A modelling study of road traffic contributions to ambient $PM_{2.5}$ concentrations in Lagos

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Abstract

As the fastest growing city in Africa, Lagos experiences extremely high levels of air pollution. While there are many sources of air pollution in Lagos, road traffic has been widely reported as the most prominent.

Due to a dearth of studies on modelling of pollutant dispersions from vehicular emissions, this study adapted the OSCAR System to model the contributions of road traffic to ambient concentrations of $PM_{2.5}$ in the megacity.

The model was evaluated by comparing its predicted $PM_{2.5}$ concentrations with the observed concentrations in the study area. This comparison was carried out using a number of conventional statistical parameters: model bias, normalised mean square error, fractional bias, correlation coefficient (R) and factor of 2 analysis (F2). The evaluation showed aggregate R and F2 values of 0.66 and 0.80 respectively. This implies a good level of agreement between the measured and the predicted $PM_{2.5}$ concentrations.

For November 2018, the model predicted mean traffic increment of 28.1$\mu g/m^3$ (37.2%) - 29.3 $\mu g/m^3$ (38.2%) along the Mile 12 – Ikorodu road. However, the predicted increment around the Expressway (a busier road) was 36.5 $\mu g/m^3$ (43.5%). The Ikorodu -Mile 12 road is a very important traffic corridor in the Lagos Metropolitan Area – being the pioneering route for the government's Bus Rapid Transit scheme.

A scenario analysis carried out in this study shows that under a fixed meteorological condition, traffic contributions (to ambient concentrations of $PM_{2.5}$) would increase by a factor of 7 (from November 2010 to November 2018) near the Ikorodu road. Further, it reveals that cars are the highest emitters of $PM_{2.5}$ along the Ikorodu road. Hence, the government's "Non- Motorised Transport (NMT)" policy could enhance reduction of $PM_{2.5}$ emission along the Ikorodu road.

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LIST OF ABBREVIATIONS

LASG	Lagos State Government
UNEP	United Nation Environment Programme
SNAQ	Sensor Network for Air Quality
UNILAG	University of Lagos
LGA	Local Government Authority
LMA	Lagos Metropolitan Area
FAA	Federal Aviation Administration
LAMATA	Lagos Metropolitan Area Transport Authority
CARNARSDA	Centre for Atmospheric Research, National Space Research and Development Agency
OSCAR	Optimised Expert System for Conducting Environmental Assessments of Urban Road Traffic**.**
USEPA	United States Environmental Protection Agency
ADMS	Air Quality Dispersion Model Setup
GHG	Green House Gases
DEFRA	Department of the Environment, Fisheries and Rural Affairs
CAIR	Centre for Atmospheric and Instrumentation Research
AERMOD	American Meteorological Society/Environmental Protection Agency Regulatory Model
CAR	Centre for Atmospheric Research

WHO	World Health Organization
CDC	Centres for Disease Control and Prevention
UoP	University of Portsmouth
FEMEN	Federal Ministry of Environment, Nigeria.
NASA	National Aeronautics and Space Administration
FMI	Finish Meteorological Institute
UH	University of Hertfordshire
GMAO	Global Modelling and Assimilation Office
GPS	Global Positioning System
NMT	Non- Motorised Transport
NIMET	Nigeria Meteorological Agency
NAEI	National Atmospheric and Emission Inventory
NERC	Natural Environmental Research Council

Chapter 1

1.0 Introduction

Air pollution remains one of the major problems being encountered by African nations (United Nation Environment Programme (UNEP),2016). Hence, it is not surprising that this subject matter continues to attract the attentions of various organizations, individuals and research groups with interest in air pollution and environmental health studies.

In a report from one of those groups of researchers, Brauer et al. (2012), the Sub-Saharan Africa was rated as having the highest concentrations of $PM_{2.5}$ in the world. In corroboration, FEMEN (2015) also asserts that the highest concentrations of atmospheric aerosols were observed in the region. Likewise, Liousse and Galy-Lacaux (2010) report that the average daily NO_2 concentrations measured in Africa was far above the safe limit set by the World Health Organization.

Considering the adverse health implication of long-term exposures to particulate matters and pollutant gases, the aforementioned report (and others like it) may have caused a great deal of concerns for the various governments of the African nations. As particulate matters are easily inhalable (especially the fine components, $PM_{2.5}$), exposures to them have been consistently linked to respiratory and cardiovascular problems (Sokhi et al, 2008; World Health Organization (WHO), 2013).

Particulate matters (PM)exist in the atmosphere through natural and anthropogenic processes. In a typical urban area in Africa, the main anthropogenic sources of PM include combustion of fuels in automobile engines; combustion of fuel in homes for cooking and heating; and combustion of fuels for generating energy in industries (WHO,2013 and Olajire et al, 2011). However, findings from various studies have shown that, in a representative megacity, particulate matters are predominantly from road traffic (Abam and Unachukwu,2009; Hopkins et al,2009).

1.1. Air pollution in an African megacity

As the fastest growing city in Africa (Lagos State Government (LASG),2017), Lagos experiences very high levels of air pollution when compared with other cities in Nigeria. Sources of air pollution in Lagos include wood burning, waste incineration, gas flaring, emissions from industries, vehicular emissions and the Saharan desert (Baumbach et al.,1994; Marias et al., 2014; Oketola and Osinbajo, 2007).

However, road traffic has been reported to be mostly responsible for air pollution in the city (Ajayi and Dosunmu, 2002; Baumbach et al, 1994). This is because there are more vehicles in Lagos than in any other city in Nigeria.

Describing the road traffic situation in Lagos, Owoade et al. (2013) report that over 1 million vehicles ply the roads in Lagos every day and this causes frequent traffic congestions. In concordance, Okunola (2005) also reports that the vehicle density for Lagos (which is 222 per kilometre) is higher than the national average of 11vehicle per km. This invariably implies that traffic-induced air pollution may be higher in Lagos than in any other city in Nigeria.

1.2. Research aim and justification

Some studies have been carried out on the subject of air pollution in Lagos. While a significant number of them has pointed at vehicular emissions as the highest contributor to the ambient concentration of particulate matters (especially $PM_{2.5}$), none has quantitatively described how these particles disperse from road traffic to the surrounding areas.

A thorough understanding of air pollutant dispersion, through atmospheric processes, can be achieved through mathematical simulations- which usually involve using a conventional dispersion model (United States Environmental Protection Agency (USEPA),2017).

Similarly, health-related and other types of benefits associated with modelling of air pollutants dispersion are well documented in the literature. Therefore, the aims of this study are to:

(i) select the most appropriate sets of emission factors for computing emission rates of $PM_{2.5}$ from Lagos' roads.

(ii) describe dispersion characteristics of $PM_{2.5}$ from roads in Lagos.

(iii) quantify the contributions of road traffic, to ambient concentrations of $PM_{2.5}$ in representative streets of Lagos.

(iv) describe the influence of changing vehicular emissions on ambient concentrations of $PM_{2.5}$ in a representative street of Lagos.

1.3. Specific Objectives

In respect of the aim of this research, the specific objectives are:

(i) To conduct a thorough critical review focussing on previous work, observations, emissions, and modelling.

(ii) To collate necessary emissions, source and meteorological data for the study area

(iii) To set up a model for processing meteorological fields based on available datasets

(iv) To configure an atmospheric dispersion model for this study

(v)To evaluate the model by comparing the predicted $PM_{2.5}$ concentrations with the observed concentrations

(vi) To undertake sensitivity analysis which investigates the influence of local emissions on ambient $PM_{2.5}$ concentrations.

(vii) To test the suitability, for this study, of emission factors from local and other sources.

Further, to achieve the aforementioned objectives, the steps taken are detailed in the succeeding chapters of this report. First, a critical review of air pollution in Africa was conducted and presented in the next chapter. This, in chapter 3, is followed by detailed description of dispersion modelling, with a focus on Gaussian plume models. In chapter 4, the methodology employed in this study is discussed while chapter 5 involves the presentation, analysis and discussion of the results obtained from this work. Finally, in chapter 6, specific conclusions were drawn and recommendations were made, based on the findings from this study.

Chapter 2

2.0 A Review of air pollution in Africa

An overview of air pollution in Africa is carried out in this chapter – with a special focus on Lagos, the fastest growing city on the continent. As prelude, a global perception of air pollution is presented. This is followed by a discussion on Africans' increasing awareness of air pollution. As the most populous country in Africa, air pollution in Nigeria is examined in detail and compared with the experiences of other African nations of the subject matter. Finally, in the chapter, a detailed account of air pollution in Lagos, is given.

2.1. Global perception

Air pollutants find their ways into the atmosphere through anthropogenic and non-anthropogenic sources. Examples of anthropogenic sources are combustion of fuels in automobile engines; building constructions, road constructions; mining processes and industrial activities. Non-anthropogenic sources include chemical transformation of gases in the atmosphere and natural disasters (Owoade et al., 2013; WHO, 2013).

In addition, in some cases (depending on their physio-chemical properties), pollutant particles travel several thousands of kilometres from their sources to other locations resulting in increased concentration of the pollutants at such locations. This always have negative effects on human well-being and the overall health of the environment (Leelössy et al., 2014; Araujo et al., 2017). On global scale, air pollutions have been linked to a growing number of health problems, poor visibility and climate change (Arya,1999 cited in Owoade, 2013; Beelen et al, 2013 cited in Njoku et al, 2016). Air pollution – induced health problems include respiratory, cardiovascular and pulmonary diseases which usual result to incapacitation and untimely death (WHO, 2013). According to WHO (2019), about 4.2 million and 3.8 million people die every year as a consequence of exposure to outdoor and indoor air pollution respectively.

Although there are many types of pollutants in the atmosphere, the concentrations of particulate matters (PM), carbon dioxide, nitrogen oxides and sulphur oxides are usually considered when assessing the air quality of a place (Araujo et al., 2017).

2.2 A growing awareness

A good number of air pollution studies has been carried out on Africa. Some of these focus on observations of ambient pollutant concentrations, effects of air pollution, political views on air pollution and emission reduction strategies. Consequently, there is an increasing awareness of air pollution (and its attendant problems) throughout the continent (Assamoi and Liousse, 2012). Specifically, the recent attentions being given to air pollution problems, by policy-makers, was stirred -up by available records on the number of premature deaths and illnesses attributable to poor air quality. For example, the United Nation Environmental Programme (UNEP) estimates the annual number of deaths on the continent (due to air pollution) to be around 600,000 (UNEP, 2016).

This, however, is about 3.4 times of 176,000 which was reported as the number of air pollution-related deaths in Africa for the year 2012 by the World Health Organization (WHO, 2014). In contrast to the UNEP's estimate, the University of Portsmouth (UoP, 2018) reported 920,000 as the number of death due to exposure to particulate matters (PM).

Notwithstanding the contradiction in the available records of air pollution-related death, a common submission from most of the existing reports is that air pollution problems in Africa is worse than imagined. Brauer et al. (2012) report that with an annual average estimate of $100µg/m^3$, the sub-Saharan Africa can be described as the region of the world with the highest concentration of $PM_{2.5}$ considering the estimated annual average value of less than $20µg/ m^3$ recorded in Europe and North-America. In 2004, as part of the POLICAP (Pollution de Capitals Africaines) program, the preliminary observations of some pollutants (NO_2, SO_2, NH_3) in 15 African countries showed that average daily NO_2 concentration was higher than 40µg/m3 which was the safe limit set by the World Health Organization (Liousse and Galy-Lacaux,2010). In the same vein, this part of the world has also been classified as one of the regions with the highest concentrations of atmospheric aerosol (FEMEN, 2015). The driving force for air pollution in African countries is increasing growth in population and urbanization which are responsible for increased energy demand, increased ownership of automobiles and difficulty in waste management (Amegah and Agyei-Mensah, 2016). While they agree with this assertion, Doumbia et al. (2012) added poor fuel quality and meteorological conditions as contributing factors to air pollution problems in the region. Similarly, the United Nations Environment Programme (UNEP, 2016) attributes air pollution problems in Africa to continuous rise in urbanization and use of sub-standard qualities of fuels and vehicles.

2.3 Air pollution in Africa's most populous nation

2.3.1. Background information

With 170 million people (data of 2012), Nigeria is the most populous country not only in the sub-Saharan African belt but also in the whole of the continent of Africa (Marias et al., 2014). Globally, Nigeria's population occupies the 7th position, and is growing at the fastest rate. It has been projected to surpass that of the United States of America by 2050 (UN, 2015). In addition, Nigeria is ranked as having the highest population of urban dweller in Africa and is placed 9th in the world. It is estimated that by 2013, there were about 80 million urban dwellers in Nigeria (Rafei and Tabary., 2014).

In parallel to a growing population, Nigeria's economy is also enlarging due to its wide range of natural resources which include solid minerals, crude oil and natural gas reserves. The country's proven reserve of natural gas is estimated to be about 182 trillion cubic metre which is ranked 7th in the world (Shaaban and Petitin, 2014; Oyedepo, 2014). Having surpassed the South Africa, Nigeria's economy recently became the largest in Africa and the 23rd largest in the world (Magnowski, 2014; Rafei and Tabary, 2014).

2.3.2. Air pollution in Nigeria

Due to lack of adequate infrastructure to minimise the impacts of population and economic growth on the environment, Nigeria's urban air pollution is increasing at an alarming rate (FEMEN, 2015).

According to the air quality database of the World Health Organization, Onitsha is the city with the highest concentration of PM_{10} in the world. Apart from Onitsha, there are three other

Nigeria' cities (Aba, Kaduna and Umuahia) on the list of the World's worst twenty cities for air pollution (Mc McCarthy, 2016). However, due to their status or economic importance, other cities (such as Lagos and Abuja) are also receiving increasing interest from the science research communities. Abuja is the capital city of Nigeria while Lagos accounts for more than 70% of all commercial and industrial activities in the country (Owoade et.al, 2013; Olajire et al,2011; Hopkin et al., 2009).

Sources of air pollution in Nigeria include vehicular traffic, gas flaring, biomass burning, industrial activities and transportation of dust particles from the Sahara Desert (Baumbach et al., 1995, Shaaban and Petitin, 2014; Oyedepo,2014). Due to the high level of air pollutants emanating from these sources, there is an increasing risk on public health in most of the urban areas in the country. To illustrate, in major cities like Lagos, PM_{10} has been linked to an increase in the incidence of asthma, and cardiovascular diseases (Olowoporoku, 2012).

2.3.3. Comparing Nigeria with other African nations

Although the driving factors for air pollution are similar across the continent, the problem of air pollution in Nigeria is of a higher magnitude when compared with the situations in other countries on the continent. This due to Nigeria's position as the nation with the highest population and the largest economy on the continent. In corroboration, Assamoi and Liousse (2010) conclude that the highest numbers of two and four- wheel vehicles in West Africa are found in Nigeria, and this puts vehicle-induced air pollution in Nigeria on a larger scale than in any other country in the region. As shown in the Figure 2.1, the amount of black carbon emitted (from two-wheel vehicles in Sub-Saharan Africa) was highest in Nigeria, for the year 2002.

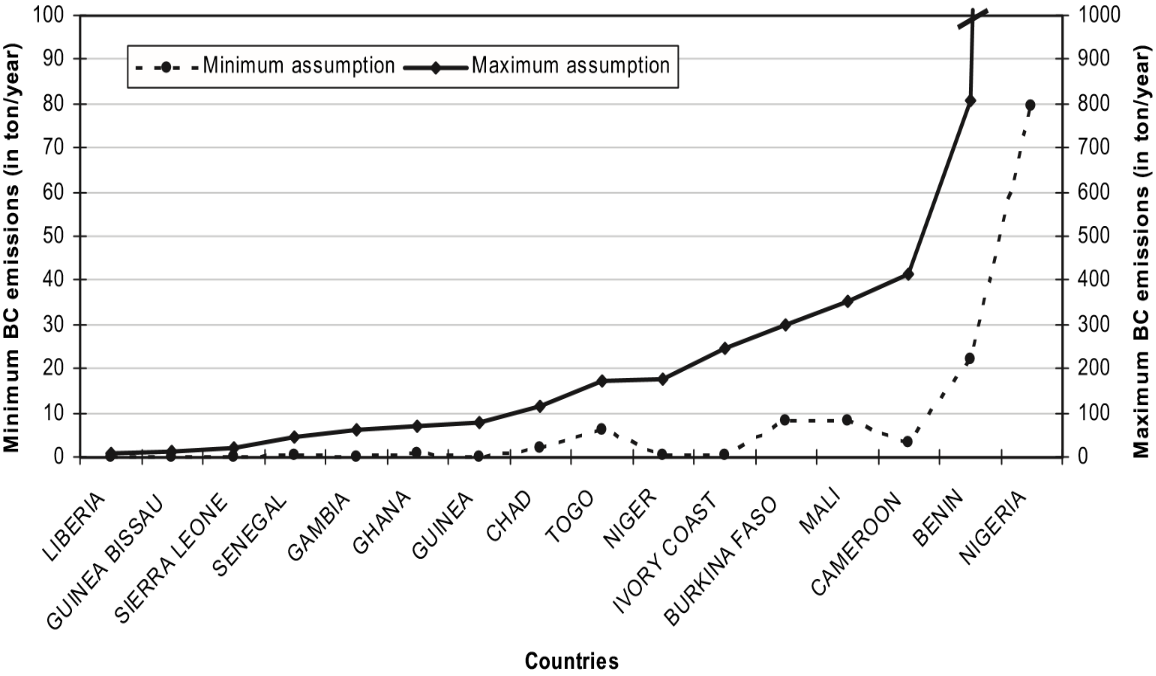

Figure 2.1: Black carbon (BC) emissions from two-wheel vehicles in Sub-Sahara African countries. Assamoi and Louise (2010, p.6)

Apart from vehicular emission, gas flaring is another major source of air pollution Nigeria because of the country's huge natural gas reserve which is ranked as the seventh in the world (Shaaban and Petitin, 2014; Oyedepo,2014). However, as other West African countries are non-oil producing, their air qualities are not affected by pollutants from this source. The pollutants emanating from gas flaring activities include volatile organic compound (VOC), NO_x, SO_2, CO, organic carbon and $PM_{2.5}$ (Chuwah and Santillo, 2017; Giwa et al. 2017).

In addition to vehicular emissions, transportation of coarse particles from the Sahara Desert is also a common source of air pollution across the Sub-Saharan African belt (Baumbach et al., 1995). This view was also held by the Federal Ministry of Environment in Nigeria (FEMEN) as it concludes that particles from the Sahara Desert are major contributors to the problem of air pollution in Nigeria (FEMEN, 2015).

Furthermore, the air quality database of the World Health Organization ranks Onitsha (a city in Nigeria) as the city with the highest concentration of PM_{10} in the world. Apart from Onitsha, there are three other Nigeria' cities (Aba, Kaduna and Umuahia) on the list of the World's worst twenty cities for air pollution (Mc McCarthy, 2016). This further establishes Nigeria as the country with the greatest air pollution challenges in Africa.

2.4. Air quality: the Lagos' perspective

Lagos is the fastest growing city in Africa and the seventh in the world. The city's population is currently estimated at 21 million (LASG, 2017).

Lagos is located in the southwestern area of Nigeria. It lies within latitudes 6° 23' N & 6° 41'N and longitudes 2° 42'E & 3° 42'E (Njoku et al., 2016). The Figure 2.2 shows the location of Lagos in Nigeria.

Figure 2.2: A map showing the location of Lagos in Nigeria (CDC, 2019).

Likewise, Lagos is the economic backbone of Nigeria as it accounts for more than 70% of all commercial and industrial activities in the country (Owoade et.al, 2013; Olajire et al,2011; Hopkin et al., 2009). As at the year 2000, there were about 12 industrial estates in Lagos accommodating more than 300 industries (Oresanya, 2000 cited in Odukoya and Abimbola (2011)).

Currently, more than 53% of all employments in the Nigeria's manufacturing sector are based in the city of Lagos (Nwagwu and Oni, 2015).

