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Meteorological Factors Influencing Dispersion of Vehicular Pollution in Typical Highway Condition: A Case Study of Lagos-Ibadan Nightmare Highway in the South-West Nigeria

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Abstract
The air quality models can be classified as point, area or line source models depending upon the source of pollutants being modelled. Line source models are used to simulate the dispersion of vehicular pollutants near highways or roads where vehicles continuously emit pollutants. Several models have been formulated to predict pollutant concentrations near highways or roads by approximating them as line sources. Vehicular pollution modelling, in general, refers to carrying out air pollution prediction estimates by simulating the impact of emissions from vehicular activity in a given region. In an urban environment, its effect needs to be taken into consideration in addition to the contribution of other types of sources, namely the area and/or point source for air quality predictions.
Highway dispersion models are generally used for analyzing the output of an existing or proposed highways/roads at a distance of tens to hundreds of meters downwind. In this region, the effect of vehicular pollution and vehicular activity is considered to be the primary consideration for air quality prediction analysis.
Further, there is an immediate need to improve the monitoring and emission inventory capabilities that are a prerequisite and essential for formulating various air pollution control and management strategies. Moreover, there is an urgent need to develop further modelling capabilities that are more appropriate for Nigerian conditions

Keywords: Meteorological, Highway, Vehicular, Pollution and Dispersion

1.0 Introduction

Use of highways dispersion models has increased over the years in policy support for large road infrastructure projects (Banta et al. 2014). Accuracy of various highways dispersion models like any other the air pollution dispersion model results relies on the accuracy of its input parameters. It is important to identify those input variable(s) (or combination of two or more inputs) which significantly influences the output of the model most. In order to establish the importance of individual parameters in the model, models are subjected to sensitivity analysis under wide range of conditions. Sensitivity analysis indicates how much of the overall uncertainty in the model predictions is associated with the individual uncertainty in each model input(s).
Sensitivity analysis of the model is carried out to identify key variables in modelling system and helps in focusing on collection and estimation of those influencing parameters (Bhaskar, 2010). The CALINE4 (Dhyani 2015) line source dispersion model is used extensively throughout the world including Nigeria for predicting air quality along highways under prevailing traffic and meteorological conditions. CALINE4 model requires relatively lesser expertise and has comparatively less input data requirement than other vehicular dispersion models (Gimson et al. 2010).
In Nigeria, CALINE4 vehicular pollution dispersion model is extensively use for prediction of air quality along the highway corridors (Sharma et al. 2015; Dhyani et al. 2015; Majumdar et al. 2017; Lao 2010). However, few studies have been carried out in Nigeria regarding validation and performance evaluation of CALINE4 under mix traffic Conditions (Majumdar

et al. 2010; Dhyani et al. 2014; Konar and Chakrabarty 2016). Most of the vehicular pollution dispersion models like CALINE4 used in Nigeria are developed in western countries for their traffic and meteorological conditions.

Further, most models developed in western countries (homogeneous traffic conditions and mete- orological conditions) are unable to do fair representation real-world complexities (e.g. mixed traffic conditions) common (in the form of meteorological and traffic condition) are still unresolved (Karim et al. 2015). Sensitivity analysis is an important tool to examine model performance in the presence of uncertainty in the model input variables and development of new models.

2.0 Review of Related Works

Few studies have been carried out to identify the influential parameters in CALINE4 model and for further improvement in new models.

Benson (2014) comprises most of its input parameters of CALINE4 model, such as, P-G stability class, mixing height, wind speed, wind direction, highway width and highway length; under homogeneous traffic and open terrain conditions for which model has been developed.

MoRTH et al. (2015) used CALINE4 and reported that wind direction, traffic volume receptor heights and composite emission factors affect the output of the model most and atmospheric stability and mixing height affect the output least.

Bhaskar et al. (2010) developed the multiplicative emission and dispersion sub-models by identifying the influential variables through sensitivity analysis of MOBILE6.2 (USEPA 2016) and CALINE4 model, respectively. The sub-model (a reduced-model form of CALINE4) did not include the mixing height and stability class due to their minor contribution in CALINE4 output (i.e. predicted concentrations). However, no such study has been carried out under mixed traffic conditions. In the present study, an effort has been made to identify the input parameters, which influence the output of the CALINE4 model most under mix traffic condition.

