km road, whose construction was meant to commence in 2015 but started in November 2018.

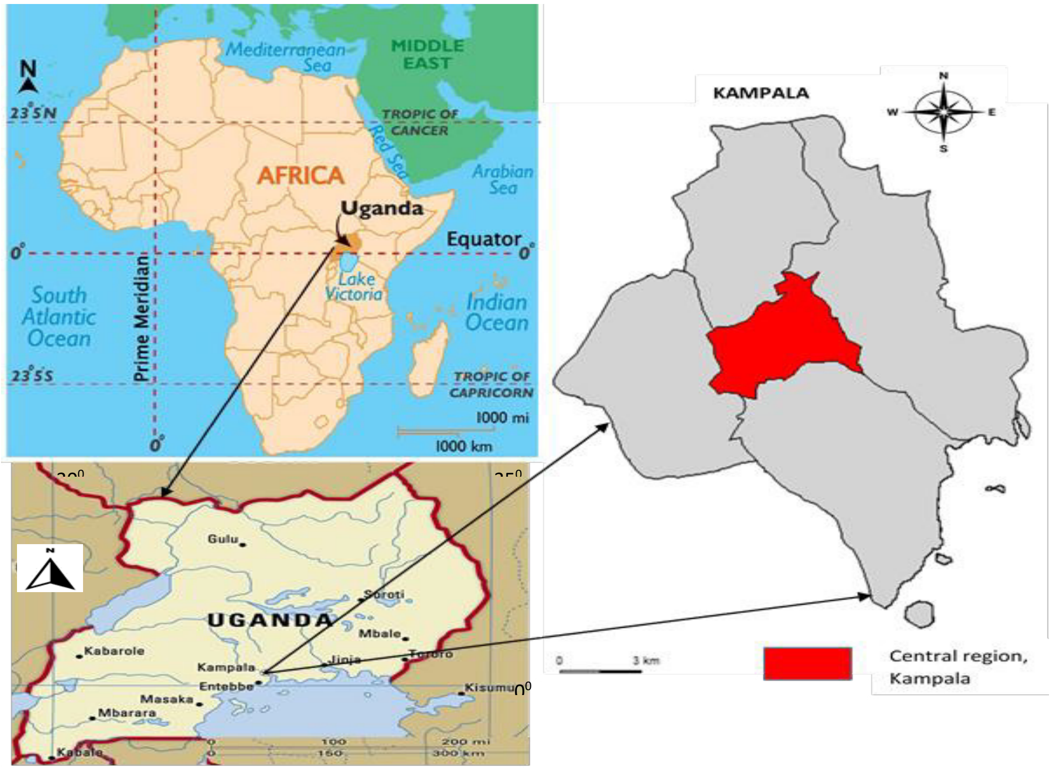


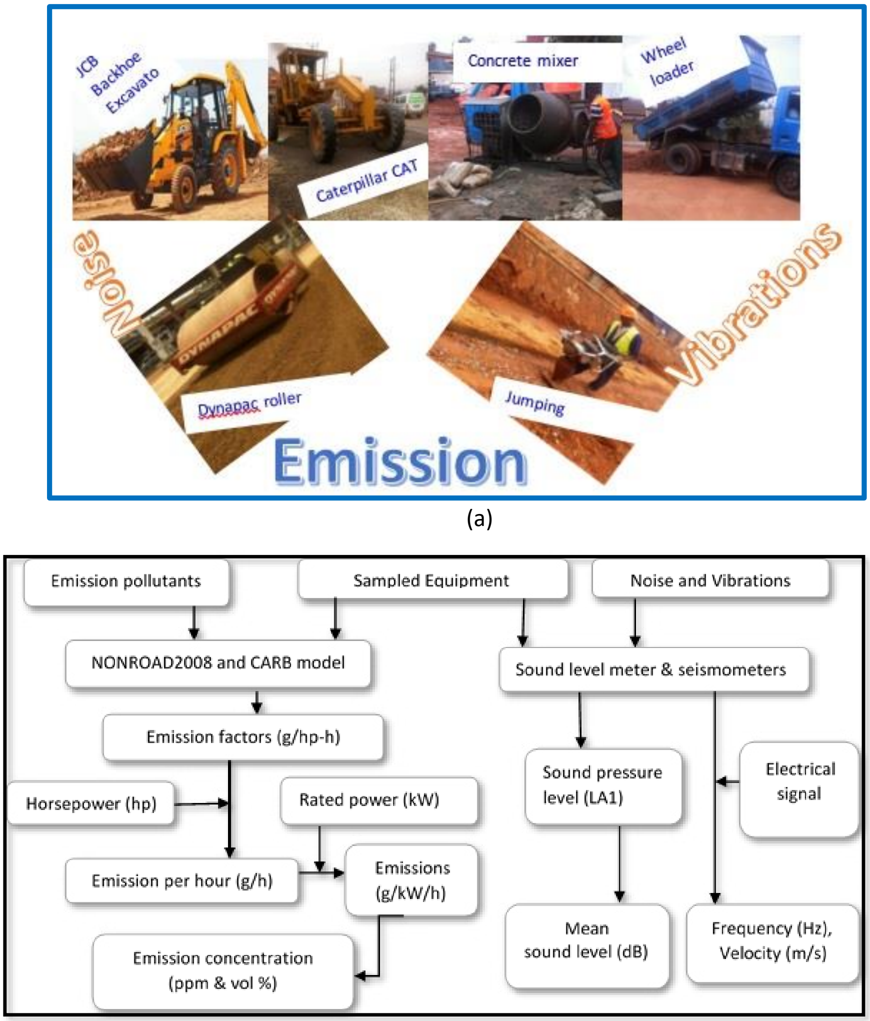
Fig. 1: Geographic location of the case study in Central region, Kampala city, Uganda

The project was a 3 billion Uganda shillings project, funded by the World Bank, and executed by M/S Stirling Engineering LTD. The project employed 3 rollers-flat and foot, 2 wheel loaders, 2 graders, 1 bulldozer, 2 excavators, 3 hand-held tampers, and 1 concrete mixer. The project employed about 60 workers both skilled and unskilled. It is part of the street construction projects, which are dealt with in categories of new construction, rehabilitation, and resurfacing in urban centers. It was also selected because it typically suited Barati and Shen (2016) conditions, and its categorization was of the projects which consist most of the top 10 construction equipment, considered as the highest contributors to NOx, CO, and PM as per (EPA, 2005).

Measurement of research data

To achieve the objectives of the study, several procedures as identified from previous studies were adopted for measuring the data required. The study centered on field data recording, modelling, observations, and participation. Field visits were made to the road construction site to obtain the required data for analysis. The Fig. 2b is a flowchart of the methodology used to obtain the air emissions, noise, and vibrations from the equipment studied. The non-road (EPA, 2008) and the off-road- California Air Resources Board (CARB, 2009) models were used to compute emissions of the sampled construction equipment. These categorize emission rates according to the type of equipment basing on