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CASE STUDY

Impact of road infrastructure equipment on the environment and surroundings

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ABSTRACT

BACKGROUND AND OBJECTIVES: The effect of infrastructure equipment is taking a toll on the health and economic well-being of residents all around the world. This is mainly because it contributes to ambient air pollution, noise, and vibration in the surroundings. The study aimed at analyzing the effects of the road infrastructure equipment on the surroundings in Uganda. The emissions of carbon dioxide, carbon monoxide, nitrogen dioxide, hydrocarbons, and particulate matter were analyzed.
METHODS: Six road infrastructure equipment were sampled consisting of an excavator, roller, grader, concrete mixer, tamper, and wheel loader, obtained from a case study project in Kampala city, Uganda. The diesel exhaust air emissions were computed and analyzed using the emissions rate equation model for non-road equipment, developed by Environmental Protection Agency. This was based on the horsepower and power rating of the equipment. Noise and vibrations levels were obtained using a sound level meter, seismometers, and accelerators, while following the National Environment Regulations.
FINDINGS: The greenhouse gas of carbon dioxide was the most predominant accounting for 84.1 percent of the total emissions. The grader was the highest emitter of this greenhouse gas, at 1,531.5 g/h, representing 37.1%. The lowest air pollutant emission was nitrogen dioxide at 1.43 g/h for the concrete mixer, representing 1.4%. Overall, the equipment emitted more greenhouse gases than air criteria pollutants at 88.8% and 11.2% respectively. The highest criteria air pollutant was particulate matter at 100.5 g/h, emitted by the grader. Most of the emissions met the standards stipulated by Environmental Protection Agency, for reducing emissions back to the environment, except particulate matter. However, the concentrations of some pollutants like carbon monoxide and nitrogen dioxide did not satisfy the limits required for ambient air quality that is safe for workers. All the equipment had noise levels way above the recommended 70.00 decibel, except for the wheel loader. Only the excavator produced vibrations higher than permissible vibration limit by 4%.
CONCLUSION: The criteria air pollutants of carbon monoxide, nitrogen dioxide, and particulate matter emitted by the equipment were all not safe to the workers. They exceeded the permissible limits of 50 ppm, 5 ppm, and 0.02 g/kW/h respectively. This partly shows why ambient air pollution had been reported in urban centers in Uganda. The study shows the need for strengthening the regulations and monitoring of the construction equipment being used, in order to protect the surroundings.

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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.