Another important driving factor for economic in Lagos are its sea ports which are among the largest and the biggest in Africa (LASG,2017).

Lagos is divided into 20 local government areas for administrative purposes and the entire city has a total land area of 2797. 72Km^2 and water area of 779.56km^2- that is a total landmass of 3577.28km2 (LASG,2017). However, Elias and Omojola (2015) report the landmass of Lagos to be about 3345km2 including the 22% occupied by water. The Figure 2.3 shows the Local Government Authorities within the Metropolitan Area of Lagos.

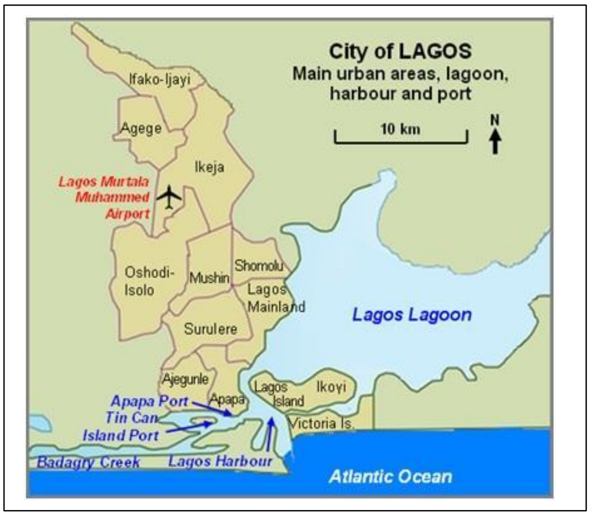

Figure 2.3: Map of Lagos showing the Local Government Authorities in the Metropolitan Area of Lagos. Nwagwu and Oni (2015)

Lagos has a flat terrain with an average height of about 24 metres above the sea level (Braimoh, 2014; Baumbach, 1995).

2.4.1. Land use pattern for Lagos

Over the past few decades, Lagos has experienced growth and remarkable expansion which has brought about important physical projects such as construction of roads, residential buildings and industrial estates. This has resulted to significant changes in the land use pattern for the megacity (Ukor et al., 2016).

The different studies accessed show that researchers use slightly similar classification to describe the land use pattern in Lagos. Braimoh (2014) classifies land -use types as residential, industrial (or commercial), non-urban (comprising of forests and farmlands) and water. In the same vein, Abiodun et al. (2011) categorize land use type in Lagos as “built-up area, Vegetation, Undeveloped areas and water bodies.”. Ukor et al. (2016) used three categories which are settlement, vegetation and shrubland.

However, it is noteworthy to mention that these studies were conducted on different parts of the metropolitan Lagos area. While Abiodun et al. (2011) and Braimoh (2014) focused on the entire area of Lagos, Ukor et al. (2016) focused their study on Ikeja local government; and Dekolo et al. (2013) focused their study on Ikorodu local government area. Across all the studies, the terms “built-up area” and “Urban area” are synonymously used and refer to areas occupied by residential, commercial and industrial buildings.

Similarly, all the studies agree the land cover for the urban/built-up category has increased tremendously over time at the expense of the other categories especially vegetation and the water bodies. An example is given in the Table 2.1 which shows the land use pattern for Ikeja (or Ikeja local government area) which is the capital of Lagos State.

Land Use Land cover 2013	**Area in hectares**	**percentage**
Settlement	3625.2	78.10
Vegetation	509.76	10.92
Shrubland	507.06	10.98
Total	**4642.02**	**100.00**

Table 2.1: Land Use Land Cover for Ikeja- a major part of the chosen area for this study. Ikeja is the administrative seat of the Lagos State Government. Ukor et al. (2016)

2.4.2. Lagos’ weather and climate

“The megacity has a tropical wet and dry climate that borders on a tropical monsoon climate” (LASG,2017). The climatic conditions in Lagos can be broadly characterised into two rainy seasons and two dry seasons. These are summarised in Figure 2.4 below. With the major dry season comes the Harmattan which is a strong Northern wind from the Sahara Desert (Baumbach et al., 1995; LASG,2017).

Figure 2.4: An outline of the Lagos' climatic seasons.

The descriptive features of a weather include sunshine, temperature, rain, wind, cloud cover, heat waves, and others (NASA, 2017). Some of these have been used, in different studies, to describe the average weather conditions of Lagos.

For instance, Adaramola and Oyewola (2011) report the mean wind speed for Lagos to be between 2.1m/s and 3.0m/s. This totally agrees with the 3m/s stated by the Nigeria Metrological Agency (NiMet) (2013). However, Olajire et al. (2011) report an average daily wind velocity of 142-395 ft/min (0.72-2.06m/s) which is significantly different from values reported by NiMet (2013).

The wind speed and other weather parameters for the city, as stated by LASG and NiMet, are shown in the Table 2.3 below.

Parameter	**Source**	**Average Monthly Value**
Wind speed	NiMet	3m/s
Cloud cover	NiMet	75%
Precipitation	NiMet	144 mm
Visibility	NiMet	10 km
Pressure	NiMet	1014mb
Humidity	NiMet	67%
Temperature	LASG	31^{o}C

Table 2.2: Average monthly meteorological parameters for Lagos.

2.4.3. Existing studies on Lagos

As there are no sustainable air pollution abatement mechanisms, the atmosphere around the city of Lagos has become immensely polluted due to rapid growth in population and economy (Oketola and Osinbajo, 2007). These factors are directly responsible for increasing demand for vehicular transportation, energy and open incineration of solid waste.

The attendant consequence of the above-mentioned is the emission of pollutants such as CO, SO, NO_x and particulate matters (PM) into the Lagos airspace (Njoku et al., 2016). Other sources of air pollutants, in Lagos, include gas flaring, oil pipeline vandalization, poor road network and use of mobile power generator as back up to the unreliable power supply (Marias et al., 2014).

Several observations have been carried out to assess the extents of air pollution in Lagos and these are reported in the literature. For instance, the ambient concentrations for CO, O_3, SO_2, CH_4 and PM_{10} were measured around various receptor sites along Oba Akran road to assess the impact of vehicular emission on the quality of the surrounding air (Olajire et al, 2011).

A study was conducted on personal exposure, to $PM_{2.5}$ and PM_{10}, of people travelling (using different modes of transportation) on six major roadways in Lagos (Odekanle et al, 2016). Sonibare (2010) studied the emission of pollutants from existing power stations in Lagos. An estimation of industrial pollution load (from employment standpoint) was carried out in Lagos using a system developed by the World Bank for industrial pollution projection (Oketola and Osinbajo,2007). In an EU funded project (titled 'Environmental Monitoring and Impact Assessment in Nigeria') involving universities in Nigeria, Germany and Britain, observations were carried out to determine the level of air pollution around areas with high vehicular and human activities (such as a bus-stop surrounded by market places) (Baumbach et al, 1995). Likewise, Obayan et al (2018) conducted air quality monitoring around traffic corridors and residential areas in Lagos mainland. From this study, the overall (hourly) mean concentration of $PM_{2.5}$ (around traffic corridors) was reported as 69.6 $\mu g/m^3 \pm$ 35. 1 $\mu g/m^3$.

Considering the reports from existing observations, it is very clear that particulate matters (PM) make the highest contribution to air pollution in Lagos. Further, these reports also point at vehicle emissions as the major source of particulate matters- thus implying that vehicular emissions or road traffic is majorly responsible for the deteriorating Lagos' air quality. In addition, Odekanle et al. (2015) posit that PM_{10} are in a larger proportion (of particulate matters) than $PM_{2.5}$ in Lagos. This is also observed by Owoade et al. (2013) and Ezeh et al. (2014).

In addition to measuring ambient concentrations of pollutants at different sites within the city, other studies have been carried out on the subject matter. Some of these are stated in the following paragraphs.

Emetere et al. (2015) developed models to characterise atmospheric aerosols, in Lagos, based on size; the use of ion beams analytical techniques to determine the constituent elements for samples of $PM_{2.5}$ and PM_{10} collected from various receptor sites around Mushin has been reported by Eze et al. (2014). As part of the African Monsoon Multidisciplinary Analysis (AMMA) Project, emission estimates for Lagos was carried out using a top-down approach (Hopkins et al., 2009). There has also been a report on characterisation and source apportionment of PM for air samples collected from different categories of receptor sites around Lagos (Owoade et al., 2013). Marais et al (2014) investigated air pollution due to ozone using a chemical-transport mode.

The study by Odekanle et al. (2015) was carried out during the dry season. Consequently, the PM concentrations reported appear to be very high. A strong explanation for this is provided in Baumbach et al. (1995) and FEMEN (2015). Both assert that a large quantity of dust particles is transported from the Sahara Desert by the Harmattan during the major dry season. Baumbach et al. (1995) also conclude that both dust particles and particles of CO are simultaneously transported by the strong wind. The Harmattan is a north-easterly trade wind which blows over the West African region from the Sahara Desert into the Gulf of Guinea. The Harmattan is dry, cold and causes advection of large quantity of dust across the region. It occurs as a result of "synoptic-scale pressure gradients that align north–south across the Saharan desert" (Burton et al.,2012). The effect of the Harmattan on PM concentrations, as observed by Baumbach et al. (1995), is shown in the Figure 2.5 below.

Conversely, due to precipitation, lower concentrations of PM were reported in the study conducted by Ezeh et al. (2014), during the rainy season.

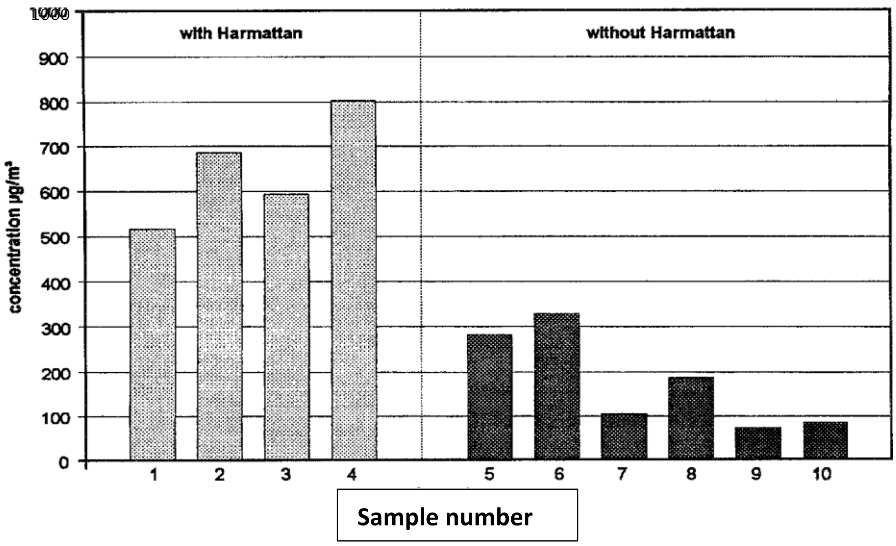

Figure 2.5: Measured concentrations of PM at Lagos' monitoring station, with and without the Northern wind (Harmattan) (Baumbach et al. (1995).

Further, in some of the studies on Lagos, measured pollutant concentrations are compared with those reported for other cities in the world, and with standards given by established environmental protection authorities. For instance, in Odekanle et al. (2015), the 24- hour average PM_{10} concentration of 216.60 $\mu g/m^3$ was considered too high when compared to 214 $\mu g/m^3$ and 27.7 $\mu g/m^3$ reported for Taiwan and London respectively – under similar experimental conditions. Likewise, this value was also reported too high in comparison to safe limit of 150 $\mu g/m^3$ (for a 24-hour average) set by USEPA.

2.5 The gap in existing studies

Considering the available reports, it is evident that existing studies on air pollution in Lagos has been largely centred on ambient concentration measurements, emission estimates and characterization of pollutants. Therefore, it can be arguably concluded that there are few or no existing studies on how these pollutants are dispersed from their sources to various receptor sites in the city. Therefore, there is a justifiable need for such studies to be conducted- especially on vehicular emissions which have been reported to be mostly responsible for air pollution in Lagos (Enemeri, 2001; Ajayi and Dosunmu, 2002; Olukayode, 2005; Baumbach et al, 1995). This type of study, which usually involves the application of an appropriate dispersion model, has been carried out on many urban areas all over the world and the corresponding reports are well documented in the literature.

Chapter 3

3.0. Dispersion Modelling

The concluding section of the preceding chapter highlights the need for more air pollution studies involving applications of dispersion models, in Lagos. Consequently, in this chapter, a review of dispersion modelling is presented- focusing on Gaussian models. Similarly, as an example and being the model employed for this study, a detailed description (including configuration and data requirements) of the OSCAR System is presented in section 3.2.1 of this chapter.

3.1. Synopsis

The mechanisms governing the transport, transformation and accumulation of pollutants in the atmosphere include advection (wind field), chemical reactions, turbulence, diffusion, and deposition. The distance that a pollutant can be transported depends on its lifetime. If the emitted pollutant has “a short lifetime (minutes-hours) in the atmosphere”, it can only be transported a short distance (before it transforms). Therefore, its effects will only be on a local scale. Reactive pollutants (except some like NO_x and SO_x) and aerosols have short lifetimes. Pollutants with long lifetimes (hours-days) can be transported further away and, consequently, have regional or continental scale impacts. For this category, a regional or continental approach to dispersion modelling is required (Leelö ssy et al, 2014).

Dispersion modelling is a mathematical simulation of how atmospheric processes disperse pollutants to various locations away from their emission sources (USEPA, 2017). A dispersion model can enhance a thorough understanding of how emission sources affect the quality of air in a location; it can be used to predict the downwind concentrations of pollutants at specific distances away from their sources thereby creating an avenue to quickly identify areas which are most likely to be severely affected by these pollutants (USEPA, 2017; Borrego et al, 2003).

Dispersion models can be classified as Gaussian, Langrangian or Eulerian based on their mathematics (Leelö ssy et al, 2014). A number of models in these classes have been widely used in investigating air pollution problems on street, local and regional scales.

3.2 Gaussian plume Models

Gaussian plume model's development is based on the Gaussian distribution of plumes in both the horizontal and vertical directions under steady state conditions; for this type of model the atmospheric turbulence is assumed to be stationary and homogeneous-conditions which are rarely absolutely satisfied (Adel-Rahman,2008; Holmes and Morawska 2006).

One of the key limitations of this model type is its poor prediction of concentrations under low wind conditions which usually involve the diffusion of wind in three dimensions (Leelö ssy et al, 2014; Sokhi et al.,2008). This approach is also not suitable for modelling dispersion at a distance less than 100m from the source (Leelö ssy et al, 2014; Holmes and Morawska, 2006). Furthermore, Holmes and Morawska (2006) suggest that Gaussian - based models do not consider the time taken for pollutants' transportation to the receptors since they use steady state approximation; consequently, particle dynamics have to be considered in the post-processing of the data obtained from the simulations.

Despite all its limitations, this model type is the most widely used especially for regulatory purposes. Similarly, most of the USEPA recommended- models is based on this approach for dispersion modelling (Abdel-Raham,2008; Holmes and Morawska ,2006; Leelö ssy et al, 2014).

Gaussian models have been adjudged to give a very quick response compared to the other categories as it involves solving a single equation for each point receptor. The cost of computing using this model-type is also very low, compared with other models, as ordinary computers can be used (Leelö ssy et al.,2014). This could be one of the reasons why it is widely used in dispersion modelling.

A good number of commercial and open- source models belong to this class of models. These include ADMS, AERMOND and OSCAR.

3.2.1 The OSCAR System

The OSCAR System for Air Quality Assessment System was developed at the Center for Atmospheric and Climate Physics Research (CACP), University of Hertfordshire. It was designed to facilitate air quality assessments at diverse levels of complexity and varying availability of required data (Sokhi et al., 2008).

The OSCAR System is an integration of multiple models which includes a meteorological pre-processor, an emission model, a scenario analysis tool kit, a semi-empirical model (referred to as CAR II) and a line- source dispersion model (referred to as CAR-FMI) (Sokhi et al., 2008).

In previous evaluation using data from Vallila (Helsinki) and Cromwell Road (London), CAR II and CAR-FMI generally showed good agreement for NO_x, NO_2, $PM_{2.5}$ and PM_{10} (Singh et al., 2014). A schematic description of the OSCAR System is shown in the Figure 3.1 below.

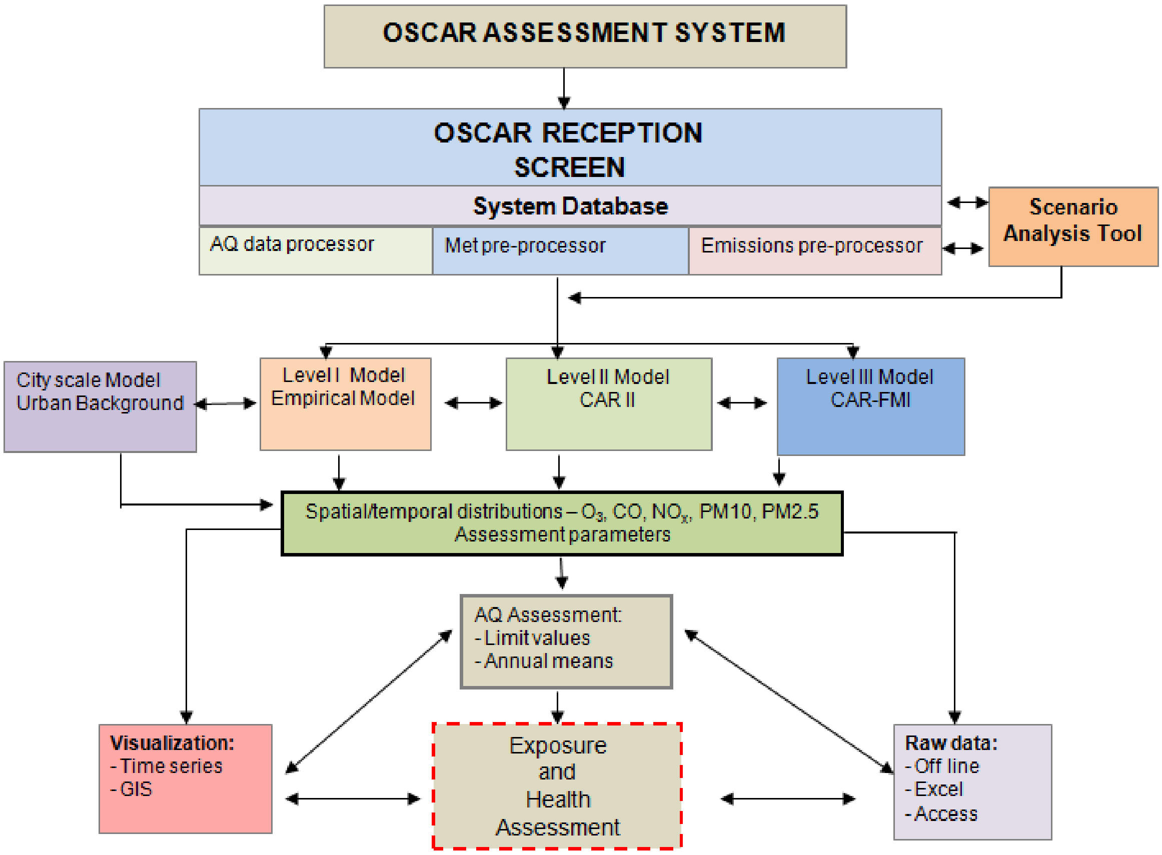

Figure 3.1: A schematic description of the OSCAR System. Sokhi et al. (2008).

The meteorological pre-processor in the OSCAR System (referred to as GAMMA met) estimates atmospheric stability parameters (such as Monin – Obukhov lengths and mixing heights) using meteorological data like heat flux, solar radiation and roughness lengths.