3.0 Methodology

3.1 Site Characteristics

The present study was carried out in Lagos, Nigeria. Lagos has the highest vehicular population in Nigeria with nearly 8.5 million (Gimson, 2010) vehicles, which constitute nearly 4.6% of the vehicular population of Nigeria (MoRTH 2015). Lagos has mixed traffic conditions (or heterogeneous traffic condition with both motorized and non-motorized vehicles, no lane following by traffic). For the study, Ring Road Corridor, near Tinubu Park was selected. The selected corridor is a part of major city road connecting outer Lagos areas to Central Lagos. The stretch selected is nearly 2 km in length and width of the study corridor is 30 m. intercity commercial vehicles do not ply during peak hour. The selected stretch is fairly open terrain with good dispersion conditions and free flow traffic. The corridor has been selected as it represents the typical highway conditions that exist in western countries for which model has been developed (Fig. 3.1).

3.2 Traffic Characteristics

The traffic volume count was carried out through videography at Shoprite Ikeja City Mall, near Tinubu Park, further; video pad editor software was used for

Fig. 3.1 Shoprite Ikeja City Mall, near Tinubu Park

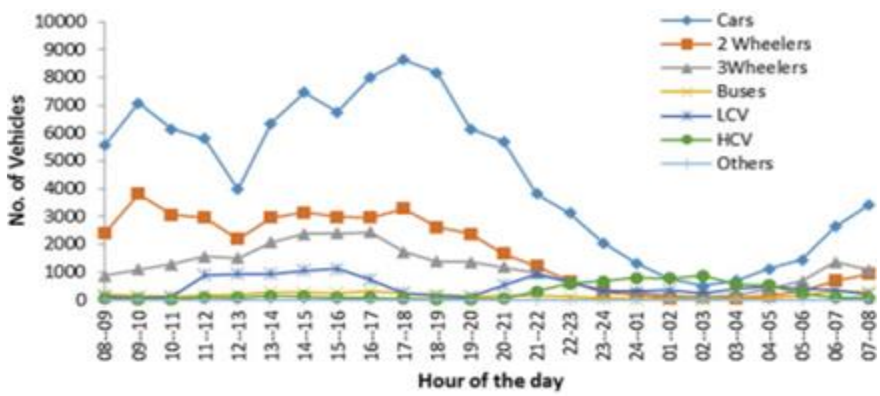

Fig. 3.2 Diurnal distribution of traffic volume along Shoprite Ikeja City Mall near Tinubu Park

Counting the vehicles from the recorded video. The total number of vehicles were 196,440 (*0.2 million) vehicles per day. Diurnal distribution of various categories of vehicles has been shown in Fig. 3.2. Unlike the typical urban roads, no distinct morning and evening traffic peaks were observed, during morning hours (0900- 1000 h) there was 12,213 numbers of vehicles. High traffic counts were observed during 1400-1500 h (*14,400 vehicles) and during 1700-1800 h (14,158 vehicles). Fuel station survey was carried out along the selected road corridor to know the age profile of vehicles, engine technology (2 stroke or 4 stroke) and fuel type (petrol, diesel, CNG and LPG) used by various categories of vehicles. From fuel station survey it was observed that share of cars was highest followed by 2Ws, 3Ws, LCV, buses and HCV (Fig. 3.3). The results (in terms of their age profile, engine technology and composition) obtained from fuel station surveys were applied on the traffic volume of selected corridors assuming that the vehicles plying on the road have the similar characteristics as captured during the fuel station surveys. It was observed that *62% of vehicles were petrol driven followed by *20% diesel vehicles, CNG 17% and LPG 1%. The information obtained through