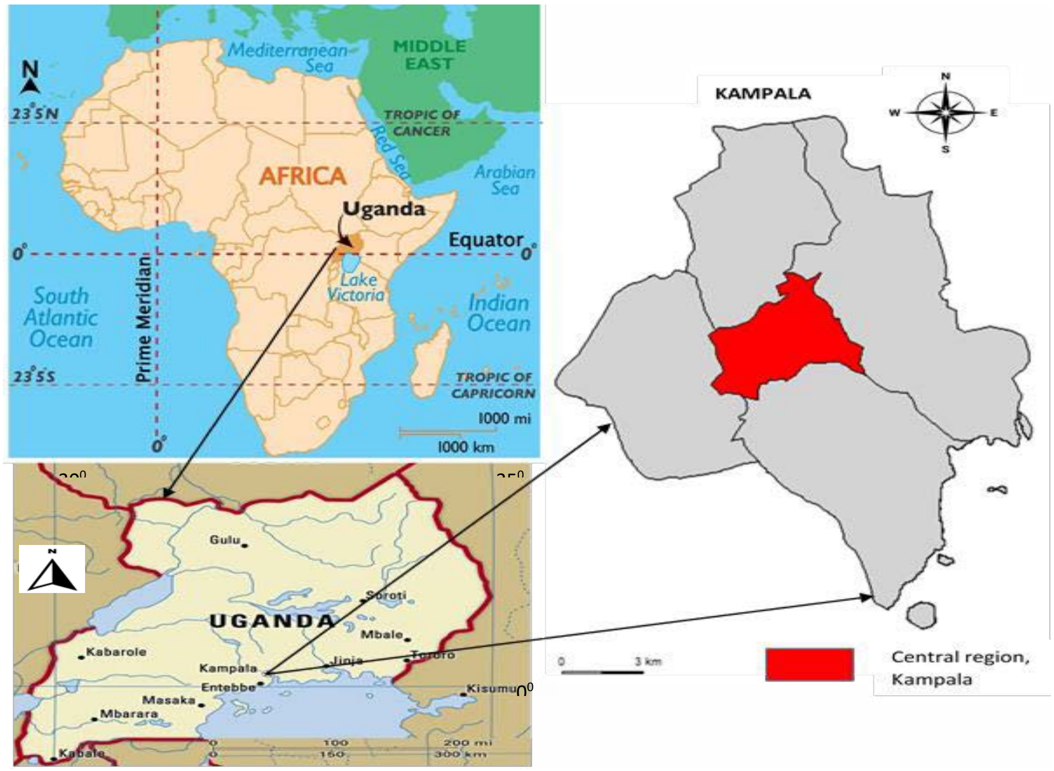


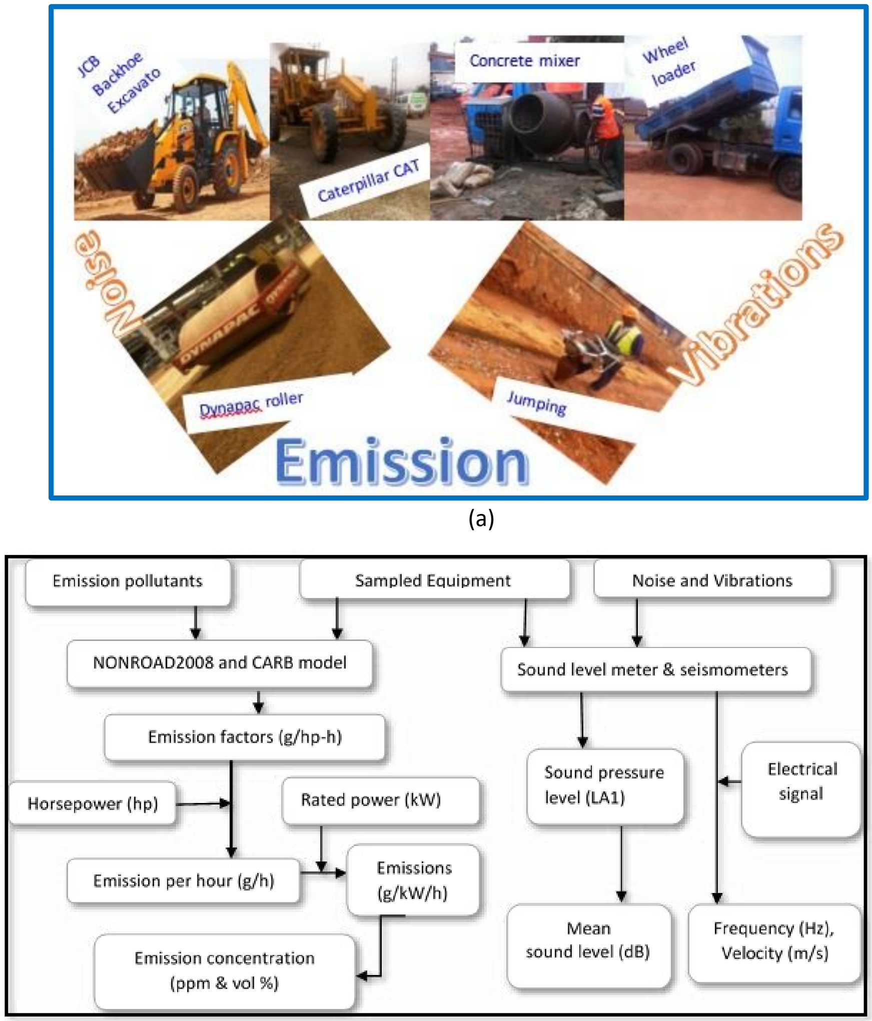
Fig. 1: Geographic location of the case study in Central region, Kampala city, Uganda

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.

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

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

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.

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

$$NOx\left(\frac{g}{kW/h}\right) = 6.636\ x10^{-3}\ NOx\,(ppm) \quad (4)$$

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

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.

