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# Spatial distribution and policy implications of the exhaust emissions of two-stroke motorcycle taxis: a case study of southwestern state in Nigeria

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## Abstract

Two-stroke motorcycles emit harmful exhaust fumes because of incomplete combustion. Although they constitute the main fleet of motorcycle taxis in sub-Saharan Africa, monitoring, spatial assessment, and regulation are weak, leaving dire health consequences in cities. This study collected motorcycle raw exhaust emissions of 1,950 two-stroke petrol-driven motorcycle taxis, otherwise called *okada*, in Ogun State, Nigeria, using an idle mode test approach under 10 minutes and employed correlations, hierarchical multiple linear regression models, and spatial analysis. It was found that carbon monoxide (CO) and hydrocarbons (HC) were the most highly concentrated, and the latter were beyond allowable limits. The concentration of CO was found to be at the minimum of 0.00 % and the highest being at 6.40% (an average of 1.05%), while the HC concentration was reported at the minimum of 18.00 ppm and the highest at 15446 ppm (an average of 3560 ppm). Notably, Kriging interpolation analysis indicated that cumulative effects due to the clustering and operations of motorcycle taxis could increase these concentrations over time, extending their long-term impacts. Given the severe effects of these emissions on health and the wider environment, a DPSIR policy framework is proposed to regulate two-stroke motorcycle taxis in sub-Saharan Africa.

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*Keywords:* Motorcycle taxi, Motorcycle emission, Two-stroke engines, Idle mode test, Spatial analysis

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## 1. Introduction

Air pollution is a leading threat to human health globally, causing approximately 4.2 million premature deaths [1, 2]. Transportation contributes 23% of total carbon emissions [3]. In sub-Saharan Africa, two-stroke motorcycle taxis, preferentially called 'Okada', constitute a major source of traffic pollution [4, 5]. Most motorcycle taxis are composed of two-stroke powered engines banned in some countries outside sub-Saharan Africa due to their high carbon emission rates and incomplete combustion [6, 7]. However, they are preferred for first-and-last-mile transport in at least 27 countries [8–10], generating income for the unemployed youth [11–14]. Therefore, how to regulate the increasing demand for two-stroke motorcycle taxis amid their health consequences remains a significant policy concern.

The engine capacities of motorcycles are a distinguishing feature [15]. Chen *et al.* [16] observed that two-stroke engines have elevated emissions of hydrocarbons (HC) and low nitrogen oxides (NOx). Similarly, two-stroke motorcycles make more ozone ($O_3$) than other motorcycles. Tsai *et al.* [17] investigated the carbon monoxide (CO), total hydrocarbon (THC), and NOx emissions from seven new and twelve in-use motorcycles with and without catalysts. They observed that in-use motorcycles exhibited higher CO and HC and lower NOx emissions than the new ones. Additionally, volatile organic compounds (VOCs) at varying operation modes were reported to emit more during decelerating and idling modes [17, 18].

However, there is little empirical evidence of the proportions of chemical compositions and the spatial distribution of two-stroke motorcycle exhaust emissions in sub-Saharan African cities. This knowledge gap makes it challenging for policymakers to propose enforcement and environmental mitigation measures to curb the situation. Despite the more hazardous health implications of two-stroke motorcycle emissions, road-based and simulated emission tests have extensively focused on cars due to their higher city densities.

In addition, all exhaust emission limit values proposed by developed countries (Euro I-IV) have primarily focused on four-stroke powered engines, as two-stroke engines are now considered obsolete. However, these two-stroke engines are still largely depended upon in Africa. Chan *et al.* [19] reported that motorcycles emit twelve times more total hydrocarbons (THCs) and CO than cars. In contrast, the emission profiles (CO, HC, NOx, and $CO_2$) of motorcycles, when correlated to passenger cars, revealed that emissions of NOx from motorcycles were elevated [20, 21]. The higher emissions of motorcycles are caused by their incomplete fuel combustion and poor emission control technologies [22–24]. Benzene emissions were observed to have been emitted at low proportions for cars fitted with catalytic converters compared to motorcycles [25, 26]. However, Benzene emissions were found to be very low for cars and other vehicles without a catalytic converter [19, 27]. These indications suggest that policies targeting controlling and reducing two-stroke motorcycles' emissions must be centered around high empirical data.

This empirical study was conducted in Ogun State in southwestern Nigeria to address these research gaps. In Ogun State, two-stroke motorcycles constitute 33% of vehicular traffic alone. The high preference for motorcycle taxis has rendered it challenging for regulation and impossible for an outright ban [13, 28, 29]. The calls for motorcycle bans have been premised on their susceptibility to crashes rather than their emissions and environmental/health hazards [30]. Besides, it has been found that outright bans on motorcycles can lead to increased private car ownership, which also has adverse effects on the environment [31]. Thus, rather than discussing bans, knowing the hot spots and finding regulatory solutions is more productive.

Notably, Nigeria does not follow the standards of the European Union (EU) or the United States but has its local vehicular standards [32]. The operating requirements applicable to these motorcycles, as set out in Section 98 of the National Road Traffic Regulations, 2012 (Act, 2007), specify that motorcycles with engines between 100 and 200cc shall carry no more than one passenger, with the rider required to wear a crash helmet, while restriction of carrying cargo is gazetted. These regulations lack enforcement, making motorcycle taxi operations significantly contribute to several environmental consequences. An empirical investigation will help improve transport policies in Ogun State toward controlling motorcycle emissions.

Given the increasing number of two-stroke motorcycles in Ogun State, motorcycle taxis were hypothesized to significantly contribute to emissions in the study area [33, 34]. The second hypothesis posits that fuel consumption has a significant relationship with exhaust emission rates. Thirdly, it was hypothesized that CO and $O_2$ have a significant predictive effect on $CO_2$. The fourth hypothesis posits that towns with higher motorcycle densities are more likely to be hot spots of CO, $O_2$, $CO_2$, and HC than those with smaller densities.

Therefore, using an idle mode test involving 1950 two-stoke petrol-driven motorcycle taxis in Ogun State, Nigeria, the raw exhaust of tail-pipe emissions are reported by answering the following questions:

- What are the temporal and spatial dynamics of motorcycle emissions and their extent across Ogun State?
- Which policy interventions can promote efficient motorcycle usage and lower emission rates?

The contributions of this study to the literature are as follows. This study adds to the growing literature on motorcycle taxi emission in sub-Saharan Africa by using direct exhaust emission and idle mode tests for the first time in motorcycle studies from sub-Saharan Africa. This new dataset helped to identify the primary pollutants and the major hot spots of emissions in a whole state, making it easy for policymakers to track. Additionally, this study proposes a policy framework for controlling motorcycle emissions in the study area, which other urban areas in sub-Saharan Africa can adopt.

The ensuing part of this study is structured as follows. Section 2 explains the idle mode test, the formulation of related

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assumptions, and the statistical and spatial analyses. Section 3 presents and discusses the key results. Section 3 has a proposed policy regulation framework. Section 5 has the conclusion and also details the future research areas.

## 2. Materials and methodology

### 2.1. Study area and sampling locations

The study area was Ogun State, which is one of Nigeria's thirty-six states and is situated in the Southwest part. It shares borders with Lagos State (the commercial nerve center of the country) and the Atlantic Ocean on the south, Oyo and Osun States on the north, Ondo State on the east, and the Republic of Benin on the west. Ogun State is home to the highest number of industries in Nigeria and has the longest stretch of road connecting Lagos to other parts of the country [35, 36].

The sampling locations within the state were categorized under the Local Government Areas (LGAs), including Abeokuta North, Abeokuta South, Odeda, Egbado (Yewa) North, Egbado (Yewa) South, Ewekoro, Ifo, Ijebu North, Ijebu Ode, Ijebu East, Ijebu North-East, Ikenne, Imeko-Afon, Remo North, Odogbolu, Obafemi Owode, Sagamu, and Ado-Odo/Ota as shown in Figure 1.

### 2.2. Monitoring and data collection

Raw exhaust emissions from motorcycle taxis were sampled using a hand-held KANE Automotive 4-Gas Analyzer (Model 4-2) (Figure 2a-d).

The selection of this analyzer was not only due to its portability, lightweight, and ease of use with its long-lasting battery (battery run time (>4 h from a full charge with the pump running) but also due to its ability to log up to 500 readings in its memory. The instrument was programmed to detect and measure carbon dioxide, $CO_2$ with an accuracy of ± 0.5% volume of reading at a resolution of 0.1% and 0-16% range and 25% over-range), oxygen, $O_2$ (with an accuracy of ± 0.1% volume of reading at a resolution of 0.01%, 0-21% range and 25% over-range), hydrocarbons, HC (with an accuracy of ± 12 parts per million volume (ppm vol.) of reading at a resolution of 1 ppm, 0-5000 ppm range and 10000 ppm over-range) and carbon monoxide, CO (with accuracy of ± 0.06% volume of reading at a resolution of 0.01%, 0-10% range and 20% over-range). Lambda, ? (at a resolution of 0.001 and a range of 0.8-1.2) was calculated per equation (1) [37, 38].

$$\lambda = \frac{[CO_2]+\left[\frac{\mathrm{CO}}{2}\right]+[O_2]-\left[\frac{\mathrm{NO}}{2}\right]+\left(\left(\frac{H_{CV}}{4}\times\frac{3.5}{3.5+\frac{[CO]}{[CO_2]}}\right)-\frac{O_{CV}}{2}\right)\times([CO_2]+[\mathrm{CO}])}{\left(1+\frac{H_{CV}}{4}-\frac{O_{\mathrm{CV}}}{2}\right)\times([CO_2]+[\mathrm{CO}]+(K_1\times[\mathrm{HC}]))}, \quad (1)$$

where CO, $CO_2$, and $O_2$ are measured in percentage volume (% vol.), and HC is measured in ppm vol. $K_1$ is the HC conversion factor expressed in ppm vol. equivalent to normal hexane ($C_6H_{14}$). The value is given as $6.0\times10^{-4}$ according to equation 1. $H_{\mathrm{CV}}$ denotes the hydrogen-carbon atomic ratio of the fuel (minimal value is 1.7261), and $O_{\mathrm{CV}}$ denotes the oxygen-carbon atomic ratio of the fuel (minimal value is 0.0176) [39].

The test was conducted on a total of 1950 motorcycles, which were done in eighteen out of the twenty LGAs in the state, as presented in Table 1.

