AERMOD MODELING OF AIR POLLUTANT EMISSIONS FROM BACKUP GENERATOR USE IN LAGOS, NIGERIA

BY

TEMITOPE ABAYOMI

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ABSTRACT

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Temitope Abayomi

The University of Texas of Arlington, 2017

Supervising Professor: Melanie L. Sattler

Generator emissions contribute to increase in air pollution. In developing countries with inadequate electricity supply, many people rely on back-up generators for long-term electricity supply. Nigeria is the second biggest importer of generators in Africa. As of 2009, it was estimated that 60 million people in Nigeria owned and operated small to medium size generators to provide electricity for their daily use. The sheer number of generators in use suggests that generator emissions are a significant source of air pollution in the country, particularly in urban cities. In this work, the concentrations of pollutants emitted from 50 generators in a 200 m x 200 m area are modeled using the AERMOD Gaussian modeling software. USEPA AP-42 (1995), DICE-Africa (2013), and Shah et al. (2016) emission factors are utilized to calculate emission rates for both diesel and gasoline generators. Results of the model runs are compared with the USEPA NAAQS as well as the WHO air quality standards. Modeled concentrations of NO_2 (1-hour averaging time) is shown to exceed both the USEPA and WHO guidelines. The modeled concentrations of NO_2 also exceed measured concentrations of NO_2 due to transportation sources in Lagos, as reported in the literature. Modeled concentrations of SO_2 (1-hour and 24-hour averaging times) exceed both the USEPA and WHO guidelines. Results for PM_{10} exceed the

WHO guideline only. To reduce the risk to human health as a result of air pollution caused by the use of numerous backup generators within the Lagos metropolis, it is recommended that the government invest in infrastructure to provide a stable electricity supply, and emission standards for backup generators be adopted. It is also recommended that monitored air pollutant values be compared with modeled results, once monitoring data is available.

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CHAPTER 1

INTRODUCTION

1.1 Electricity supply in Nigeria

As world population increases, many developing countries are unable to generate adequate electricity to meet their ever-increasing demand. Urban cities within developing countries are awash with people who rely on portable generators to produce electricity in the absence of a functional centralized system. Nigeria is one such country unable to provide adequate electricity to sustain its growing population (Ohiare, 2015; Shaaban, 2014). Thus far, the electricity supply is far below the demand, and many people still go without electricity for several weeks at a time. As of 2009, it was estimated that 60 million people in Nigeria owned and operated small to medium size generators to provide electricity for their daily use (Energy Commission of Nigeria, 2009).

1.2 Air pollution emissions from electricity generators

Primary causes of air pollution in developing countries include deforestation, industrialization and the burning of fossil fuel. Studies have shown that generator emissions are also a major source of air pollution in developing countries (Marais et al, 2016; Oguntoke and Adeyemi, 2016). Diesel and petrol-powered generators are prevalent in urban cities within Nigeria. There have been several recorded deaths due to the improper operation of generators (Afolayan, 2014; Oseni, 2016; Thisday, 2017). On one hand, the government has taken steps to educate the public on proper handling and operation of private generators to prevent catastrophic accidents. Unfortunately, air pollution ensuing from generator emissions has largely been neglected.

Combustion of fuel used to power generators produces carbon monoxide and particulate matter, and facilitates the formation of secondary pollutants like ozone (Marais et al, 2016; McGranahan et al 2003). The 2016 World Health Organization (WHO) Ambient Air Pollution report concludes that air pollution represents the biggest environmental health risk especially in Africa, Asia and the Middle East. In 2012, one out of every nine deaths worldwide was attributed to air pollution related conditions (WHO, 2016). The number of deaths in Africa attributed to air pollution will most likely be greater due to the limited healthcare system in many regions and the higher concentrations of pollutants in the atmosphere (Marais et al 2016; WHO 2016).

1.3 Dispersion modeling

Air quality dispersion models are used to estimate air pollutant concentrations in the atmosphere for a specific location and time. Several models are available based on the types of pollutants, nature of the dispersion, as well as the potential effects of the pollutant on human health and the environment. In this paper, the United State Environmental Protection Agency (USEPA) AERMOD modeling system is used to estimate the concentrations of pollutants emitted from back-up generators within the Lagos, Nigeria metropolis. AERMOD is a steady-state Gaussian dispersion model that incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources, and both simple and complex terrain (USEPA, 2017).

1.4 Purpose of research and organizational structure

Currently, there is limited reference information for appropriate air quality policy and planning in Nigeria. The overall goal of this research is to help fill that gap, in order to protect public health. Specific objectives are:

1) To estimate emissions of air pollutants from portable diesel and petrol generators in Lagos, the largest city in Nigeria, and the resulting atmospheric concentrations, using emission factors and the Gaussian dispersion model AERMOD.
2) To compare the modeled concentrations with air quality guidelines to determine whether the generators pose a health risk.
3) To make recommendations to reduce air quality impacts from generators.

Our hypothesis is that a large numbers of generators operating simultaneously in close proximity will exceed air quality guidelines.

The contribution of this research is that it is the first study to assess the air quality and human health impact of many back-up generators operating simultaneously in close proximity in an urban area in a developing country.

Chapter 2 of this paper provides background information on air pollutant modeling and pollution dispersion. The chapter also contains the literature review on the subject matter and the objectives of the study.

Chapter 3 describes the methodology applied in modeling the concentrations of air pollutant emitted from the use of backup generators.

Finally, Chapter 4 presents the results of the study while Chapter 5 provides the conclusions and recommendations to minimize emissions from generators.

CHAPTER 2

BACKGROUND, LITERATURE REVIEW AND OBJECTIVES

2.1 Introduction

Anthropogenic pollution occurs when gas and aerosol particle concentrations rise above natural background concentrations (Jacobson, 2012). By dry volume, 99.997% of the atmosphere consists of four gases, molecular nitrogen (78%), oxygen (21%), argon (0.93%), and carbon dioxide (0.04%). The troposphere and stratosphere, reaching to 50 kilometers (km) of the earth's surface, contain approximately 99% of the mass of the atmosphere. This is where air pollution occurs (Haerens & Gale Group, 2011; Vallero, 2014). Table 2.1 lists the proportions of the major constituents in the dry atmosphere. Water vapor is also a significant portion of the atmosphere. The amount of water vapor present depends on local conditions and the history of the air.

Table 2.1 Proportions of molecules in clean dry air

Molecule	*Symbol*	*Proportion by volume*
Nitrogen	N_2	78.1%
Oxygen	O_2	20.9%
Argon	Ar	0.93%
Carbon dioxide	CO_2	370 ppm
Neon	Ne	18 ppm
Helium	He	5 ppm
Methane	CH_4	1.7 ppm
Hydrogen	H_2	0.53 ppm
Nitrous oxide	N_2O	0.31 ppm

Source: Colls (2002)

Emissions from several human endeavors increase the concentration of gases in the atmosphere either through primary discharges from a host of sources or reactions in the troposphere. The use of generators is one such activity. Generators are internal combustion engines that run on fossil fuel to generate electricity. Combustion of fossil fuel in generator engines produces a variety of undesirable compounds that include carbon monoxide (CO), unburned hydrocarbons (HC), sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (PM) (Reif, 2010). These atmospheric pollutants are responsible for both acute and chronic effects on human health (Sydbom et al. 2001; WHO, 2016).

Pollutants are regulated based on their effects on human health with respect to different exposure times. CO inhibits the ability of humans to absorb oxygen into the blood, leading to carboxyhemoglobin poisoning (Wexler, 2014). Even short-term exposure to high CO concentrations will most likely cause acute health impacts. Hydrocarbons are chemical compounds of carbon and hydrogen like benzene, toluene, ethylene, and ethane. Some hydrocarbons are carcinogens with long-term exposure resulting in a significant threat to human health (Todd et al. & US Agency for Toxic Substances and Disease Registry, 1999). Baumbach et al. (1995) measured average concentrations of the carcinogen benzene in Lagos in particular to be 80 ppbv; this is 8 times more than the highest concentrations found in Chinese cities. Long-term exposure to persistent level of SO_2 can also affect lung function (US Agency for Toxic Substances & Disease Registry, 1998). The main forms of NOx produced from the use of generators are NO_2 and NO. NO_2 is responsible for both short and long-term health effects. Particulate matter comprised of chains of carbon particles may also be carcinogens, depending on size.

Pollutants emitted from the use of generators also contribute to climate change. N_2O, a potent greenhouse gas, is emitted. CO is considered an indirect greenhouse gas due to its close coupling to atmospheric methane (CH_4), a strong greenhouse gas (IPCC, 1990; Khalil and Rasmussen, 1985). Additionally, CO released into the atmosphere affects the concentration of the hydroxyl radical (OH°) and the cycle of tropospheric ozone (O_3) (Seinfeld and Pandis, 1998). Carbon dioxide (CO_2), an important greenhouse gas, is also released during use of generators.

The government-owned Power Holding Company of Nigeria (PHCN) dominates the electricity supply market in Nigeria. Primary electricity generation sources include oil and gas, fueled thermal plants and hydropower. The PHCN has been unsuccessful in providing reliable and accessible electricity service for the past three decades (Babatunde, 2011; Aliyu et al., 2013; Ibitoye and Adenikinju, 2007; Nnaji et al. 2013). In comparison to other developing countries, electricity consumption is Nigeria is very low. Per capita annual consumption of electricity is approximately 125 kWh in Nigeria, while South Africa, Brazil and China annual per capita consumption is 4500 kWh, 1934 kWh and 1379 kWh, respectively (World Bank, 2014). To supplement the PHCN electricity supply, domestic, commercial, and industrial sectors in Nigeria rely heavily on private back-up generators for extended periods of time for everyday use (Awofeso, 2011; Oseni, 2016; Sonibare, 2010) It is estimated that around 60 million Nigerians own and operate generators for their electricity supply (Energy Commission of Nigeria, 2009).

Based on information obtained from the United Nations Statistics Division, Nigeria is the second biggest market for generators/generator-driven economy in Africa, after Egypt, whose imports stood at $58.6 million. Nigeria's generator import was around $51 million (Vanguard Newspaper, 2016). The Vanguard newspaper in Nigeria reported in 2016 that there has been a surge in imports of 75-375 KVA diesel generators. Generators in Nigeria, particularly in Lagos, are numerous and it is projected that generator use will continue to increase as importation of generators increases. Based on the number and extensive use of generators, they are most likely a significant source of influence on global and regional pollutant concentrations (Awofeso, 2011).

2.2 Meteorology and geographical characteristics of Lagos, Nigeria

Nigeria is the most populous country in West Africa, encompassing a total area of 923,768 km^3 with a population of about 180 million people (USCIA). Nigeria shares a border with Benin, Cameroon, Chad and Niger. Climate within Nigeria varies from tropical coastal plains in the south to the Sahelian savannas in the north. The mean elevation is 380 m, with the Atlantic Ocean (0 m) being the lowest point, while the highest point is the Chappal Waddi at 2,419 m above sea level. Environmental issues plaguing Nigeria include rapid urbanization, air and water pollution, rapid deforestation, desertification, and soil degradation (Madu, 2009).