The input parameters required by GAMMA met are global radiation(W/m2), surface temperature (K), cloud cover (Okta), relative humidity (percent), pressure (mini bar), wind speed (m/s), wind direction (degrees) and time (year, month, day and hour). Given the aforementioned input parameters, the GAMMA met generates an output file which is used as meteorological input for the appropriate dispersion model (Sokhi et al.,2008). The output file generated by GAMMA met contains time (year, month, day, global radiation(W/m2), surface temperature (K), relative humidity (percent), pressure (mini bar), wind speed (m/s), wind direction (degrees), inverse of Monin – Obukhov lengths and mixing heights (m).

For emission pre-processing, the traffic data for each road link and the emission factor for each vehicle category are fed into the emission pre-processor. The pre-processor uses these data to produce an emission input file for the dispersion model (Sokhi et al.,2008).

For each road link in the modelling domain, the output file from the pre-processor contains the road link detail and the emission rates for NO_x, PM_{10}, $PM_{2.5}$, EC, BaP, and PNC. The emission rates are measured in $\mu g\ m^{-1}\ s^{-1}$.

In this study, the emission rates are computed using the equation presented in Singh et al (2014). The details of this computations are discussed in section 4 of the following chapter.

In Franco et al. (2013), emission factor is defined as empirical functional relation between emitted pollutant and the activity responsible for the emission. For road-traffic, emission factor is usually measured as the mass of pollutant emitted per unit distance travelled by the vehicle.

Emission factors are derived through emission measurements or modelling. For instance, the COPERT emission model is used by many European countries to report their national emission-related information. Apart from European countries, this model is widely used internationally specially to generate emission factors for various vehicle categories (Emisia, 2018). Deriving emission factors through measurement could be achieved by using chassis and engine dynamometer; and through remote sensing and tunnel studies. Emission measurements have been carried out in various studies across the globe. For example, from a tunnel study carried out by Martins et al. (2006), emission factors were reported for light - and heavy- duty vehicles in the metropolitan area of Sao Paulo. In a related study, Perez-Martinez et al. (2014) also carried out a tunnel study to derive emission factors for light and heavy-duty vehicles in the metropolitan area of Sao Paulo.
Similar to the studies conducted in Sao Paulo, in Africa, Keita et al. (2018) carried out measurements to determine emission factors for Total Particulate Matter (TPM) and other pollutants from road vehicles and other sources. These measurements were carried out in combustion chambers to replicate “field burning conditions”. According to Keita et al. (2018), their study was borne out of the need to have emission factors which truly depicts emission activities on the continent- instead of using values extracted from “global emission products”.

However, the emission factors reported in Keita et al. (2018) are for Total Particulate Matters (TPM) emitted from light- duty and heavy-duty vehicles with gasoline and diesel engines. Consequently, it was unclear which proportion of the emitted particles is $PM_{2.5}$. In addition, the emission factors are expressed in g/kg of fuel consumed by the vehicle. These are converted to g/km using appropriate fuel data. The conversion process is discussed in detail in section 4 of the next chapter.

The emission factors obtained from COPERT 5 are speed dependent and expressed in g/km. Regarding the emission factors for PM from this model, the UK's 2016 NAEI recommends that "the fraction of PM_{10} emitted as $PM_{2.5}$", should be assumed to be 1.0 for all vehicle exhaust emissions (NAEI,2018). Hence, these values (emission factors for PM in COPERT 5) are considered as the emission factors for $PM_{2.5}$.

Similar to other Gaussian models mentioned in 3.2 above, the OSCAR's dispersion model is "based on an analytical solution of the Gaussian diffusion equation of a finite line source." This equation (shown below) is solved using computer codes (written in Fortran) developed by CAR-FMI.

$$C = \frac{Q}{2\sqrt{2\pi}\sigma_Z(u\sin\theta+u_o)}\left[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right] \times \left[\operatorname{erf}\left(\frac{\sin\theta(p-y)-x\cos\theta}{\sqrt{2}\sigma_y}\right)+\operatorname{erf}\left(\frac{\sin\theta(p+y)+x\cos\theta}{\sqrt{2}\sigma_y}\right)\right] \quad \text{…………………..} \ (1)$$

where C is the concentration of the pollutant at a receptor point, Q is the source strength per unit length, u is the average wind speed, θ is the angle between the road and the wind direction, x, y and z are spatial coordinates, σ_y and σ_z are the vertical and lateral dispersion parameters, erf is the error function, H is the effective source height, p is the half-length of the line source and u_o is the wind speed correctio due to the turbulence (Sokhi et al., 2008).

Input data	Corresponding OSCAR file
weekly activity profiles of vehicles (expressed as hourly fractions)	Weeklyprofile.txt
Domain information: lower left corner, number of road links, number of user-defined height, domain's dimension, modelling period, number of monitoring stations	Config.txt
road link co-ordinates, road elevation, surface roughness	roadlink.csv
coordinates for user-defined receptors	userecepoints.csv
emission rates for each road link: for PM, NOx, EC, BaP, PNC (in µg/m^3)	emission.csv
temperature, relative humidity, time (year, month, day and hour), pressure, mixing height, global radiation, wind speed, wind direction, inverse of Monin – Obukhov length.	CarFMIMetro.txt
background concentrations for NO_x	CarFMIBackground.txt

Table 3.1: The input data required by the OSCAR model and the name of the file containing each data set in the model's database (OSCARNOTE, 2016).

As previously stated, the output files obtained from emission and meteorological pre-processing are transferred as inputs into a database folder of the dispersion model. A summary of all the input data with the corresponding location in the model's database is shown in the Table 3.1 above. Following the transfer of the input files, the model is configured by " specifying the origin of the area of interest (UTM or local coordinates), the extent of the area (m), the computational height (the receptor point height - this can be set to match that of the measurement station inlet), output grid resolution (50m or 100m), the required computed percentile to be saved, output pollutants and the receptor point coordinates" (OSCARNOTE, 2016).

A version of the OSCAR model is available for users of the Window Operating System (OS). However, in this study, the Linux based framework (which is installed on the university's HPC) was used. Hence, running the model involves submission of a job script (containing the resources and the time needed for job execution) to the UH cluster.

The model's output files contain predicted hourly concentrations of NO_x, NO_2, PM_{10}. $PM_{2.5}$, EC, BaP, PNC (in µg/m^3) – for each of the user- defined receptor points. Based on the modelling objectives, users can modify the configuration file to indicate the pollutants to be on the output files,

Chapter 4

Methodology

The methodology adopted in this study involves the adaption of the OSCAR model to predict traffic contributions to ambient $PM_{2.5}$ concentrations in the study area. This involves collating traffic, meteorological and emission data. The collated emission and meteorological data are processed, as explained in the sections 3.2.1.1 and 3.2.1.2, to generate emission and meteorology input -files for the dispersion model. While an outline of all the required input data is presented in the Table 3.1, in this chapter, the specific tasks carried out in preparing the input data are discussed in detail. Similarly, descriptions of the study area, the project domain and the post modelling activities, are presented in this chapter.

4.1 The study area

The study area is 479.88 km^2 (about 40 percent of the LMA) in size. It comprises a large portion of the Ikeja LGA and small parts of the Agege, Alimosho, Oshodi-Isolo, and Ikorodu Local Government Areas (LGAs). A map of the Metropolitan Area of Lagos – showing the aforementioned LGAs - has been presented as the Figure 2.3.

The land use for the study area can be described as mainly industrial and residential (see section 2.4.2). For instance, the Ikeja LGA (which is the largest part of the study area) is the capital of Lagos State. Consequently, it houses the secretariat of the Lagos State Government and other important buildings.

Further, the study area is a representation of the Lagos mainland – in terms of vehicular activities, road networks and demography. The study area (including the road links and the monitoring stations) is shown in the Figure 4.1 below.

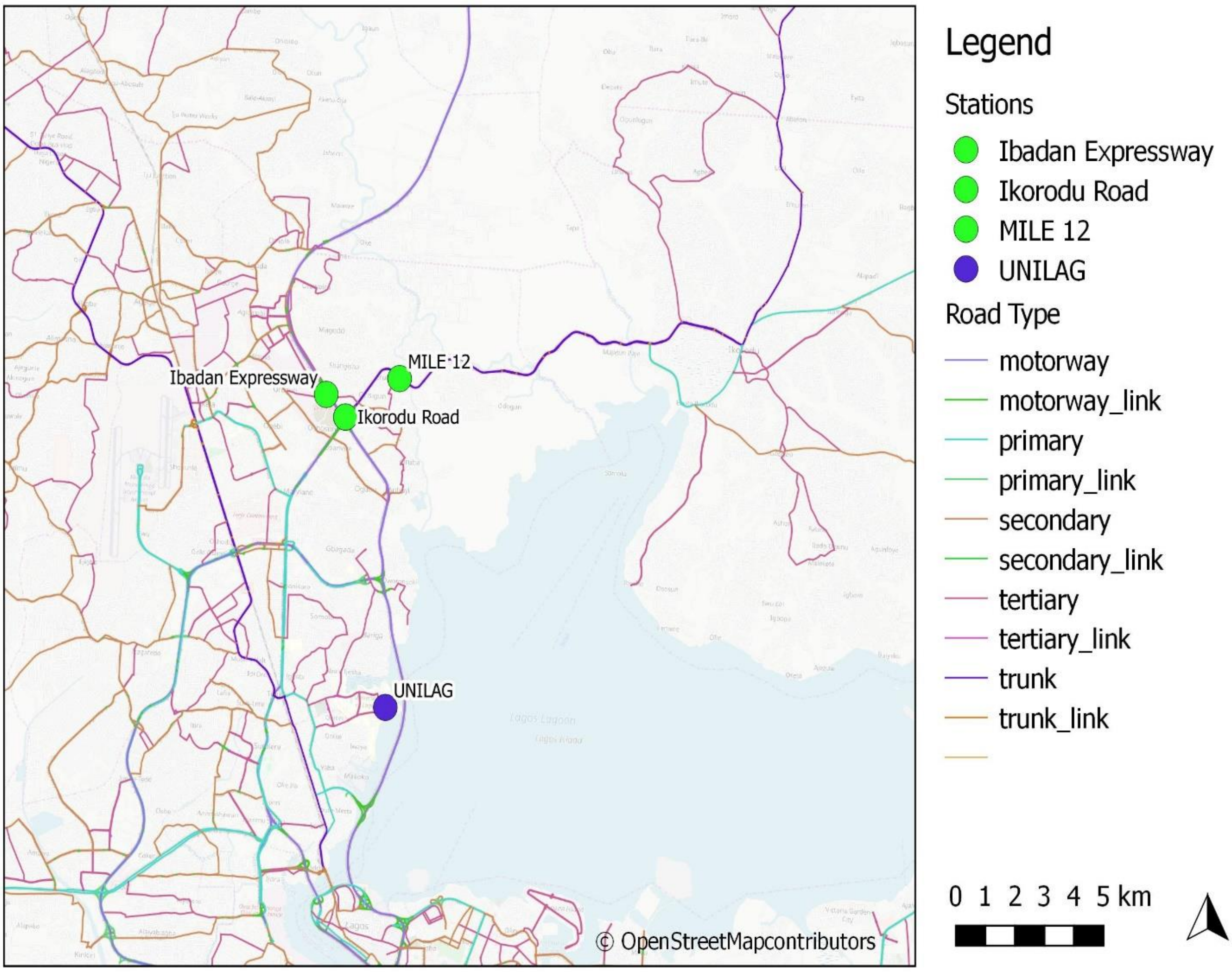

Figure 4.1: Map of the study area showing road links and the monitoring stations.

4.1.1 Air quality stations

Concentrations of $PM_{2.5}$ were observed at specific locations in the study area. At these locations (referred to as stations on the map), Sensor Network for Air Quality Measurements (SNAQ) boxes were used to measure the concentrations of $PM_{2.5}$ and some meteorological parameters. These measurements were taken as part of an on-going study at the Department of Physics, Obafemi Awolowo University, Ile-Ife, Nigeria (Fawole, 2018).

SNAQ boxes are low-cost portable devices for measuring ambient concentrations of air pollutants (gas phase and particulate) and meteorological variables. SNAQ box was "developed at the Department of Chemistry, the University of Cambridge, UK, as part of NERC (Natural Environmental Research Council) funded Sensor Network for Air Quality (SNAQ) project at London Heathrow airport "(Popoola et al., 2018). Each box can be mains or battery operated and is equipped with GPS for near- real time data transmission (Popoola et al., 2018; Borrego et al, 2016).

As shown in the Figure 4.1, the SNAQ boxes were positioned along two traffic corridors and within the campus of the University of Lagos (UNILAG). The aforementioned traffic corridors are: the Ikorodu – Mile 12 road and Ikeja -Ibadan Expressway. Similarly, the SNAQ box at UNILAG was sited behind the Computer Science building. Consequently, this SNAQ box measured background concentrations as there is no vehicular activity near the site.

The SNAQ boxes placed in the traffic corridors were assigned to measure the traffic contributions in those corridors (Fawole,2018). However, in this work, the stations at Ikorodu and Mile 12 have not been classified as either kerbside or road side – as they are too far away from the kerbs of the nearest road to each of them. Notwithstanding, the station near the Expressway has been considered to be roadside as it is approximately 3.7m away from one of the roads in its vicinity. A summary of the locations of the SNAQ boxes is given in the Table 4.1 below.

Location	Distance from Kerb (m)	Latitude	Longitude	Surroundings	Approximate hourly -traffic volume
Expressway	3.70	6.6003N	3.3770E	nearby buildings are mostly offices	12555
University of Lagos.	no road nearby	6.5153 N	3.3996 E	within a university campus	not applicable
Mile 12	30.74	6.6058N	3.3992E	near a large market and local restaurants	10018
Ikorodu road	14.30	6.5944N	3.3832E	close to a popular farm-produce market and a large wood mill.	10099

Table 4.1: Descriptions of the locations of the SNAQ boxes: showing the coordinates of the locations and average hourly-traffic volume on the nearby roads

The data obtained from these stations were used in the evaluation of the model's performance. This is further discussed in the sections 4.5.7 and 5.1 of this report.

4.2 The Modelling System

The dispersion model used in this study was OSCAR. A detailed description of this model has been given in the section 3.2.1 of this report.

4.3 The project domain

The study area described in section 4.1 was set up as a domain in the OSCAR System, to simulate road traffic contributions to ambient concentrations of $PM_{2.5}$ in the area. Table 4.1 below shows the key features of the domain. These are used to configure the dispersion model as mentioned in the section 3.2.1.3.

Feature	Description
Lower Left Corner coordinate (in Universal Transverse Mercator)	530000,718200
Length (X)	26800 m
Width (Y)	19200 m
Receptor (gridded and non-gridded)	27889
Number of modelled line sources	50
Number of measurement stations considered	4

Table 4.2: The features of the domain. These are used in the configuration of the dispersion model.

4.4 The study periods

Simulations of hourly dispersion of $PM_{2.5}$ were carried out in the domain for the following periods:

(i) 01 October 2010 – 20th January 2011

(ii) 09 November 2018 – 14th November 2018.

The choice of these periods was influenced by the search for and availability of measured data. For instance, 09 November 2018 – 14th November 2018 was chosen as it was the only period with continuously- measured data of $PM_{2.5}$ concentrations.

4.5 The input data

The sets of data fed into the CAR-FMI dispersion model are already shown in the Table 3.1. Therefore, the collation and preparations of these data sets are discussed in this section. It may be important to mention that each of the input data set was prepared offline as either a text or csv file and transferred thereafter into the database of the modelling system.

4.5.1 The road links

A total of fifty roads and seventy-four road links, within the domain, were considered in this study. The coordinates (longitude and latitude expressed in decimal degrees) for these road links were obtained from the Google Map. These were converted to the Universal Transverse Mercator (UTM) using a conversion tool developed by the Wood Hole Oceanography Institution (WHOI) (2019). The identification codes and the locations are provided in the Appendices A – C. In the Appendices A and B, the links are expressed as points – using the latitude and longitude; and the UTM coordinates respectively. Similarly, “X” and “Y” in Appendix C are the road links coordinates, relative to the lower left-hand corner of the domain.

To minimize errors in traffic volume estimation, the roads were categorized using a 3- tier classification approach. This involves grouping roads based on their geographical locations (LGA), types (trunk A, B or C) and geometry (number of lanes). First, roads located within the same the Local Government Area (LGA) were grouped together. Second, roads in the same LGA were grouped as trunk A, B or C. Lastly, roads of the same trunk were grouped based on their numbers of lanes- 2,4, or 6 lanes. A schematic diagram of this approach is given below.

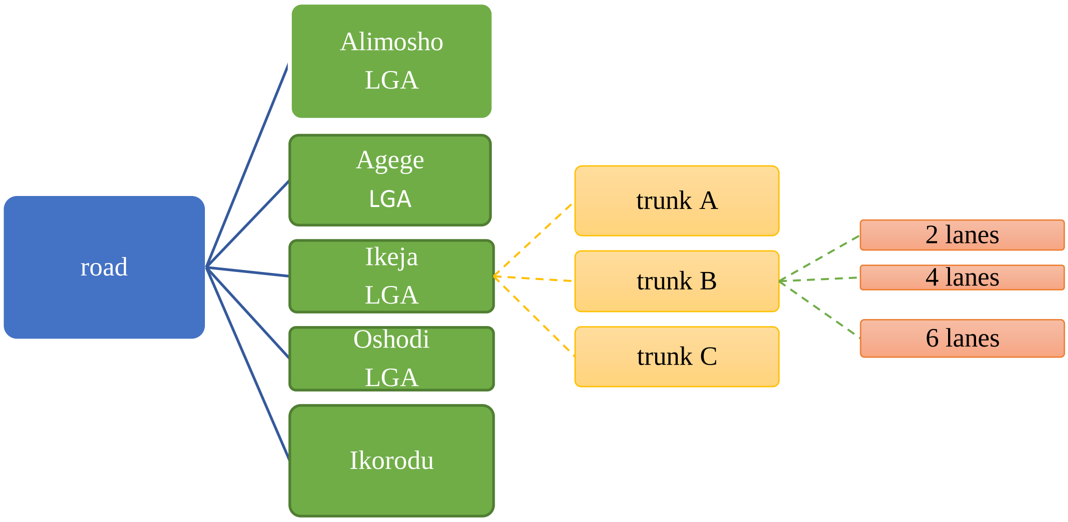

Figure 4.2: The method used for classifications of the roads in the project domain

Further, as most of the building along the roads in the Ikeja LGA are between 8 and 12 metres, the surface roughness length (for each of the roads in the domain) was estimated to be 1.0 m. As recommended in the OSCAR Users' guide (OSCARHELP, 2005), surface roughness length can be calculated as a tenth of the average building height in a street. It is the height at which the logarithmic mean of the horizontal wind velocity is approximately zero. Surface roughness can be used to calculate frictional and convective velocity scales - which are required variables for computing the Monin-Obukhov length. Monin-Obukhov length is a parameter used to determine the atmospheric stability class for a boundary layer (Dobariya et al., 2016; Barnes et al.,2014).

The classification of the modelled roads based on location (LGA), type (trunk A, B or C) and number of lanes, is shown in the Appendix D.

4.5.2 Emission

For road traffic-induced emissions, the quantity of a pollutant emitted (E) (by an average vehicle in a category) is the product of the emission factor(F) – for the vehicle category - and transport activity (A). This can be expressed as:

$$E = F \times A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

In Singh et al. (2014), the emission rate (Q) of a line source was expressed as the product of the "number of vehicles per hour (n_j) and emission factors (q_j)(g/km) summed over" the number of vehicle categories (k) being considered. This can be expressed as:

$$\sum_i Q = n_i \, q_i \; for \; i = 1, 2, \ldots \ldots \ldots \ldots \ldots . k \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The unit of the emission rate obtained from the equation (2) above is $g/km/h$. This was converted to $\mu g/m/s$ as required for the dispersion modelling. For this study, the value of k is eighteen which is the number of vehicle categories being considered. A Fortran program was written in this work to compute the emission rate, as expressed in the equation (2) above. This program is shown in Appendix E.