Before each measurement round, the motorcycle taxis were allowed to travel 50 m from their stations, and the 'No–Load Short Test,' commonly referred to as 'idle mode tests,' was performed on each motorcycle taxi. The idle mode test approach has been recently reported in similar studies as effective in collecting emission data since motorcycles are not required to move at constant load, mimicking stationary equipment [39–41]. The exhaust probe of the sampling instrument was inserted into the motorcycle's exhaust pipe end and clamped to the tail end to avoid falling off (Figure 2d). Measurements were recorded in (%) volume for $CO_2$, CO, and $O_2$ concentrations and ppm for HC. Each measurement round lasted 10 minutes. All recorded data is automatically stored in the instrument's memory drive for later download. After each round of measurements, the sampling analyzer was calibrated to 'zero' by exposing the probes to ambient conditions while ensuring that the exhaust probe tips were clean of any dirt or debris. All samples and testing events were undertaken in November 2020-February 2021, coinciding with Nigeria's dry season. Therefore, during all testing, the air temperature was between 31 and 40 °C, and the relative humidity was between 45 and 60%. Sampling events were conducted in triplicate for each motorcycle taxi within the sampling period to determine statistical variations in the datasets.

### 2.3. Statistical analysis

The normality of the obtained datasets was checked using Kolmogorov-Smirnov test ($p > 0.05$). "Using a correlation matrix, the associations between roadworthiness (RW), CO, $CO_2$, $O_2$, HC, motorcycle model, and city of registration were calculated. Correlation coefficients were elucidated by comparing small ($r = 0.10$), medium ($r = 0.30$), or large ($r = 0.50$)″ [42]. Hierarchical multiple linear regression models were used to determine the predictive effect of CO, O2, and motorcycle models on the CO2 of total motorcycles investigated in this study. The city of registration, RW, and HC were excluded because they had no predictive effect on $CO_2$ based on the stepwise approach adopted for the regression analysis. "Model 1 explored the predictive effect of $O_2$ on $CO_2$. Model 2 explored the enhanced forecasting value of CO attributes to model 1. Model 3 showed the added predictive effect of the motorcycle model on model 2. The regression model's effect sizes and p-values are reported as an overall fit by 'adjusted $R^2$' statistics, while $R$-change and F-test show the importance of adjustments in model fit. The regression coefficient values in the models ($\beta$) were interpreted as $\beta = 0.1$ indicating a small, $\beta = 0.3$ a medium, and $\beta = 0.5$ a large effect [42]. For all analyses, the significance level was set at $p < 0.05$.

Data standardization was done by dividing original values by their standard deviation. The standardized scale for each variable was indicated to enable easy comparison on a similar scale. This reduced multicollinearity and helped deal with significant differences in data (noise) since not all were measured

Table 1. Distribution of motorcycles tested from the sampled LGAs.

| LGA | Samples of motorcycles tested |
|---|---|
| Abeokuta North | 158 |
| Abeokuta South | 147 |
| Ado Odo/Ota | 126 |
| Ewekoro | 14 |
| Ifo | 122 |
| Ijebu East | 4 |
| Ijebu North | 254 |
| Ijebu North-East | 19 |
| Ijebu Ode | 717 |
| Ikenne | 28 |
| Imeko Afon | 10 |
| Obafemi Owode | 18 |
| Odeda | 9 |
| Odogbolu | 33 |
| Remo North | 52 |
| Sagamu | 228 |
| Yewa North | 5 |
| Yewa South | 6 |

Table 2. Motorcycle models tested in the study area.

| Model | Frequency | Percentages (%) |
|---|---|---|
| Bajaj | 130 | 6.7 |
| Hague Suzuki | 90 | 4.6 |
| Jincheng | 1489 | 76.4 |
| Lifan | 167 | 8.6 |
| Qlink | 17 | 0.9 |
| Sinoki Supra | 57 | 2.9 |
| Total | 1950 | 100 |

Table 3. Mean, Standard Deviation, and Correlation Matrix ($N$ = 1950).

| Variable | M | Std. D | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|
| RW | .86 | .344 | 1 | -.529** | .147** | .123** | -.646** | .043 | -.067** |
| CO | 1.6062 | .99564 | | 1 | -.257** | -.245** | .385** | -.105** | -.064** |
| $CO_2$ | 3.6002 | 1.27684 | | | 1 | -.664** | -.076** | .093** | .004 |
| $O_2$ | 14.9303 | 1.86508 | | | | 1 | -.125** | -.005 | .047* |
| HC | 1.6097 | 1.0 | | | | | 1 | -.042 | .260** |
| Motorcycle Model | 3.01 | .835 | | | | | | 1 | .024 |
| City | 4.39 | 1.938 | | | | | | | 1 |

Note: p-value significant at **p<0.01, *p<0.05 (two tailed); M/Std.D: Mean/Standard Deviation; RW: Pass/Fail; CO: $CO_2$; $O_2$; HC; Model; City.

on the same scale. The technique also has common applicability, especially in a regression analysis, to standardize predictor variables and to determine those with higher effects while controlling for variations in scale. Data standardization, statistical correlation, and regression analysis were performed on Minitab 19.0 and IBM SPSS Version 26.

Furthermore, it is noteworthy to state that the RW of each sampled motorcycle is arrived at based on the vehicular exhaust emission standard limit set by the Ogun State Environmental Protection Agency (OGEPA) that the CO limit should be 4.0%, while HC is set at 6000 ppm for 2- and 3-stroke vehicles. Any of the sampled motorcycles whose exhaust reading is within the state's set standard limit is a certified pass (roadworthy, RW). In contrast, those whose reading exceeds the limit are certified fail (non-roadworthy, NRW).

### 2.4. *Spatial analysis*

Geostatistical analysis revealed the Spatio-temporal dynamics of motorcycle taxi emissions over the study area. The Getis–Ord Gi*spatial analysis and Kriging interpolation approaches were employed in the ESRI [43] ArcGIS 10.8 environment. Getis–Ord Gi* spatial analysis using the Hot Spot Analysis

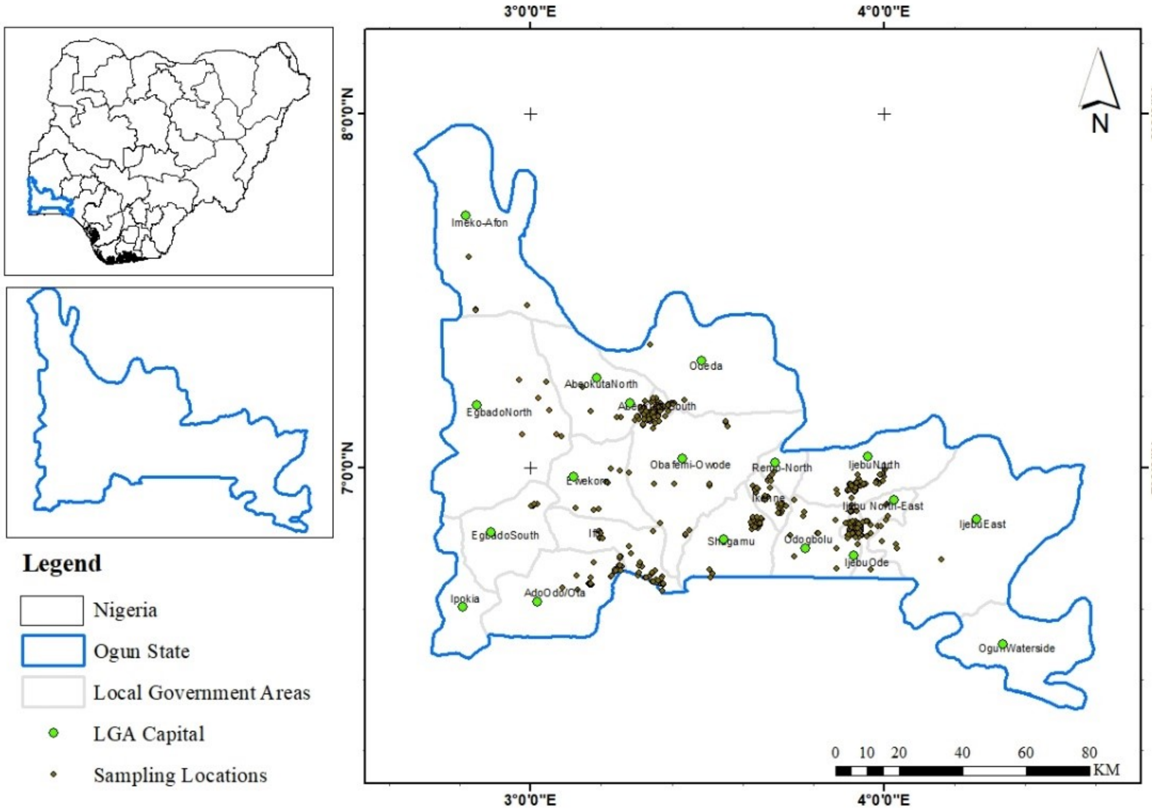


Figure 1. Study area and sampling locations.

Table 4. Hierarchical multiple regression models exploring $CO_2$, $O_2$, CO, and Motorcycle Models in Abeokuta Metropolis ($N$ = 1950).

| Parameters | *B* | *SE* | **Β** | *p* | *Adjusted $R^2$* | **Δ***F* | *p*Δ*F* |
|---|---|---|---|---|---|---|---|
| Model 1 | | | | | 0.440 | 1534.81 | 0.001 |
| *Constant* | 10.386* | 0.175 | | .000 | | | |
| $O_2$ | -0.454* | 0.012 | -0.664 | .000 | | | |
| Model 2 | | | | | 0.628 | 978.98 | 0.001 |
| *Constant* | 12.42* | 0.157 | | .000 | | | |
| $O_2$ | -.529* | 0.010 | -0.773 | .000 | | | |
| CO | -572* | 0.18 | -0.446 | | | | |
| Model 3 | | | | | 0.629 | 9.338 | 0.002 |
| *Constant* | 12.203* | 0.172 | | .000 | | | |
| $O_2$ | -0.528* | 0.010 | -0.772 | .000 | | | |
| CO | -0.566* | 0.018 | -0.441 | .000 | | | |
| Motorcycle Model | .0.65* | 0.021 | 0.042 | .002 | | | |

Note: Constant: $CO_2$
Model 1: Constant, $O_2$
Model 2: Constant, $O_2$, CO
Model 3: Constant, $O_2$, CO, Motorcycle Model
$P<0.05$

function tool uses spatial association of high and low emission values from motorcycles to identify the spatial association among neighboring sampled locations within a particular area (Equations (2)–(4)). This effectively identified spatial clusters of high and low emission values observed through hotspots and coldspots for measured parameters over the study area. The tool considers each sampled emission within the context of the neighboring sampled emission. At the same time, the local sum for each location is compared proportionally to the sum of all neighboring features. The z-scores and p-values that are generated for features show whether there are high-value or low-value clusters in space. Hence, a high-emission location may


Figure 2. (a-b) KANE Automotive 4-Gas Analyzer (Model 4-2) used; Photographs of (c) typical motorcycle taxis terminus (d) field exhaust emission test of the sampled motorcycles.

not be a statistically significant hotspot [44]. The tool has been adopted in related studies and found to be suitable for this case study [45–47].