About half of Nigerians are urban dwellers (UN, 2014). There are about 11 cities with over 1 million inhabitants, and more than 70 cities with over 100,000 inhabitants (Onibokun and Faniran, 1995). Population in Nigeria is concentrated in and around four city centers, which are in Kano, Lagos, Port Harcourt and the capital Abuja. Population density in these cities is considerably more than other urban areas with similar populations, like London, Nairobi and Dares Salam (UN, 2014). Lagos is in the forefront as the most populous city in Nigeria. The CIA fact book estimates population in Lagos to be about 14 million people. The Lagos state government estimates the population to be closer to 18 million people, while the National Population Commission of Nigeria estimates population in Lagos to be about 21 million people (Lagos State Government, 2017).

Lagos has a tropical wet and dry climate that borders on a tropical monsoon climate with short dry seasons (Lagos State Government, 2017). The heavier rainy season is from April to July, while the longer dry season is from December to March, with accompanying Harmattan winds from the Sahara Desert. The West African Monsoon (WAM) ventilates the region during the rainy season, while during the dry season, winds are stagnant over central Nigeria and vertical ventilation is suppressed by a strong temperature inversion due to warm northeasterly Harmattan winds (Marais, et al 2014; Cornforth, 2012). The highest average monthly rainfall is typically between May and July, while the lowest monthly rainfall is in December, with rain as low as 25 mm (0.98 in). The highest maximum temperature ever recorded in Lagos was 37.3 °C (99.1 °F), while the minimum was 13.9 °C (57.0 °F).

2.3 Atmospheric dispersion and pollutant modeling

A dispersion model can be described as a mathematical description of meteorological transport and dispersion processes, using source and meteorological parameters, over a set period (Harbawi, 2013). There are five types of air pollution dispersion models, as well as several variations of these models (Colls, 2002; Harbawi, 2013). One of the primary models is the Lagrangian model, often used to cover long periods of time. The Lagrangian model mathematically describes pollution plume parcels as they move through the atmosphere using a random walk process (Builtjes, 2001). The box model is used to analyze observations of selected chemical species and study tropospheric chemistry under specific conditions (Brasseur et al. 2003; Harbawi, 2013). The Eulerian approach describes the behavior of pollutants relative to a fixed coordinate system (Harbawi, 2013). The dense gas model simulates the dispersion of gas plumes that are heavier than air. (Harbawi, 2013) The Gaussian model is the most accepted computational model and is used to calculate the concentration of a pollutant at a certain point.

The AERMOD modeling system developed by American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee (AERMIC) used in this paper utilizes the steady state Gaussian model to estimate the concentration of pollutants emitted into the atmosphere. The Gaussian plume equation assumes a point source under stationary meteorological and emission conditions. The equation is given below.

$$c(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u}\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left(\exp\left(\frac{-(z-h)^2}{2\sigma_z^2}\right)+\exp\left(\frac{-(z+h)^2}{2\sigma_z^2}\right)\right)$$

Where

c (*x*, *y*, *z*) = concentration at a given point, g/m^3;

Q = source emission rate, g/s;

h = height of the release, m;

u = wind speed at source height, m/s;

z = height of the receptor, m

σ_y, σ_x = horizontal and vertical standard deviations which describe the crosswind and vertical mixing of the pollutant, m.

Details of the AERMOD formulations are discussed in Cimorelli et al. (2004a, 2004b).

To better evaluate the concentrations of pollutants in the atmosphere, several emission inventories have been established. Some air pollutant inventories typically used in chemical transport models (CTMs) include the Emissions for Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), USEPA National Emission Inventory (NEI), Emissions Database for Global Atmospheric Research (EDGAR), Reanalysis of the Tropospheric Chemical Composition (RETRO), and Regional Emission Inventory in Asia (REAS) (Harbawi, 2013; Marais et al., 2016; Ohara et al., 2007). These inventories are used to estimate emissions and resulting concentrations of various pollutants in the atmosphere.

Air pollution sources unique to Africa not represented in many inventories include generators, motorcycles, kerosene use, open waste burning, and ad hoc oil refining (Marais et al., 2016). The exclusion of several sources of pollution unique to Africa limits the accuracy of the model results, which do not necessarily reflect the actual concentrations of pollutants in the atmosphere.

There have also been inventories developed for specific conditions prevalent in Africa. Zhang (1999) developed emission factors for carbon monoxide emissions from cook stoves in developing countries. Assamoi and Liousse (2010) developed a regional inventory of anthropogenic emissions for two-wheel vehicles in Africa. Many emission factors in the inventory by Assamoi and Liousse are representative of efficient combustion conditions unlike inefficient combustion that is dominant in developing countries. Marais et al. (2016) went further to develop air pollution inventories for Diffuse and Inefficient Combustion Emissions in Africa (DICE-Africa).

Factors that affect concentrations of air pollutants from generators include quality of fuel used to power the generator, exit temperature of the exhaust gas, exhaust gas velocity, loading of the generator and any manufacturer technology installed to mitigate emissions (Zhu et al., 2009). Other factors which affect the transport, dilution and dispersion of air pollutants emitted from the generator exhaust include nature of the pollutant, meteorological characteristics, and effects of the terrain. It should be noted that emissions from small to medium sized generators within urban areas are released close to ground level between tightly spaced buildings which makes transport, dilution and dispersion of pollutants less effective.

2.4 Influence of meteorology on pollutant dispersion

The concentration of pollutants in the atmosphere are affected by, wind, temperature, vertical temperature profiles, clouds and the relative humidity (Jacobson, 2012). Horizontal air movements aid in the transport of pollutants in the prevailing wind direction. In some cases pollutants travel long range and cross political boundaries (Fridgen, 2011).

Vertical air motions affect both weather and the mixing processes of importance to air pollution (Jacobson, 2012). The atmosphere is stable when there are negligible vertical wind motions. Alternatively, when the atmosphere enhances vertical motions, it is unstable. Hence the stability of the atmosphere determines the tendency of the pollutant to convectively rise and disperse or build up near the surface.

Temperature also governs the concentration of pollutants in the atmosphere. Usually temperature decreases with higher altitude. However, when temperature increases as altitude increases, there is an inversion. Temperature inversion limits vertical movements of air thus trapping pollutants near the surface and restricting dispersion. Temperature can also increase or decrease the relative humidity. Relative humidity refers to the percentage of water vapor in the air at a given temperature, compared with water vapor that the air can hold at that temperature. When the relative humidity is high, particulate matter increases in size by absorbing liquid water (Jacobson, 2012). Clouds can also increase the concentration of pollutants in the atmosphere by acting like blankets trapping heat close to the Earth’s surface thus limiting the dispersion of pollutants.

2.5 Literature survey

There have been some studies attempting to estimate the concentration of air pollutants in Nigeria. However, these studies have had to rely on limited data and information on the regional emission of air pollutants as well as the regional air quality.

In Abiye et al. (2016), atmospheric dispersion modeling of emissions from a scrap-iron recycling factory in Ile-Ife, Southwest Nigeria was conducted to estimate the concentrations of

SO_2 and NOx in the atmosphere caused by the recycling process. At the time of the study, the factory had no stacks and emissions were escaping through all the orifices along the length and breadth of the building; hence the factory was modeled assuming a volume source configuration. Meteorological parameters measured at the factory location in 2012 and 2013 were used as input into the AERMOD system. AP-42 (USEPA, 1995) emission factor methodology was used to estimate the source emission rate since source specific emission factor measurements were not available. The study concluded that higher concentrations were more likely in the early morning period since less thermal energy was available at the surface to enhance the buoyancy of air parcels for dispersing pollutants species. In addition, the prevailing wind flow pattern had a significant effect on the concentration isopleth obtained for SO_2 and NOx for the study period.

Marias et al. (2016) utilized the GEO-Chem chemical transport model to estimate the concentrations of pollutants in the atmosphere within Nigeria. Results were compared with aircraft and satellite observations. It was determined that the maximum 8-hr ozone exceeds 70 ppbv over the region on a seasonal mean basis, with significant contributions from both open fires and fuel/industrial emissions.

In 2005, a study was conducted to estimate the concentration of pollutants emitted from gas flaring activities in the Niger Delta region of Nigeria. Air samples were collected at various distances from the point source. Gas flaring is the controlled burning of the waste natural gas associated with oil production. In addition, Gaussian dispersion modeling equations were used to predict the concentrations of pollutants released into the atmosphere with respect to distance from the point source. The result of the experiments as well as the results from the Gaussian modeling equations revealed that concentrations of CO, NO, and SO_2 within 60m from the emission source exceeded the Federal Environmental Protection Agency (FEPA) set limits for petroleum refinery emissions (Abdulkareem, 2005).

A similar study was conducted by Jimoh and Alhassan (2006) to predict air pollutant concentrations due to a textile manufacturing plant located in Lagos, Nigeria. The Gaussian dispersion model was used to successfully estimate the concentrations. Conclusions also revealed that pollutants emitted from the textile plant exceeded the FEPA set limits for textile manufacturing industries, except carbon monoxide concentrations.

Oguntoke and Adeyemi (2016) conducted a study to monitor emissions from generator use in Abeokuta, Nigeria. Portable gas samplers were used to monitor concentrations of SO_x, CO, CO_2, CH_4, PM, NO_2 and H_2S emitted from seventeen generators. Generator capacity ranged from 1 to 25 kVA. The highest concentration of CO was established to be 4167.0 ppm from a 1.5 kVA generator at 0 m from the site of the generator use. Highest concentration of NO_2 was 31.0 ppm while highest concentration of SO_x was 65.6 ppm. The study concluded that out of the seven pollutants monitored, CO, CO_2, NO_2, SO_x and PM values within 0m to 5m from the generator use exceeded the maximum limits for human exposure.

Another study by Adeniran et al. (2017) utilized the USEPA AP-42 emission factors as well as the Australian National Pollution Inventory (NPI) emission factors to estimate air pollutant emissions from diesel-powered generators in mobile telecommunication base transceiver stations (BTS) sites in Nigeria. It was observed that quantities of pollutants particularly, NOx, CO, SO_2, PM_{10}, $PM_{2.5}$ and volatile organic compounds emitted were proportional to the quantity of the fuel consumed, as well as the number of backup generators operated at the BTS sites. At the time of the research, there were 22,000 BTS stations operating backup generators for extended periods of time, with an additional 50,000 BTS likely to be in operation within a year of the study. It was concluded that significant increase in air pollutant emissions will occur with the accumulation of additional BTS.

2.6 Summary of literature review

The studies above describe several instances where emissions from difference industries have exceeded the emission standards set by the FEPA. The petroleum refinery industry, the telecommunication industry as well as the textile manufacturing industry all have guidelines regulating emissions from daily operations. On the other hand, generators operated by private individuals do not fall under these categories. Consequently, there are limited regulations relating to generator use. From the foregoing, it is clear that a study of back-up generator emissions should be conducted to determine whether there are potential human health impacts. To our knowledge, no previous study has been conducted for Nigeria, or any other developing country.