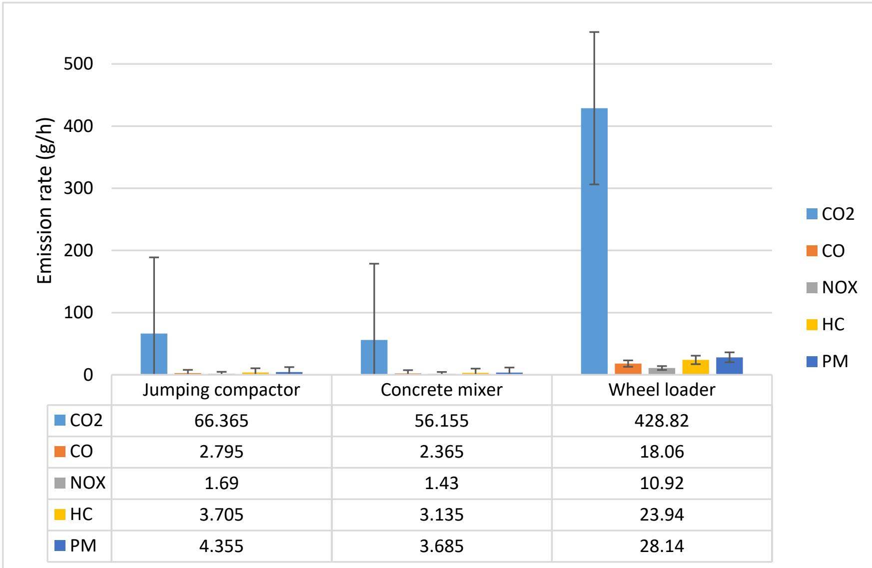
Air (diesel exhaust) emissions

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

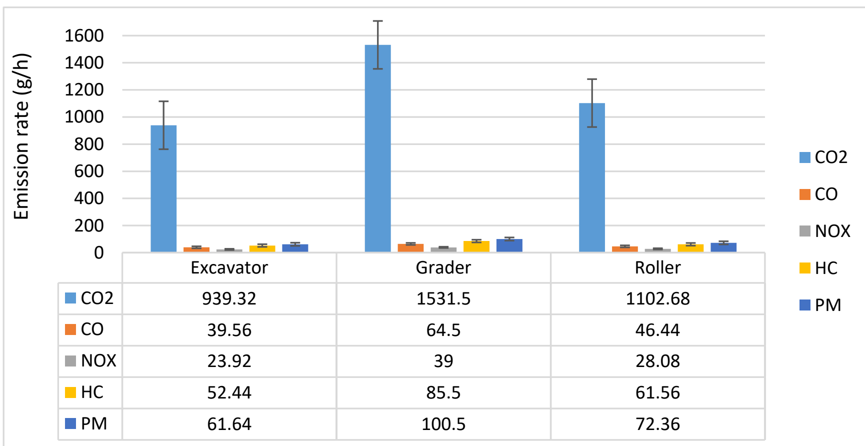
Table 1: Measured parameters for air pollutant emissions' calculation

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



	Jumping compactor	Concrete mixer	Wheel loader
CO2	66.365	56.155	428.82
CO	2.795	2.365	18.06
NOX	1.69	1.43	10.92
HC	3.705	3.135	23.94
PM	4.355	3.685	28.14

(a)

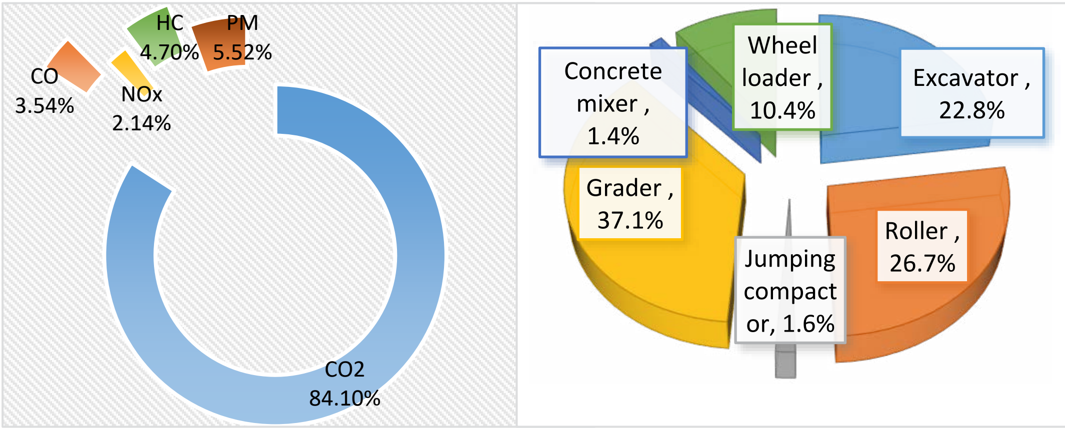


	Excavator	Grader	Roller
CO2	939.32	1531.5	1102.68
CO	39.56	64.5	46.44
NOX	23.92	39	28.08
HC	52.44	85.5	61.56
PM	61.64	100.5	72.36