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{\sqrt[s]{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}}, \tag{2}$$

where $x_j$ is the emission parameter value for feature $j$, $w_{i,j}$ is the spatial weight between feature $i$ and $j$, $n$ is equal to the total number of sampled locations:

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n}. \tag{3}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x^2{}_j}{n}} - (\overline{X})^2. \tag{4}$$

Kriging is a geostatistical interpolation method that uses statistical models to establish statistical relationships among measured points and can produce prediction surfaces between sampled locations [48, 49]. Kriging uses the distance or direction between sampled locations to establish a spatial relationship that explains differences in the predicted surface. The Kriging tool fits a scientific operation (Equation 5) to a specified number of points, or all points within a defined radius, to identify the output value for each location and finally assigns weights to the surrounding measured points to predict an unmeasured location.

$$\hat{Z}(s_o) = \sum_{i=1}^{N} \lambda_i Z(S_i), \tag{5}$$

where $Z(S_i)$ denotes the calculated value at the $i$th location, $\lambda_i$ is an unknown weight for the calculated value at the $i$th location, $s_o$ is the prediction location, and $N$ denotes the number of calculated values.

The weight, $\lambda_i$, is based on the distance between the measured points and the location to be predicted, as well as the overall spatial layout of the measured points. The study employed the spherical kriging model where there is a progressive decrease in spatial autocorrelation (equivalent to an increase in semivariance) to a distance where autocorrelation is zero. Using kriging to predict a surface based on measured points across a location has been extensively used [48–52].

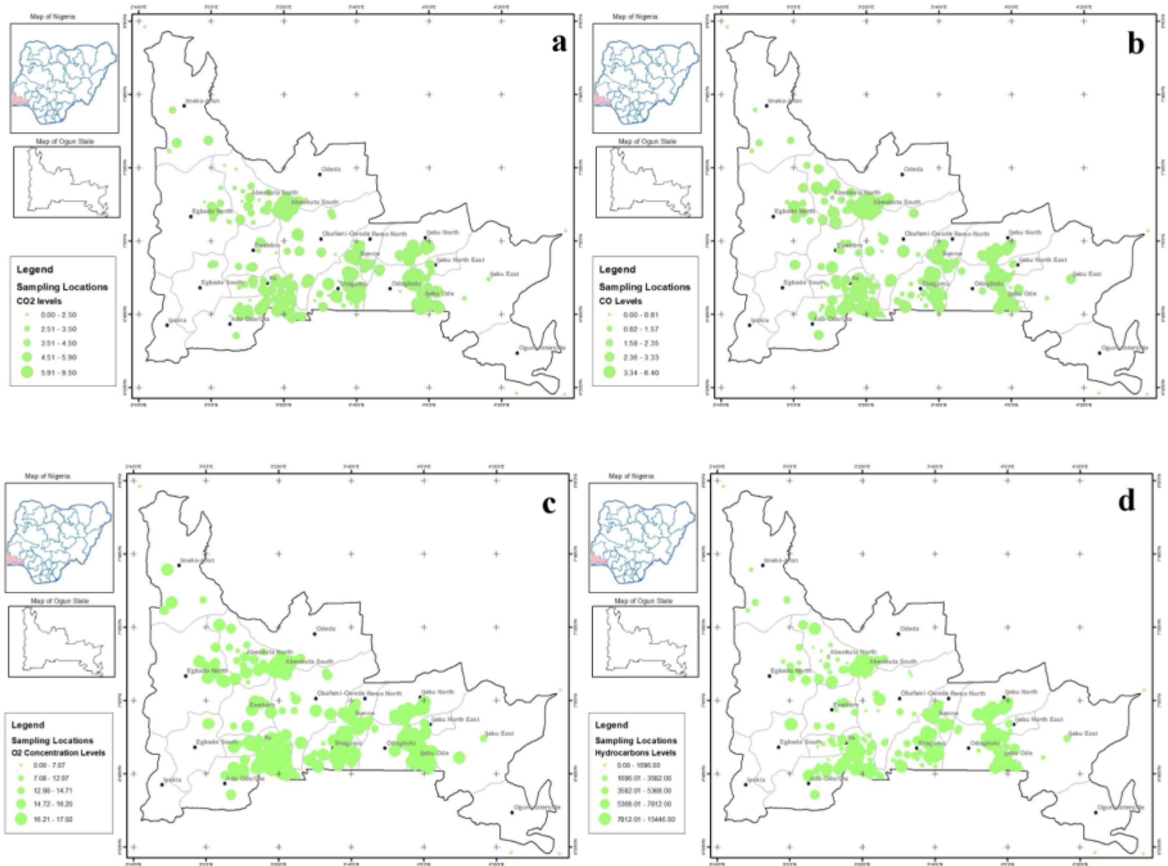


Figure 3. Spatial distribution of motorcycle emissions across the study area (a) CO2, (b) CO, (c) O2, (d) Hydrocarbons (HC).

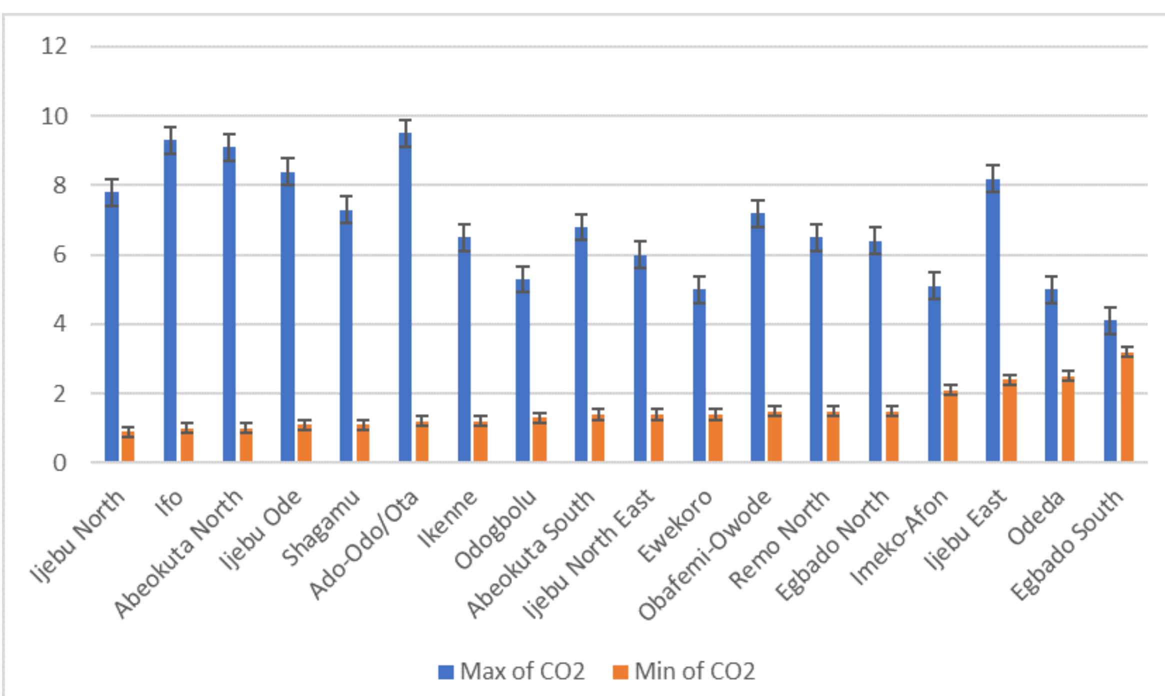


Figure 4. Recorded max and min CO2 levels.

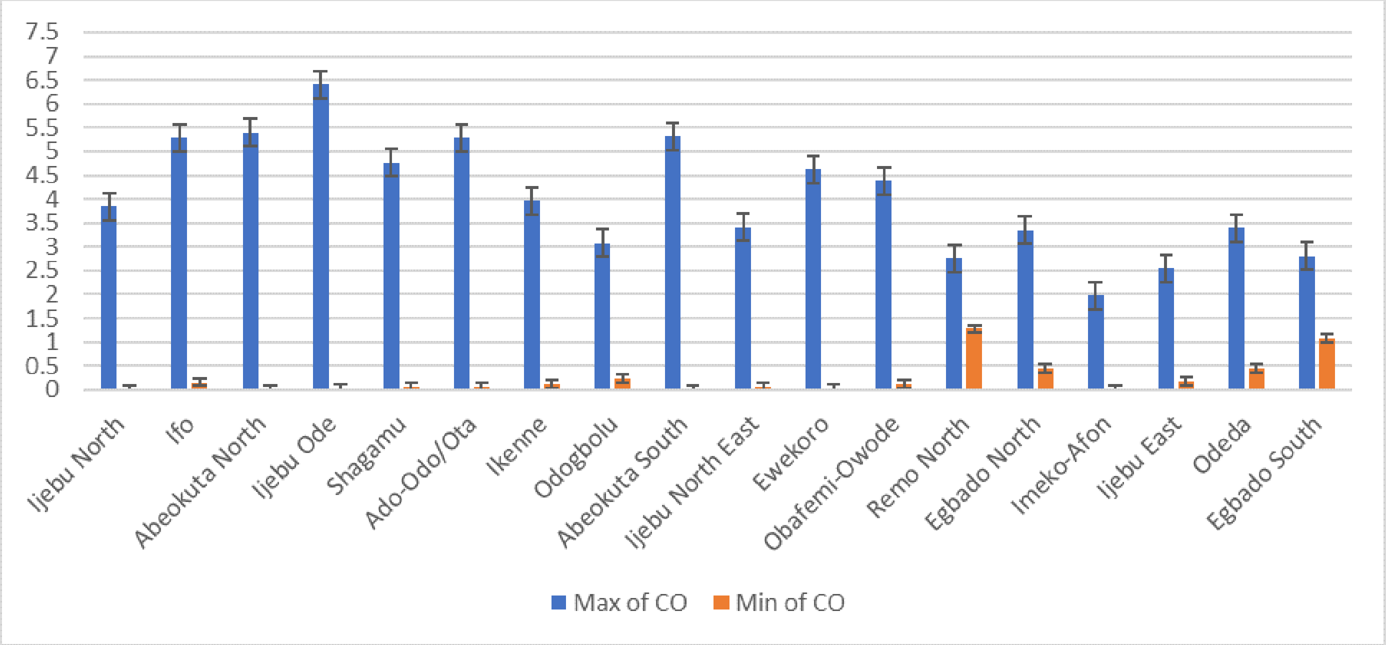


Figure 5. Max and Min CO Levels.