2.7 Objectives of research

Due to limited regulations of emissions from the use of backup generators and the subsequent threat to human health, this paper intends to provide information for policy makers and serve as a basis for reform. Thus, the objectives of this study are:

1) To estimate emissions of air pollutants from portable diesel and petrol generators in Lagos, the largest city in Nigeria, and the resulting atmospheric concentrations, using emission factors and the Gaussian dispersion model AERMOD.
2) To compare the modeled concentrations with air quality guidelines to determine whether the generators pose a health risk.
3) To make recommendations to reduce air quality impacts from generators.

CHAPTER 3

METHODOLOGY

3.1 Overview

The modeling of air pollutants from diesel and gasoline-powered backup generators in this study relies solely on research information obtained from different sources. No experiments were conducted. Several assumptions were made based on available information that reflects the average working conditions of the types of generators available for sale on the Nigerian market. AERMOD View Gaussian dispersion model software version 9.5 developed by Lakes Environmental was run on a personal computer with a Windows 10 operating system.

The methodology was carried out in 3 steps, which are:

- Input of required information through interface pathways,
- Execution of the runs, and
- Post processing of the results obtained from different runs.

Each step is described in detail below.

3.2 Model inputs

The AERMOD View interface utilizes five data input pathways for site-specific data required for the dispersion modeling. The pathways are described below:

- Control pathway – The entire control of the modeling run and specific model scenario are specified via this pathway.
- Source pathway – Defines source and source parameters by which pollutant is discharged into the atmosphere.
- Receptor pathway – Defines where pollutants will be deposited.

- Meteorological pathway – Atmospheric conditions for the modeled site are provided via this pathway.
- Output pathway – User defines which output results are necessary to meet the needs of the modeling analyses.

Requisite data used for each pathway is described below.

3.2.1 Control pathway

Basic frameworks of the modeling run are defined in this section. The “Regulatory Default Options” specifies the output type designation. In this section, a concentration in $\mu g/m^3$ without accounting for wet or dry depositions is selected. The pollutant of interest is also selected. Different pollutants are modeled in separate runs. Some regulatory bodies like the USEPA for permitting purposes require specific averaging times. However, since this study is not for regulatory purposes, the averaging time options for 1-hour and 24-hour averaging periods are selected.

The dispersion coefficient selected is for an urban area. For a site to be classified as urban or rural, the decision is based on either the Land Use Procedure or the Population Density Procedure. The Land Use procedure specifies that where land use type I1, I2, C1, R2 and R3 account for 50% or more of a 3-km radius circle about the source, then the area is urban. If not, the area is designated rural. These categories are defined by the amount of vegetative cover within each category. A summary of the Auer Land Use Procedure urban categories is shown in Table 3.1 below.

Table 3.1 Auer Land Use Procedure Categories

Auer Land Use Categories	
Designation	Description
I1	Heavy Industrial - Major chemical, steel and fabrication industries. Generally 3-5 story buildings, flat roof. Grass and tree growth extremely rare, vegetation less than 5 percent
I2	Light - Moderate Industrial. Rail yard, warehouses, industrial parks. Generally 1-3 story building, flat roofs. Very limited grass, trees almost absent, vegetation less than 5 percent
C1	Commercial - Office and apartment buildings, hotels, greater than 10 story heights, flat roofs. Limited grass and trees; vegetation less than 15 percent
R2	Compact Residential - Single, some multiple family dwelling with close spacing; generally less than 2 story, pitched roof structures. Limited lawn sizes and shade trees; vegetation less than 30 percent
R3	Compact Residential - Old multifamily dwellings with close (less than 2m) lateral separation; generally 2 story, flat roof structures. Limited lawn sizes, old established shade trees; vegetation less than 32 percent.

The population density procedure requires the computation of the average population density per square kilometer. Where the average population density is greater than 750 people per square kilometer, then the area is designated urban. If population density is equal to or less than 750 people per kilometer, the area is rural. Of the two methods, the Land Use Procedure is considered a more definitive criterion. Lagos is categorized as an urban area based on the Auer land use procedure. Finally, elevated terrain is selected since receptors are located above the base elevation of the source. All other data remain at the default setting.

3.2.2 Source pathway

Backup generators are modeled as point sources since generators typically emit air pollutants from stacks. Multiple UTM coordinates are entered to simulate several generators operating during a blackout. The source release parameters are also designated. The parameters include emission rate (g/s), gas exit temperature (^oC), stack inside diameter (m), and gas exit velocity (m/s). The gas exit flow rate is automatically calculated. These variables affect the concentrations of pollutants emitted directly from the generator exhaust. Backup generators operate at near steady-state load conditions with slight variations in load causing short-lived transient events (Gullett et al., 2010).

The emission rates are calculated using the emission factor procedure. Multiple emission factors from the AP-42 (USEPA 1995), Diffuse and Inefficient Combustion Emissions in Africa (DICE-Africa, 2013) (Marais et al., 2016), and Shah et al. (2006) are utilized to arrive at the emission rates used in this study. Multiple emission factors were utilized since actual measurements were not available for the study. Hence a comparison of the results from the emission rate factors and the effect on concentration of the pollutant will also be evaluated. Table 3.2 provides modeled pollutants and emission factors used in this study.

Table 3.2: Emission Factors

Pollutant	USEPA AP-42 Emission Factors (fuel input for gasoline generator) (Ib/MMBtu)	USEPA AP-42 Emission Factors (fuel input for deisel generator) (Ib/MMBtu)	DICE-Africa Emission Factors (fuel input for gasoline generator) (10^3g/GWh)	Shah et al. (2006) Emission Factors (fuel input for deisel generator) (g/kWh)
CO	0.99	0.95	4120	2.30
NOx	1.63	4.41	*	7.16
SO_2	0.084	0.290	820	*
CO_2	154	164	*	799
PM_{10}	0.10	0.31	*	0.47
NO	*	*	11880	*
NO_2	*	*	3210	*

*Emission factor not available.

The USEPA AP-42 emission factors shown in Table 3.2 are for uncontrolled gasoline and diesel industrial engines. Although the AP-42 emission factors are one of the more widely used factors, these factors are given a "D" rating by the USEPA, meaning the factors are based on limited information. The inadequacy of the available emission factors was the basis for the experiments by Shah et al. (2006) on several diesel generators to determine applicable emission factors. DICE-Africa (2013) went further to address deficiencies in the applicability of the current emission factors to the African continent. DICE-Africa considers unique sources of air pollution in Africa as well as inefficient combustion sources that are misrepresented or out-of-date in more commonly used emission factor inventories. The DICE-Africa emission factors apply to gasoline-powered generators. Shah et al. and DICE-Africa are used to model the concentrations of pollutants in addition to the AP-42 emission factors to obtain a more accurate result, as AP-42 emission factors have a "D" rating.

The equation to calculate the emission rate based on the emission factor is shown below.

$$E_R = E_F \; x \; H \; x \; C_R$$

Where

E_R = emission rate, g/s

E_F = emission factor, g/MJ

H = heat value of fuel, MJ/L

C_R = fuel consumption rate. L/s

The assumptions made as source parameters for a generic gasoline-powered generator are:

- The gas exit temperature is assumed to be 500^{o}C. This is within the range of experimental results (Ganesan et al., 2015; Tong and Zhang, 2015; Yusaf et al., 2009).
- Stack inside diameter is assumed to be 0.025m based on survey of information from multiple sites offering piping exhaust for small to medium size generators.
- Release height of air emissions is 0.15 m. It is assumed that the stack is a third of the height from the base of an Elemax SH7600EX gasoline-powered generator. The Elemax brand is one of the common models available for sale on the Nigerian market. SH7600EX model was selected since it represents the mid-range capacity of generators considered.
- Exit gas velocity is 1.5 m/s (Abu-Qudais, 1997; Kateusz, 2015; Tong and Zhang, 2015).
- According to the Elemax SH7600EX manufacturer specification, the generator consumes 3.29 L/h of gasoline at 100% loading.

For diesel-powered generators, the CAT C1.1 (DE7.5E3S) is used to determine the concentrations of air pollutant emissions. This is one of the models of diesel generators available in Nigeria. The generator was selected because it has similar specifications to CAT generators studied in Shah et al. (2006). The manufacturer specifications provide the following information used in the modeling.

- The gas exit temperature is 420^{o}C at prime operation
- Release height of air emissions is assumed to be 1 m. This is at the top of the generator.

- Exhaust gas flow is 1.7 m^3/min.
- Fuel consumption is 2.5 L/h at 100% loading.

The input emission rates in g/s for gasoline and diesel generators calculated from the emission factors are shown in Tables 3.3 and 3.4.

Table 3.3: Gasoline-powered generator emission rates

Emissions rates for gasoline-powered generators (g/s)		
Pollutant	AP-42 (1995) USEPA	DICE-Africa (2013) Marais et al.
CO	0.0120	0.0335
CO_2	1.88	*
NO	*	0.0965
NO_2	*	0.0253
NOx	0.0200	*
SO_2	0.00103	0.00670
PM_{10}	0.00122	*

*No emission factors.

Table 3.4: Diesel-powered generator emission rates

Emissions rates for diesel-powered generators (g/s)		
Pollutant	AP-42 (1995) USEPA	Shah et al. (2006)
CO	0.111	0.0173
CO_2	1.91	6.01
NOx	0.0514	0.0539
SO_2	0.0034	*
PM_{10}	0.0036	0.0035

*No emission factors

Finally, in the source pathway, the "Source Groups" option is selected so that all the sources are grouped to ensure their cumulative effects can be modeled. All other parameters remain on default values.

The generators were randomly placed in a study area of 200 m x 200 m, situated close to the weather station to obtain more accurate modeling results. The weather station is located at the Murtala Muhammed International Airport located in Ikeja at Latitude 6.583N and Longitude 3.333E, as shown in Figure 3.1.

Demographia (2017) estimates the population density in Lagos to be around 9,400 people per square kilometer. Hence, it is approximated that within a 200 m by 200 m-square source area, there are around 376 people with four persons per family (Oseni, 2016). Oseni (2016) further approximates that 54% of Nigerians own and operate generators in their homes. This means there are about 50 generators within the study area. Fig 3.1 below shows the placement of the generators within the study area. The generators are shown as red points.

Thirty 5.6 kVA Elemax SH7600EX gasoline-powered generators and twenty CAT C1.1 (DE7.5E3S) diesel generators are used as the standard to model air emissions within the source area. The number of gasoline generators outnumbers diesel generators because more people tend to use gasoline generators due to the high cost of diesel fuel in Nigeria. It is assumed that during a blackout, the generators will be used at the same time for some hours during the day for at least a minimum of 1 hour. Electricity supply is sporadic in Lagos, and blackouts usually occur on a daily basis.