The traffic volumes used for the computation of emission rates (as expressed in equation 2 above), are the 14- hour traffic count data obtained from LAMATA. This contains the number of vehicles (in each of the traffic fleet composition) plying a road between the hours 06:00 and 20:00 (LAMATA,2018).

Although this data was unavailable for a substantial number of the modelled roads, appropriate assumptions were made to estimate traffic volumes where traffic volume data (from LAMATA) is unavailable. These assumptions were based on the road classification approach discussed in the section 3.4.1.

The classification implies that roads with equal number of lanes, of the same type (trunk A, B or C) and within the same Local Government Area (LGA), have the same traffic volume. Scale factors were also used to derive traffic volumes for the same type of road in the same LGA but with different numbers of lanes. The estimated 14- hour traffic volume (per vehicle type) on each of the 50 roads are given in the Appendices F and G respectively for the first and second study periods.

The eighteen vehicle categories referred to in the equation (2) are shown in the Table 3.1 below

<table>
<tr><th>Fuel Technology</th><th colspan="9">Traffic fleet compositions</th></tr>
<tr><td>Diesel</td><td rowspan="2">cars/ taxi</td><td rowspan="2">Bicycle</td><td rowspan="2">Small trucks / pickup/ Small van</td><td rowspan="2">Heavy truck/ trailer/ container</td><td rowspan="2">medium truck</td><td rowspan="2">motorcycles</td><td rowspan="2">large buses</td><td rowspan="2">mini buses</td><td rowspan="2">coaster</td></tr>
<tr><td>Petrol</td></tr>
</table>

Table 4.3: The eighteen vehicle categories considered in the computation of the emission rate for each of the line sources. The fleet compositions are further divided based on fuel technology.

To determine the proportion of each vehicle category operated on either gasoline or diesel technology, a set of data obtained from LAMATA (2016) was analysed. This data set emanated from the study it conducted on GHG emission along some traffic corridors in the study area. A summary of the analysis is shown in the Figure 4.3 below.

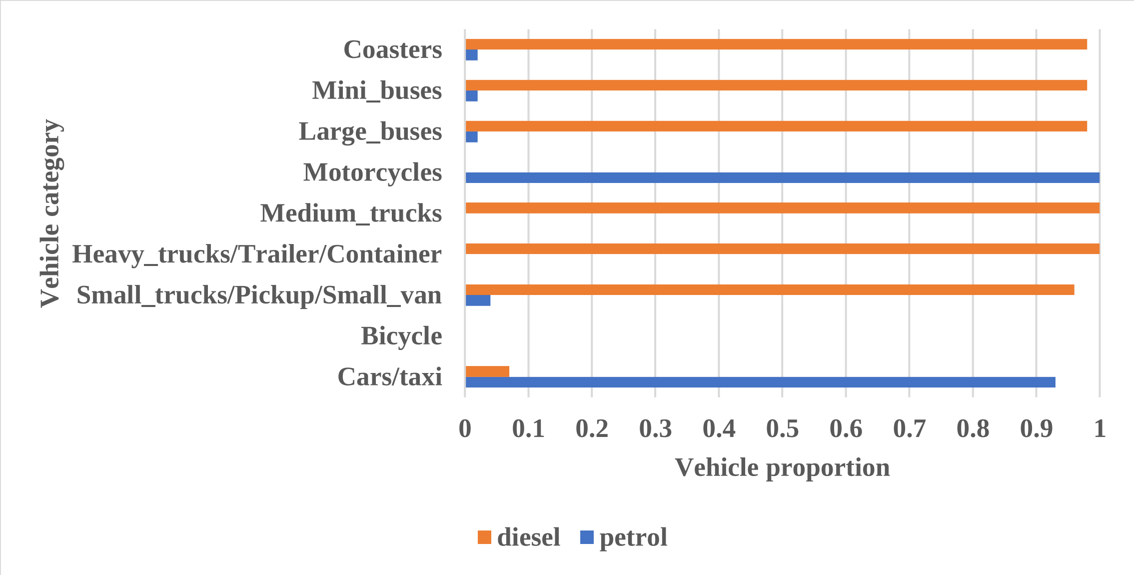

Figure 4.3: Vehicle volume distribution in the study area – based on fuel technology.

Similarly, the same data set was analysed to determine the vehicle fleet distribution for the study area, based on emission control technology. A summary of this distribution is shown in the Figures 4.4 and 4.5 below- for petrol and diesel vehicles respectively.

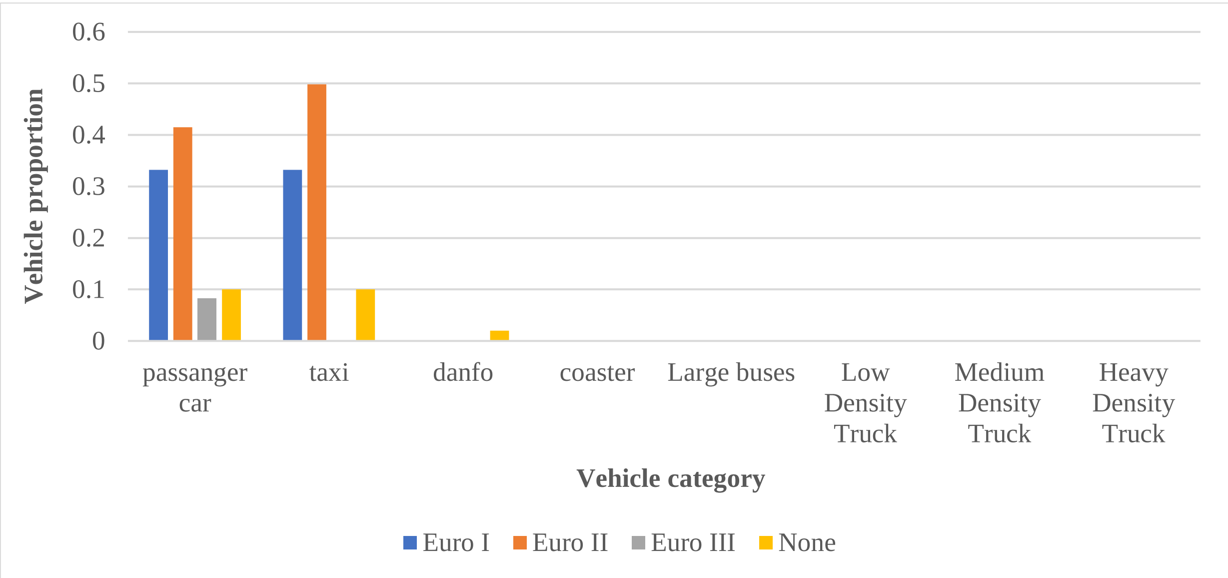

Figure 4.4: Distribution of petrol vehicles in the study area – based on emission control technology.

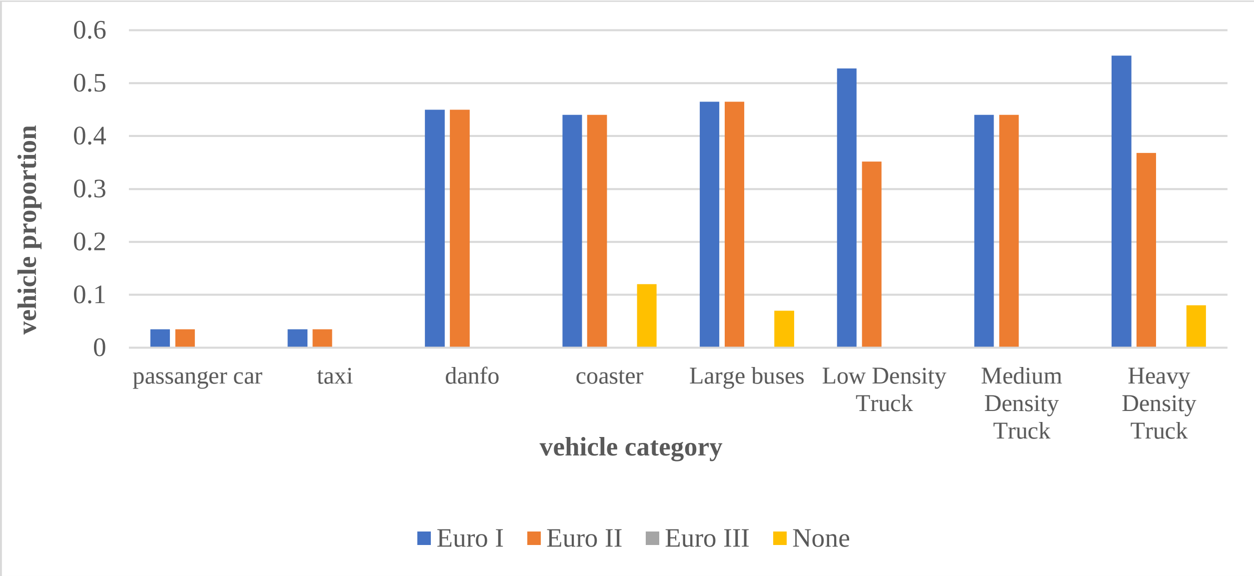

Figure 4.5: Distribution of diesel vehicles in the study area – based on emission control technology.

Considering the summary of the aforementioned analysis (shown in the Figures 4.4 and 4.5), this study concluded that the modal emission control technology is Euro II.

In the section 3.2.1. an overview of potential sources of emission factors is presented. However, after the initial experimental runs of the OSCAR model, emission factors from the following sources were considered as likely to be suitable for this study:

(i) COPERT5 – an emission model commissioned by the European Union

(ii) Keita et al (2018)- a study on emission factors of pollutants from fuel combustion in West Africa.

(i) Using the emission factors from COPERT5

The analysis described in the preceding section shows that most of the vehicles in the study area use the Euro II mission control technology. Hence, the emission factors extracted from COPERT5 are for vehicles in this category.

However, due to unavailability of data on road gradient and load, values of 0 and 50 percent were assumed respectively for these parameters as recommended by the model's developers. In the same vein, the weights of the vehicles in the study area are unknown. Consequently, the vehicles were assumed to be of maximum capacity and emission factors were extracted accordingly from the model.

Emission factors from COPERT5 are speed- dependent. Therefore, the average speed (in km/h) for each road type (obtained from LAMATA) were used as inputs in COPERT5 to obtain the corresponding emission factors. The average speed for the classified roads (shown in the Appendix D) is presented in the Table 4. 4 below.

Road class/ Trunk	**Average Speed (km/h)**	**Road ID**
A	55	R1,2, 3, 5, 6, 13, 14, 15,16,17, 18,19,20,29,30,31,45
B	50	R4, 7, 8,9,10,11,12,21,22,32,38,39,40,41,42,43,46,47,48,49,50
C	40	R23, 24, 25, 26,27,28,33,34,35,36,37,44

Table 4.4: Average speed for each of the road classes in the study area. It also shows the identity of the roads in each class. This classification is based on the method discussed in the section 4.5.1.

(ii) Using local emission factors.

The emission factors obtained from Keita et al (2018) were expressed as mass of pollutant emitted per unit mass of fuel consumed by a vehicle (g/kg fuel). These were converted to mass of pollutant emitted per unit distance (g/km), and subsequently referred to as the local emission factors throughout this study. The conversion was carried out through the following steps:

(a) The total particulate matter (TPM) emitted by a vehicle was assumed to be 100% of the type $PM_{2.5}$

(b) These emission factors were converted to mass per unit distance travelled (µg/m) as described below.

$$L_F = F_k \times \frac{1}{U_e} \times U_d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where L_F is the local emission factor (for a specific vehicle category); F_K is the emission factor obtained from Keita et al (2018); U_e is the fuel efficiency of an average vehicle (in Africa) in that category; U_d is the density (at 20^oC) of the fuel type for the vehicle. From Keita et al (2018), only the emission factors for old vehicles were considered as majority of the vehicles in Lagos are old (Olajire et al, 2011).

The densities (U_d) of gasoline and diesel at 20^{o}C (as used in equation 4) are 750 kg/m^3 and 825kg/m^3 respectively (Martinez, 2018; Schaschke et al., 2013). Similarly, in Madueke et al (2015), the sources of the fuel efficiency (U_e) data (used for the computation described in the equation 3) are cited as the International Association of Public Transport (UITP) and African Association of Public Transport (UATP). For light duty vehicles (car, taxi, motorcycles, mini bus), the values of U_e range from 10 km/L to 40 km/L whereas these range from 3km/L to 20 km/L for heavy duty vehicles (heavy trucks, trailers, Coasters, large buses).

4.5.3 Meteorology

Information on the meteorological conditions of the study area was obtained through ground level measurement; satellite observation; and computations (based on atmospheric stability theories) carried out in this study.

Measured meteorological factors were obtained from the Centre for Atmospheric Research of the National Space and Research Development Agency (CAR-NASRDA) of Nigeria. These measurements were carried out at the agency's Automatic Weather Station (located at the coordinates 6.434N,3.322E) in Lagos. The measured parameters were provided as 5 -minutes averages of surface temperature (^{o} C), pressure (millibar), wind speed(m/s), wind direction(degrees), relative humidity (percent), and global radiation(W/m^2).

As the OSCAR System works with hourly-time series of input data, hourly averages were computed for these measured parameters, through a Fortran code written in this work. This code is in the Appendix H of this report.

The total cloud cover over Lagos was not measured at the CAR-NASRDA's Automatic Weather Station. Consequently, the hourly series for this parameter was obtained from The Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) which is operated by NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) (GMAO, 2015).

The cloud-based heights (CBH) for the study area was also not measured or observed by any equipment. Therefore, hourly-time series were obtained by computation -based on estimation of this parameter from convergence rate of surface temperature and dew point (FAA,2016).

The corresponding mathematical expression is:

$$CBH = \left(\frac{(T-DP)}{CR}\right) \times \ 1000 \ \ldots\ldots\ldots\ldots\ldots.. \quad (4)$$

where CBH is cloud based height; T is surface temperature, DP is dew point and CR is the surface temperature - dewpoint convergence rate. The value for CR is 4.4 ^{o} F or 2.5 ^{o} C. Since the surface temperature data (obtained from CAR-NASRDA) were measured in ^{o} C, 2.5^{o} C was used as the value of CR in this study.

Similarly, dew point was calculated using an abridged format of the Clausius Clapeyron equation, by Lawrence (2004). This relates relative humidity to dew point as follows:

$$td = t - (100 - RH)/5 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (5)$$

where td is dew-point, t is surface temperature, and RH is relative humidity

Using the equations (4) and (5), a Fortran program was written in this study to generate the hourly time series of the cloud-based height for the domain. This program is presented in Appendix I.

To estimate the Monin- Obukhov length and mixing heights for the domain, the data set mentioned in the preceding paragraphs were fed into the GAMMA met. The input data fed into and the output file generated by the GAMMA met have been described in the section 3.2.1.

4.5.4 User-defined receptors

A cartesian - grid system (with grid resolution of 50m) was used for spatial distribution of receptors over the domain. However, a number of receptors were discretely placed (at varied distances from the line sources) in the domain. In total, 27,889 receptor points were defined for the simulation, using the cartesian grids. The computer program written to generate the gridded receptor points is in the Appendix J.

4.5.5 Weekly Profile

From the study conducted by LAMATA (previously mentioned in section 4.5.2.1.2), a 14-hour traffic profile was derived for this research. To make a complete profile, the last 10 hours (hours 15 – 24) of the default weekly profile of the model were used.

4.6 Model configuration and run

Having fed the input files into the OSCAR System's database, the model was configured and run to predict PM 2.5 concentrations at each receptor point: as described in the section 3.2.1.

4.7 Model evaluation and analysis of modelled data

4.7.1 Modelled data

The output data from the dispersion model is hourly- time series of $PM_{2.5}$ concentrations. These concentrations are the predicted road -traffic increments. As seen in Sokhi et al (2008), hourly -time series of the modelled (total) concentrations was obtained by adding each data in the OSCAR output to the mean background concentrations. The background station was located at UNILAG (see section 4.1.1).

4.7.2 Data obtained from measurements

The observed data was obtained from an on-going study being conducted by the Department of Physics of the Obafemi Awolowo University, Ile-Ife, Nigeria. The study involves measurements (using SNAQ boxes) of particulate matters, gases and meteorological variables along some traffic corridors in the study area.

Further, measured data for 130 hours (5 days and 10 hours) have been used for comparison with the modelled data. These represent the period when continuous measurements were obtained from the SNAQ boxes: 9th – 14th November 2018. The measured data were obtained as 20 second- averages of $PM_{2.5}$ concentrations (µg/m3), temperature (^{o} C), relative humidity (percent), wind speed (m/s) and wind direction (degrees). For model evaluation purposes, these were converted to hourly time series using a Fortran program written in this work (see appendix K).

4.7.3 Model calibration

Prior to its evaluation, the model was calibrated with measured $PM_{2.5}$ concentrations from the station on the Ikorodu road. This was carried out to address any uncertainty which may negatively influence the accuracy of the model's predictions. These uncertainties may be due to measurements of parameters, model's poor representation of key processes or " randomness in physical processes"(Garcia et al, 2018). First, a regression model was developed to show the relationship between predicted- hourly concentrations and measured – hourly data. Second, the slope and the intercept of the regression model were adjusted so that model concentrations are the same as the measured data. Subsequently, the adjusted regression equation is applied to modify predicted $PM_{2.5}$ concentrations for the other stations.

4.7.4 Model evaluation and sensitivity analysis

To evaluate the model, the predicted concentrations were compared with observed data. The statistical parameters used for this comparison are model bias, correlation coefficient, normalised mean square error, fractional bias and the fraction of the predicted data which fall within a factor of 2 of the observed data. These parameters have been previously applied for the same purposes in Sokhi et al (2008), Chang and Hanna (2003), Singh et al (2014) and Gibson et al. (2013). In addition, using a scenario, the modelled results were analysed to investigate its sensitivity to changes in emission.

Chapter 5

Results and discussions

The road-traffic contributions to $PM_{2.5}$ concentrations in the study area has been modelled as described in the preceding chapter – the methodology. The emission factors considered to be suitable were those obtained from COPERT5 While local emission factors were also considered (as mentioned in the sections 3.2.1.), they were found to be unsuitable for the simulations carried out in this study. The explanation for this conclusion is provided in section 5.3 of this chapter. Consequently, for model calibration, evaluation and application of results, the model (OSCAR) outputs obtained from the simulation carried out with COPERT 5 emission factors were used. The model was calibrated with the measured data from the station at Ikorodu and evaluated with measured data from other stations (Mile 12 and Expressway). Variation of modelled concentrations with distance from the centre line of the roads was also investigated; traffic increments were predicted for the roads near the stations at Ikorodu, Mile 12 and the Expressway. Further, a scenario analysis was carried out which illustrates the model's response to changes in emission data, under a constant meteorological condition.

5.1 Model Evaluation

5.1.1 Model calibration

As discussed in the section 4.7.3, the model was calibrated with measured $PM_{2.5}$ concentrations from the station on the Ikorodu road. Thereafter, the calibration was applied to the modelled $PM_{2.5}$ concentrations for the other stations. A scatter plot and the regression model for the calibration are shown in Figure 5.1 below.