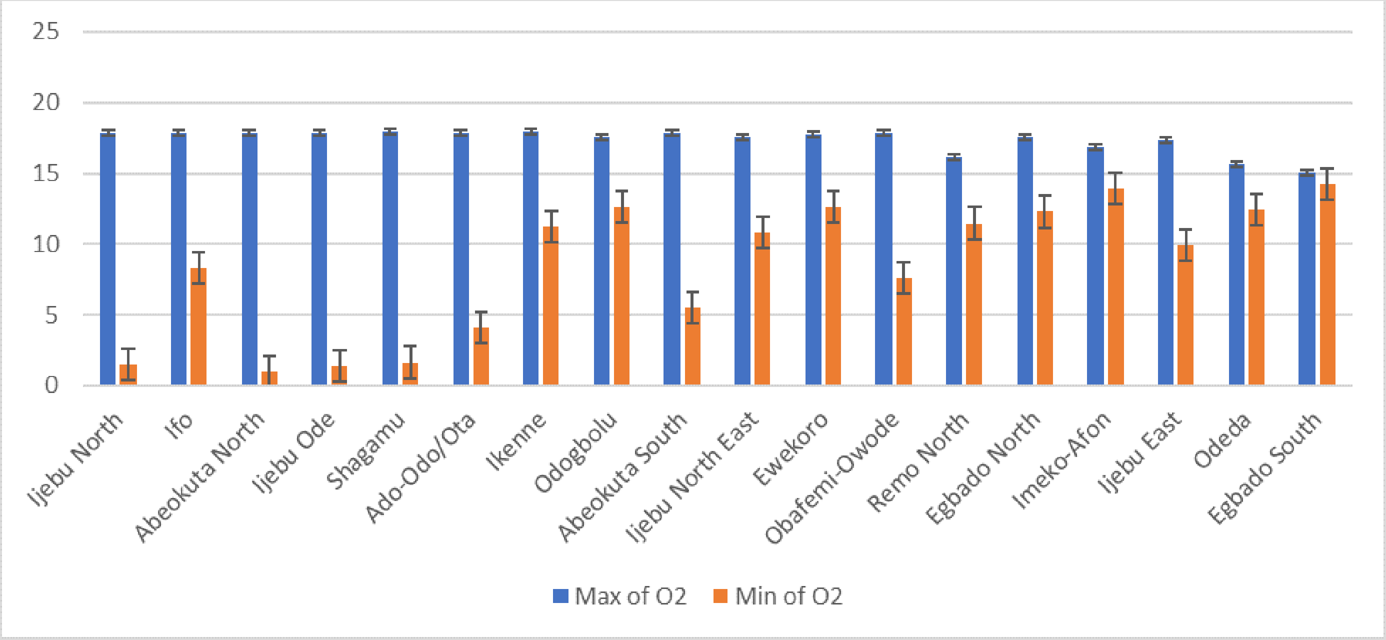


Figure 6. Max and Min O2 Levels.

Table 5. Semi-variogram and model parameters.

| Motorcycle emission parameter | Model type | Nugget ($C_0$) | Partial sill (C) | Sill (C0 + C) | Nugget/sill ratio (%) | Spatial class | Range |
|---|---|---|---|---|---|---|---|
| $CO_2$ | Spherical | 0.992 | 0.794 | 1.787 | 55.55 | Moderate | 2.88 |
| CO | Spherical | 0.164 | 0.690 | 0.855 | 19.21 | Strong | 4.047 |
| $O_2$ | Spherical | 1.309 | 1.617 | 2.927 | 44.74 | Moderate | 3.428 |
| HC | Spherical | 953350 | 3165300 | 4118650 | 23.15 | Strong | 4.278 |

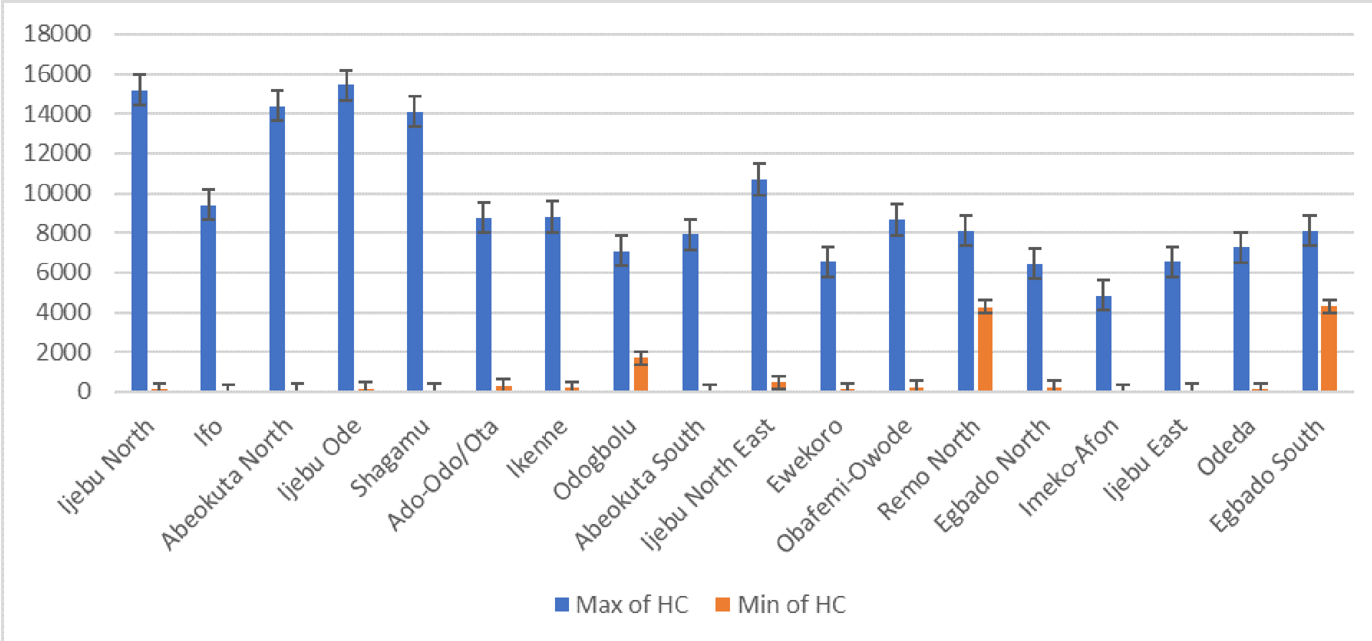


Figure 7. Max and Min HC Levels.

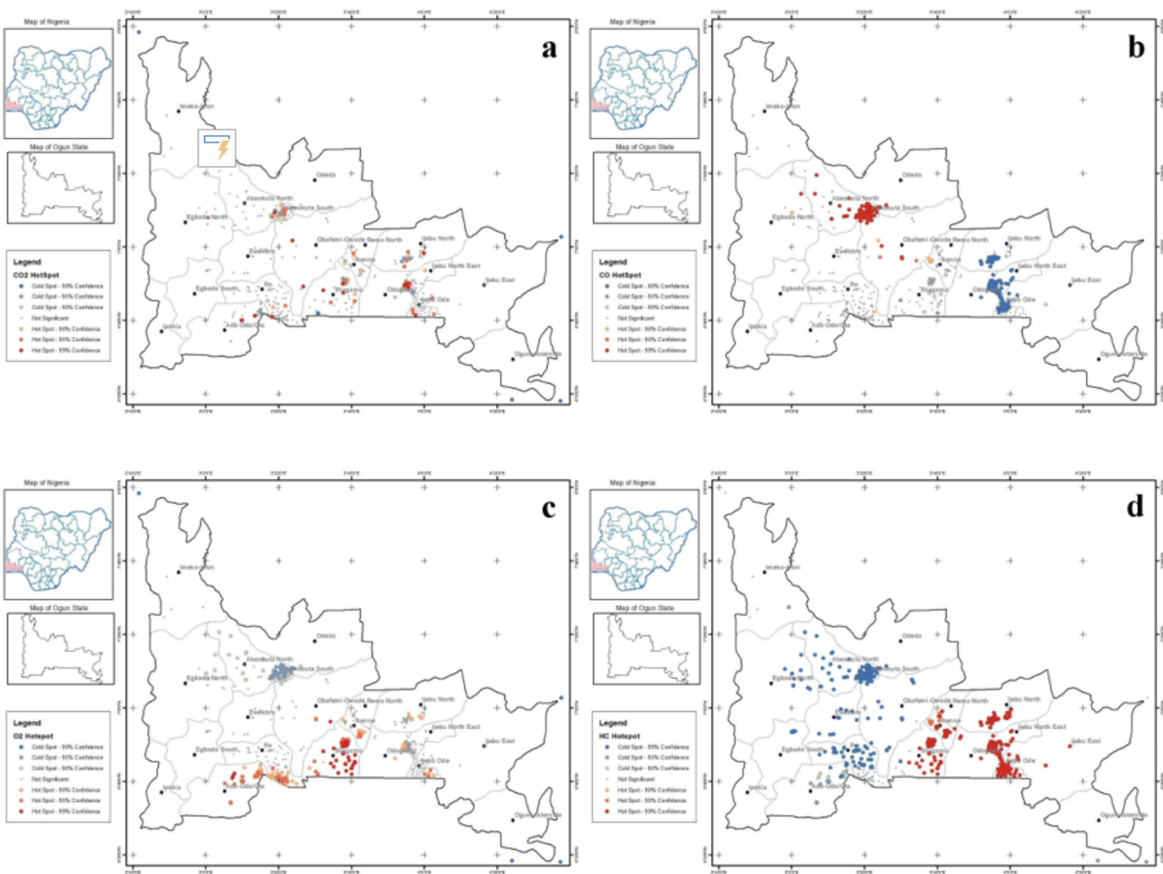


Figure 8. Hot and cold analysis of motorcycle emissions across the study area (a). CO2, (b). CO, (c). O2 and (d) Hydrocarbons (HC).