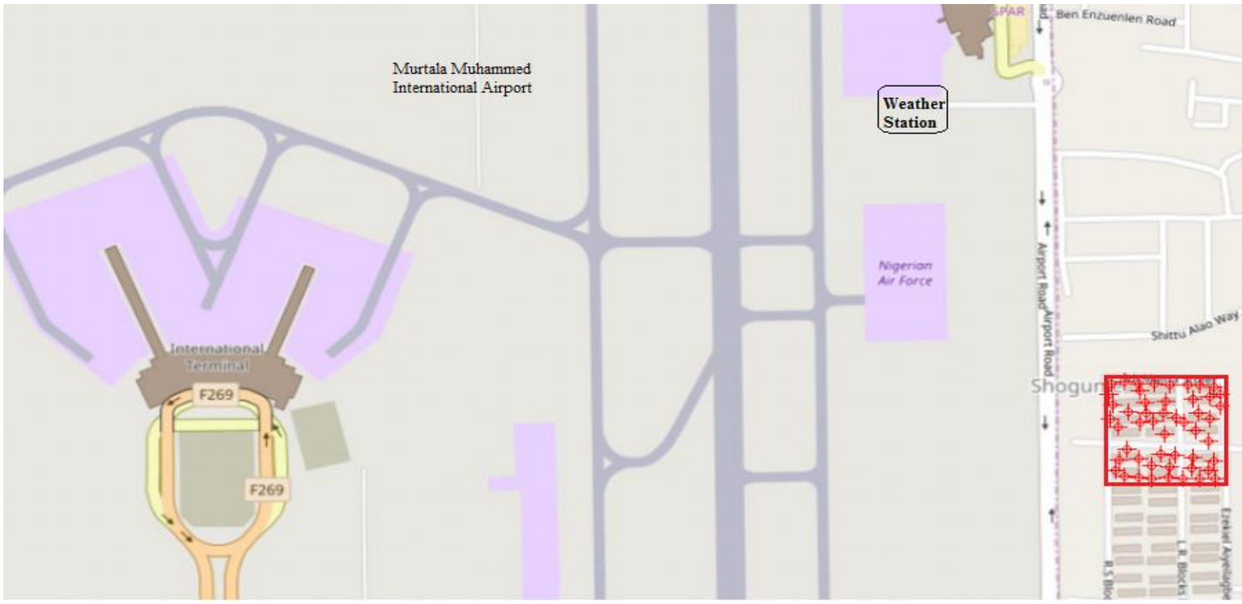

Fig. 3.1: Placement of generators within study area

3.2.3 Receptor pathway

There are several ways to define a receptor in AERMOD. For this project, a uniform Cartesian receptor grid is used with 100 m by 100 m spacing and 625 receptor locations, for total dimensions of 2 km x 2 km. The elevated terrain height option is selected because emissions from small- to medium-sized generators within urban areas are released close to the ground. Thus, there is the assumption that terrain height exceeds stack base elevation. All other values remain at the default values.

3.2.4 Meteorology pathway

Surface and upper air meteorological data preprocessed by AERMET is entered in this section. Three years of meteorological data is used to simulate the concentration of selected pollutants in the atmosphere and to identify any variance due to changing weather patterns.

AERMET is a preprocessor used to process the surface air data and upper air data. While AERMAP preprocessor is used to process the terrain data. Required upper air and surface air data for the AERMET preprocessor are obtained from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) website (formerly National Climatic Data Center (NCDC)). The AERMAP data was retrieved from WebGIS. There is a WebGIS tab in the AERMOD View system that automatically uploads the selected map. For this study, the SRTM3 (Shuttle Radar Topography Mission) map was selected.

The surface air data for Nigeria is obtained from the Integrated Surface Hourly (ISH) data stations. The station for this project is located at the Murtala Muhammed International Airport located in Ikeja at Latitude 6.583N and Longitude 3.333E. The instruments are usually mounted on a single rail with the anemometer standing about 10 meters above ground level. A potential concern for the use of the ISH data is the high incidence of calms and variable wind conditions which may affect the dispersion modeling results.

The upper air data, unlike the surface air data for Nigeria, is not available from the NOAA website. Hence the upper air data for the neighboring Cameroon is used in lieu of data for Nigeria. The upper air data includes weather data from the atmosphere beginning at 3 meters above the Earth's surface. Weather balloon data for Cameroon is obtained from the Integrated Global Radiosonde Archive (IGRA) since upper air data for Nigeria is not available. The IGRA consists of radiosonde and pilot balloon observations at over 2,700 globally distributed stations. Observations are available at standard and variable pressure levels, fixed and variable height with wind levels at the surface and tropopause. The data obtained from the site has undergone a comprehensive set of quality control procedures to remove gross errors. However, jumps and other discontinuities caused by changes in instrumentation, observing practice, or station location are still present. Cameroon borders Nigeria to the east and shares similar meteorological characteristics. The map below shows the location of the two countries within West Africa.

Fig. 3.2: Map of West Africa.

Default values for the albedo, Bowen ratio and surface roughness length were applied, and the default urban terrain option was selected since no AERSURFACE-compatible maps for Nigeria were available.

Model runs for year 2011, 2012, and 2013 based on available data were completed. The three years of meteorological data were combined to complete the runs since the data were similar and there was no outlier weather event in any one year.

3.2.5 Output pathway

Multiple output formats are selected to give summaries of the run results. The RECTABLE output option produces tables of first high values summarized by receptor for each short-term averaging period. The MAXTABLE option defines the number of overall highest values that will be summarized in the output file for each short-term averaging period being modeled. A separate maximum overall value table is produced for each source group. Since 20 is specified for the maximum values option, then the model will produce a table for each short-term averaging period and each source group containing the 20 highest values.

3.2.6 BPIP

The presence of buildings can affect plume rise and dispersion of pollutants within the atmosphere. Building downwash effects are considered for point source emissions. Generator use in Lagos is widespread between tightly spaced buildings, meaning that Building Profile Input Program (BPIP) function in AERMOD View needs to be run. The building downwash analysis is performed before running AERMOD. There are eighteen buildings located within the 200 m by 200 m square area. Dimensions of the buildings are estimated using Google Earth Pro. The height of the buildings is approximated using the elevations at the top of the buildings shown on Google Earth Pro and the base height of the generators imported into AERMOD View via the SRTM3 map.

3.3 Model runs

Multiple runs using the AP-42 (USEPA, 1995), DICE-Africa (Marais et al., 2016), and Shah et al. (2006) emission factors were completed. Model runs were also conducted with and without BPIP to examine the impact of building downwash.

3.4 Post processing of results obtained from runs.

Output files containing concentrations for different averaging times were created through the output pathway hence limited post processing of results was required. A spreadsheet was used to calculate the number of exceedances of concentrations of NO_2, SO_2, CO, PM_{10} and NOx. Isopleths showing maximum 1-hour and 24-hr concentrations at receptors are exported and used to identify the pollutant dispersion within the study area. Results from the runs are compared with the USEPA National Ambient Air Quality Standards (NAAQS) as well as the World Health Organization (WHO) air quality guidelines.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Comparison of modeled pollutant concentrations resulting from US EPA AP-42 vs. DICE-Africa/Shah et al. emission factors

Emission rates in g/s were calculated using the emission factors from USEPA AP-42 (1995), Shah et al. (2006), and DICE-Africa (2013). The emission rates are used in AERMOD to estimate the ambient concentrations of air pollutants resulting from use of 30 gasoline and 20 diesel generators in proximity to each other within a 200 m by 200 m square area. Tables 4.1 and 4.2 show maximum concentrations resulting from the model runs. Table 4.1 contains results based on model runs using the AP-42 gasoline engine factors for the 30 gasoline generators and diesel engine emission factors for the 20 diesel generators. Table 4.2 contains results based on model runs using the DICE-Africa and Shah et al. emission factors: CO concentrations are based on 30 gasoline generators using DICE-Africa emission rates and 20 diesel generators using Shah et al. emission rates, and SO_2 and NO_2 concentrations are based on the use of 50 gasoline generators since Shah et al. had no emission factors for SO_2 and NO_2.

Table 4.1: Maximum pollutant concentrations based on AP-42 emission factors

AP-42 pollutant concentrations without BPIP ($\mu g/m^3$)		
Pollutant	1-hr	24-hr
SO_2	73	37
PM_{10}	110	57
NOx	1175	625
CO	456	238
CO_2	72700	37896

Table 4.2: Maximum pollutant concentrations based on DICE-Africa and Shah et al. emission factors

DICE-Africa and Shah et al- pollutant concentrations without BPIP ($\mu g/m^3$)		
Pollutant	1-hr	24-hr
SO_2	261	136
NO_2	985	513
CO	1166	609

The results from the table above show that the SO_2 and CO concentrations for DICE-Africa and Shah et al. exceed the concentrations from AP-42. The concentrations for NO_x using AP-42 factors were somewhat higher than the concentrations for NO_2 using DICE-Africa; however, NO_x includes both NO_2 and NO. From most combustion sources, around 90% of NO_x is emitted as NO. This means that total NO_x, if available from DICE-Africa, would likely have exceeded total NO_x from AP-42. As mentioned in Ch. 3, the DICE-Africa/Shah emission factors are likely more accurate, since the AP-42 factors had a rating of D.

In Tables 4.1 and 4.2, the 1-hour concentrations are higher than the 24-hour concentrations. This is anticipated, because more changes in wind direction occur in a 24-hour period, which causes greater dispersion of pollutants and results in lower concentrations.

4.2 Comparison of modeled pollutant concentrations with and without consideration of building downwash

1-Hr, and 24-Hr CO, SO_2 and NO_2 isopleths for the multi-year runs based on DICE-Africa and Shah et al. emission factors with and without BPIP are shown below. The highest concentrations of pollutants surround the generators, with the highest value at UTM coordinates x = 537103.02 and y = 727081.69. Maximum concentrations with and without BPIP are shown in Tables 4.3 and 4.4.

Table 4.3: Maximum pollutant concentrations based on AP-42 emission factors with and without BPIP

AP-42 pollutant concentrations (µg/m^3)				
	Without BPIP		**With BPIP**	
Pollutant	1-hr	24-hr	1-hr	24-hr
SO_2	73	37	162	44
PM_{10}	110	57	180	56
NOx	1175	625	2518	693
CO	456	238	681	200
CO_2	72700	37896	113496	32039

Table 4.4: Maximum pollutant concentrations based on DICE-Africa and Shah et al. emission factors with and without BPIP

DICE-Africa and Shah et al- pollutant concentrations (µg/m^3)				
	Without BPIP		**With BPIP**	
Pollutant	1-hr	24-hr	1-hr	24-hr
SO_2	261	136	406	113
NO_2	985	513	1535	429
CO	1166	609	1453	519

Isopleths show that the highest concentrations of pollutants are around the source of emission with concentrations decreasing farther out from the sources. 1-hr maximum concentrations of pollutants are higher when BPIP is run. This is not surprising, since tightly-spaced buildings limit pollutant dispersion, resulting in higher concentrations. 24-hr maximum concentrations of CO and NO_2 are markedly higher with BPIP, but for SO_2, the 24-hr maximum concentrations are comparable with and without BPIP. The reason for this is unclear.