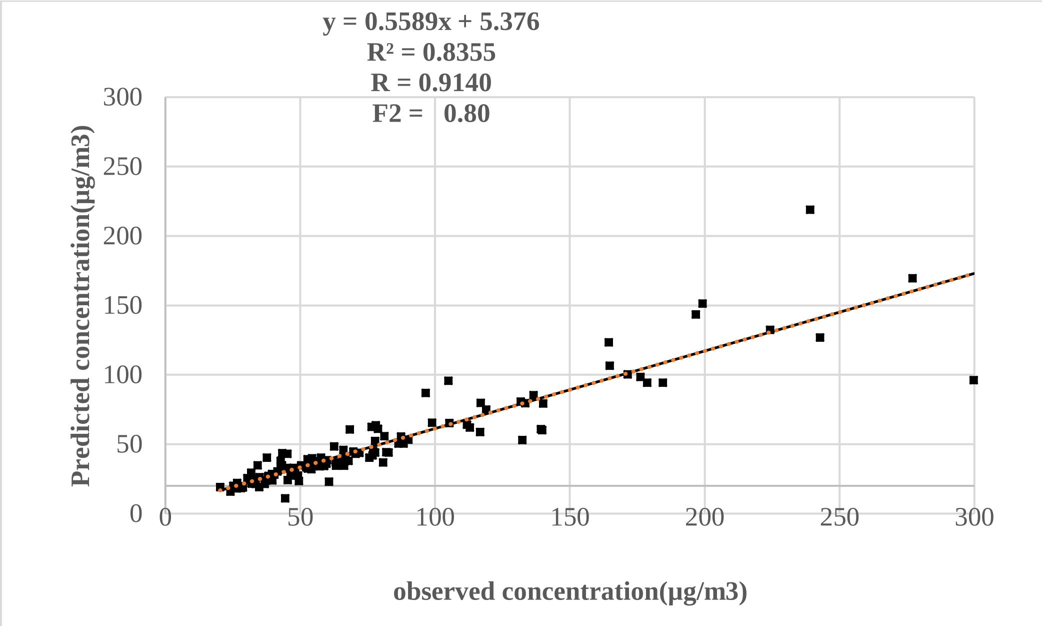

Figure 5.1: A scatter plot of the modelled against the observed concentrations at the station on the Ikorodu road.

The solid line on the scatter plot shows the possible-best relationship between predicted and observed data -without calibration; the dash line shows the relationship with calibration. The calibration process has been discussed in the section 4.7.3. Hence, to calibrate the model, the gradient and the intercept of the regression equation, y = 0.5589x +5.376, are adjusted to give the equation y = x: which is shown with a dash line in the Figure 5.1 above. Thereafter, the adjusted regression equation is applied to modify the predicted $PM_{2.5}$ concentrations for other stations.

5.1.2 Comparison of mean concentrations

As a first step in the assessment of the model's performance, the mean (over 130 hours) values of the modelled data are compared with the mean measured concentrations for the stations at Mile-12 road and the Expressway. This comparison is shown in Figure 5.2 below.

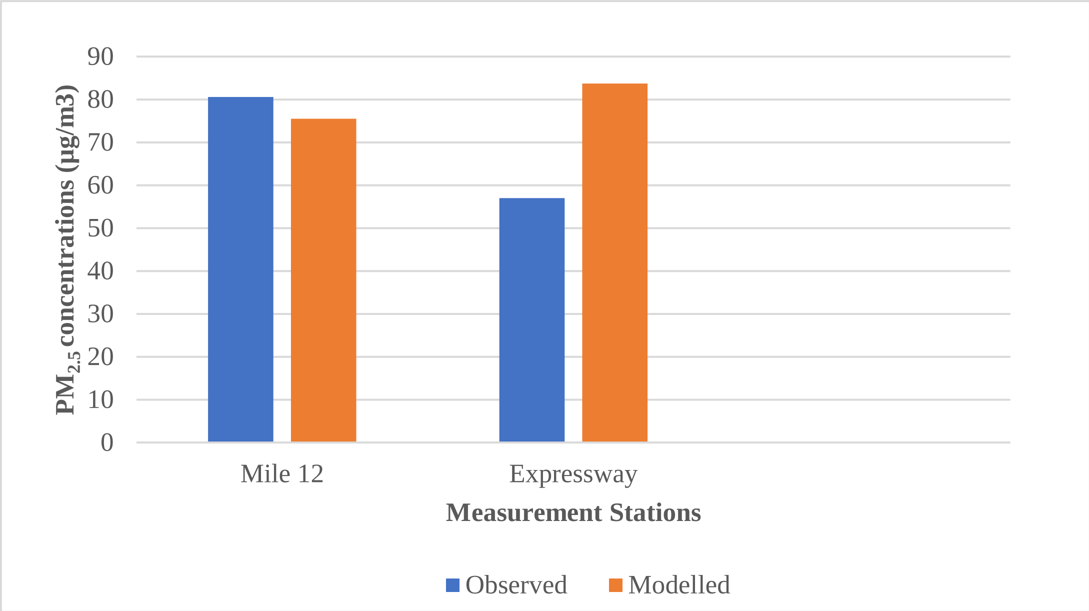

Figure 5.2: Comparing the modelled with the observed $PM_{2.5}$ concentrations at Mile12 road and Expressway

As shown in the figure above, the model underpredicted the observed data at Mile 12 but overpredicted at the Expressway. The underprediction cannot be attributed to uncertainty in the estimation of vehicular emissions, as the Mile 12 station was about 30.7m away from the kerb of its nearest road – and cannot be categorized as either roadside or kerbside. Therefore, the underprediction may be due to having a higher mean background concentration at the Mile 12 site when compared with the observed background concentrations at UNILAG. As stated in the section 4.7.1, the background concentrations were observed at the UNILAG. These concentrations were added to the outputs from the OSCAR model to compute the modelled $PM_{2.5}$ concentrations.

The Expressway station has been categorized as roadside due to its distance from the kerb of the nearest road (see section 4.7.1). Therefore, the model's overprediction of the $PM_{2.5}$ concentration at this station can be largely linked to calibration. The reason for this is: the model was calibrated with observed data from the Ikorodu road which has a higher mean $PM_{2.5}$ background concentration than observed at the background station sited at UNILAG.

As shown in the Figure 4.1, the stations at Mile 12 and Ikorodu road are along the same traffic corridor. Further, the Table 4.1 shows that they are far away from road side and surrounded by other potential sources of $PM_{2.5}$ (such as cooking at the surrounding restaurants, fuel burning in generators, dust from the wood mill).

Consequently, higher mean background concentration of $PM_{2.5}$ (than observed at the designated background station) was expected at these two stations- this could be responsible for the underprediction at the Mile 12 station.

The Figure 5.3 below compares the mean $PM_{2.5}$ concentrations for the stations.

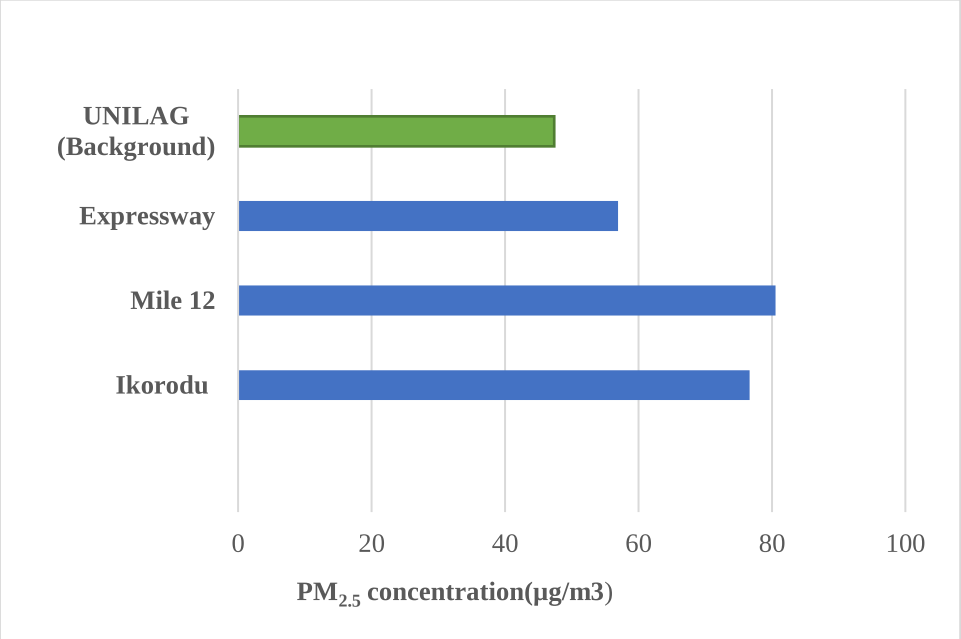

Figure 5.3: Mean values of measured (over 130 hours) $PM_{2.5}$ concentration at the stations.

Since the model was calibrated with the measured data at the Ikorodu station, the Figures 5.2 and 5.3 show that the model overpredicts at the stations with lower mean $PM_{2.5}$ concentrations, and underpredicts at the station with higher mean concentrations – compared with the mean -measured concentrations at the Ikorodu station.

5.1.3 Scatter plots and statistical performance evaluation

The hourly modelled and observed concentrations are compared using scatter plots and statistical parameters. These statistical parameters are used to quantify the extent of agreement between modelled and observed concentrations. In this study, statistical evaluation has been carried out with the following parameters: Model Bias (MB), Normalised Mean Square Error (NMSE), Fractional Bias (FB), correlation coefficient (R), and the fraction of points which lie within the factor of 2 (F2). These parameters were recommended in Sokhi et al (2008), Chang and Hanna (2003), Singh et al (2014) and Gibson et al. (2013). A summary of the outcomes of these evaluations is shown in the Table 5.1 below.

LOCATION	MB	FB	NMSE	R	F2
Mile 12 Road	-5.08	0.07	0.26	0.73	0.92
Expressway	26.80	-0.38	0.71	0.59	0.68

Table 5.1: Outcome of the model evaluation with statistical measures.

In addition to the table above, the scatter plots of the modelled concentrations against the observed data are shown in the Figures 5.4 and 5.5– for the Mile 12 road and the Expressway respectively. Included on each scatter plot are coefficient of determination (R^2), a regression equation, the lines y= x, y= 2x, and y= 0.5 x.

From the Table 5.1, the Model Bias shows that the model underpredicts the observed data at Mile 12 and overpredicts the measured concentrations for the Expressway. However, the model's error for the Expressway is higher when compared with the values for Mile 12 road. The model's error is the absolute value of its bias.

Considering FB, Table 4.1 shows a lower value for the Mile 12 in comparison with the value for the Expressway. This implies that the model's systematic error is lower for Mile 12 than for the Expressway. Similarly, it exhibits lower random errors (systematic and nonsystematic) at Mile12. The information shown on the table is in order as the monitoring stations in Mile 12 and Ikorodu are sited along the same traffic corridor.

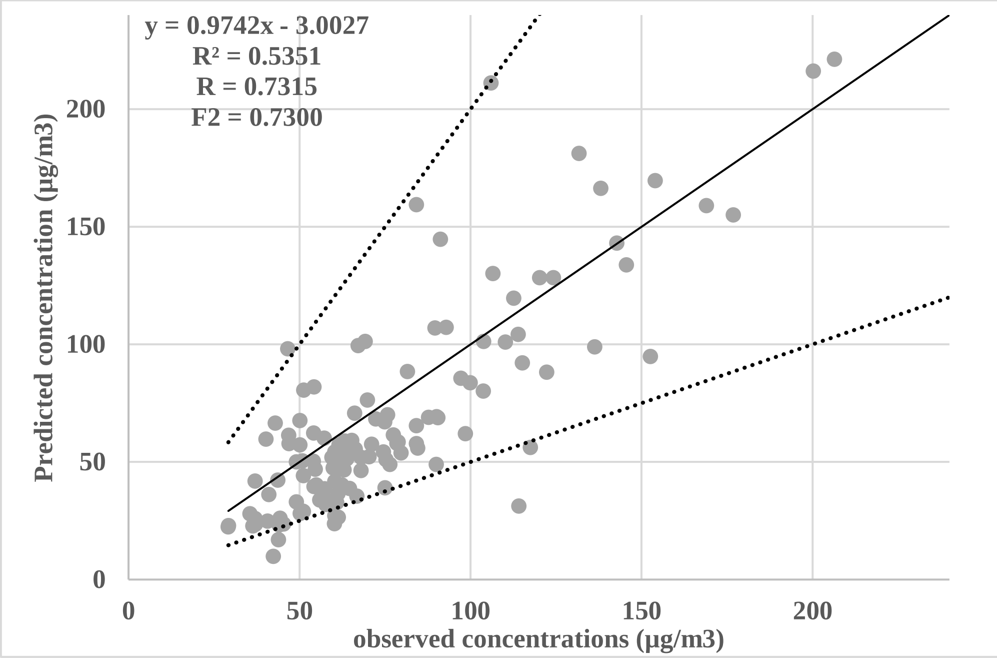

Figure 5.4: Scatter plot of modelled against observed $PM_{2.5}$ concentration at the Mile12 road.

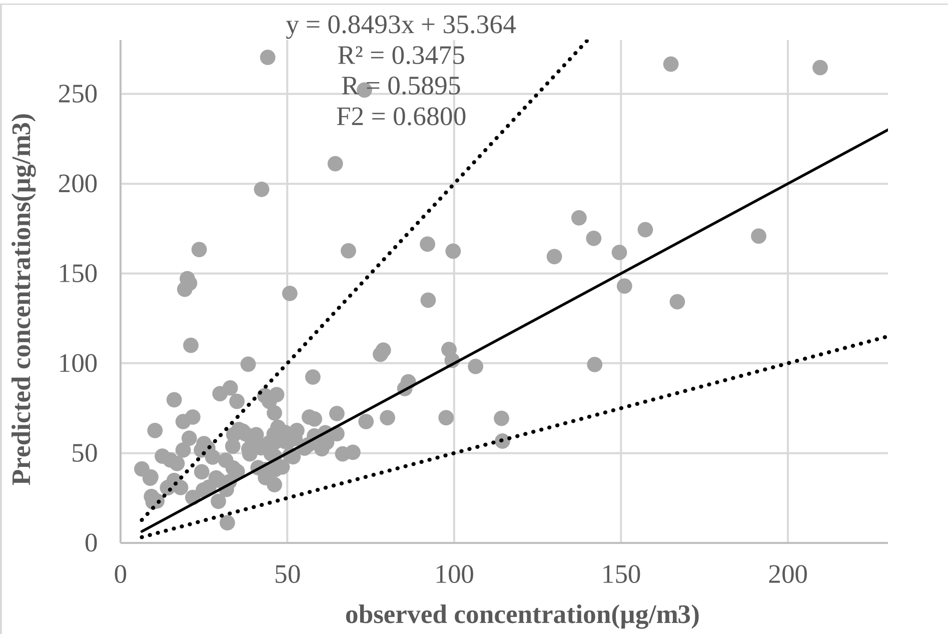

Figure 5.5: Scatter plot of modelled against observed $PM_{2.5}$ concentrations at the Expressway.

The MB, FB and NMSE are measures of difference between the model's predictions and observations. Hence, for a set of data, moments of underpredictions can be cancelled out by moments of overpredictions. In view of the above, it is necessary to consider the parameters measuring the relationship between the observed and the predicted data – R and F2. The Table 5.1 shows that in spite of the model's random and systematic errors, it generally has a good level of agreement with observations – especially when considering its R and F2 values across both locations.

However, Table 5.1 also shows that the model's performance at the Expressway is not as good as its performance in the 2 other sites. At the Expressway, the model shows more bias, more systematic error, low correlation with observation, and a lower fraction of data which falls within a factor of 2.

A possible explanation for this is: Mile-12 is in the same traffic corridor as the Ikorodu station whose observed data was used to calibrate the model. Similarly, as indicated in the Figure 5.2, the mean background concentration for Mile 12 station is most likely similar to that of the Ikorodu road. Therefore, it can be inferred that the calibration is more applicable to the station at Mile 12.

Consequently, as the Expressway station is roadside, its uncalibrated and calibrated – modelled concentrations were compared with measurements- to assess the impact of calibration on the model evaluation for this station. This is shown in the Figure 5.6 below.

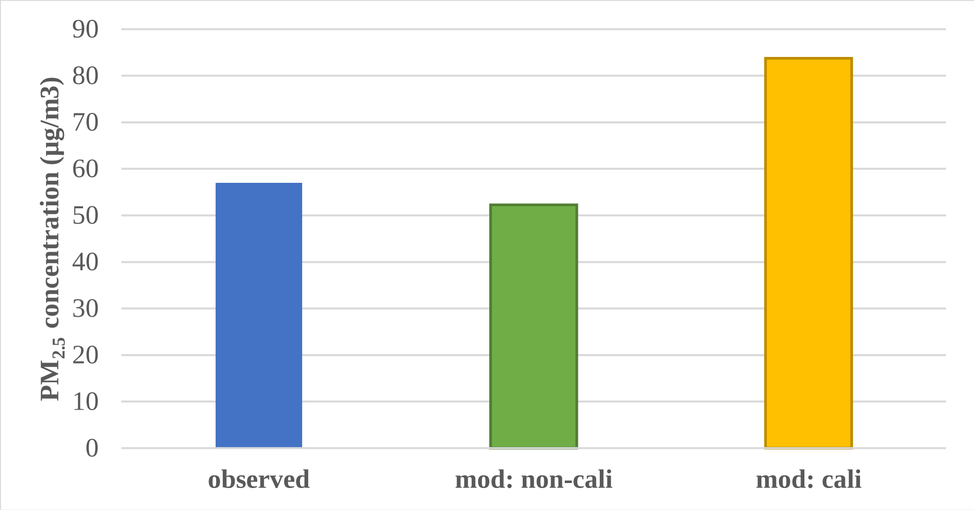

Figure 5.6: Comparing the mean observed data with the mean of calibrated and uncalibrated modelled concentrations, at the Expressway- a roadside station. The mean was taken over a period of 130 hours. The terms 'non-cali' and 'cali' referrer to uncalibrated and calibrated modelled concentrations respectively.

The Figure 5.6 shows that the uncalibrated model underpredicts the observed data (by about 8%) whereas the overprediction due to model calibration was about 47%. This shows that the calibration may be effective at reducing model's bias when applied to sites with similar geophysical attributes.

The aggregated FB, NMSE, R and F2 for the model (after calibration) are shown in the Table 5.2 below.

	MB	FB	NMSE	R	F2
Minimum	-5.08	-0.38	0.26	0.59	0.68
Lower quartile	2.89	-0.2675	0.3725	0.625	0.74
Median	10.86	-0.155	0.485	0.66	0.8
Upper quartile	18.83	-0.0425	0.5975	0.695	0.86
Maximum	26.8	0.07	0.71	0.73	0.92

Table 5.2: The aggregated values of the statistical measures used for the model's evaluation (after calibration) for the station

5.2 Variation of $PM_{2.5}$ concentrations with distance

In order to investigate the dispersion characteristic of $PM_{2.5}$ from the closest roads to the Expressway and the Mile 12 sites, graphs of the modelled $PM_{2.5}$ concentrations against perpendicular distances from the centre line of the roads were plotted. These are shown in the Figures 5.8 and 5.9 respectively.

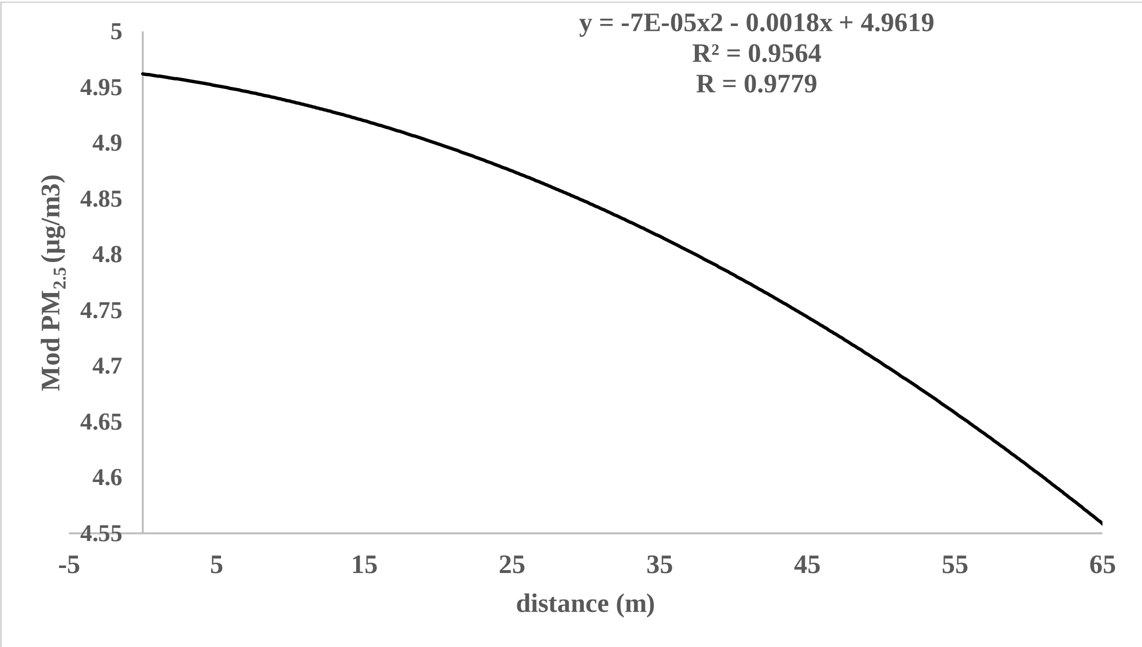

Figure 5.7: Variation of mean -modelled traffic contribution with perpendicular distance from the centre line of the Expressway. This variation is expressed as a second order polynomial. Both the R^2 and R values are very close to 1. The equation for the polynomial is also shown on the graph.