## 2.5. *Policy analysis and resolution*

The second objective of this study is to find a policy framework that can help address the pollution created by motorcycles and enhance public health. The policy framework is essential because it is the only way to control emissions. Accordingly, a DPSIR framework (Drivers, Pressures, State, Impacts, Re-

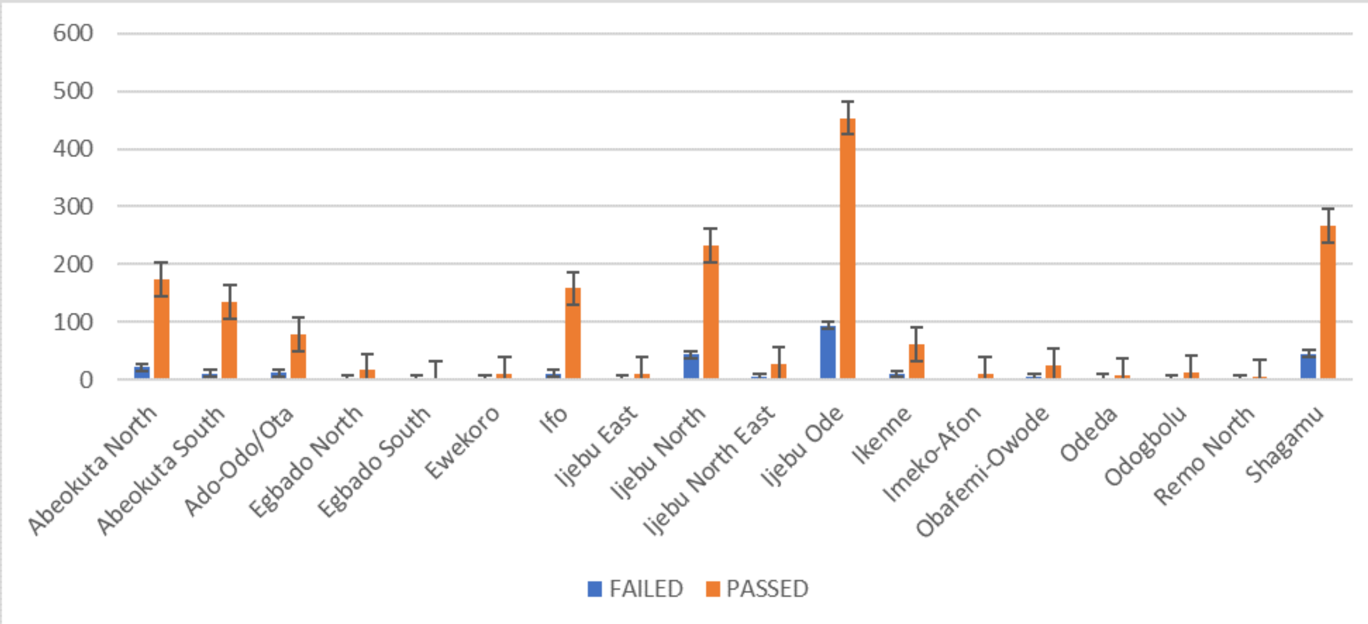


Figure 9. Roadworthiness of motorcycles across study areas.

sponses) [53, 54] was employed to analyze the case of emissions associated with motorcycle taxis in Ogun State and propose policy interventions. The influencing elements linked with motorcycle usage are called Drivers. The effects of motorcycle taxi activities on the environment are the Pressure. States depict the current condition of the environment, economy, and society due to external forces. Impacts originate from particular consequences detected in the socio-economic or political environment of the state. Responses illustrate recommended policies that could resolve prevailing conditions by intervening with Pressures, States, and Impacts.

## 3. Results and discussion

### 3.1. Statistical results

Datasets were non-uniformly distributed across the study areas. The majority of the datasets attained skewness (> 0) in most of the sampled regions. The datasets also displayed a typical leptokurtic ($K > 3$) and platykurtic ($K < 3$) distribution across the study area. The descriptive analysis of the indicators based on the mean ($M$) and standard deviation ($SD$) result shows that RW had a mean score of (0.86 ± 0.344). Other indicator scores were CO (1.61 ± 0.99), $CO_2$ (3.6 ± 1.28), and $O_2$ (14.93 ± 1.87). The highly uneven distribution in the datasets could be associated with the sampling approach, distribution, and location of motorcycle taxis.

A correlation matrix was used to appraise the associations between RW, CO, $CO_2$, $O_2$, HC, Motorcycle Model, and sampling LGAs where the motorcycles were registered. Motorcycle model refers to the brand of motorcycles used in the study area. These brands are presented in Table 2. Notably, there is no apparent reason for the predictive effects of the Motorcycle model except that the frequency may play a role since the Jincheng brand is mainly used and has the most impact compared to other brands.

The evidence in Table 3a shows that RW was negatively associated with CO ($r = -0.53$; $p < 0.01$), suggesting that when CO increases, there is a reduction in RW. In addition, RW was negatively associated with HC ($r = -0.65$; $p < 0.01$), indicating that when HC increases, there is a reduction in RW. Similarly, RW was negatively related to the city of motorcycle registration ($r = -0.07$; $p < 0.01$), with a clear indication that the city of motorcycle registration is a determinant of RW (note: city and RW are captured as a categorical variable such that the statistical direction is not measured on a scale).

However, there was a notable positive association between RW and $CO_2$ ($r = 0.15$; $p < 0.01$), indicating that when $CO_2$ increases, RW is likely to increase. The results further show a positive association between RW and $O_2$ ($r = 0.12$; $p < 0.01$), suggesting an increase in RW when $O_2$ increases. While exploring the correlation of CO with other indicators besides RW, CO was negatively correlated with $CO_2$ ($r = -0.26$; $p < 0.01$), $O_2$ ($r = -0.25$; $p < 0.01$), Motorcycle Model ($r = -0.11$; $p < 0.01$), and city of motorcycle registration ($r = -0.06$; $p < 0.01$), suggesting that when CO increases, there is a reduction in $CO_2$ and $O_2$ which are further a reflection of motorcycle models and city of registration. Meanwhile, CO and HC were positively correlated ($r = 0.39$; $p < 0.01$), suggesting that when CO increases, there is a further increase in HC. The $CO_2$ indicator had a negative correlation to $O_2$ ($r = -0.66$; $p < 0.01$) and HC ($r = -0.08$; $p < 0.01$), which means when $CO_2$ increases, there is a reduction in $O_2$ and HC. $CO_2$ was positively associated with Motorcycle Models ($r = 0.09$; $p < 0.01$), suggesting that depending on the motorcycle model, there is a possible increase in $CO_2$.

The hierarchical multiple linear regression (Model 1) in

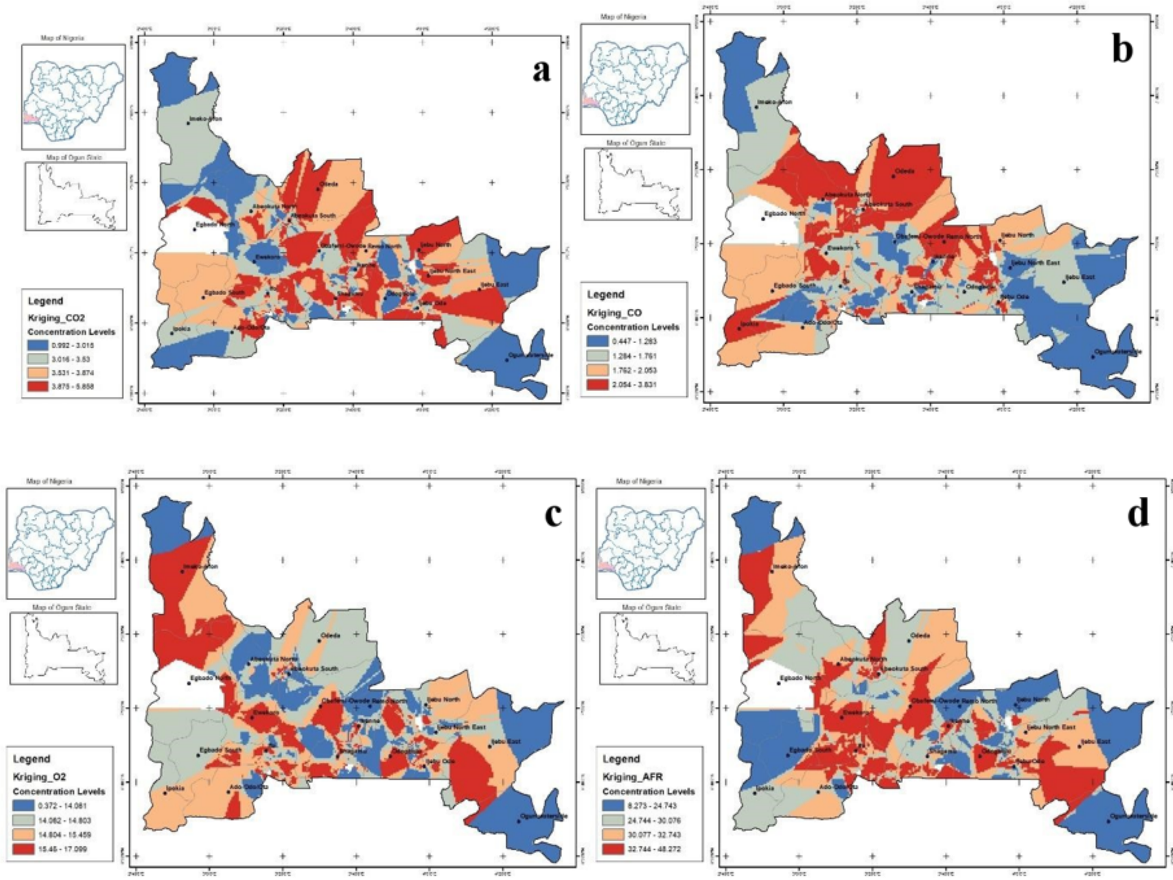


Figure 10. Kriging interpolation of motorcycle emissions across the study area (a) CO2, (b). CO, (c) O2 (d) Hydrocarbons (HC).