horsepower/power rating group on the measured CO_2, CO, NO_x, CH, and PM pollutants. This is different from other numerous models which use fuel consumed and coefficients attached to them, but not based on the equipment type (Ahn *et al.,* 2009). The model was based on the horsepower (hp) and power rating (kW) of the selected study sample equipment (Fig. 2a). Their emission factors and load factors were obtained from secondary data.

Emissions were calculated using Eqs. 1 and 2 to ascertain the emission rates of the respective equipment per hour. This was based on other studies' finding like Heidari and Marr (2015) who found



(a)

(b)

Fig. 2: The different; a) road infrastructure equipment studied; b) methods used schematic diagram

that there is much agreement between modelled emissions and real-time emissions for a number of equipment studied. The emission rates from construction equipment were calculated for the 5 air pollutants selected.

$$\text{Emissions rate}\left(\mathrm{g/h}\right)=\text{Engine power}\left(\mathrm{hp}\right)* \text{Emissions factor}\left(\frac{\mathrm{g}}{\mathrm{hp-h}}\right)*\text{ load factor} \quad (1)$$

$$\text{Emissions rate}\left(g/kW/h\right)=\frac{Emission\,rate\; g/h}{\text{Power}\left(\mathrm{kW}\right)} \quad (2)$$

The emission concentration levels for some of the air the air pollutants were determined using Eq. 3 – 5 (Pilusa *et al.,* 2012) and compared with permissible levels of exposure to employees like OSHA and EPA. This was needed so as to compare with permissible limits related to health of workers on construction sites constantly exposed to these air pollutants. Doing this ensured that emissions were conforming to the safety and health regulations for construction.