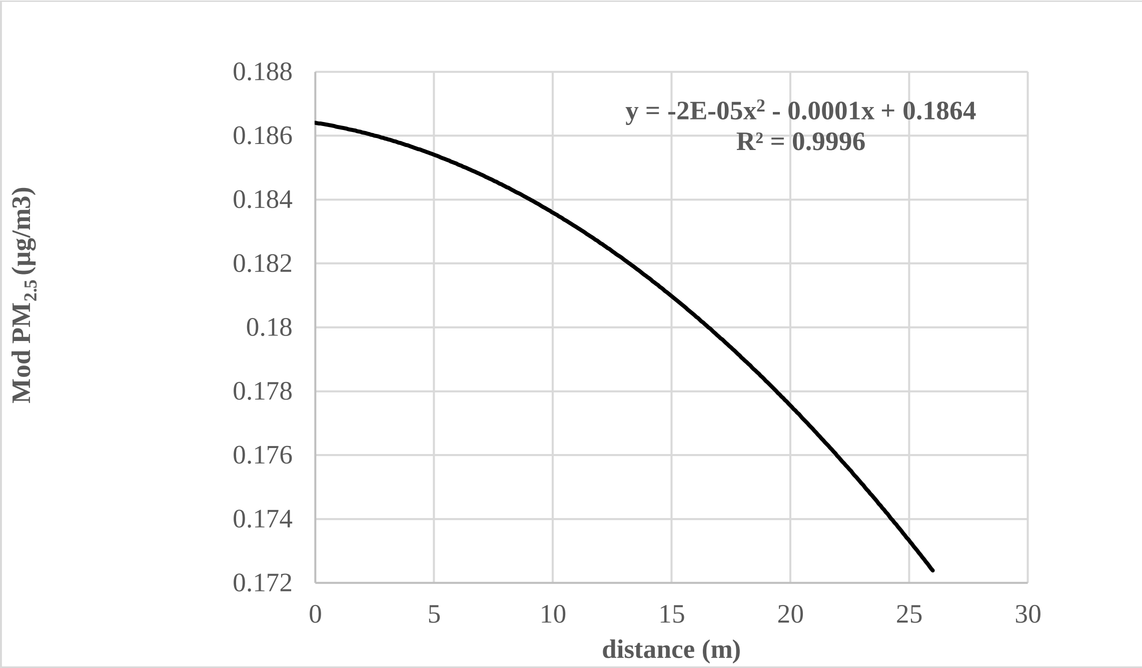

Figure 5.8: Variation of mean-modelled traffic contribution with perpendicular distance from the centre line of the Mile 12 road. This variation is expressed as a second order polynomial. Both the R^2 and R values are very close to 1. The equation for the polynomial is also shown on the graph.

The polynomials shown in the figures above are simple forms of parabolic second order equations. Comparing both figures show that traffic contribution is higher near the expressway and decreases more rapidly. This conclusion can also be deduced from the slopes of the equations representing the concentration gradients from the centre line of both roads. At a specified distance, the slope of the polynomial for the Expressway has a higher negative value- when compared with the slope of the equation for the Mile 12 road. However, in general, Figures 5.7 and 5.8 show that $PM_{2.5}$ concentration decreases as distance (from the centre line) increases. This is due to the pollutant's dispersion from roads by meteorological forces -especially wind.

In addition, the polynomials in both figures can be used to compute modelled traffic increments at any point within the range of distance shown in the figures. As an illustration, the distance (measured with the Google Map) from the centreline of the (nearest road to) Expressway to its kerb is approximately 2.5 metres. If the SNAQ box was placed a meter away from the kerb, the modelled traffic contribution would had been 4.96µg/m3 (by substituting 3.5 for x in the concentration gradient equation).

5.3 Predicted traffic increment

The predicted mean traffic increment for the stations at Ikorodu, Mile 12 and the Expressway are shown in the Figure 5.9 below. As both stations at Ikorodu and Mile 12 roads are not considered to be roadsides or kerbsides, the OSCAR model was used to predict $PM_{2.5}$ concentrations at approximately 3.7m away from the kerbs of the Ikorodu-Mile 12 road – using the input data for the study period 2. These OSCAR outputs were used to compute the (total) modelled - roadside $PM_{2.5}$ concentrations at both stations (with calibrated model). This process was also applied to the Expressway station.

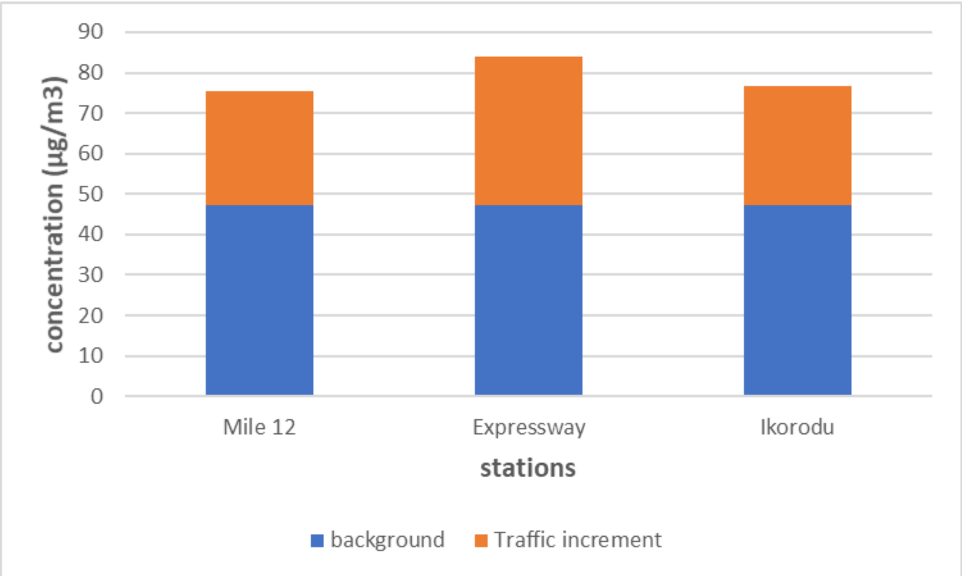

Figure 5.9: Total $PM_{2.5}$ concentrations at 3.7m away from the kerbs of the nearest roads to the stations at Mile 12, Expressway and Ikorodu. The figure also shows the modelled mean traffic increments at these stations (for the simulations based on study period 2).

The Figure 5.9 above shows that traffic increment was highest at the Expressway and very similar at the Mile 12 and Ikorodu. This is consistent with the information presented in the

Table 4.1. The Table 4.1 shows that hourly- traffic volume was highest around the Expressway. The similarity seen in the traffic increment at Mile 12 and Ikorodu is because both stations were sited along the same traffic corridor.

In summary, with model calibration, the predicted traffic increments are 28.1µg/m^3 (37.2%), 36.5 µg/m^3 (43.5%) and 29.3 µg/m^3 (38.2%) respectively for Mile 12, Expressway and Ikorodu road. A similar pattern is noticed without model calibrations and this is shown in the Figure 5.10 below.

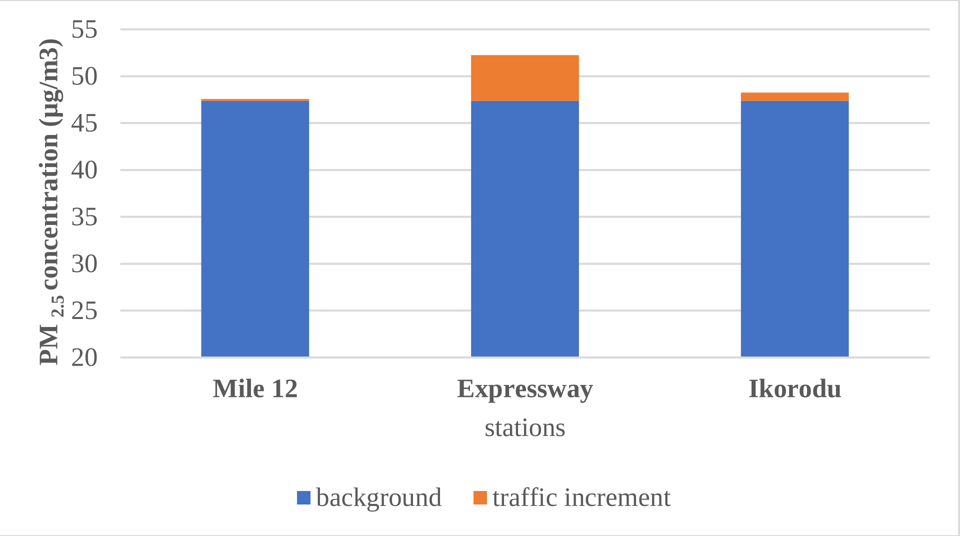

Figure 5.10: Total $PM_{2.5}$ concentrations at 3.7m away from the kerbs of the nearest roads to the stations at Mile 12, Expressway and Ikorodu- without model calibration. The figure also shows the modelled mean traffic increments (without model calibration) at these stations (for the simulations based on study period 2).

The figure above also shows that traffic increment is highest at the Expressway. The mean predicted traffic increments are 0.19 µg/m^3, 4.88 µg/m^3 and 0.86 µg/m^3 respectively for Mile 12, Expressway and Ikorodu stations. A similar pattern was reported for London. In Singh et al. (2014), the predicted values for "roadside and busy roadsides" were 1.89 ± 1.09 µg/m^3, and 2.48 ±0.91 µg/m^3 respectively.

5.4 The local emission factors

As described in section 3.4.2, local emission factors were computed for this study using the equation 3. However, these emission factors were extremely high, in comparison to the emission factors from COPERT 5. Figures 5. 10 and 5.11 compare the local emission factors with those obtained from COPERT 5.

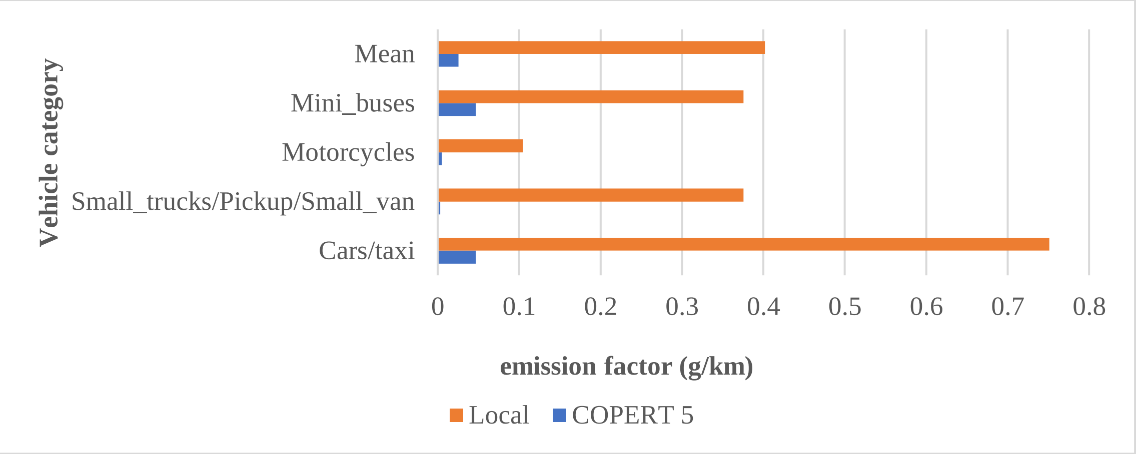

Figure 5.11: Comparing the emission factors (for gasoline vehicles) from COPERT 5 and local (West African) sources.

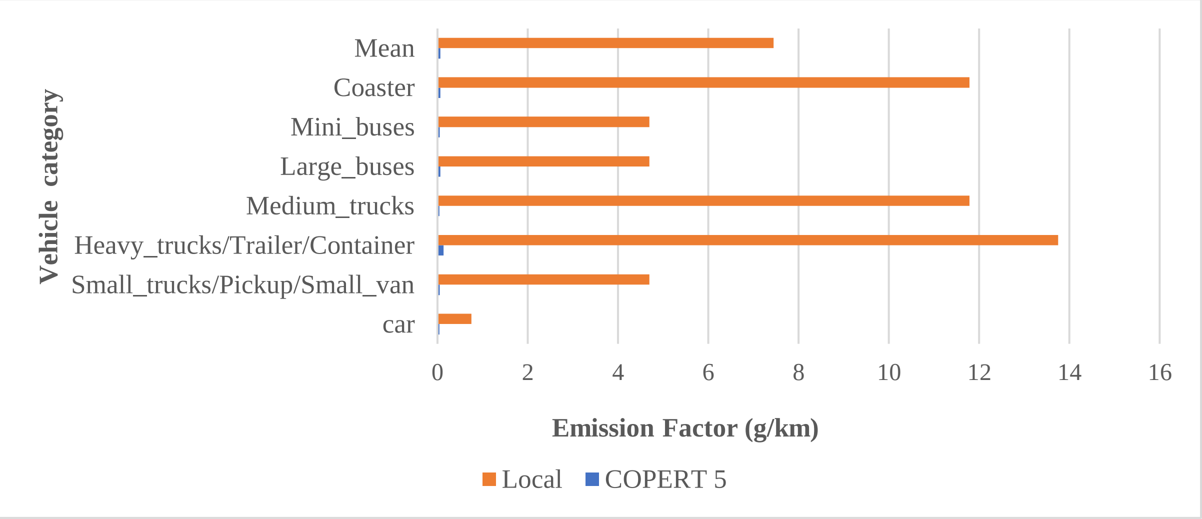

Figure 5.12: Comparing the emission factors (for diesel vehicles) from COPERT 5 and local (West African) sources.

As shown in the Figures above, the mean values of the local emission factors are 16 and 120 times higher than those obtained from COPERT 5 - for gasoline and diesel vehicles respectively.

Similarly, the simulation carried out with these emission factors produced total modelled $PM_{2.5}$ concentrations which were extremely higher than the observed $PM_{2.5}$ concentrations at the monitoring stations. This is shown in Figure 5.13 below.

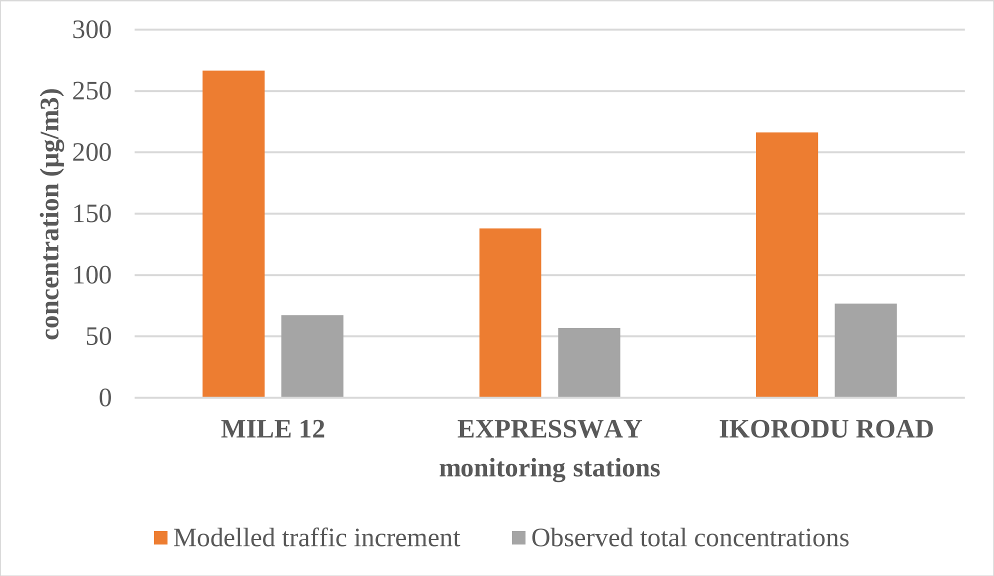

Figure 5.13: Comparing modelled traffic increment with measured total $PM_{2.5}$ concentrations. The emission factors used for this simulation are from the local (West African) sources.

The suitability of the emission factors from both sources (COPERT 5 and local) was also investigated by considering the correlation factors (R), the coefficient of determination (R^2) and the calculated values of F2 obtained while calibrating the model. As shown in the Figure 5.14 (a), for the simulations carried out with the EFs from COPERT 5, the values of R^2, R and F2 are 0.84,0.91 and 0.80 respectively. These values are close to unity which is the expected value for a perfect model.

Conversely (as shown in the Figure 5.14 (b)), for the simulations carried out with the EFs from local sources, the values of R^2, R and F2 are 0.07,0.26 and 0.05 respectively. These values are extremely close to zero- indicating that agreement between modelled and observed concentrations is almost non-existent.

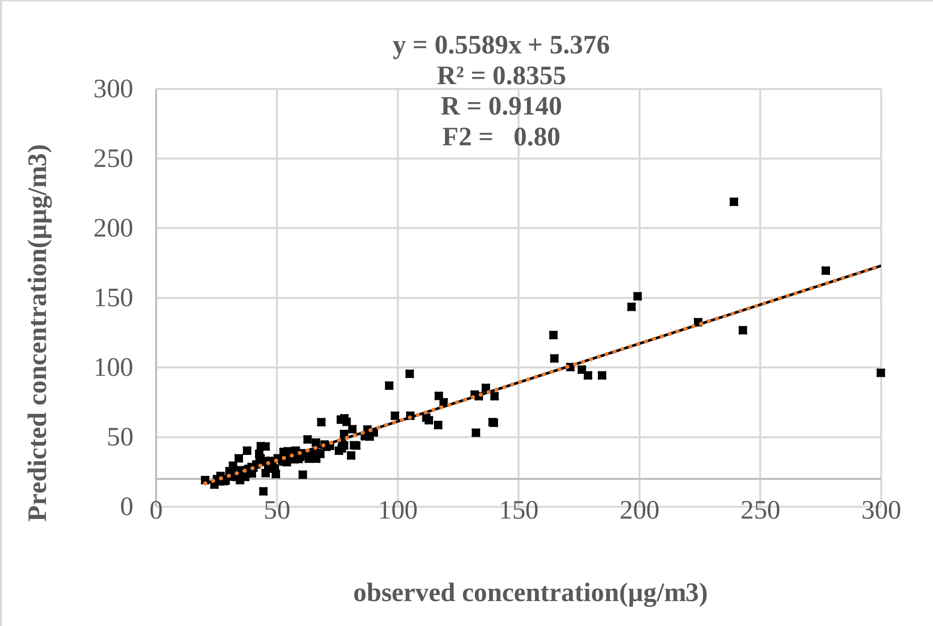

Figure 5.14(a): Comparing modelled and observed total PM $_{2.5}$ concentrations during model calibration for simulations carried out with emission factors from COPERT 5.