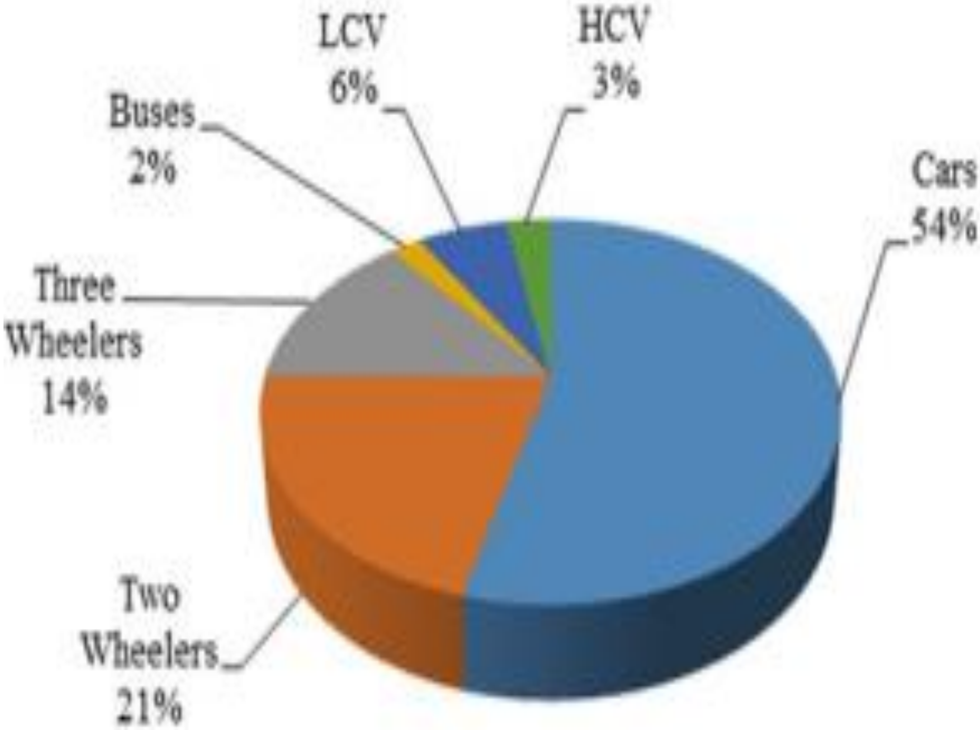

Fig. 3.3 3 % share of different categories of vehicles at Ring Road Corridor near Tinubu Park

Fuel station survey and traffic volume videography (e.g. percentage of 2W-2S and 2W-4S vehicles, percentage of petrol- and diesel-driven vehicles in 4W categories) were used to estimate weighted/composite emission factors (WEFs or CEFs) as an input in the CALINE 4 model.

The WEF (input parameter for CALINE4) is a function of vehicle emission factor (vehicle category, type, fuel type, age profile, vintage, etc.) and vehicle activity (traffic volume). For estimation of WEF (gm/mile) (representative values for all categories of vehicles), emission factors for Nigerian vehicles were used (Majumdar et al. 2017).

The study was carried out in winter season in the month of February. The micro-meteorological input parameters such as, wind speed, wind direction and relative humidity, were measured on-site with the help of Air Pollution Mobile Van fitted with meteorological sensors. The hourly mixing height values were obtained from the Nigerian Meteorological Department (IMD) (Majumdar et al. 2017). In addition, hourly P-G stability class was estimated using wind speed, solar insolation and cloud cover (daytime and night time) (Sharma, 2015). The predominant wind condition was blowing from south-east. The ventilation coefficient is a function of wind speed and mixing height. It is a product of wind speed and mixing height and represents the mixing potential and ventilation capacity over a region. During daytime ventilation, coefficients have higher values (unstable conditions with high mixing height) and low during night time (Table 1). Higher the ventilation coefficient the more will be pollutant dispersion and vice versa However, it is not directly used in CALINE4 model as an input (Fig. 3.4).

3.3 CALINE 4 Model Description

CALINE4 model is the fourth generation simple line source Gaussian plume dispersion model. It predicts the concentrations of CO, NO_2 and $PM_{10}/PM_{2.5}$ near roadways. It employs mixing zone concept to characterize pollutant dispersion over the roadway. CALINE4 model uses the concept of mixing zone width, i.e. region above roadway as zone of uniform emissions and turbulence which accounts for vehicle induced turbulence. Mixing zone width includes sum of roadway width, median width and 3 m on either side of the roadway. Under standard run (1-h) conditions, the model uses given meteorological parameters to predict CO concentrations at pre-identified receptors points. The CO being the indicator pollutant for vehicular activities was chosen for the present Study.