Table 4 showed the statistical significance of the dependent variable, $CO_2$, and the predictor ($O_2$) (adjusted $R^2 = 0.44$; $p < 0.001$) for the total sample of the motorcycles explored in the study.

Model 2 appraises the added effect of CO, which propounded added predictive effects of about 18.7% for the total motorcycle sample (adjusted $R^2 = 0.628$, $p < 0.001$). The result from (Model 1) also supports $O_2$ as an important predictor of $CO_2$ for the total motorcycle sample ($\beta = -0.664$; $p < 0.001$), indicating that with every 1 SD increase in $O_2$, there is a 0.664 SD decrease in $CO_2$. The result from (Model 2) also supports CO as a predictor of $CO_2$ ($\beta = -0.446$; $p < 0.001$), indicating that with every 1 SD increase in CO, there is a 0.466 SD reduction in $CO_2$.

Interestingly, while adding the motorcycle models as Model 3, the added effect of motorcycle model features on Model 2 proposed an added predictive effect of about 0.002% for the total motorcycle sample (adjusted $R^2 = 0.629$; $p < 0.001$). Also, Model 3 supports the motorcycle model as a predictor of $CO_2$ ($\beta = 0.004$; $p < 0.002$), highlighting that when there is a 1 SD change in the motorcycle model, there is a 0.004 increase in $CO_2$. Overall, the results show that CO, $O_2$, and motorcycle models explained about 63% of the variance explained in $CO_2$ emissions (adjusted $R^2 = 0.629$; $p < 0.001$).

### 3.2. Spatial distribution of emissions

The general extent of $CO_2$, CO, $O_2$, and HC distribution across the study area is shown in Figure 3.

$CO_2$ represents the ‘desirable’ end-product produced when fuel is combusted. The ideal (optimal) value of $CO_2$ for a perfectly working engine is about 15.5% [55]. However, functional issues such as air/fuel imbalances, misfires (i.e., the release of unburned fuel), engine mechanical problems, or sample dilution could cause decreases in $CO_2$. Therefore, high $CO_2$ readings show that the engine operates optimally, exhibiting high combustion efficiency [39, 56]. The $CO_2$ levels over the study area were heavily distributed from the central to southeastern and southwestern regions, mainly within Shagamu, Ikenne, Abeokuta North and South, Ijebu North and North-East, Ifo, Ado-Odo/Ota, and Ijebu Ode (Figure 3a) and Figure 4.

The high distributions could be associated with the frequency of use of motorcycles. LGAs such as Abeokuta South & North are densely populated, with about 80% of residents relying on motorcycles and triclyes (2-stroke engines) daily. The highest $CO_2$ concentration was measured at 9.5% in Ado-Odo/Ota, in the southwestern region, where 90 bikes were sampled, while the lowest $CO_2$ concentration was 0.9% in Ijebu North, in the southeastern region, where 276 motorcycles were sampled. However, the high $CO_2$ emissions across the state could contribute cumulatively to carbon stock additions and en-

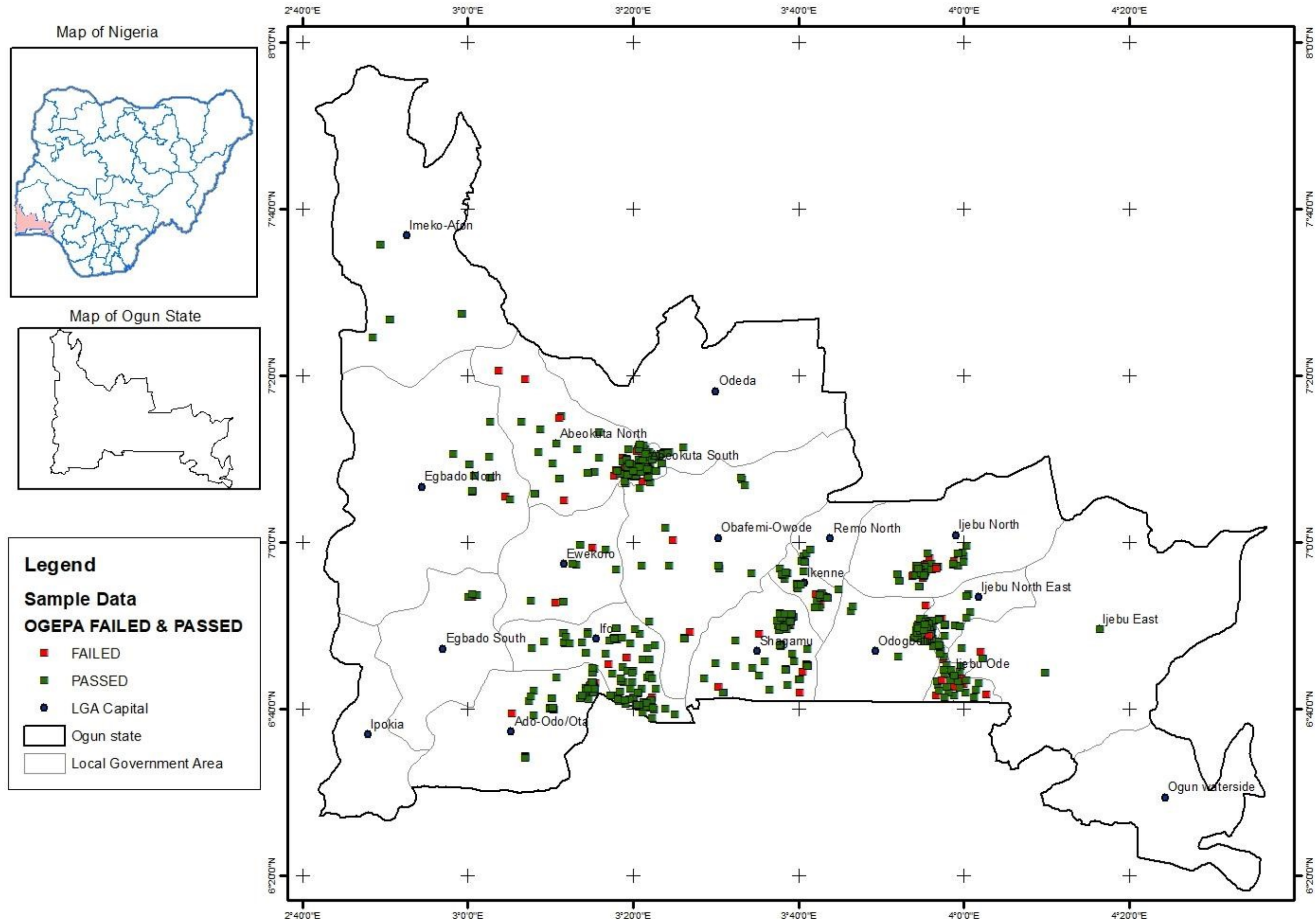


Figure 11. Spatial trend of motorcycles across study areas.

vironmental effects within the study area [57].

CO is produced due to variations in fuel-to-air supply, resulting in incomplete combustion. High CO readings indicate that the engine is experiencing a fuel load, insufficient air, or both (i.e., rich air/fuel mixture). The highest CO level of 6.4% was recorded in Ijebu Ode, which was above the compliance limit of OGEPA and EURO IV standards (See Figure 5). OGEPA [58] has a 4.0% emission standard limit of CO for 2 and 3-wheeled vehicles. The lowest CO recorded during the study was 0.01 % in Imeko-Afon. CO levels were above the OGEPA CO limits in most studied areas except for Remo North, Imeko-Afon, Ijebu East, and Egbado (Yewa) South, where concentrations were within the OGEPA standards. The spatial distribution of CO levels indicated a high concentration from the central to southeastern and southwestern areas of the study area comprising Shagamu, Ikenne, Abeokuta North and South, Ijebu North and North-East, Ifo, Ado-Odo/Ota, and Ijebu Ode (Figure 3b). The CO level was highest at 6.4 % in Ijebu Ode, in the southeastern part of Ogun State, where 548 motorcycles were sampled. The level of CO in Ijebu Ode was above the Ogun State Environmental Protection Agency's compliance limit.

Contrary to high $CO_2$ levels, the lowest CO levels of 0.0% were recorded in Abeokuta North & South. The low levels could be attributed to the high economic status of residents, which allows for regular maintenance of the motorcycles, thereby resulting in lowered emissions. At the same time, law enforcement agencies' compliance with vehicular and roadworthiness regulations is also strictly monitored. The LGAs that did not comply with the Ogun State Environmental Protection Agency's CO emission standard were found in the study area's central, southwestern, and southeastern areas. Although CO levels in the study region were below regulation limits, their large extent and distribution are concerning. Recent research has proven that motorcycle taxi drivers are particularly susceptible to respiratory health effects from these emissions [59]. Previous studies have also established some correlations between drivers' behavior and emissions. Huang [60] found that under high speeding conditions, CO emissions are high. Although the speed of such association is not established in this study, it is proposed in future research.