(b)

Fig. 3: Total emissions per hour for the sampled equipment: (a) and b)

high horsepower as per (Rasdorf *et al*. (2010); Arocho *et al.* (2014); Fan (2017). All the sampled equipment emitted more CO_2 than any other emissions, which accounted for about 84.1% of the total emissions (Fig. 4a). The trend is similar to other studies like Reddy (2017) where CO_2 was 99.6%, Barati and Shen (2016) at 98.8%, Heidari and Marr (2015) at 98%. In this study the air pollutant emissions were lower than what was obtained by Barati and Shen (2016) for all the pollutants in grams per hour, except HC for the excavator and the loader plus the CO for the excavator. The lowest emitted air pollutant from all the sampled equipment was NOx, accounting for 2.1% of the total emissions (Fig. 4a). The concrete mixer contributed the least emissions of NOx at 1.43 g/h. In Barati and Shen (2016), who studied the loader and the excavator, their findings differ also on the lowest emitter which was found to be HC at 0.08 %. The grader was still the overall greatest contributor of the other air pollutants of CO, NO_x, HC, and PM at 37.1%, followed by the roller at 26.7% (Fig. 4b). These very high and very low emissions from the grader



(a) (b)

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

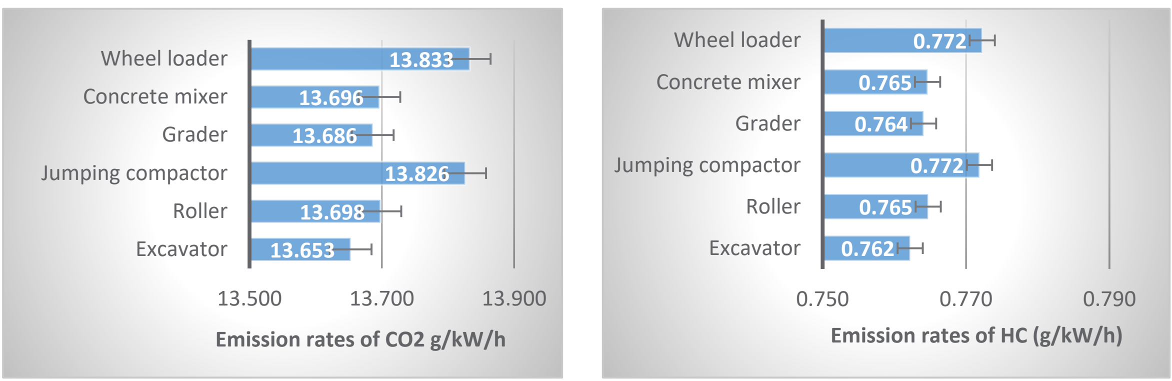
and concrete mixer respectively were attributed to their horsepower values. The emissions were then analyzed based on grams per kilowatt-hour and their respective concentration levels at the source, so as to compare with various permissible limits (Table 2). Among the air pollutant category, NOx emitted 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

Table 2: Estimated modelled emission rates of the sampled construction equipment

Equipment (Make)	Emission rate (g/kW/h						Concentration		
	Rated power kW	CO_2	CO	NO_X	HC	PM	NOx (ppm)	CO (ppm)	CO_2 (vol %)
Excavator (JCB backhoe site master)	68.8	13.653	0.575	0.348	0.762	0.896	52.392	160.123	0.215
Roller (Dynapac CA 301)	80.5	13.698	0.577	0.349	0.765	0.899	52.565	160.65	0.216
Jumping compactor	4.8	13.826	0.582	0.352	0.772	0.907	53.057	162.153	0.218
Grader (CAT 140G)	111.9	13.686	0.576	0.349	0.764	0.898	52.52	160.514	0.216
Concrete mixer (BC-260-4 Honda GX 160)	4.1	13.696	0.577	0.349	0.765	0.899	52.559	160.632	0.216
Wheel loader (CAT 903D Compact)	31	13.833	0.583	0.352	0.772	0.908	53.083	162.234	0.216



(a) (b)

Fig. 5: Emissions rates of GHGs for sampled in g/kW/h; a) CO2; b) HC

emissions per kilowatt-hour because of their relative power rating as seen in Fig. 5 for GHGs.