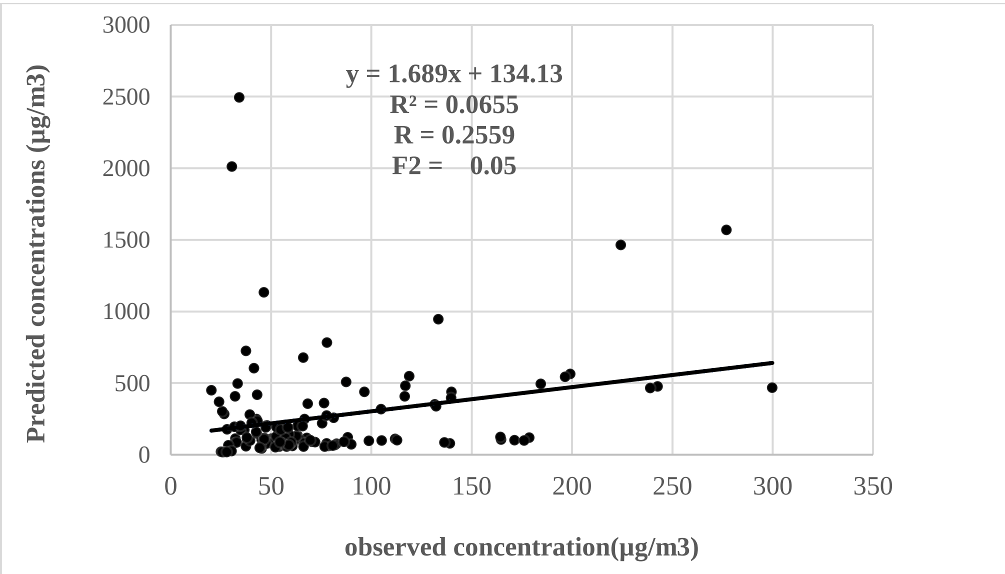

Figure 5.14(b): Comparing modelled and observed total PM $_{2.5}$ concentrations during model calibration for simulations carried out with emission factors from local sources.

From the Figures 5.14 (a and b), it is evident that the emission factors obtained from the local sources were unsuitable and were not applied in the post-calibration activities (model evaluation and application of results). Therefore, the emission factors from COPERT 5 were rightly considered as appropriate for this modelling study.

5.5 Scenario Analysis

5.5.1 The Scenario

In March 2008, the Lagos State Government introduced Bus Rapid Transit system in a bid to enhance mass transits in the metropolitan area of Lagos. The scheme started with the Mile 12 – CMS traffic corridor. At the inception, services were provided by two operators: the LAGBUS Asset Management company and the NURTW/ LAMATA partnership. Buses from each of the service providers could be easily identified with their colours – red for LAGBUS and blue for NURTW/ LAMATA.

However, in November 2016, the government “banned” the red buses from plying the Mile 12 - Ikorodu route, due to continuous commuters’ complaints of incessant poor services- from the provider. Thereafter, only the blue (BRT) buses are permitted to ply the route. The BRT buses are categorised as large buses (by LAMATA and in this study).

Therefore, in this study, this scenario is analysed to estimate the impact of this policy on the traffic increment of $PM_{2.5}$ concentration near the Ikorodu road, under a constant meteorological condition.

5.5.2 Analysis

Figure 5.15 below shows the difference in the number of large buses (including the red and the blue BRT buses) plying the road per hour, between 2010 (before the ban) and 2018 (after the ban).

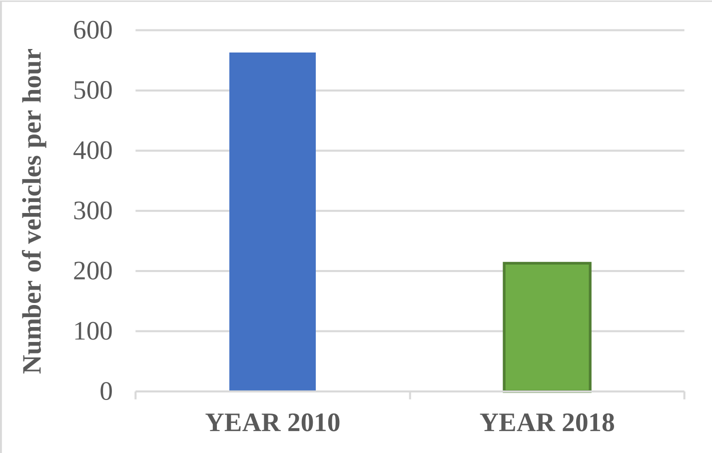

Figure 5.15: Reduction in the number of large (BRT) buses plying the road before and after the ban.

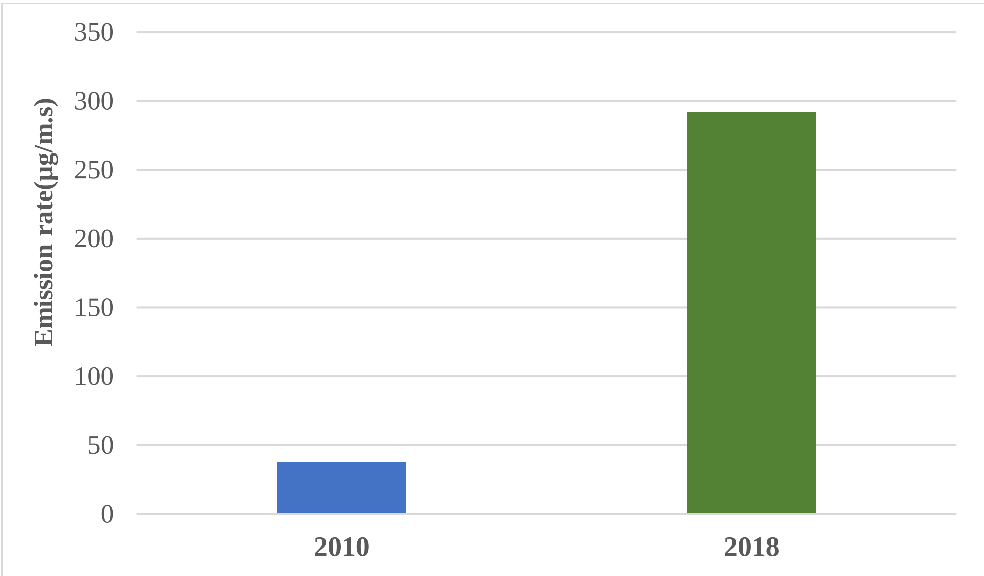

Figure 5.16: Change in the total emission rates of the line sources from the various segment of the road - before and after the ban.

From Figures 5.13 and 5.14, it can be deduced that in spite of about 62 % decrease in the hourly volume of large buses on the road, the total emission rate (due to all vehicular activity) of $PM_{2.5}$ increased by a factor of 7, after the ban. The reason for this observation is: the higher emitting motor vehicles are not banned from plying the road. Figures 5.17

below shows the emission rate of each vehicle type, as a percentage of the total – for 2010 (before the ban) and 2018 (a year after the ban).

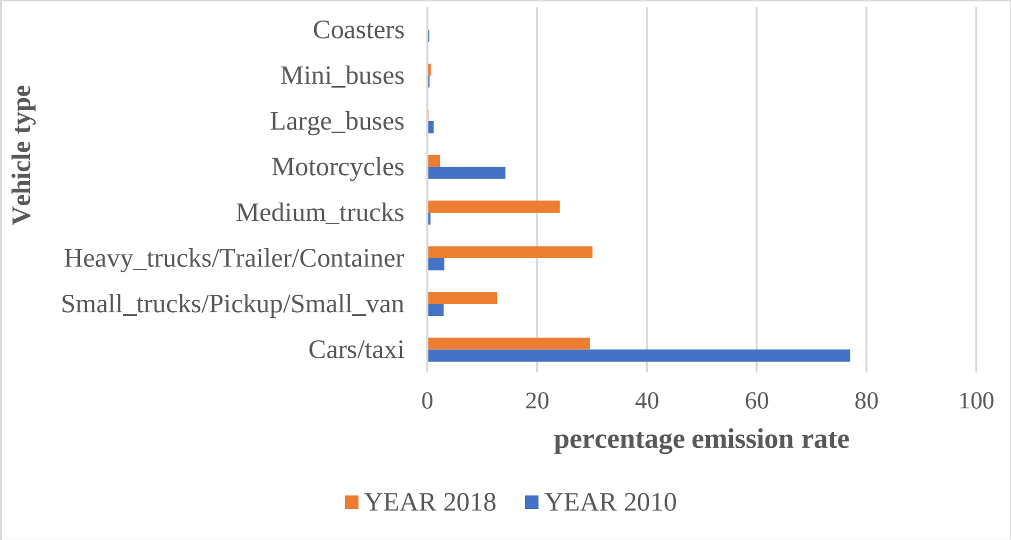

Figure 5.17: The total emission rate of each vehicle category before and after the ban. The emission rates are expressed as percentages of the total rate for the road links.

To evaluate the resultant change in traffic contribution to $PM_{2.5}$ concentration, the mean modelled- traffic increment for November 2010 and November 2018 are compared as shown in the Figure 5.18 below.

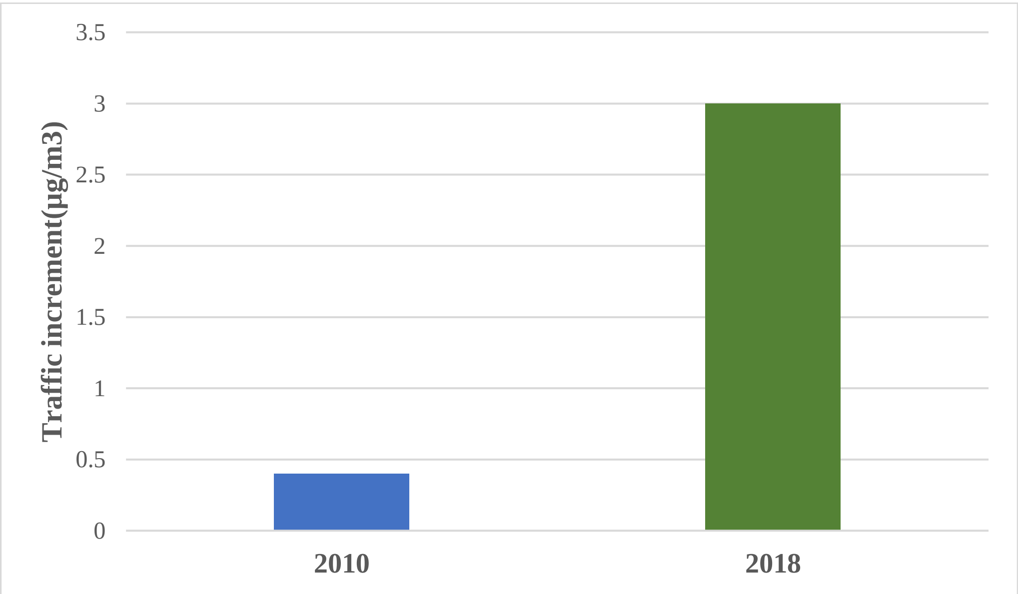

Figure 5.18: Change in modelled traffic increment over both periods.

The Figures 5.18 shows that traffic contribution increased by a factor of 7, between 2010 and 2018 - assuming the meteorological conditions in 2010 was the same as in 2018. This change in traffic contribution is proportionate to the increase in emission rate which is also by a factor of 7. The aforementioned is a confirmation of the OSCAR model's consistency with the Gaussian Dispersion Equation, as shown in the section 3.2.1.

Reductions in traffic contribution can be achieved by reducing the volume of the high emitting vehicle categories on the road. As shown in the Figure 5.17, the first and the second highest emitters are cars/taxi and heavy trucks/trailers respectively. Coincidentally, in April 2018, the Lagos State Government and UNEP initiated the creation of a "Non- Motorised Transport (NMT)" policy to meet the transportation needs of its growing urban population. The key component of this policy is to reduce demand for use of "personal motor vehicles" while expanding the Bus Rapid System. An additional benefit of the NMT policy is, based on the findings of this study, reduction in ambient $PM_{2.5}$ concentration along the Mile 12 - Ikorodu road as cars, which are the most common "personal motor vehicles" in Lagos, are the highest emitter of $PM_{2.5}$.

Chapter 6

Conclusions and recommendations

The OSCAR System has been used to modelled road traffic contributions to $PM_{2.5}$ concentrations in a selected part of the metropolitan area of Lagos. Following its applications in London and Helsinki, the model has been evaluated in Africa for the first time, through this study. Similarly, this study is arguably the first of its kind on Lagos.

6.1 Conclusions

6.1.1 Model Evaluation

The statistical parameters used in the evaluation show a good level of performance by the model. For instance, the model's low MNSE and FB values implies minimal systematic and random errors. Similarly, the aggregated median R and F2 value for the model are 0.66 and 0.80 respectively. These values are not too far from unity which is the expected value for a perfect model. As F2 is regarded as the most robust performance measure, a value of 0.8 for the model indicates highly acceptable performance. However, the model's overpredicted the measured data in one site and underpredicted in the other. This has been linked to its calibration which is influenced by variation in background concentrations across the stations.

6.1.2 Modelled Traffic Increment

The model predicted mean traffic increment of 28.1µg/m^3 (37.2%) - 29.3 µg/m^3 (38.2%) along the Mile 12 – Ikorodu road. However, the predicted increment around the

Expressway (a busier road) was 36.5 µg/m^3 (43.5%). The Mile 12 -Ikorodu road.is a very important traffic corridor in the Lagos Metropolitan Area. It was the pioneering route for the government's Bus Rapid Transit scheme, and currently has the largest volume of BRT buses.

6.1.3 Emission Inputs

Emission factors from COPERT 5 were used for the simulations carried out in this study. Although emission factors from local sources (obtained from a study conducted on emissions in West Africa) were also considered, they were found to be unsuitable due to their extremely high values.

6.1.4 Dispersion characteristic of $PM_{2.5}$

Generally, traffic contributions to $PM_{2.5}$ decreases rapidly as the perpendicular distance from the centre line of the road increases. In this study, dispersions of $PM_{2.5}$ from the nearest roads to the measurement stations, are expressed as polynomials of the second order. Comparing the slopes of these polynomials shows a higher dispersion rate for the Expressway.

6.1.5 Scenario analysis

The scenario analysed demonstrate how dispersion modelling can guide policy makers in making decisions relating to air quality improvement. For instance, the analysis shows that in addition to improved mass transits, the government's "Non-Motorized Transport" policy will go a long way in reducing road traffic contributions to ambient $PM_{2.5}$ concentrations in the city. The key component of this policy is to reduce demand for use of personal motor vehicles while expanding the Bus Rapid System. As shown in this study, cars/taxi are the highest emitting vehicle type, along the Mile 12 – Ikorodu road. Therefore, if the government's policy is adhered to, reduction in the use of personal cars could reduce traffic-induced ambient $PM_{2.5}$ concentrations.

6.2 Recommendations

The following recommendations are being made due to the aforementioned conclusions:

(i) In this study, model evaluation was carried out with measured data for a period of 130 hours (due to paucity of observation data). For future modelling studies on Lagos, more air quality data (which is properly categorised as roadside or kerbside) is needed. This will facilitate more robust model evaluation and analysis of results.

(ii) Appropriate emission factors for modelling traffic contributions in Africa, should be determined through further studies. Improved emission factors can then be included in future analysis with the OSCAR System to simulate $PM_{2.5}$ dispersion from Lagos' roads.

(iii) Further studies should include simulation or at least survey of traffic characteristics and contributions over a larger domain – possibly the entire metropolitan area of Lagos.

(iv) There is a need for verified air quality monitoring to undertake longer term research in air quality for African cities such as Lagos. This will enhance future modelling studies and also guide the ministries of Environment and transportations in making policies which promotes environmental health.

(v) In order to improve model performance development and evaluation, there is need for automated (continuous) traffic counters collocated with air quality monitoring stations as this will improve efficiency and reliability in traffic data collections.

APPENDIX A

Road links coordinates: in latitude - longitude

Road ID	START Decimal Degrees (DD)		END Decimal Degrees (DD)		LINK
	LAT	LONG	LAT	LONG	
R1	6.602267	3.332827	6.64788	3.306218	L1-L2
R2	6.602267	3.332827	6.64788	3.306218	L1 - L2
R3	6.64788	3.306218	6.663395	3.285961	L2-L3
R4	6.595617	3.33566	6.618691	3.36423	L4 -L5
R5	6.51702	3.365271	3.36423	3.382952	L7 -L6
R6	6.546779	3.337719	6.558377	3.366902	L9 - L8
R7	6.546779	3.337719	6.566818	3.321322	L9-L10
R8	6.566818	3.321322	6.590352	3.337632	L10-L11
R9	6.590352	3.337632	6.593059	3.343169	L11 -L12
R10	6.593059	3.343169	6.571485	3.367802	L12 -L13
R11	6.571485	3.367802	6.597237	3.341023	L13 -L14
R12	6.597237	3.341023	6.616761	3.335444	L14 -L15
R13	6.558377	3.366902	6.550829	3.396856	L8 -L16
R14	6.596324	3.384715	6.596452	3.381089	L18 -L17
R15	6.591336	3.385059	6.595471	3.384848	L19 - L20
R16	6.5961	3.380605	6.591081	3.380926	L21 -L22
R17	6.591294	3.381796	6.591074	3.38444	L23 -L24
R18	6.593761	3.383168	6.604131	3.302587	L25 -L26
R19	6.604131	3.302587	6.605889	3.302587	L26-L27
R20	6.586537	3.378206	6.606212	3.398977	L28-L29
R21	6.60967	3.352917	6.588482	3.378925	L30 -L31
R22	6.586266	3.363904	6.607198	3.349184	L32 -L33
R23	6.597819	3.367338	6.591722	3.359398	L34 -L35
R24	6.586223	3.363776	6.583878	3.358626	L36 -L37
R25	6.604759	3.337043	6.610408	3.344896	L38 - L39
R26	6.610408	3.344896	6.607253	3.348941	L39 -L40
R27	6.61336	3.328374	6.614202	3.335616	L41 -L42
R28	6.614567	3.335804	6.614641	3.346082	L43 -L44
R29	6.616837	3.33545	6.628134	3.324635	L45 -L46

R30	6.627419	3.322607	6.628134	3.324635	L47 -L46
R31	6.585049	3.389628	6.629199	3.364284	L48 -L49
R32	6.600161	3.377622	6.60046	3.364672	L50 -L51
R33	6.599629	3.37524	6.616073	3.363718	L52 -L53
R34	6.603468	3.372435	6.610758	3.358594	L54 -L55
R35	6.601459	3.395951	6.606212	3.398977	L56 -L57
R36	6.608392	3.39627	6.624591	3.392236	L58- L59
R37	6.606194	3.399801	6.60969	3.397677	L60 - L61
R38	6.571913	3.397355	6.588438	3.379684	L48 -L62
R39	6.616761	3.335444	6.628385	3.324618	L15 - L63
R40	6.627419	3.322607	6.623536	3.319475	L47-L64
R41	6.623536	3.319475	6.619657	3.301343	L64 -L65
R42	6.627419	3.322607	6.614392	3.327908	L47 -L66
R43	6.618691	3.36423	6.629199	3.364284	L5 - L49
R44	6.612788	3.501138	6.620291	3.503455	L67 -L68
R45	6.606212	3.398977	6.620291	3.503455	L29 - L68
R46	6.616761	3.335444	6.626485	3.336593	L15 - L69
R47	6.626485	3.336593	6.635362	3.345015	L69-L70
R48	6.646986	3.323449	6.635362	3.345015	L71 -L70
R49	6.635362	3.345015	6.642579	3.375307	L70 -L72
R50	6.61368	3.355192	6.63459	3.353283	L73 - L74