Table1: Summary of the on-site meteorological parameters at selected Tinubu site (Feb, 2015)

Time (h)	Wind direction (°)	Wind speed at 10 m (power formula)	Stability class	Mixing height (m)	Wind direction standard deviation (°)	Temperature (°C)	Relative humidity (%)
8:00	113.3	3.7	B	50	18	22.1	75.1
9:00	117.7	3.8	B	60	18	23.6	70.6
10:00	119.9	3.8	B	175	18	23.9	70.6
11:00	127.3	3.8	B	325	18	24.2	65.9
12:00	123.8	3.8	B	450	18	26.2	61.8
13:00	129.2	3.8	B	700	18	27.0	59.6
14:00	126.5	3.8	B	725	18	27.2	61.1
15:00	121.5	3.7	B	825	18	27.0	62.7
16:00	125.3	3.8	C	850	13	26.9	64.8
17:00	127.6	3.9	C	738	13	25.9	69.4
18:00	128.4	3.9	C	600	13	25.0	72.2
19:00	133.8	4.2	D	400	10	24.2	75.7
20:00	147.1	3.7	E	300	6	23.9	76.0
21:00	126.8	3.8	E	225	6	23.1	82.4
22:00	128.5	3.9	E	200	6	22.8	81.0
23:00	131.0	3.8	E	150	6	22.5	81.3
0:00	132.1	3.9	E	125	6	22.2	82.7
1:00	132.0	3.5	E	100	6	21.8	84.4
2:00	126.0	3.5	E	75	6	22.1	81.6
3:00	131.1	2.9	F	50	6	22.2	77.5
4:00	134.1	2.5	F	52	6	21.7	74.9
5:00	156.2	3.5	D	40	10	21.6	73.3
6:00	161.8	3.5	D	45	10	21.2	76.1
7:00	111.8	3.7	C	60	13	21.4	75.9

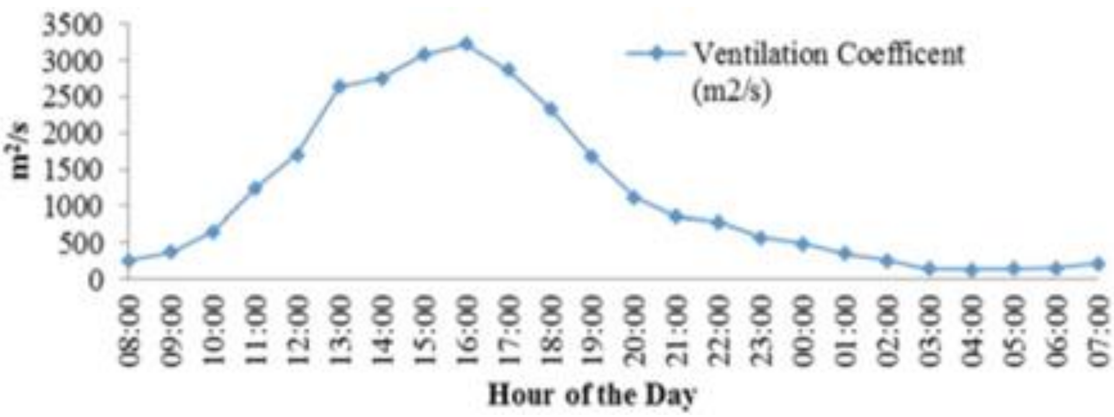

Fig. 3.4 Diurnal variation in ventilation coefficient (m^2/s) at selected corridor

Table 2: Data set selected for sensitivity analysis

Time(h)	Wind direction (°)	Wind speed (m/s)	Stabiliy class (P–G)	Mixing height(m)	Wind direction ±SD	Pollutant background	Temperature (°C)	Traffic volume (no. of vehicles)	WEF (g/mile)
1000	119.9	3.8	B	175	18	0	23.9	10,701	3.75

3.4 Sensitivity Analysis of CALINE4 Model

Sensitivity analysis of CALINE4 model was carried out to determine the significance and contribution of each input variable in the model's output. According to Banta (2014), all input parameters act independently within the model and interaction between two or more variables was presumed to be insignificant. Therefore, for sensitivity analysis, selected input variables were changed systematically changing one input variable at a time keeping other variables constant and effect of each input variable on predicted concentration was observed. Morning peak hour (1000 h) data set has been selected for the sensitivity analysis of the CALINE4 model. Primarily meteorological parameters like wind speed; wind direction, P-G stability class and mixing height were considered for sensitivity analysis (Table 2).

The sensitivity analysis results consist of CO concentration-wind angle (PHI or roadway to wind angle) graphs. Wind angle has been taken with respect to roadway, thus, 0° means parallel to the roadway and 90° means perpendicular to roadway. The CO concentration was observed/ estimated at pre-identified receptors locations selected at a distance of 1, 5, 10, 25, 50, 100, 150 and 200 m at either side of the mixing zone width. The sensitivity analysis was carried out for standard run (1-h) condition.