Based on the findings, there is a need to adopt exhaust regulations and also adoption of diesel soot reduction techniques like the use of particle filter systems and selective catalytic reduction. This will greatly improve air quality (Notter and Schmied, 2015).

Sound (noise) pollution levels

The sound levels from the respective equipment used in this research were recorded for 10 working days from Monday to Friday. These were used to compute mean sound levels for all the construction equipment as seen in Table 3. It can be observed that the lowest sound level was 67.08 decibel (dB) for the wheel loader. The highest was recorded for the roller at 90.86 dB, 29.8% higher than the acceptable sound level for the roads and road construction from Monday to Friday (07:00 to 19:00 hours) (NER, 2013). This was followed by the concrete mixer and the jumping compactor at 18.6% and 18.56% higher than the permissible limit of 70 dB respectively. The results compared well with other studies like Roberts (2009), were his excavator was 81 dB, front end wheel loader 78 dB and Caterpillar scrapper at 83 dB. On average the sound mean level produced by all the construction equipment was at 79.06 dB, hence higher than allowable noise levels for the roads and the road construction of 70 dB. The findings indicate

Table 3: The mean sound levels from the construction equipment studied

Equipment	Sound level decibel (dB)										
	March 2019			April 2019							Mean sound level (dB)
	27th	28th	29th	1st	2nd	3rd	4th	5th	8th	9th	
Excavator	69.43	80.07	84.63	68.30	79.63	66.53	83.20	77.73	71.83	80.00	76.14
Roller	84.50	98.40	89.30	75.70	89.03	97.67	96.17	93.03	88.30	96.53	90.86
Jumping compactor	80.67	87.50	85.03	69.47	87.60	87.53	84.57	87.83	80.77	78.90	82.99
Grader	78.43	73.80	67.83	69.10	77.73	68.13	77.90	78.23	77.70	74.90	74.38
Concrete mixer	83.40	86.20	84.07	72.47	85.37	87.30	85.93	85.20	87.33	72.73	83.00
Wheel loader	68.10	69.70	59.23	59.47	68.20	68.13	68.17	69.63	70.33	69.80	67.08

Table 4: Vibration levels of the respective equipment

Equipment	Mean vibration levels	
	Frequency (Hz)	Velocity (mm/S)
Excavator	47	13
Roller	120	20
Jumping compactor	60	16
Grader	48	12
Concrete mixer	52	14
Wheel loader	35	10

that the equipment was also higher than the set hygienic limits of acoustic pressure of 65 dB from 7 am – 9 pm (Kantova, 2017).

This is in line with studies like Lee *et al.* (2017), where it was established that among all equipment studied, the peak sound levels were above 80 dB and the highest was for a vibratory pile at 100.9 dB. Since most of the construction equipment considered in this research were too noisy during operations, it is considered harmful to the human hearing system and the surroundings. The people within the nearby businesses are likely to be more affected than those passing by, because they are more connected to the construction site and constantly exposed to this noise (Andersson and Johansson, 2012). To partly reduce the effects, the regulatory authorities like NEMA need to enforce regulations like the installation of mufflers or silencers of the construction equipment considered to emit noise levels above the acceptable limits (Feng *et al.,* 2020).

Vibration levels

The permissible vibration velocity compared with the one at the closest part of any property to the source of vibration as per NER (2013) for a frequency of less than 10 Hz, 10 – 50 Hz, and 50 – 100 Hz was 8 mm/s, 12.5 mm/s, and 20 mm/s respectively. From Table 4, the study discovered that among the sampled equipment there was none in the category of frequency less than 10 Hz and the roller was above 100 Hz. The wheel loader, excavator, and grader lied in the category of 10 – 50 Hz, and they all satisfied the required permissible vibration velocity limit of 12.5 mm/s except the excavator. Its vibration velocity exceeded the permissible limit by 4%. Therefore, the excavator posed some small risk of building damage to the nearby properties. The concrete mixer and the jumping compactor in the category of 50 – 100 Hz, satisfied the permissible vibration velocity limit of 20 mm/s. The vibration values obtained however, were higher than other established by other studies like Robert (2009) whose impact pile divers, rollers, bulldozers, and loaded trucks were 6.2, 1.3, 0.6, and 0.5 mm/s respectively. This is because in his study, these vibrations were obtained at a distance of 30 m away from the construction equipment yet in this study vibrations were measured at the source. All the construction equipment were being used by workers beyond the allowable daily exposure durations. This was against the recommended practice, for example, NER (2013) provides that maximum exposure of hands to vibration in any direction for peak particle velocity above 12 mm/s should be less than one hour. Employees in this project operated this equipment for the entire day with exposure nearly up to 6 hours.