APPENDIX B

Road links coordinates: in UTM

Road ID	START meter (m)		END meter (m)	
	EASTING	NORTHING	EASTING	NORTHING
R1	536791.5	729793.5	533847	734834
R2	536791.5	729793.5	536791.5	729793.5
R3	533847	734834	531606.9	736547.8
R4	537105.2	729058.6	540261.6	731611.6
R5	540384.9	720372.2	542333.3	728807.8
R6	537336.5	723659.9	540561.9	724944.3
R7	537336.5	723659.9	535522.2	725873.9
R8	535522.2	725873.9	537323.6	728476.7
R9	537323.6	728476.7	537935.5	728776.4
R10	537935.5	728776.4	540660.3	726393.4
R11	540660.3	726393.4	537697.9	729238.1
R12	537697.9	729238.1	537079.7	731396
R13	540561.9	724944.3	543874.1	724112.4
R14	542527.9	729140.7	542127.1	729154.5
R15	542566.4	728589.3	542542.7	729046.4
R16	542073.6	729115.5	542109.5	728560.7
R17	542205.7	728584.4	542498	728560.3
R18	542357.2	728857.2	533448.6	729997.4
R19	533448.6	729997.4	533448.5	730191.8
R20	541809.2	728058.2	544103.7	730235
R21	539011.8	730613.4	541888.5	728273.3
R22	540228.2	728027.1	538599.3	730339.9
R23	540606.9	729304.5	539729.6	728629.8
R24	540214	728022.3	539644.9	727762.6
R25	537257.4	730069.3	538125.1	730694.4
R26	538125.1	730694.4	538572.4	730345.9
R27	536298.5	731019.5	537098.9	731113.1
R28	537119.7	731153.5	538255.8	731162.4
R29	537080.4	731404.4	535884.1	732652.4
R30	535660	732573.2	535884.1	732652.4
R31	543072	727894.7	540266.7	732773.2
R32	541743.5	729564.2	540311.9	729596.2
R33	541480.3	729505.2	540205.2	731322.1
R34	541169.9	729929.4	539639.2	730734.1
R35	543769.6	729709.3	544103.7	730235

R36	543804.2	730475.7	543356.9	732266.1
R37	544194.8	730233.1	543959.7	730619.4
R38	543927.4	726443.2	541972.5	728268.5
R39	537079.7	731396	535882.2	732680.2
R40	535660	732573.2	535314	732143.8
R41	535314	732143.8	533310	731713.7
R42	535660	732573.2	536246.9	731133.5
R43	540261.6	731611.6	540266.7	732773.2
R44	555396.3	730972.2	555651.6	731801.9
R45	544103.7	730235	555651.6	731801.9
R46	537079.7	731396	537206	732471
R47	537206	732471	538136.3	733453
R48	535751.6	734736.4	538136.3	733453
R49	538136.3	733453	541484.1	734253.2
R50	539262.9	731056.9	539050.3	733368.3

APPENDIX C

XY COORDINATES OF ROAD LINKS RELATIVE TO ORIGIN OF THE DOMAIN

Road ID	START meter (m)		END meter (m)	
	X1	**Y1**	**X2**	**Y2**
R1	5791.5	10993.5	2847	16034
R2	5791.5	10993.5	5791.5	10993.5
R3	2847	16034	606.9	17747.8
R4	6105.2	10258.6	9261.6	12811.6
R5	9384.9	1572.2	11333.3	10007.8
R6	6336.5	4859.9	9561.9	6144.3
R7	6336.5	4859.9	4522.2	7073.9
R8	4522.2	7073.9	6323.6	9676.7
R9	6323.6	9676.7	6935.5	9976.4
R10	6935.5	9976.4	9660.3	7593.4
R11	9660.3	7593.4	6697.9	10438.1
R12	6697.9	10438.1	6079.7	12596
R13	9561.9	6144.3	12874.1	5312.4
R14	11527.9	10340.7	11127.1	10354.5
R15	11566.4	9789.3	11542.7	10246.4
R16	11073.6	10315.5	11109.5	9760.7
R17	11205.7	9784.4	11498	9760.3
R18	11357.2	10057.2	2448.6	11197.4
R19	2448.6	11197.4	2448.5	11391.8
R20	10809.2	9258.2	13103.7	11435
R21	8011.8	11813.4	10888.5	9473.3
R22	9228.2	9227.1	7599.3	11539.9
R23	9606.9	10504.5	8729.6	9829.8
R24	9214	9222.3	8644.9	8962.6
R25	6257.4	11269.3	7125.1	11894.4
R26	7125.1	11894.4	7572.4	11545.9
R27	5298.5	12219.5	6098.9	12313.1
R28	6119.7	12353.5	7255.8	12362.4
R29	6080.4	12604.4	4884.1	13852.4
R30	4660	13773.2	4884.1	13852.4
R31	12072	9094.7	9266.7	13973.2
R32	10743.5	10764.2	9311.9	10796.2
R33	10480.3	10705.2	9205.2	12522.1
R34	10169.9	11129.4	8639.2	11934.1
R35	12769.6	10909.3	13103.7	11435

R36	12804.2	11675.7	12356.9	13466.1
R37	13194.8	11433.1	12959.7	11819.4
R38	12927.4	7643.2	10972.5	9468.5
R39	6079.7	12596	4882.2	13880.2
R40	4660	13773.2	4314	13343.8
R41	4314	13343.8	2310	12913.7
R42	4660	13773.2	5246.9	12333.5
R43	9261.6	12811.6	9266.7	13973.2
R44	24396.3	12172.2	24651.6	13001.9
R45	13103.7	11435	24651.6	13001.9
R46	6079.7	12596	6206	13671
R47	6206	13671	7136.3	14653
R48	4751.6	15936.4	7136.3	14653
R49	7136.3	14653	10484.1	15453.2
R50	8262.9	12256.9	8050.3	14568.3

APPENDIX D

Grouping road links based on LGA, trunks, lanes

LGA	Road ID	Trunk	Number of Lanes
Agege	R1	A	6
	R30	B	4
	R40	B	4
	R41	B	4
Alimosho	R2	A	6
	R3	A	6
Ikeja	R10	B	4
	R11	B	4
	R12	B	4
	R21	B	4
	R4	B	4
	R22	B	4
	R23	C	4
	R24	C	4
	R25	C	2
	R26	C	2
	R27	C	2
	R28	C	2
	R29	A	2
	R32	B	2
	R33	C	4
	R34	C	2
	R38	B	2
	R39	B	2
	R21	B	4
	R43	B	6
	R46	B	4
	R47	B	4
	R48	B	4
	R49	B	4
	R50	B	4
Ikorodu	R5	A	6
	R14	A	2
	R15	A	2
	R16	A	2
	R17	A	2
	R18	A	6

	R44	C	2
	R19	A	4
	R20	A	4
	R35	C	2
	R36	B	4
	R37	B	4
Oshodi -Isolo	R7	B	4
	R6	A	6
	R8	B	4
	R9	B	4
	R13	A	6

APPENDIX E

A program code (written in Fortran) to compute the total emission rate of PM2.5 from each of the 50 roads.

```
program emirate

!This program computes the emission rate for a line source-

!using traffic volume,fuel split within each vehicle category

!and emission factor for each vehicle category.

implicit none

real,dimension(9,50)::trafvo

real,dimension(9,6):: emifac

real,dimension(9,2):: prop

real,dimension(9)::pa,da,pb,db,pc,dc

real,dimension(9)::p_pro,d_pro,p_vol,d_vol

!pa=emission factors for petrol vehicles on trunk A road,da =

!emission factors for diesel vehicles on trunk A road.

!pb,db,pc,dc follow the above descriptions.

real,dimension(9)::emit_p,emit_d,emit_rate

real,dimension(9):: road_tot_emit

real,dimension(9):: facp,facd,tot_emit

real:: tot

integer::i,j

open(unit= 23,file="trafvolume.csv")

read(23,*)trafvo

open(unit= 27,file="emitfac.csv")
```

```
    r
read(27,*)emifac

pa = emifac(:,1)

da = emifac(:,2)

pb = emifac(:,3)

db = emifac(:,4)

pc = emifac(:,5)

dc = emifac(:,6)

open(unit = 29,file ="fuelprop.csv")

read(29,*) prop

p_pro = prop(:,1)

d_pro = prop(:,2)

do j = 1,50

  do i = 1,9

    p_vol(i) = p_pro(i) * trafvo(i,j)

    d_vol(i) = d_pro(i) * trafvo(i,j)

    if (j>= 1.or.j<=17) then

      facp(i)= pa(i)

      facd(i)= da(i)

    else if (j>=18.or.j<=38) then

       facp(i) = pb(i)

       facd(i) = db(i)

    else if (j>=19.or.j<=50) then

       facp(i) = pc(i)
```

```
          facd(i) = dc(i)

        end if

        emit_p(i) = p_vol(i)* facp(i)

        emit_d(i) = d_vol(i) * facd(i)

        tot_emit(i) = emit_p(i) + emit_d(i)

        emit_rate(i) = tot_emit(i)*1000

! The above converts the total emission rate from g/km to microgram/m

        emit_rate(i) = emit_rate(i)/(14*3600)
! The above compute the emission rate for each vehicle category in
! mg/m.s


      end do

      tot = sum(emit_rate(1:9))

      open(unit=33,file="emissionLag.csv")

      write(33,*)  tot

end do

close(33)

end
```

APPENDIX F

Traffic counts for the fleet compositions of the 50 roads in the modelling domain - for the first study period (October 2010 - January 2011)

ROAD	Cars/ taxi	Bicy cle	Small_ trucks/ Small_ van	Heavy_ trucks/ Trailer	Medium_ trucks	Motor cycles	Large _buses	Mini_ buses	Coasters
R1	22032	2	992	574	586	20700	1096	9779	523
R2	22032	2	992	574	586	20700	1096	9779	523
R3	22032	2	992	574	586	20700	1096	9779	523
R4	15272	10	639	51	118	3078	67	5744	28
R5	22032	2	992	574	586	20700	1096	9779	523
R6	33048	3	1488	861	879	31050	1644	14669	785
R7	15285	3	1305	134	186	4109	4	2875	132
R8	15285	3	1305	134	186	4109	4	2875	132
R9	15285	3	1305	134	186	4109	4	2875	132
R10	15285	3	1305	134	186	4109	4	2875	132
R11	15272	10	639	51	118	3078	67	5744	28
R12	15272	10	639	51	118	3078	67	5744	28
R13	33048	3	1488	861	879	31050	1644	14669	785
R14	11790	4	444	158	102	19038	125	719	39
R15	11790	4	444	158	102	19038	125	719	39
R16	11790	4	444	158	102	19038	125	719	39
R17	11790	4	444	158	102	19038	125	719	39
R18	22032	2	992	574	586	20700	1096	9779	523
R19	23580	8	888	316	204	38076	250	1438	78
R20	23580	8	888	316	204	38076	250	1438	78
R21	24496	1	1200	1020	1013	3606	2789	7717	394
R22	15272	10	639	51	118	3078	67	5744	28
R23	15272	10	639	51	118	3078	67	5744	28
R24	15272	10	639	51	118	3078	67	5744	28
R25	7636	5	320	26	59	1539	34	2872	14
R26	7636	5	320	26	59	1539	34	2872	14
R27	7636	5	320	26	59	1539	34	2872	14
R28	7636	5	320	26	59	1539	34	2872	14
R29	7636	5	320	26	59	1539	34	2872	14
R30	7932	1	357	207	211	7452	395	3520	188
R31	33048	3	1488	861	879	31050	1644	14669	785
R32	7636	5	320	26	59	1539	34	2872	14
R33	15272	10	639	51	118	3078	67	5744	28
R34	7636	5	320	26	59	1539	34	2872	14

R35	11790	4	444	158	102	19038	125	719	39
R36	5895	2	222	79	51	9519	63	360	20
R37	5895	2	222	79	51	9519	63	360	20
R38	24496	1	1200	1020	1013	3606	2789	7717	394
R39	15272	10	639	51	118	3078	67	5744	28
R40	7932	1	357	207	211	7452	395	3520	188
R41	7932	1	357	207	211	7452	395	3520	188
R42	15272	10	639	51	118	3078	67	5744	28
R43	33048	3	1488	861	879	31050	1644	14669	785
R44	11790	4	444	158	102	19038	125	719	39
R45	23580	8	888	316	204	38076	250	1438	78
R46	15272	10	639	51	118	3078	67	5744	28
R47	15272	10	639	51	118	3078	67	5744	28
R48	15272	10	639	51	118	3078	67	5744	28
R49	15272	10	639	51	118	3078	67	5744	28
R50	15272	10	639	51	118	3078	67	5744	28

APPENDIX G

Traffic counts for the fleet compositions of the 50 roads in the modelling domain - for the first study period (9-14 November 2018)

ROAD	Cars /taxi	Bicycle	Small trucks/Small van	Heavy_ trucks/ Trailer	Medium _trucks	Motorcycles	Large buses	Mini buses	Coasters
R1	28117	2	1264	731	747	26419	1398	12484	669
R2	29547	9	2350	1004	1128	21682	1399	16470	1036
R3	29547	9	2350	1004	1128	21682	1399	16470	1036
R5	29547	9	2350	1004	1128	21682	1399	16470	1036
R6	15948	0	2839	3693	1956	3838	647	15725	618
R13	15948	0	2839	3693	1956	3838	647	15725	618
R14	1332	1312	4484	3866	10357	525	0	0	0
R15	1332	1312	4484	3866	10357	525	0	0	0
R16	1332	1312	4484	3866	10357	525	0	0	0
R17	1332	1312	4484	3866	10357	525	0	0	0
R18	29547	9	2350	1004	1128	21682	1399	16470	1036
R19	2665	2624	8967	7732	20714	1049	0	0	0
R20	2665	2624	8967	7732	20714	1049	0	0	0
R29	9745	7	408	33	75	1965	44	3666	18
R30	10122	1	455	263	269	9511	503	4494	241
R31	15948	0	2839	3693	1956	3838	647	15725	618
R45	2665	2624	8967	7732	20714	1049	0	0	0
R4	19490	13	816	65	150	3930	87	7331	35
R7	19507	4	1666	173	238	5245	5	3670	167
R8	19507	4	1666	173	238	5245	5	3670	167
R9	19507	4	1666	173	238	5245	5	3670	167
R10	19507	4	1666	173	238	5245	5	3670	167
R11	19490	13	816	65	150	3930	87	7331	35
R12	19490	13	816	65	150	3930	87	7331	35
R21	31265	1	1531	1301	1291	4601	3559	9848	501
R22	19490	13	816	65	150	3930	87	7331	35
R32	9745	7	408	33	75	1965	44	3666	18
R38	31265	1	1531	1301	1291	4601	3559	9848	501
R39	19490	13	816	65	150	3930	87	7331	35
R40	10122	1	455	263	269	9511	503	4494	241
R41	10122	1	455	263	269	9511	503	4494	241
R42	19490	13	816	65	150	3930	87	7331	35
R43	44320.5	13.5	3525	1506	1692	32523	2098.5	24705	1554
R46	19490	13	816	65	150	3930	87	7331	35
R47	19490	13	816	65	150	3930	87	7331	35

R48	19490	13	816	65	150	3930	87	7331	35
R49	19490	13	816	65	150	3930	87	7331	35
R50	19490	13	816	65	150	3930	87	7331	35
R23	19490	13	816	65	150	3930	87	7331	35
R24	19490	13	816	65	150	3930	87	7331	35
R25	9745	7	408	33	75	1965	44	3666	18
R26	9745	7	408	33	75	1965	44	3666	18
R27	9745	7	408	33	75	1965	44	3666	18
R28	9745	7	408	33	75	1965	44	3666	18
R33	19490	13	816	65	150	3930	87	7331	35
R34	9745	7	408	33	75	1965	44	3666	18
R35	1332	1312	4484	3866	10357	525	0	0	0
R36	9745	7	408	33	75	1965	44	3666	18
R37	9745	7	408	33	75	1965	44	3666	18
R44	1332	1312	4484	3866	10357	525	0	0	0

APPENDIX H

A program code (written in Fortran) to compute hourly time series of the meteorological data received from Nigeria. The original measured data are recorded as 5 minutes- average values.

```
program Lagosmet

implicit none

!This program calculates the hourly mean value of meterological

!boundary layer data based on 5-minutes averaging period.

real,dimension(7,32256)::akmet

real,dimension(32256)::RD,AT,AT2,RH,WS,WD,AP

real,dimension(32256)::RD2,T,T2,H,S2,D,P2

integer::i

integer::k = 1

character(10)::s='Rad',n='Temp',m='Rhum',p='WinS',r='WinD'

character(10)::u='AtmP',q='Hr'

open(unit=37, file ="Met-Lagos-Canas-adjust5.csv")

 read(37,*) akmet

RD = akmet(1,:)

AT2 = akmet(3,:)

RH = akmet(4,:)

WS = akmet(5,:)

WD = akmet(6,:)

AP = akmet(7,:)

open(unit=87,file="Met_Lagos_Out.csv")
```

```
write(87,*) q,s,n,m,p,r,u
do i = 1,32256,12
  open(unit=87,file="Met_Lagos_Out.csv")
  RD2= sum(RD(i:i+11))/12
  T2(k)= sum(AT2(i:i+11))/12
  H(k)= sum(RH(i:i+11))/12
  S2(k)= sum(WS(i:i+11))/12
  D(k)= sum(WD(i:i+11))/12
  P2(k)= sum(AP(i:i+11))/12
  write(87,*) k,RD2(k),T2(k),H(k),S2(k),D(k),P2(k)
  k = k + 1
  end do
close(87)
end
```

APPENDIX I

A program code (written in Fortran) to compute the hourly time series of the cloud – based heights over the domain.

```
program CBH

! This program computes cloud-based height from relative humidity and surface temperature

!  The dew point is computed using Mark's (2005) approximation of the Clasius Clapeyon equation

real,dimension(2,2688)::lagsy

real,dimension(2688)::T,RH,Td,H,G

!"H" is the cloud based hieght where T,RH and Td are the surface

!temperature, relative humidity and dew point

!"G" is the cloud based height in decameters

integer::i

open(unit=57,file="CBH1.csv")

read(57,*)lagsy

T=lagsy(1,:)

RH=lagsy(2,:)

do i=1,2688

    open(unit=59,file="lag-CBH.txt")

    Td(i)= T(i) - ((100 -RH(i))/5)

    H(i) =(T(i)- Td(i))/2.5 * 1000

    G(i) = H(i)/10
       write(59,*) G(i)

  end do
close(59
end
```

APPENDIX J

A program code (written in Fortran) to generate gridded receptor points for the modelled domain.

```
program receptpoint

implicit none

!generating a new set of receptor points using 50 X 50 grids

integer:: i

integer::j

do i= 531000,556800,50

  do j = 718800,737400,50

    open(unit= 93, file = "newrecept.csv")

    write(93,*) i,j

  end do

end do

close(93)

end
```

APPENDIX K

A program code (written in Fortran) to compute hourly time series of the observed PM2.5 concentrations and 5 other parameters. The original measured data are recorded as 20 minutes- average values.

```
program observe data

implicit none

!This program calculates the hourly mean value of observation original data are  based on 20-seconds averaging period.

real,dimension(6,23400)::akmet

real,dimension(23400)::PM2,PM10,AT,RH,WS,WD

real,dimension(23400)::RD2,T2,H,S2,D,P2

integer::i

integer::k = 1

character(10)::s='PM25',n='PM10',m='Temp',p='RH',r='WS'

character(10)::u='WD'

open(unit=37, file ="back_pro3.csv")

read(37,*) akmet

PM2 = akmet(1,:)
```

```
PM10 = akmet(2,:)

AT = akmet(3,:)

RH = akmet(4,:)

WS = akmet(5,:)

WD = akmet(6,:)
do i = 1,23400,180

  open(unit=87,file="obs_out.csv")

  RD2= sum(PM2(i:i+179))/180

  T2(k)= sum(PM10(i:i+179))/180

  H(k)= sum(AT(i:i+179))/180

  S2(k)= sum(RH(i:i+179))/180

  D(k)= sum(WS(i:i+179))/180

  P2(k)= sum(WD(i:i+179))/180

  Write (87, *) RD2(k),T2(k),H(k),S2(k),D(k),P2(k)

  k = k + 1

  end
close (87)
 end
```

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