$$\mathrm{CO}\left(\frac{\mathrm{g}}{\mathrm{kW/h}}\right)=3.591\text{ x}10^{-3}\text{ x CO}\left(\mathrm{ppm}\right) \quad (3)$$

$$NOx\left(\frac{g}{kW/h}\right) = 6.636 \text{ x}10^{-3} \text{ NOx}(\text{ppm}) \quad (4)$$

$$CO_2\left(\frac{g}{kW/h}\right) = 63.470 \text{ x } CO_2(\text{vol }\%) \quad (5)$$

Where, ppm = concentration in parts per million and vol % = concentration in parts volume percent. The air pollutant emissions studied were grouped under criteria air pollutants (PM, CO, and NOx) and greenhouse gases (CO_2 and HC). Since the engine data of their model years was not readily available, comparison of the emissions was based only their satisfaction of tier emissions limits for tier 1 (1994 to 2000), tier 2 (2004 -2009), tier 3, and tier 4 (from 2008 to 2015). This was based on the case study project manager's disclosure that all their equipment were of models below manufacture year of 2015.

Noise pollution and vibration levels

The noise generated at the construction sites has been reported with the likelihood to affect humans' right to silence, comfort, and health of residents plus their visitors (Feng *et al.,* 2020). The noise levels from the sampled equipment was measured using a sound level meter with a microphone pointer (Mangalekar *et al.*, 2012), at a distance of approximately 1.0 meters from the equipment. The results obtained were analyzed and compared with the permissible national construction noise levels of NER (2013). Vibration is defined by the NER (2013), to mean "*movement of the body caused by mechanical rotating or revolving tools and entering the body at the feet, the seat or the fingers or the palm of the hands such as from the organ in contact with vibrating equipment*". Field visits were made to the road construction site to observe and record the respective vibration levels from the sampled construction equipment. It was done with the help of seismometers and accelerators (vibration sensors). Ground vibration was typically measured at the source with a sensor that produces an electrical signal which is proportional to the amplitude of the ground motion.

RESULTS AND DISCUSSION

The findings present results of the emissions, noise pollution, and vibration levels for each of the six sampled road infrastructure equipment.

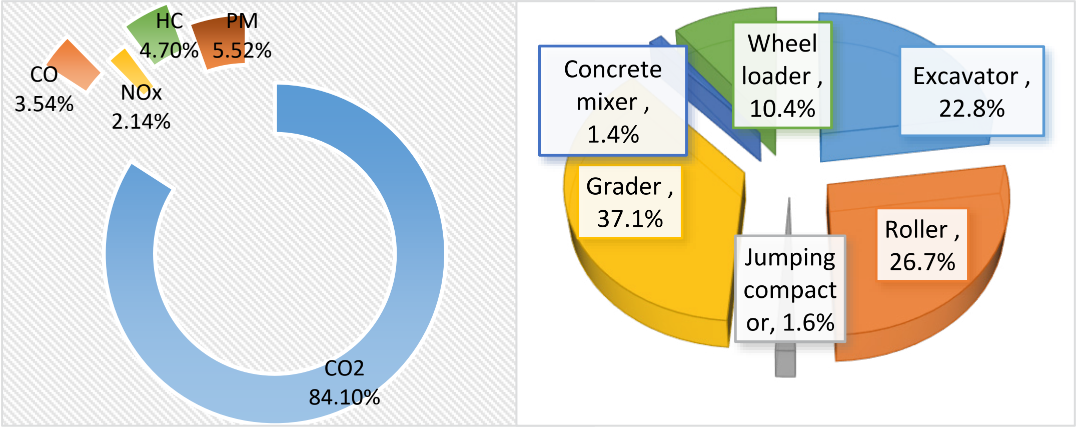
Air (diesel exhaust) emissions

The collected data from the sampled road construction equipment and their emission rates were tabulated in Table 1. Emission factors for CO_2, NO_x, and HC which were directly related to the brake-specific fuel consumption as availed with EPA publication were used.