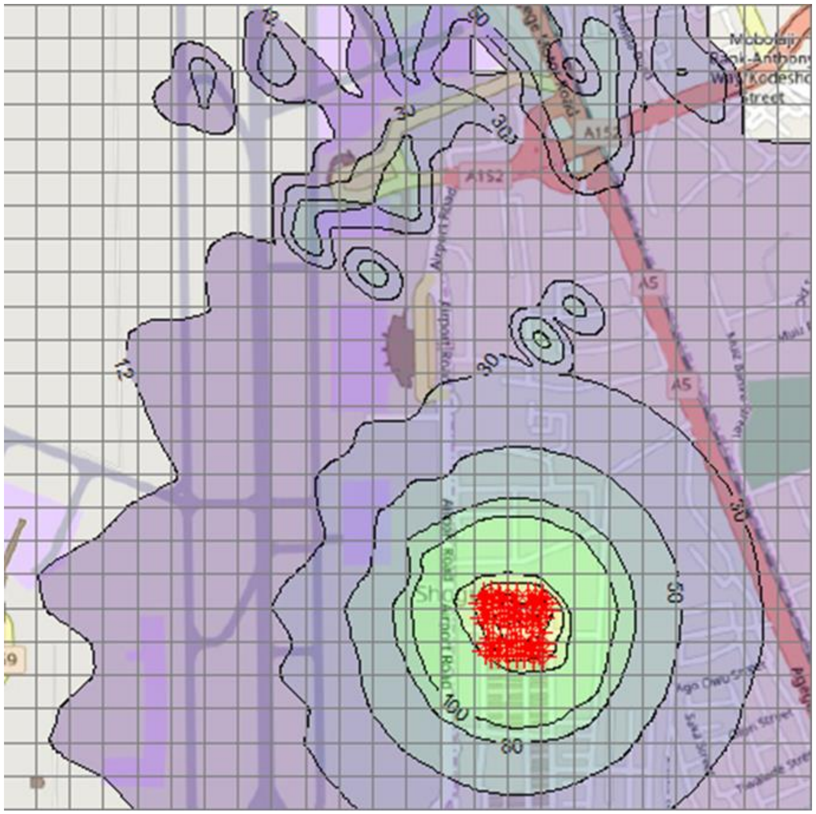

Fig 4.1: 1-Hr CO isopleth without BPIP

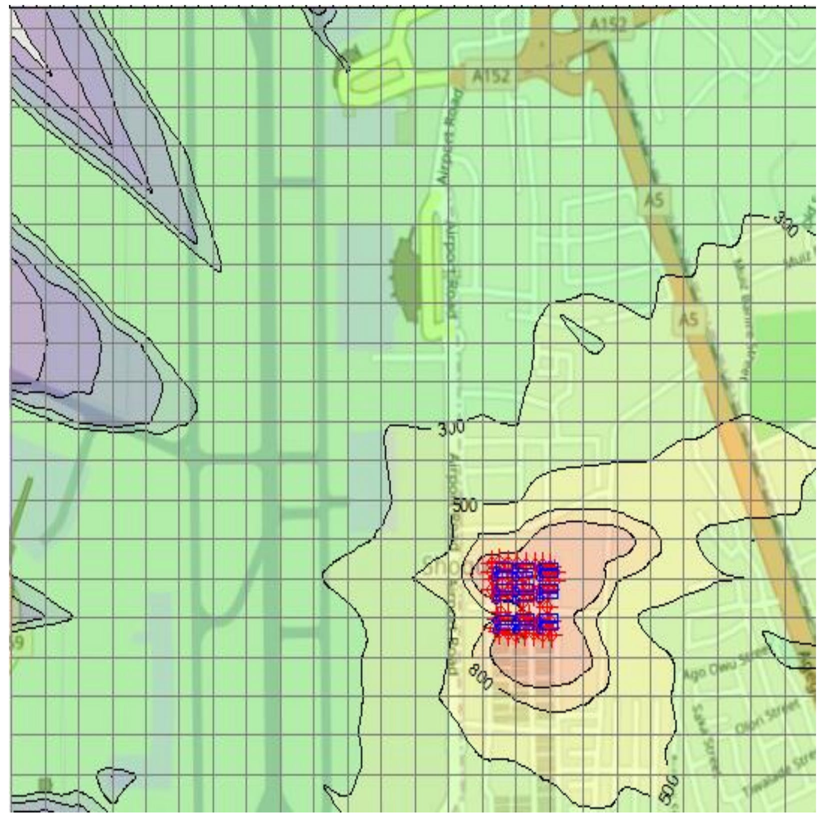

Fig 4.2: 1-Hr CO isopleth with BPIP

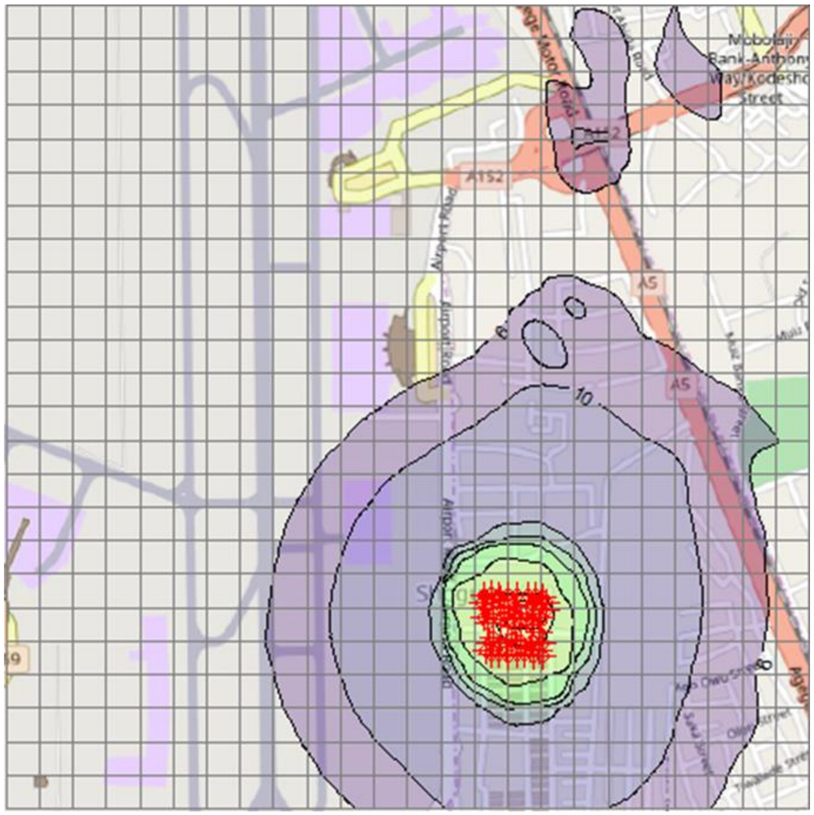

Fig 4.3: 24-Hr CO isopleth without BPIP

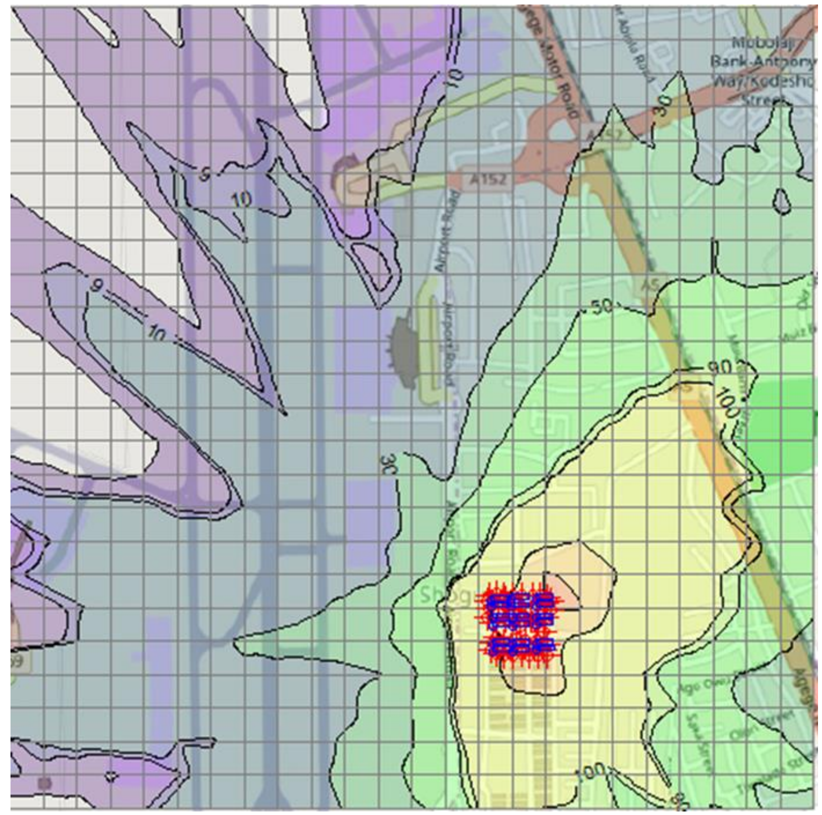

Fig 4.4: 24-Hr CO isopleth with BPIP

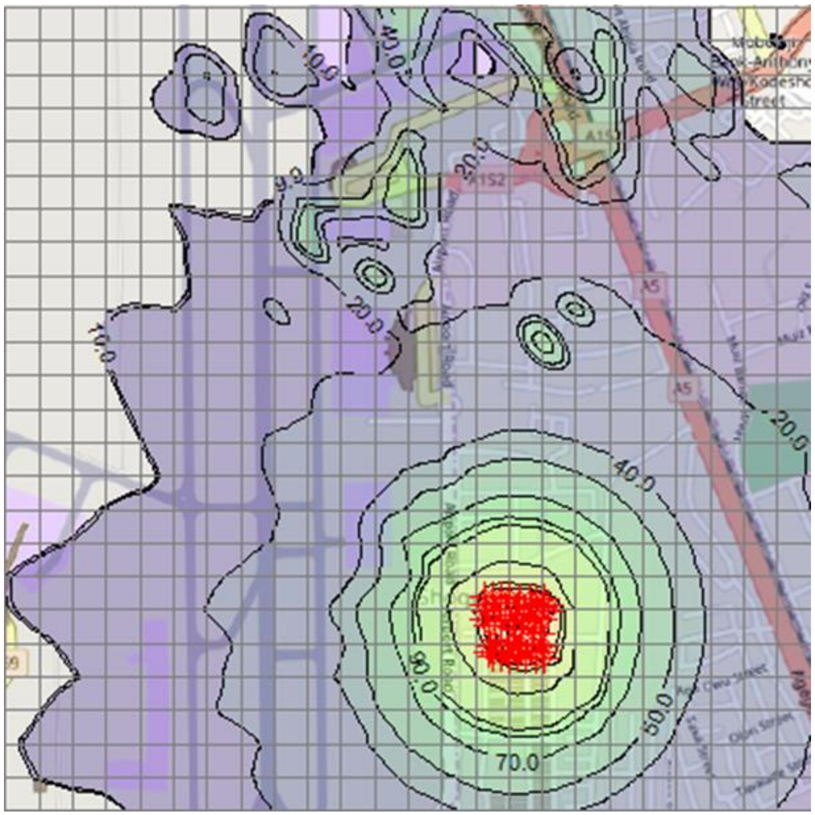

Fig 4.5: 1-Hr SO_2 isopleth without BPIP

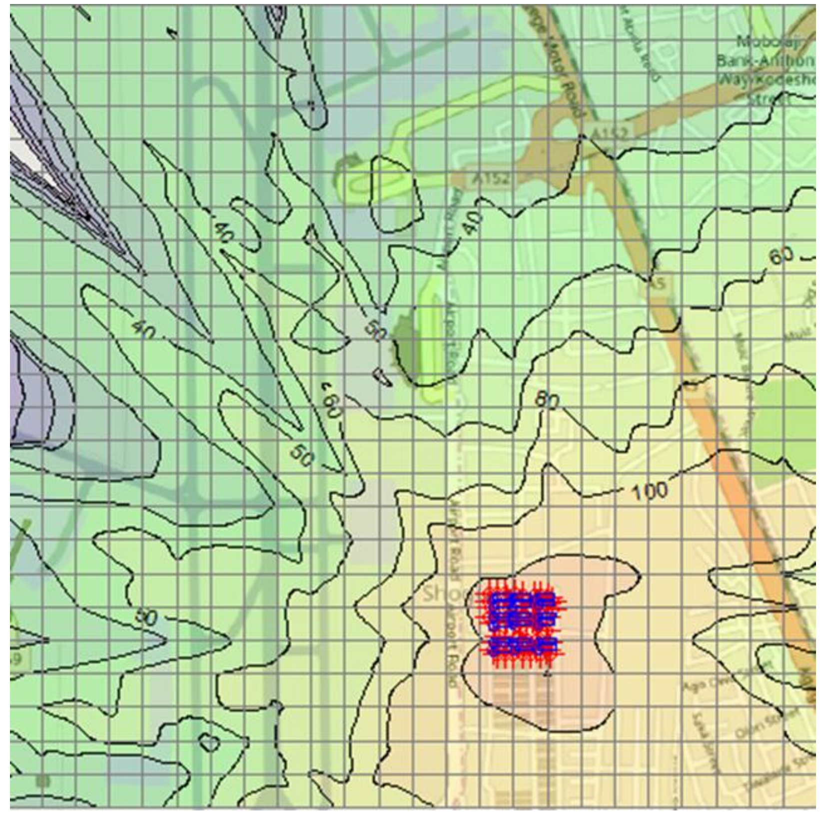

Fig 4.6: 1-Hr SO_2 isopleth with BPIP

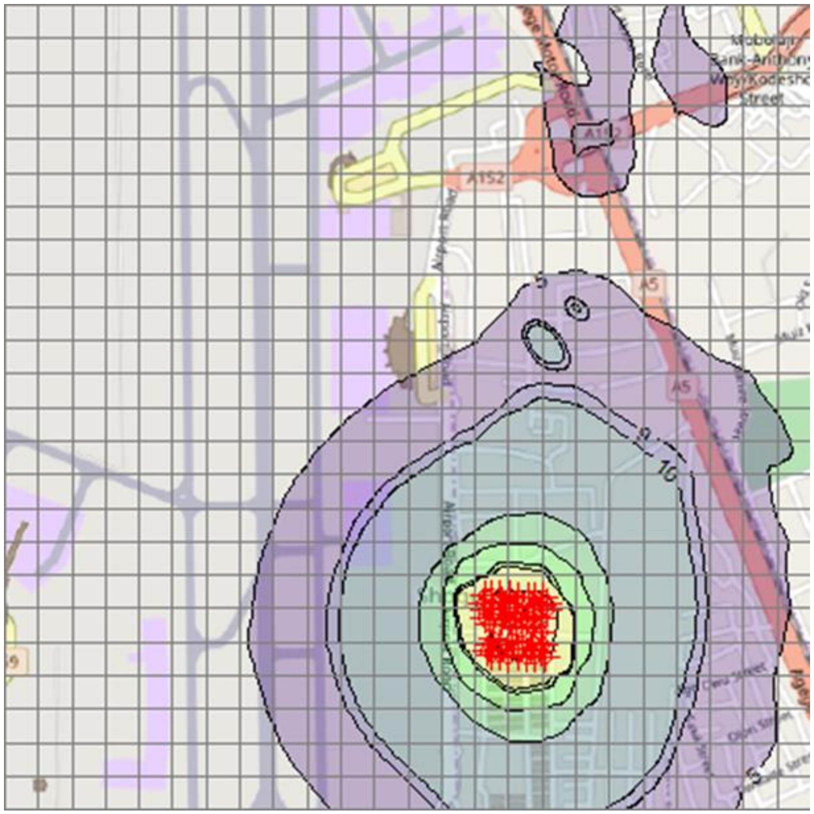

Fig 4.7: 24-Hr SO_2 isopleth without BPIP

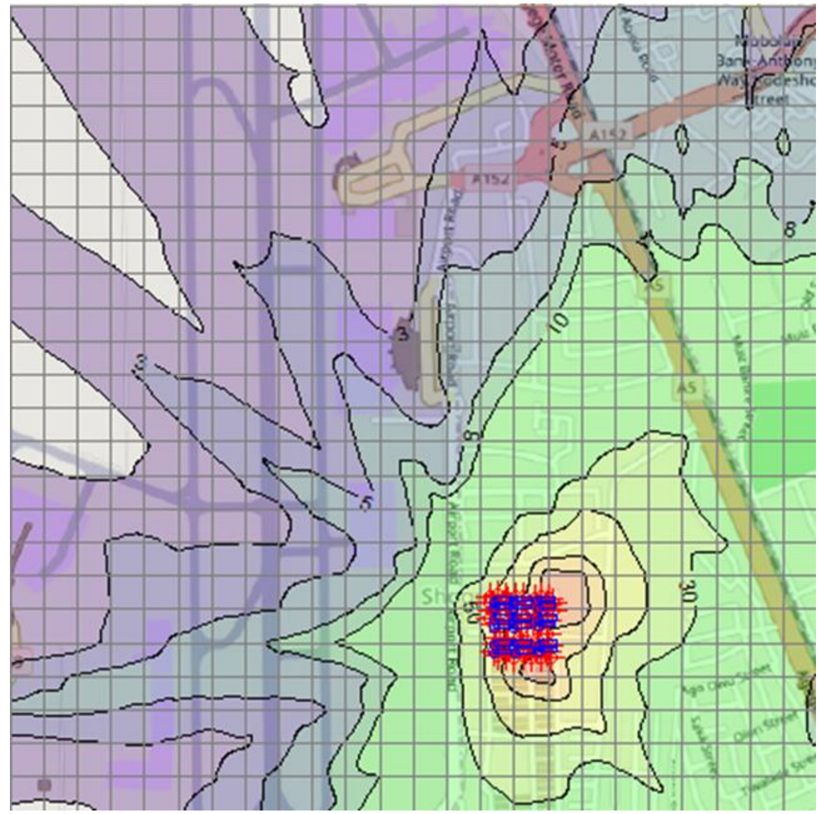

Fig 4.8: 24-Hr SO_2 isopleth with BPIP

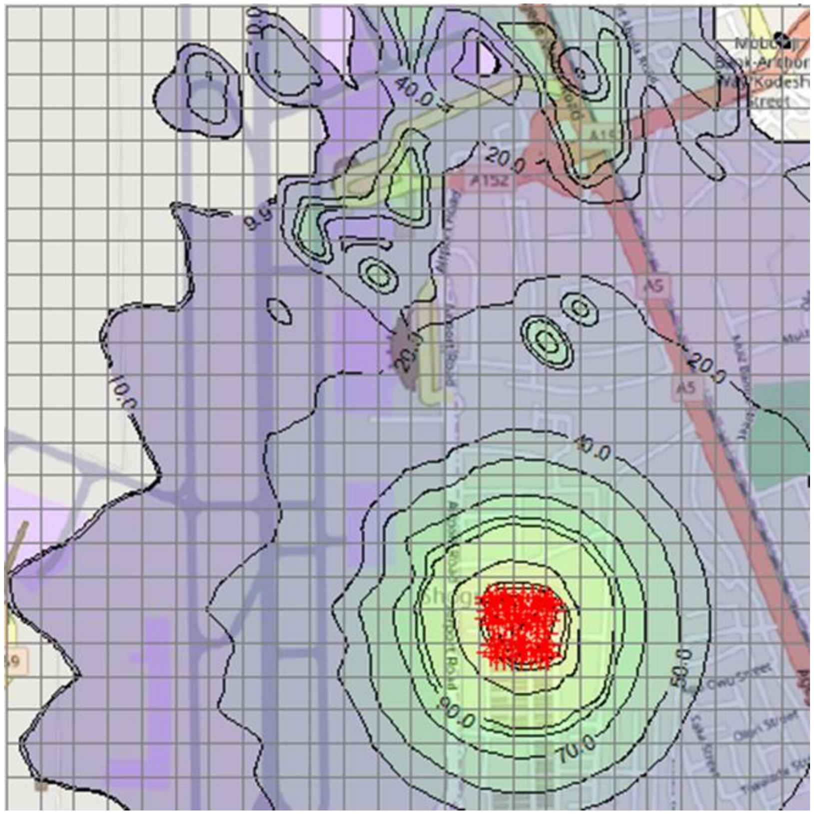

Fig 4.9: 1-Hr NO_2 isopleth without BPIP

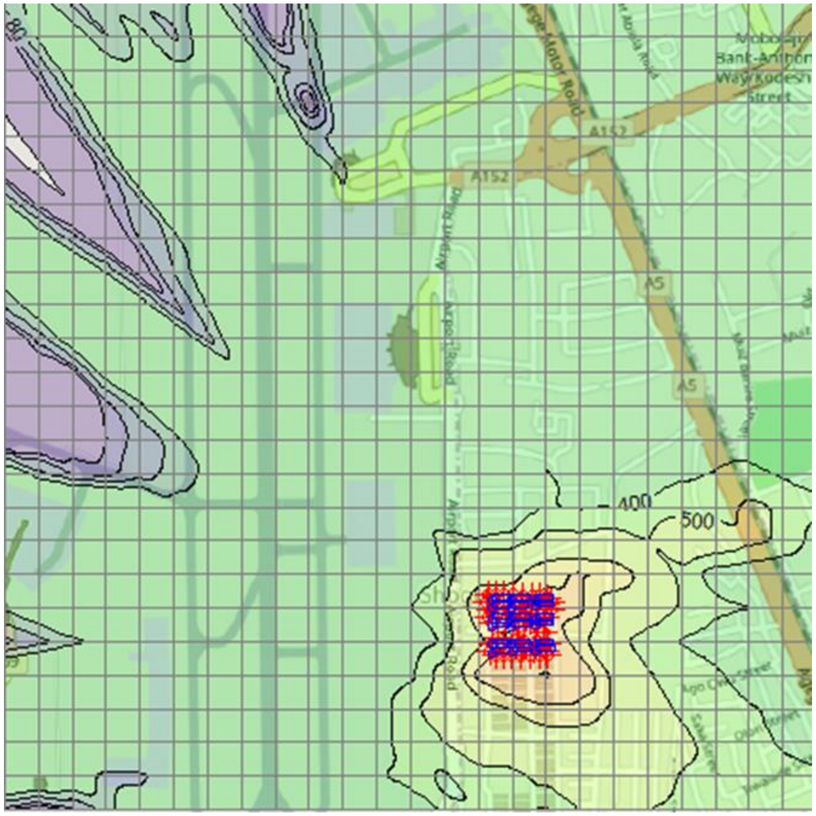

Fig 4.10: 1-Hr NO_2 isopleth with BPIP

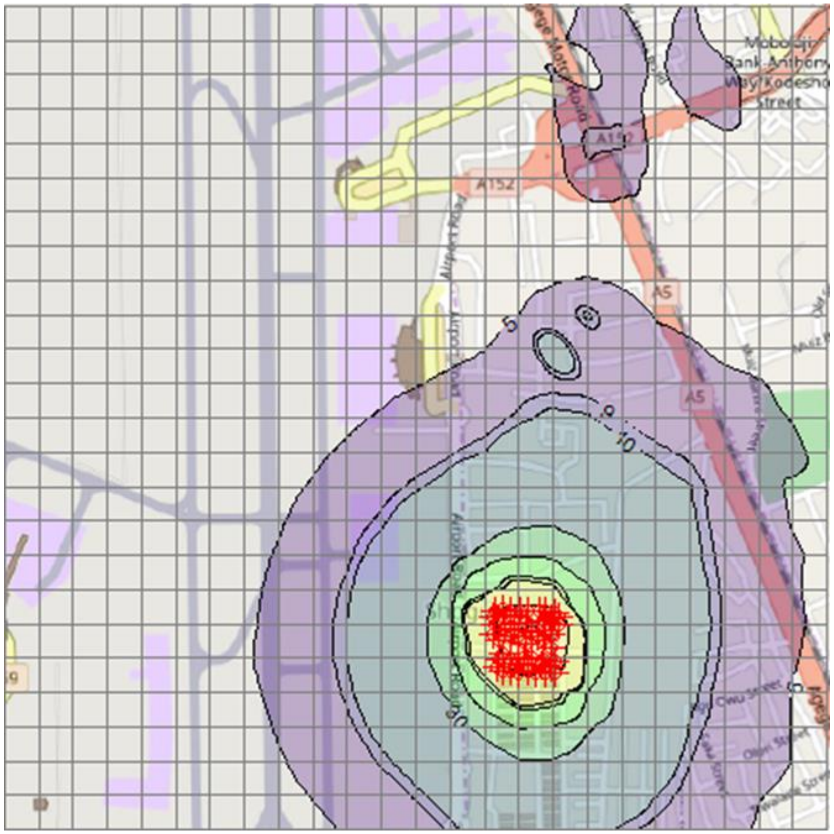

Fig 4.11: 24-Hr NO_2 isopleth without BPIP

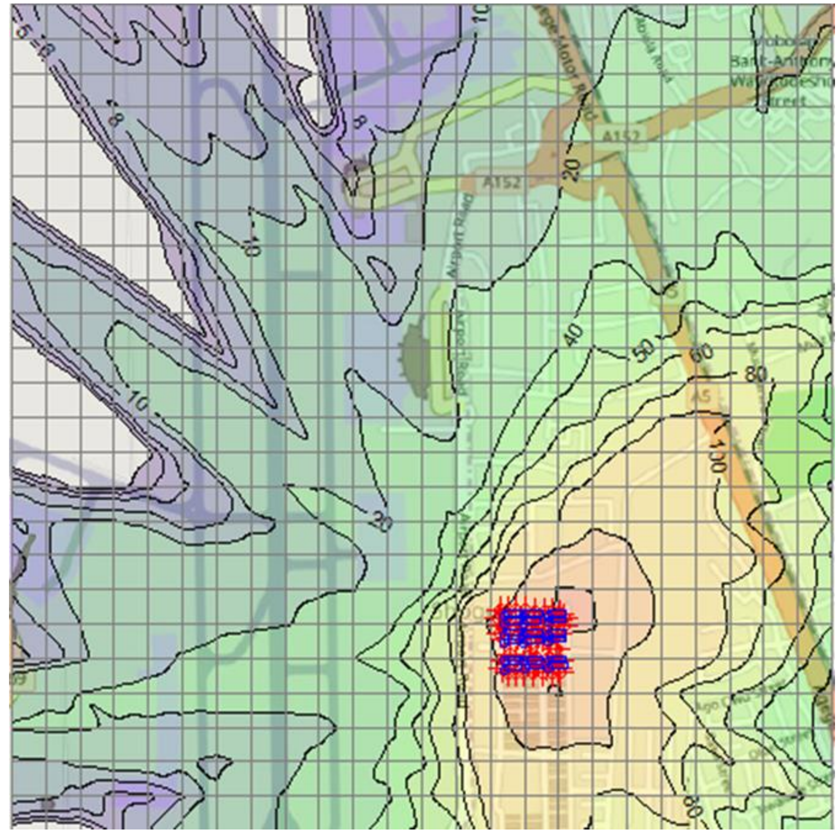

Fig 4.12: 24-Hr NO_2 isopleth with BPIP

4.3 Comparison of modeled pollutant concentrations with air quality standards

There are currently no standards in Nigeria governing emissions from generators. There are also no national ambient air quality standards to regulate ambient air pollution levels. Hence, the USEPA National Ambient Air Quality Standards (NAAQS) and the World Health Organization (WHO) air quality standards will be used as guidelines to assess exceedances.