4.0 Results and Discussion

4.1 Sensitivity Analysis of CALINE4 Model

Meteorological parameters namely, wind speed, wind direction, stability class and mixing height were varied systematically from the selected input data set. CO concentration-wind angle (PHI or roadway to wind angle) graphs have been presented at four distances from the mixing zone width—5, 10, 25 and 50 m to explain the CALINE4 sensitivity for selected input parameters of the model. CO concentration-wind angle (PHI or roadway to wind angle) graphs were presented to explain the CALINE4 sensitivity for selected input parameters of the model. Wind angle was taken with respect to roadway, i.e. 0° PHI means parallel to the roadway and PHI = 90° corresponds to perpendicular wind conditions w.r.t. roadway. Wind

direction is an important parameter in air pollution dispersion, as it fixes the course

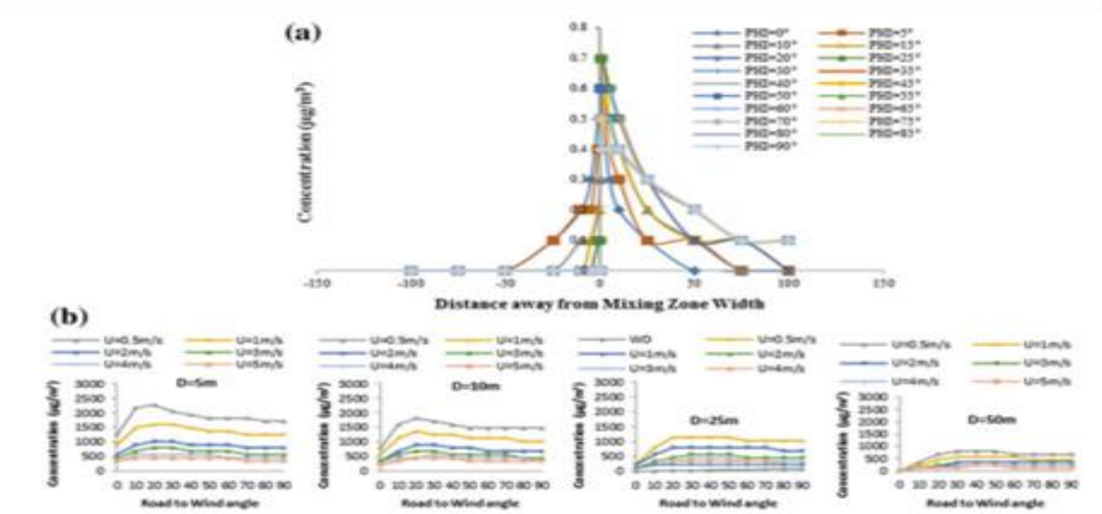

Fig. 4.1Sensitivity analysis for wind angle, PHI (°) and wind speed (m/s) of pollutant dispersion. From sensitivity analysis of CALINE4 model, it was observed that model is most sensitive to PHI between 0° and 30°. Maximum concentration was observed at PHI = 10°. Minimum pollutant concentration was observed when PHI = 80°-90° or perpendicular to roadway. During parallel PHI (0°-25°), pollutant concentrations were observed on both upwind and downwind direction (Fig. 4.1a). Wind speed impacts the dilution and dispersion of pollutants. In the CALINE4 model Gaussian equation, wind speed is inversely proportional to predicted pollutant concentration Wind speed was varied from 0.5 m/s (calm) to 5 m/s in 1 m/s interval. With every 22% increase in wind speed, i.e. 1-2 m/s, 22% decrease in predicted concentration was observed. Maximum concentration was observed during parallel wind direction (10° and 20° PHI) Fig. 4.1b. Mixing Height defines the structure of turbulence in boundary layer. Mixing height along with wind speed determine the volume available for mixing and dispersion of pollutant. Vehicular emissions are near ground emissions, therefore, the influence of mixing height is not expected in dispersion of pollutant. Moreover, in the CALINE4 model thermal turbulence from exhaust of emission and mechanical turbulence generated from vehicles are the main forces, which influence the dispersion of pollutants in mixing zone width for sensitivity analysis, mixing height was varied from 25 to 2500 m (Fig. 4.2a). It was observed that negligible change occurred when mixing height was varied. The data set selected for the study has B (unstable atmosphere) P-G stability class. Model uses Pasquill-Gifford stability class only, P-G stability class is a function of solar insolation intensity, wind speed, cloud