Therefore, continuous human exposure to these vibrations could also result in whole- body vibration (WBV) and vibration white finger (VWF) (Svinkin, 2004). The vibration annoyance potential to humans of all the construction equipment sampled was considered strongly perceptible, because it ranged between 6.3 mm/s and 22.9 mm/s at the transient source (Robert, 2009). The vibrations of the roller and jumping compactor were considered a threat to the nearby buildings and they are likely to develop cracks Ozcelik (2018).

CONCLUSION

The survey of the construction equipment on a road infrastructure development in typical urban center has presented a novel work, because it analyzed comprehensively the effects of the construction equipment. It has established the likely effects of this construction equipment in terms of air pollutant emissions, noise, and vibrations. This has not been the case for other studies who had focused on only one effect. The study revealed that construction equipment in Kampala city road infrastructure projects emits more GHGs (88.8%) compared to the criteria air pollutants (11.2 %). This is likely to highly contribute to ozone depletion because very high global warming potential of these emissions especially CO_2. The criteria air pollutants of CO and NOx did not exceed the limits of emissions as per the EPA limits of emissions to the environment. However, their concentration levels did not satisfy the permissible limits of OSHA and NAAQs considered healthy to employees operating this construction equipment. The particulate matter was way above the acceptable limit, hence, the findings confirm that the ongoing road infrastructure projects in Kampala and other urban centers, partly contribute to ambient air pollution levels reported in urban centers in Uganda. The noise levels produced by all the equipment was above recommended by the National Environment of 70 dB except the wheel loader. This means the hypothesis was accepted. This implies the ongoing infrastructure projects are likely to cause negative effects to the human hearing system of the site employees and people on the nearby economic activities around these road construction projects. Vibration velocity produced by the construction equipment considered in this study were generally within the acceptable level except for the excavator and the roller. More studies are needed which focus on the global warming potential of these emissions, so as facilitate developing of standards and monitoring by the regulatory bodies. Other studies which employ models that are based on fuel consumption and real-time measurements of these air pollutant emissions need to be conducted. Finally, the general observation made was that workers were not provided with personal protective equipment (PPE) which could limit on the effect of toxic emissions, noise, and vibration effects. This is likely to increase chances of workers health being in danger. Therefore, provision of PPEs should be highly emphasized by regulatory bodies on infrastructure projects using the identified equipment. These may include: recommended N95 masks, ear plugs, anti-vibration gloves, and install vibration damping seats.

AUTHOR CONTRIBUTIONS

N. Robinah performed the literature review, experimental design, analyzed and interpreted the data. A. Safiki prepared the manuscript text, and manuscript edition. T. Okello compiled the data and manuscript preparation. B. Annette performed the literature review and manuscript preparation.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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ABBREVIATIONS

%	Percentage
am	Before midday
μg/m³	Milligrams per cubic meter
CARB	California Air Resources Board
CAT	Caterpillar Incorporation
CMS	City Mayors Statistics
CO	carbon monoxide
CO_2	Carbon dioxide
dB	Decibel
DEQ	Department of Environmental Quality
E	Easting
JCB	Joseph Cyril Bamford
EPA	Environmental Protection Agency
Eq.	Equation
Fig	Figure
g	Grams
GHGs	Greenhouse gases
GHGs	Limited
HC	hydrocarbons
Hp	Horsepower
Hz	Hertz
h	Hour
Km	Kilometer
kW	kilowatt
Km^2	Square kilometer
LA	A-Weighted, sound level
M/S	Messrs
M^2	Square Meters
N	Northing
NAAQs	National ambient air quality standards
NEMA	National Environment management authority
NER	National Environment Regulations
NO_x	Nitrogen dioxide
OSHA	Occupational Safety and Health Administration
ppm	Parts per million
vol%	Parts volume percent
S	Southing
PM	Particulate matter
PPE	Personal protective equipment
$PM_{2.5}$	Particulate matter 2.5 times
pm	After midday
UBOS	Uganda Bureau of Statistics
US$	United States dollar
USA	United States of America
VWF	Vibration white finger
WBV	whole body vibration
WHO	World health organization

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