Four out of the six NAAQS criteria pollutants are regularly emitted during generator use. These are CO, NO_2, PM, and SO_2. The other two criteria pollutants are ozone and lead. Ozone is a secondary pollutant that is formed due to reactions of gases in the atmosphere. Lead on the other hand has been banned from use in fuel for combustion engines. The WHO guidelines apply to PM, O_3, NO_2 and SO_2. Table 4.5 shows the NAAQS and WHO pollutant averaging times and limits as well as results for modeled pollutants. Modeled pollutant concentrations of CO, NO_2 and SO_2 are from the use of DICE-Africa and Shah et al emission factors. While modeled PM_{10} results are from the use of AP-42 emission factors.

Table 4.5: Modeled pollutants with USEPA and WHO air quality standards

	USEPA NAAQS ($\mu g/m^3$)		WHO air quality guidelines ($\mu g/m^3$)		Modeled pollutant concentration with BPIP ($\mu g/m^3$)	
	Averaging Time		Averaging Time		Averaging Time	
Pollutant	1-hr	24-hr	1-hr	24-hr	1-hr	24-hr
CO	40100				1453	
NO_2	99.7		200		1535	
SO_2	200			20	406	113
PM_{10}		150		50		56

From the table above, modeled concentrations of NO_2 (1-hour averaging time) exceed both the USEPA and WHO guidelines. Modeled concentrations of SO_2 (1-hour and 24-hour averaging times) exceed both the USEPA and WHO guidelines, also. Results for PM_{10} exceed the WHO guideline only. The maximum concentration of CO is below the USEPA NAAQS limits.

4.4 Comparison of modeled pollutant concentrations with pollutants from transportation sources

Increase in concentrations of air pollutants within urban areas can also be attributed to transportation sources. Baumbach et al. (1995) measured concentrations of different pollutants, including PM, CO, and NO_x, caused by transportation sources in Lagos. Figures 4.13 and 4.14 from Baumbach et al. show measured pollutant concentrations.

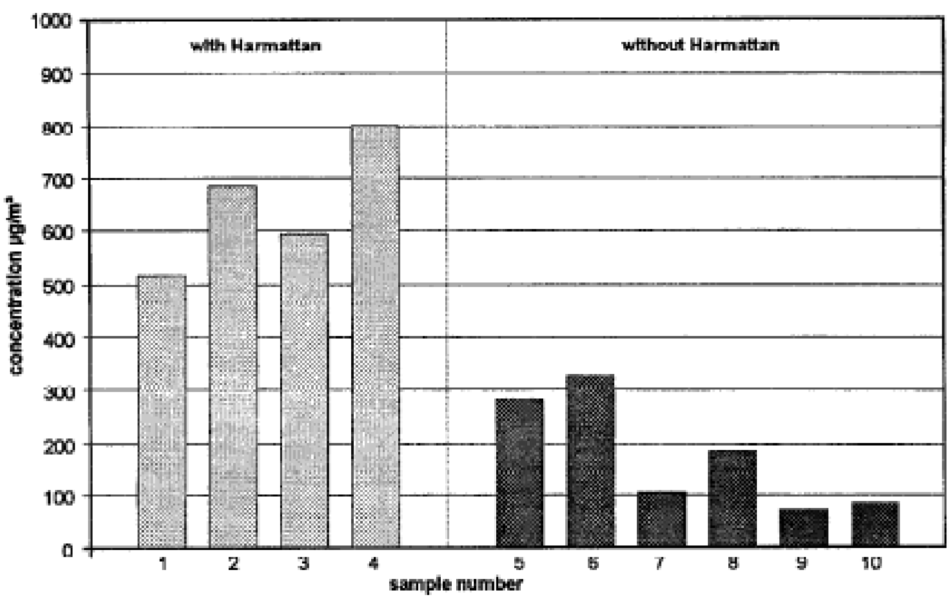

Fig 4.13: 24-Hr average PM concentrations with and without effects of Harmattan (Baumbach et al., 1995)

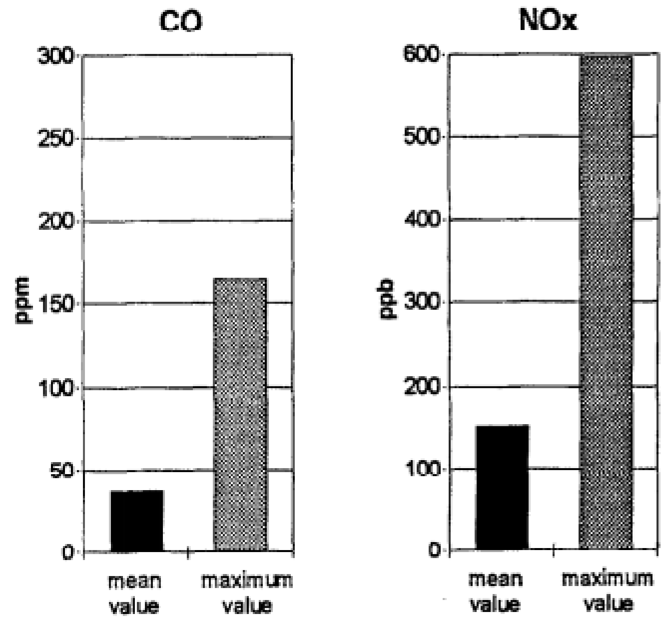

Fig 4.14: CO and NO_x mean and maximum half-hour concentrations (Baumbach et al., 1995)

From Fig. 4.13, the highest 24-hour concentration of PM without Harmattan (Sahara wind) was slightly greater than 300 µg/m^3.; the highest 1-hour concentration would presumably be greater than the 24-hour. The 300 µg/m^3 is higher that our modeled 1-hour PM_{10} concentration of 56 µg/m^3.