The highest $O_2$ level of 17.92% (Figure 6) was recorded in Ikenne and Shagamu. The OGEPA has no emission standard limits of $O_2$ for 2 and 3-wheeled vehicles. The lowest $O_2$ level

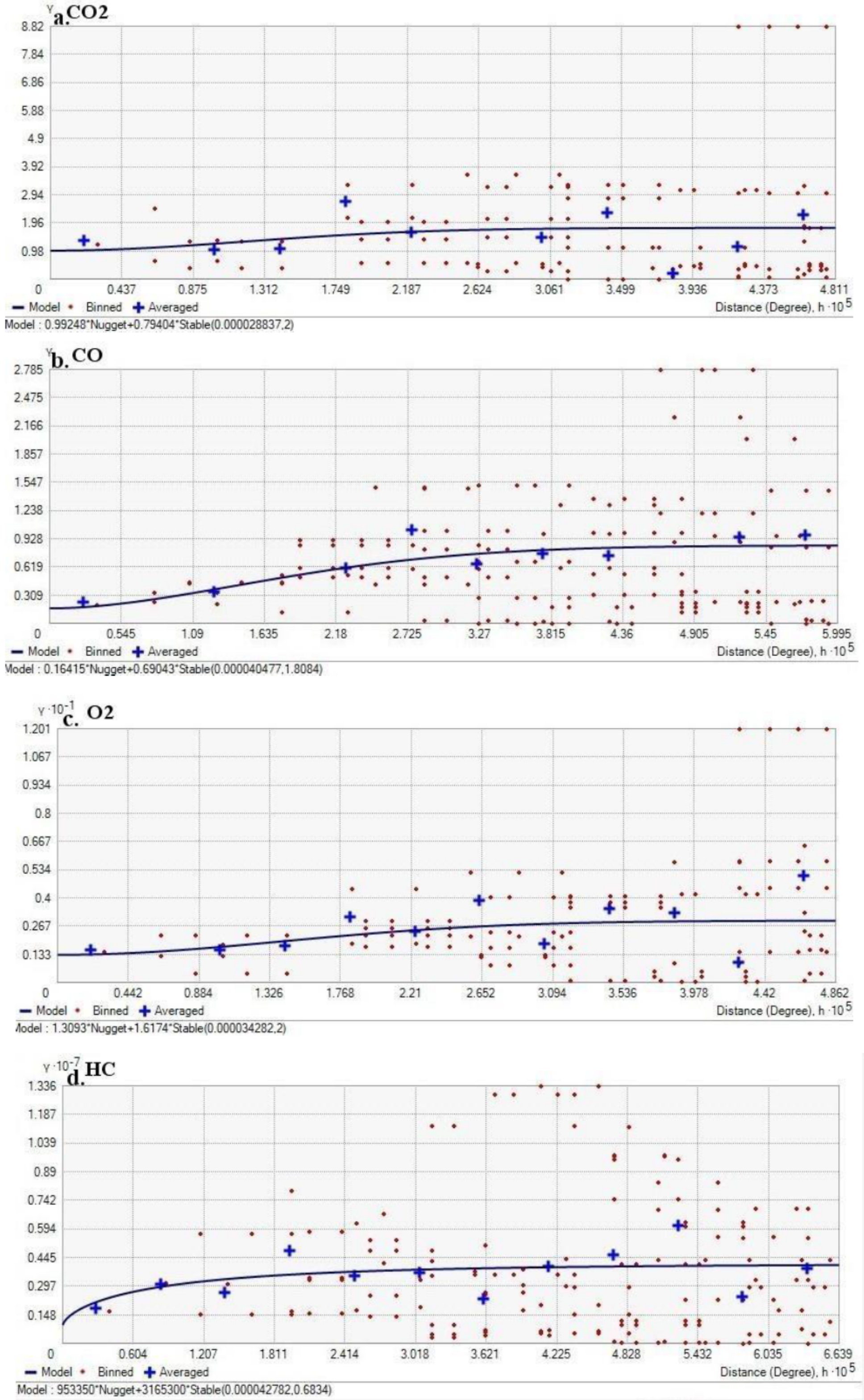


Figure 12. Semi-variograms of motorcycle emissions across the study area.

of 1% was recorded in Abeokuta North. All the LGAs of Ogun State recorded an average $O_2$ level of more than 14%. In terms of their spatial distribution, $O_2$ levels were highly distributed in the central to southeastern and southwestern areas of Ogun state, comprising Shagamu, Ikenne, Abeokuta North and South, Ijebu North and North-East, Ifo, Ado-Odo/Ota, and Ijebu Ode

(Figure 3c).

HC emission data represents the amount of unburned fuel emitted from an engine's exhaust pipe, often measured as ppm. The HC reading of a perfectly working engine, i.e., in the ideal state where the air-to-fuel (A/F) ratio is 14.7:1, should be approximately 0-120 ppm [61]. However, the OGEPA has recommended an emission standard of 6000 ppm for motorcycles and tricycles. The highest HC level recorded was 15,446 ppm in Ijebu Ode, above the OGEPA and EURO IV vehicle standards. In comparison, the lowest HC level recorded during the study was 18 ppm in Abeokuta South (Figure 7).

Overall, the LGAs did not comply with the OGEPA limit except for the Imeko-Afon LGA, which recorded a maximum HC of 4,860 ppm. HC spatial distribution was heavily clustered in the southeast and southwest regions of the research area, comprising Shagamu, Ikenne, Abeokuta North, Abeokuta South, Ifo, Ado-Odo/Ota, Ijebu North, Ijebu North-East, and Ijebu Ode (Figure 3d). High HC recordings could be related to relatively old motorcycles operating in the study area. The preference for such old motorcycles by users or owners could be due to their initial lower purchase cost for commercial and private use. HC concentrations above the maximum limit can harm human health [62].

### *3.3. Hotspot and coldspot analysis*

Cluster analysis of high and lower concentration zones enables researchers to assess the contribution of source emissions from a particular area and how they influence cumulative emission generation. These can be demonstrated by hotspot (high emission zones) and coldspot (low emission zones) analysis. Regions with significant clusters, which could be described as dense sources of emissions contributing to the overall effect in the study area, were observed by hot spot and cold spot analysis. $CO_2$ was found to have significant hot spot areas with a 99% confidence interval across Ado-Odo/Ota, Abeokuta South, Shagamu, Odogbolu, Ijebu Ode, Ijebu North, and Obafemi-Owode LGA. Only one significant coldspot with a 99% confidence interval was observed in Shagamu. Overall, hot spots and coldspots with 90% confidence intervals were distributed within the study area's central, southeastern, and southwestern parts (Figure 8a).

These areas are triggers for implementing emission control measures and monitoring programs. Continuous monitoring of $CO_2$ emissions from these hotspots could provide essential baseline data for motorcycle emission regulations. Similarly, CO-significant hotspot areas with a 99% confidence interval were clustered in Abeokuta South. In comparison, significant cold spots with a 99% confidence interval were clustered around Ijebu North, Ijebu North-East, and Odogbolu. There were also coldspots with 90% confidence intervals in Shagamu and Ado-Odo/Ota LGAs in the study area's central, southeastern, and southwestern parts (Figure 8b).

$O_2$ was found to have significant hot spot areas with a 99% confidence interval clustered in Abeokuta South. In comparison, significant cold spots with a 99% confidence interval were clustered around Ijebu North, Ijebu North-East, and Odogbolu. Coldspots with 90% confidence intervals were in Shagamu and Ado-Odo/Ota LGAs in Ogun State's central, southeastern, and southwestern parts (Figure 8c). For HC concentrations, hot spots were significantly observed at 99% in the southeast and northeast areas of the study area, mainly across Odogbolu and Ijebu-Ode, Ikenne, Ijebu North, and Shagamu. The hotspot status of these areas could be ascribed to the higher usage of motorcycles in these areas, as well as low compliance with roadworthiness regulations of the State Vehicle Monitoring Agency. A few hotspot areas were observed in Ijebu East, while 90% of significant hotspot zones were observed across a few portions of Ikenne. Cold spots were heavily distributed in the western portion of the study area. A significant 99% coldspots were observed across Abeokuta North and South, Egbado (Yewa) North, Ewekoro, and Egbado (Yewa) South. Relatively 90% significant coldspot zones were observed across Ado-Odo/Ota (Figure 8d).

The spatial extent of the RW of motorcycles across the study area was significant (Figure 9), as most operational motorcycles passed the OGEPA Exhaust Emissions compliance limits. Few motorcycles in the study area's northwest, central, and southern areas failed to meet OGEPA compliance limits. Therefore, it could be inferred that these old motorcycles contributed to a high generation of emissions and clustering across the study area. From an urban planning perspective, the spatial distribution of these related emissions could reveal important criteria for functional zone planning. It is evident from the observations that areas with high clustering are highly motorcycle taxi-dependent zones. Such hotspot areas could be decongested with motorcycles by introducing alternative modes of commuting.

Further, these hotspot zones could support creating more effective policy interventions or enhancing the compliance performance of existing instruments. For example, identified hotspot zones could receive emission reduction schemes to improve air quality. In contrast, ultra-low emission zone standards could be set for these areas. However, vehicles not meeting the criteria must pay high daily fees before operating in these areas. With the increased proliferation of motorcycle use in the study area, such novel measures for motorcycle operation/use could significantly reduce emissions and potential public health effects.

Identifying such hot and cold spots can direct the design of targeted regulatory policies to reduce emissions in high-concentration areas, such as a ban on importing secondhand motorcycles and instituting carbon emission credit schemes across the LGAs.

### *3.4. Spatial interpolation and mapping*

Kriging analysis revealed spatial patterns and interdependences in datasets at unsampled locations of the study areas, as shown in Figure 10 and Figure 11.