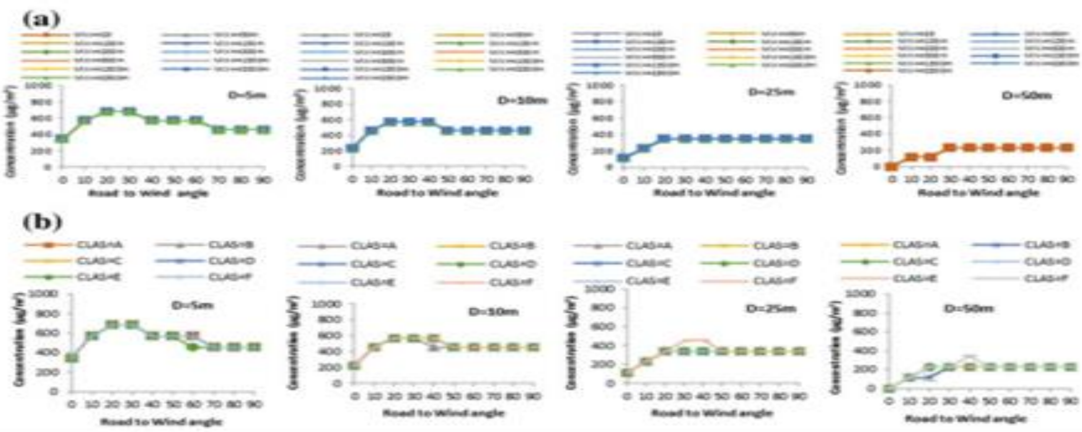

Fig. 4.2 Sensitivity analysis for mixing height (m) and stability class (P–G)

cover and time of the day. Stability class was varied from Class A (highly unstable) to Class F (highly stable). However, insignificant impact of change in stability class was observed on predicted concentration near mixing zone width. However, slight increase (15-30%) in concentration was observed as we move away from mixing zone width (25 and 50 m) (Fig. 4.2b). Thus indicating the importance of mixing zone width concept, where mechanical and thermal turbulence are predominant forces for dispersion. As we move away from the influence zone (mixing zone width), atmospheric features like stability class, mixing height become significant forces for dispersion and dilution process of air pollutants.

Conclusions and Recommendations

Conclusions

Sensitivity analysis of model was carried out to identify the most influencing input parameters in the CALINE4 model. The impact of wind speed and wind direction was more significant on dispersion of vehicular pollution. CALINE4 was found to be most sensitive to parallel wind direction. Maximum concentration was observed at PHI = 20° (parallel wind direction). Wind speed has significant impact, it is inversely proportional on predicted concentration. Nearly, 22% increase in wind speed (0.5-1 m/s) results in 22% decrease in predicted concentration. Stability class was observed to be influencing at a nearly 50 m away from mixing zone width. The impact of stability class is more prominent at receptors away from mixing zone width. Mixing height had insignificant influence on model prediction capability therefore, it could be concluded that any default value could be used for the pollutant concentration prediction. Vehicular pollution or release of exhaust is near to ground level, where vehicle-induced turbulence and mechanically induced turbulence are the most significant forces for dispersion of vehicular pollution. Therefore, effect of stability class and mixing height is not significant in that zone or near roadway receptors. Thus, it could be concluded that among meteorological parameters, wind speed and wind direction have comparatively more influence on model prediction capabilities followed by stability class and mixing height.

Recommendation

However, the accuracy of these models to a large extent depends on the accuracy of the input data. The use of on-site meteorological data along with the more reliable traffic and emission data is a prerequisite for more accurate predictions. The higher level of air pollutants in various urban centres of Nigeria mainly contributed from vehicular sources is a cause of real concern. Several initiatives have been taken to control vehicular emissions and improve the air quality in these cities. However, despite some recent improvements, the air quality in most of these cities is still far from satisfactory. Integrated land use policy that minimizes the need for transport (urban driving) and results in a reduction of total urban emissions is essential for a substantial reduction in vehicular emissions in these urban centres Further, there is an immediate need to improve the monitoring and emission inventory capabilities that are a prerequisite and essential for formulating various air pollution control and management strategies. Moreover, there is an urgent need to develop further modelling capabilities that are more appropriate for Nigerian conditions

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