These values were used in computing the emission rates of the equipment in grams per hour and g/kW/h. The findings reveal that the equipment sampled mostly was grouped under 50 hp, except for the roller and the grader which were between 100 – 175 hp and the excavator between 50 – 100 hp. The equipment with the highest hp was the grader at 150 hp and the concrete mixer had the lowest at 5.5 hp. This horsepower is an indicator of the level of emissions expected, because hp is directly proportional to the emissions produced as per the model used in Eq. 1. The emissions rates were computed using this hp of each construction equipment and presented in Fig. 3a and b**.** The findings on the air emissions given out by the road construction equipment sampled revealed that the grader was the highest contributor of emissions at 37.13% and lowest being the concrete mixer at 1.4% of total average emissions (Fig. 4b). The grader produced more toxic diesel emissions due to its

Table 1: Measured parameters for air pollutant emissions' calculation

Equipment	Rated power (kW)	Engine power (hp)	Emission factor (g/hp-h)					Load factor
			CO_2	CO	NO_x	HC	PM	
Excavator	68.8	92	10.21	0.43	0.26	0.57	0.67	1
Roller	80.5	108	10.21	0.43	0.26	0.57	0.67	1
Jumping compactor	4.8	6.5	10.21	0.43	0.26	0.57	0.67	1
Grader	111.9	150	10.21	0.43	0.26	0.57	0.67	1
Concrete mixer	4.1	5.5	10.21	0.43	0.26	0.57	0.67	1
Wheel loader	31	42	10.21	0.43	0.26	0.57	0.67	1



(a) (b)

Fig. 4: Air pollutant emissions; a) percentage contribution of each air pollutant; b) percentage contribution from each sampled equipment to the emissions

and concrete mixer respectively were attributed to their horsepower values. The emissions were then analyzed based on grams per kilowatt-hour and their respective concentration levels at the source, so as to compare with various permissible limits (Table 2). Among the air pollutant category, NOx emitted in grams per kilowatt-hour satisfied many requirements, for example the ones for European Union and China for heavy duty vehicles of 3.5 g/kW/h. All the sampled equipment did not exceed the emission standard of CO and NOx for non-road diesel engines according to EPA diesel engineNet 2016, acceptable back to the environment. The permissible limit of CO for the construction equipment with less than 130 kW is required to be less than 5.0 g/kW/h for all tiers 1 – 4. For NOx, the limit is supposed to be 9.2 g/kW/h or 0.40 g/kW/h for tier 1-3 and tier 4 respectively (DieselNet, 2016).

All the equipment fell short of the PM limit as per the European Union and China standards of 0.02 – 0.03 g/kW/h (Birol, 2016) and 0. 02 g/kW/h following EPA tier 1 - 4 (DieselNet, 2016). On assessing the concentration limits required for the health of workers, the toxic CO for all the equipment did not meet the OSHA limit of 50 ppm (OSHA, 2019) and 35 ppm as per NAAQs criteria (EPA, 2016) in an hour. The NOx also was above the ceiling value set for all the construction equipment considered hazardous to workers of 5 ppm (OSHA, 2019) as seen in Table 2. The CO$_2$ did not exceed to permissible levels of concentration in relation to human health of 0.5% (Table 2) as per OSHA. This is because it is considered minimally toxic by inhalation. In all the construction equipment sampled, the GHGs of CO$_2$ and HC emitted were more than the criteria air pollutants at approximately 88.8 % of the total air pollutants (Fig. 4a). This is in line with other studies were diesel-powered construction equipment has been established as a possible primary source of GHGS during the construction (Heidari and Marr, 2015). Therefore this equipment accounts for a significant portion of GHGs and other air pollutions in urban areas during site preparation, the foundation works, road construction, and maintenance. On the side of criteria air pollutants, PM contributed the highest portion at 5.52% followed by CO at 3.54% (Fig. 4a). This finding confirms why studies made by researchers like Kirenga *et al.* (2018), showed that ambient air pollution exists in Kampala and had led to lower lung function in this urban area.

This particle pollution which includes both the PM$_{10}$ and PM$_{2.5,}$ affects different classes of people from those on foot, on bicycles, or cars, to those working or owning shops, and restaurants among others. The businesses end up keeping their doors closed during working hours as observed on the Namirembe road project. On average, for all the 5 air pollutants studied, the grader produced 28% higher air pollution emissions than the roller. The jumping compactor and the wheel loader produced more

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