The spatial interferences of the predicted motorcycle emissions were studied through model parameters for the best-fit semi-variograms shown in Table 5. The parameters comprising the nugget effect ($Co$), the sill ($Co + C$), and the range of influence for each parameter were adopted. The extent of autocorrelation amongst the sampling units was associated with their spatial dependencies. The nugget values were derived

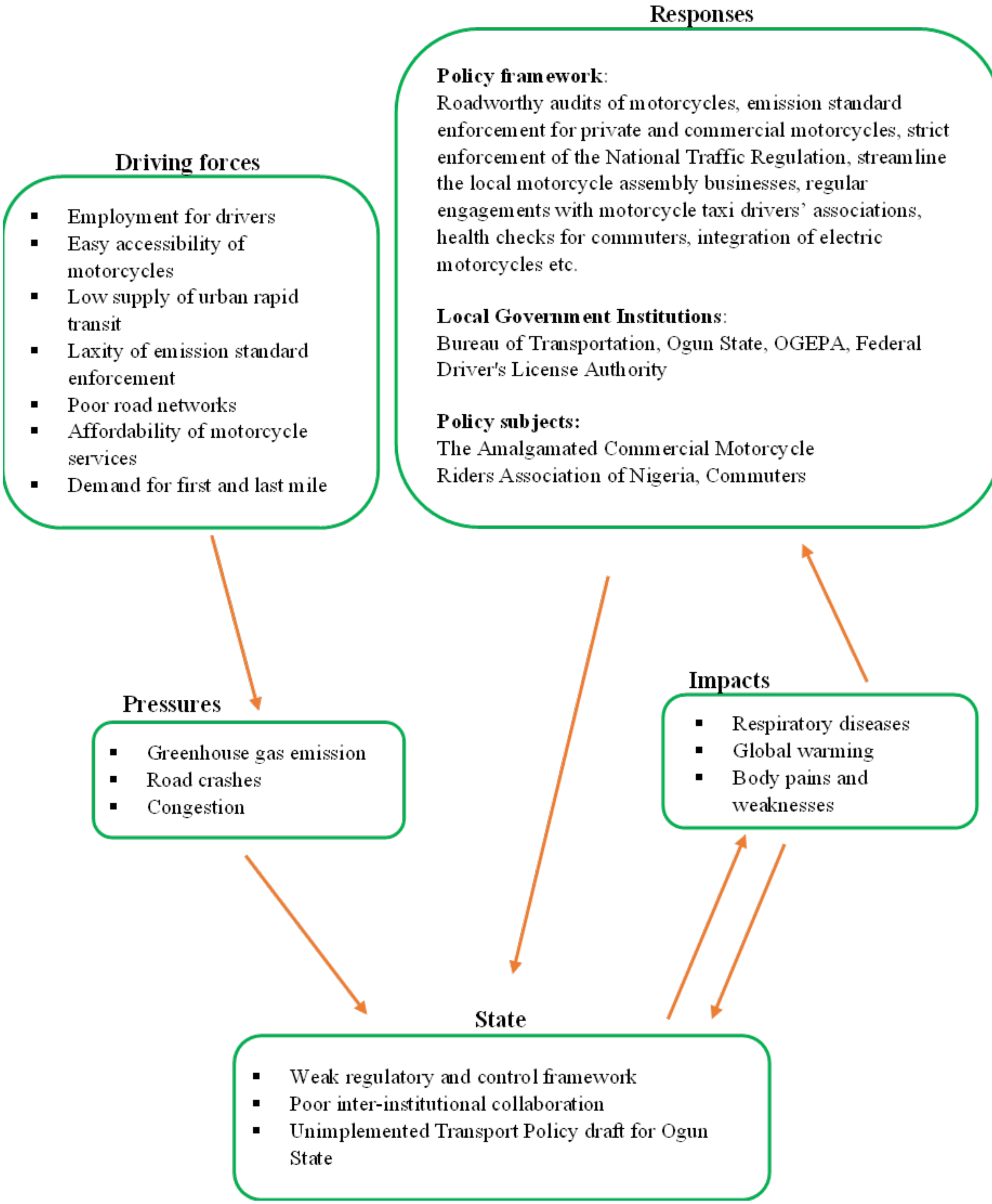


Figure 13. A DPSIR framework for motorcycle emission control in Ogun State, Nigeria.

from measurements of accuracy in variation of properties that could not be observed within the sample range and are an indicator of continuity at close distances. The sill value represented the peak of the fixed semi-variogram model. The "nugget-to-sill ratio (N/S)" was then associated with the spatial dependence of emission parameters ($CO_2$, CO, HC, $O_2$). At the same time, the range of the semi-variogram was represented by the average distance through which most of the semivariance parameters reached their highest value. The spatially dependent variables were therefore grouped as randomly spatially dependent if the N/S was >75%. This ratio is relatively spatially dependent if it is between 25% and 75% while strongly spatially dependent if < 25% [63].

The highest levels of $CO_2$ were between 3.875 and 5.858, and the lowest levels were between 0.993 and 3.015. The maximum concentrations were predicted to be generated by LGAs within the study area's central north and south portions. They comprised Abeokuta North and South, Ijebu North, North-East and East, and parts of Shagamu, Ifo, and Oba Ode (Figure 10a), similar to the original datasets obtained. This observation further strengthens the case that motorcycles in the northern portions of the study area could be a major source for compliance studies. For CO, predicted concentrations across unsampled regions in the study area ranged from a maximum of 2.054-3.831 to a minimum of 0.447-1.283. The maximum concentrations were predicted to be generated from the northwest portions of the study area, comprising Abeokuta North and South, Odeda, Obafemi-Owode, Remo-North, and Ipokia in the southwest (Figure 10b).

Similarly, for $O_2$, the maximum predicted concentration in unsampled areas ranged from 15.4-17.09, majorly in the northwestern (Imeko-Afon) and relative central portions of the study area. However, minimum predicted concentrations ranged from 0.372-14.081, primarily centrally distributed in the study area (Figure 10c). The maximum HC predicted concentration at unsampled locations in the study area ranged from 5,060.7-7,708.57 in the southwest areas, while minimum concentrations ranged from 446.28-2,782.94. Concentrations were evenly distributed between the north-central and southeast portions of the study area (Figure 10d).

From Table 5, the spatial dependencies of predicted emissions revealed a general moderate to strong association among the emission parameters. The spatial variabilities at unsampled sources of neighboring areas ranged from 2.880-4.278 meters for $CO_2$, CO, $O_2$, and HC, respectively. Although $CO_2$ and $O_2$ emissions indicated an even distribution (Figure 12a and 12c), their dependencies were only moderate (N/S = 25-75%). This could imply that variations in the observations were possibly associated with the influence of external emissions sources in the study area. Notably, the research area (State) has the highest concentration of manufacturing industries in Nigeria [35, 64], resulting in substantial industrial activity.

However, a highly uneven CO and HC emissions distribution across the study area (Figure 12b and 12d) revealed a solid spatial interdependence among the parameters. The lower (N/S < 25%) could confirm that CO and HC emission variations across the study area were majorly due to inherent/functional aspects of the motorcycle, with less impact or none at all due to external/ambient sources. These inherent aspects could be related to the low purchasing power of the operators (many live on < US $1 per day) [65–67], thereby making most of them prefer to use cheap, fairly-used (imported), sometimes substandard spare parts and engine oils for maintenance to maximize profits. These often have ultimate effects resulting in discordance in ignition timing, worn-out valves and piston rings, and faulty carburetors [39], hence the observed high CO and HC emissions.

## 4. Proposed policy and regulatory intervention

The findings indicate that CO and $CO_2$ emissions were above OGEPA emission standards. Weak regulatory regimes are one of motorcycle-related public health and traffic problems in sub-Saharan African countries such as Ghana, Togo, Benin, and Cameroon, with known public health implications [8, 9, 68–70]. The public health implications of this situation cannot be overemphasized.

The ultimate solution is to strengthen the regulatory framework in Ogun State. In line with the second objective of this study, reliance on imported, fairly-used, substandard spare parts and engine oils would require remediation. Additionally, an inter-institutional regulatory framework would be necessary to implement policies effectively. Accordingly, through a DPSIR framework (Figure 13), this study proposes policy interventions for the local governments in Ogun State.

The driving forces for motorcycle ridership, such as employment for drivers, easy accessibility of motorcycles, and laxity of emission standard enforcement, pose three significant pressures in Ogun State: greenhouse gas emissions, possible road crashes, and traffic congestion. The proposed responses include roadworthy audits of motorcycles, enforcement of emission standards for private and commercial motorcycles, strict enforcement of the National Traffic Regulation, streamlining local motorcycle assembly businesses, regular engagement with motorcycle taxi driver associations, commuter health checks, and enhanced rapid transit to address the resulting impacts of respiratory diseases, body pains and weakness, and grave environmental concerns.

Local government institutions, including the Bureau of Transportation, the Ogun State Environmental Protection Agency, and the Federal Driver's License Authority, would require enhanced collaboration to regulate motorcycle emissions. However, regular engagement of the Commercial Motorcycle Riders Association of Nigeria and commuters is imperative to make these recommendations effective. These policies could also be used in other countries in sub-Saharan Africa, where there is a high demand for motorcycle transport and a lot of dangerous pollution.

Integrating electric motorcycles (e-bikes) into the main transport modes, mixed with improved regulatory/control framework and existing road infrastructure, remains a sustainable alternative. For example, it was estimated that in Uganda, electric motorcycles have the prospects of reducing $CO_2$, CO, NOx, and HC emissions by 36%, 90%, 58%, and 99%, respectively [24]. As a result, huge benefits may accrue in Ogun State due to the development of electric motorbike paths. Such policy shift, however, is incredibly reliant on Nigeria's ability to produce and deliver power. It was already found in Bogotá and Santiago (Latin America) that electric vehicles powered with renewable energy have significantly reduced transport emissions [71]. Finally, charging infrastructure for motorcycles would be necessary. Perhaps this merits more investigation in the future.

## 5. Conclusion

This study reported comprehensive results of field emission monitoring from two-stroke commercial motorcycles, also known as 'okada,' from Ogun State, Nigeria. Particular observations were related to the uneven spatial distribution of emissions (HC, $CO_2$, CO, and $O_2$) across the study area, with a high distribution of measured parameters occurring in the northeastern and central portions of the state and a moderate distribution in its southern and western portions. Critical LGAs where motorcycles contributed to high emission concentrations were Shagamu, Ikenne, Abeokuta North, Abeokuta South, Ifo, Ado-Odo/Ota, Ijebu North, Ijebu North-East, and Ijebu Ode.

The results also corresponded to field observations where LGAs with high economic activity tended to have a high distribution of emissions, unlike areas with less economic activity. The application of statistical and interpolation analysis revealed a high correlation between emission parameters, CO, and HC and their dominance in terms of concentrations over the study area. This key finding is partly attributed to the study area's characteristic operational functions and booming motorcycle activities. Recommendations to contribute towards resolving motorcycle emissions concerns in Nigeria were formulated through a DPSIR analysis to guide plausible future decision-making by policymakers.

Since motorcycle taxis operate in at least 27 sub-Saharan African countries and predominantly use two-stroke engines, the results can significantly contribute to similar studies within the African sub-region on reducing road transport emissions and their long-term effects on air pollution and health. For example, the spatial concentrations of HC, $CO_2$, CO, and $O_2$ in dense settlements and the central business districts would require investigation in Africa's large cities. Other developing regions where motorcycles are in high demand, such as Asia-Pacific and Latin America, can employ these present study methodologies.

In the future, decision-makers in different countries could apply the policy regulations proposed in this study to control motorcycle-based emissions. In particular, the prospects of solar and hydroelectric-powered motorcycles can be explored in different countries. However, the health impacts of motorcycle emissions on motorcycle drivers and passengers remain an open question that future studies can explore.

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