Fig. 4.14 shows the highest half-hour concentration of CO to be around 160 ppm (183,230 µg/m^3), which is greater than our highest 1-hour modeled concentration of 1453 µg/m^3. The highest half-hour NO_x concentration in Fig. 4.14 is around 600 ppb (680 µg/m^3), which is considerably less than our modeled NO_2 concentration of 1535 µg/m^3. Since around 90% of NO_x is emitted as NO, our modeled concentration of NO_x would have been considerably higher, if an emission factor had been available. Thus, this comparison shows that concentrations of NOx due to generators far exceed those due to transportation sources in Lagos.

Olajire et al. (2011) measured PM_{10} concentrations from transportation in Lagos to be 274.6 μg/m^3, while CO was measured as 19.27 ppm (22,070 μg/m^3). These values are again greater than our maximum modeled values for PM_{10} (56 μg/m^3) and CO 1453 (μg/m^3). Measured concentrations of SO_2 and NO_2 were 101.2 ppb (265.1 μg/m^3) and 62.5 ppb (117.5 μg/m^3), respectively. Based on a 1-Hr averaging time, our modeled concentrations of SO_2 and NO_2 were 406 μg/m^3 and 1535 μg/m^3, respectively, both of which exceed the measured values. 24-Hr averaging time concentrations were 113 μg/m^3 for SO_2 and 429 μg/m^3 for NO_2; this modeled NO_2 value again exceeds the concentration measured from transportation sources.

4.5 Recommendations to reduce air quality impacts from generators

To reduce the risk to human health as a result of air pollution caused by the used of numerous backup generators within the Lagos metropolis, it is recommended that:

- The government invests in infrastructure to provide a stable electricity supply, especially within congested urban areas, to limit the emissions from generators. From the results, it is clear that building downwash from tightly spaced building in urban cities increase the 1-hr ambient concentration of air pollutants as dispersion of air pollutant is restricted.
- Emission standards for backup generators should be adopted to reduce levels of ambient air pollution.
- Information be disseminated to ensure citizens are aware of the implications of the use of numerous generators during weather events that may limit the dispersion of air pollutants emitted from generator use.
- There should be increased meteorological and air quality monitoring sites to serve as a basis for regulatory decisions.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

Many people in developing countries now rely on backup generators to produce electricity in the absence of a centralized system. In Lagos Nigeria, it is estimated that over 60 million people own and operate small to medium size generators to provide electricity for their daily use. The use of numerous generators by private individuals as well as businesses contributes to air pollution which increases the mortality rates in these regions. The WHO 2016 report concludes that one out of every nine deaths worldwide was attributed to air pollution related conditions. One objective of this study is to estimate the contributions of emissions from backup generators to ambient air pollution in Lagos.

AERMOD View is used to estimate the concentrations of air pollutants emitted from backup generators. Fifty generators are placed within a 200 m by 200 m square area adjacent to the Murtala Muhammed International Airport where the weather station is located. The placement of the generators is to simulate multiple generators working during a blackout. Emission factors from USEPA AP-42 (1995), Shah et al. (2006), and DICE Africa (2013) are used to calculate emission rates used as input data in AERMOD View.

The results of the runs show that concentrations of air pollutants obtained from the use of Shah et al. (2006) and DICE-Africa (2013) emission factors are higher than results obtained from the use of USEPA AP-42(1995). As expected, concentrations for a 1-hour averaging time exceeded those for a 24-hour averaging time, and concentrations considering building downwash exceeded those in which building downwash was not considered.

The results of the model run are compared with the USEPA NAAQS and the WHO air quality guidelines. Modeled concentrations of these air pollutants show that the use of multiple generators during a blackout will result in exceedances of air quality standards and guidelines for NO_2 and SO_2. The modeled concentrations of NO_2 also exceed measured concentrations of NO_2 due to transportation sources in Lagos, as reported in the literature. PM10 concentrations exceed the WHO guidelines, but not NAAQS. Concentrations of CO were below USEPA NAAQS.

To reduce the risk to human health as a result of air pollution caused by the used of numerous backup generators within the Lagos metropolis, it is recommended that the government invest in infrastructure to provide a stable electricity supply, and emission standards for backup generators be adopted.

5.2 Recommendations for Future Research

- Receptor grid spacing should be reduced to determine whether concentrations in the 200 m x 200 m source area increase.
- Similar studies of the impact of back-up generator use should be conducted for urban areas in other developing countries.
- Similar studies of other inefficient combustion sources should be conducted for urban areas in other developing countries.
- A comparison of modeled concentrations with monitoring values should be done, when monitoring value become available.
- Upper air meteorological data and terrain data should be collected and made publically available for Lagos, Nigeria. More broadly, an assessment should be conducted of the availability of upper air met data and terrain data for major urban areas in developing

countries. Based on results of the assessment, studies should be conducted to fill gaps in available data.

APPENDIX A

AERMOD VIEW SOURCE PATHWAY GENERATORS AND BUILDING COORDINATES

ID_Building	Tier_Number	Base_Elevation	Tier_Height	X_Length	Y_Length	X1	Y1
		[m]	[m]	[m]	[m]	[m]	[m]
BLD_1	1	34.9	28	52	15	537042.28	727103.86
BLD_2	1	34.38	28	52	15	537101.54	727105.12
BLD_3	1	34.96	28	52	15	537172.73	727105.39
BLD_4	1	35.61	28	52	15	537041.63	727082.41
BLD_5	1	34.77	28	52	15	537101.00	727082.45
BLD_6	1	34.97	28	52	15	537173.29	727086.04
BLD_7	1	36.01	28	52	15	537042.54	727050.91
BLD_8	1	35.08	28	52	15	537102.13	727050.29
BLD_9	1	35.43	28	52	15	537173.98	727050.11
BLD_10	1	35.97	28	52	15	537043.22	727024.60
BLD_11	1	35.02	28	52	15	537101.92	727026.41
BLD_12	1	35.3	28	52	15	537173.33	727029.44
BLD_13	1	34.99	28	52	15	537044.14	726973.42
BLD_14	1	34.12	28	52	15	537102.40	726974.12
BLD_15	1	33.64	28	52	15	537174.00	726974.12
BLD_16	1	34.99	28	52	15	537044.38	726949.43
BLD_17	1	34.13	28	52	15	537103.63	726951.24
BLD_18	1	33.67	28	52	15	537174.82	726953.05

ID	Desc	Base_Elev	Height	Release_Type	X1	Y1
		[m]	[m]		[m]	[m]
STCK1	Gasoline Generator	34.66	0.15	VERTICAL	537032.29	727119.31
STCK2	Gasoline Generator	34.48	0.15	VERTICAL	537054.55	727122.73
STCK3	Gasoline Generator	34.47	0.15	VERTICAL	537078.51	727119.31
STCK4	Gasoline Generator	34.38	0.15	VERTICAL	537105.90	727119.31
STCK5	Gasoline Generator	34.44	0.15	VERTICAL	537131.58	727117.59
STCK6	Gasoline Generator	35.01	0.15	VERTICAL	537162.39	727115.88
STCK7	Gasoline Generator	35.37	0.15	VERTICAL	537182.94	727117.59
STCK8	Gasoline Generator	35.81	0.15	VERTICAL	537206.90	727112.46
STCK9	Gasoline Generator	35.22	0.15	VERTICAL	537028.87	727098.76
STCK10	Gasoline Generator	35.52	0.15	VERTICAL	537060.68	727065.97
STCK11	Gasoline Generator	34.69	0.15	VERTICAL	537080.22	727105.61
STCK12	Gasoline Generator	34.7	0.15	VERTICAL	537126.33	727084.78
STCK13	Gasoline Generator	33.54	0.15	VERTICAL	537169.97	726960.37
STCK14	Gasoline Generator	35.33	0.15	VERTICAL	537172.67	727090.20
STCK15	Gasoline Generator	35.73	0.15	VERTICAL	537200.05	727093.63
STCK16	Gasoline Generator	35.99	0.15	VERTICAL	537217.17	727098.76
STCK17	Gasoline Generator	35.5	0.15	VERTICAL	537035.72	727078.22
STCK18	Gasoline Generator	34.65	0.15	VERTICAL	537078.55	726976.76
STCK19	Gasoline Generator	34.97	0.15	VERTICAL	537090.50	727083.36
STCK20	Gasoline Generator	34.29	0.15	VERTICAL	537100.13	726964.58
STCK21	Gasoline Generator	33.94	0.15	VERTICAL	537132.20	726962.56
STCK22	Gasoline Generator	34.52	0.15	VERTICAL	537197.36	727010.61
STCK23	Gasoline Generator	33.43	0.15	VERTICAL	537206.69	726974.09
STCK24	Gasoline Generator	35.97	0.15	VERTICAL	537218.89	727076.51
STCK25	Gasoline Generator	36.09	0.15	VERTICAL	537030.58	727052.54
STCK26	Gasoline Generator	34.99	0.15	VERTICAL	537046.85	726976.39
STCK27	Gasoline Generator	35.23	0.15	VERTICAL	537092.21	727064.53
STCK28	Gasoline Generator	34.95	0.15	VERTICAL	537121.31	727064.53
STCK29	Gasoline Generator	35.17	0.15	VERTICAL	537143.56	727054.25
STCK30	Gasoline Generator	35.57	0.15	VERTICAL	537181.22	727062.81
STCK31	Deisel Generator	34.12	1	VERTICAL	537140.99	726983.15
STCK32	Deisel Generator	35.68	1	VERTICAL	537199.51	727051.50
STCK33	Deisel Generator	33.23	1	VERTICAL	537198.86	726955.37
STCK34	Deisel Generator	33.48	1	VERTICAL	537182.51	726939.67
STCK35	Deisel Generator	34.98	1	VERTICAL	537175.31	727031.23
STCK36	Deisel Generator	33.84	1	VERTICAL	537172.70	726979.57
STCK37	Deisel Generator	33.12	1	VERTICAL	537209.32	726939.67
STCK38	Deisel Generator	35.14	1	VERTICAL	537156.35	727044.96
STCK39	Deisel Generator	34.67	1	VERTICAL	537123.65	727023.38
STCK40	Deisel Generator	33.87	1	VERTICAL	537153.73	726940.33
STCK41	Deisel Generator	34.34	1	VERTICAL	537115.80	726985.45
STCK42	Deisel Generator	35.07	1	VERTICAL	537058.25	726994.61
STCK43	Deisel Generator	34.52	1	VERTICAL	537102.07	726939.67
STCK44	Deisel Generator	35.15	1	VERTICAL	537104.03	727047.58
STCK45	Deisel Generator	35.37	1	VERTICAL	537081.14	727045.62
STCK46	Deisel Generator	34.76	1	VERTICAL	537077.87	726941.64
STCK47	Deisel Generator	35.03	1	VERTICAL	537039.94	726954.71
STCK48	Deisel Generator	34.99	1	VERTICAL	537054.33	726944.25
STCK49	Deisel Generator	35.69	1	VERTICAL	537042.56	727036.46
STCK50	Deisel Generator	34.18	1	VERTICAL	537128.88	726942.94

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