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Atmospheric Dispersion of Co and $PM_{2.5}$ Vehicular Emissions in Urban Roads using Aermod: A Case Study of Argwings Kodhek Road, Kenya

Vane Kerubo Momanyi[1], Prof. Sixtus Kinyua Mwea[2], Dr. Osano Simpson Nyambane[3]

[1]Faculty of Engineering, Department of Civil & Construction Engineering, University of Nairobi, P.O Box 30197-00100, Nairobi, Kenya
momanyivane98[at]gmail.com

[2]Faculty of Engineering, Department of Civil & Construction Engineering, University of Nairobi, P.O Box 30197-00100, Nairobi, Kenya
sosano[at]uonbi.ac.ke

[3]Faculty of Engineering |Department of Civil & Construction Engineering, University of Nairobi, P.O Box 30197-00100, Nairobi, Kenya
skmwea52[at]gmail.com

Abstract: ***This study assessed the dispersion of vehicular emissions [Carbon monoxide (CO) and Particulate Matter with an aerodynamic diameter of less than 2.5 micrometers (PM2.5)] through simulations using the AERMOD dispersion model to derive hourly, daily, monthly, and annual concentrations within a 500m buffer along Argwings Kodhek road in Hurlingham, Nairobi, Kenya. The simulation determined the extent to which pollutants dispersed from the emission source, through the atmosphere to the predetermined receptor points within the delineated buffer zone. Modelled CO concentrations ranged from 0.2 to 21.2 PPM hourly, 0.06 to 6 PPM daily, 0.02 to 2.49 PPM monthly, and 0.02 to 1.79 PPM annually. Further, modelling of CO_2 quantified the concentrations as 24 to 2094PPM hourly, 6 to 593PPM daily, 2 to 246PPM daily, and 2 to 177PPM annually. The modelled result values indicated that whereas CO was within the recommended WHO guidelines on air quality limits, the maximum PM2.5 concentration levels were beyond allowable limits.***

Keywords: AERMOD, Vehicular emissions, PM2.5, CO, Urban Air pollution

1. Introduction

Sustainable transportation endeavors to achieve an optimal balance between the economic, social, and environmental elements of the system (Burwel et al. 2006). Rapid urbanization has contributed to a large-scale proliferation in motor vehicle use globally. In Africa, the significant growth in transport emissions has resulted in high pollutant concentrations along transport corridors due to traffic congestion. The close propinquity of motor vehicles to the urban population makes traffic emissions a health concern (Kingston, Phil, & Smit, 2019). Traffic emission disburse into the abutting zones consequently affecting the health of the people inhaling the emissions (Mannuci & Franchini, 2017). According to (Berkowiez, Winther, & Ketzel, 2006), it is difficult to quantify actual traffic emissions in real-life environments. However, with advancements in technology, determination of the spatial and time distribution of pollutants from emission sources can be simulated by atmospheric dispersion modelling which entails the performance of mathematical simulations by computer programs to establish how air pollutants disperse into the ambient atmosphere (Madziel, 2023).

In preparing the Nairobi City County Air Quality Action Plan for the years 2019 to 2023 it was highlighted that Nairobi did not have an updated air quality inventory because of discontinuous monitoring of air quality ((NCCG, 2018)). Recent air quality assessments in Nairobi reveal that particle matter (PM) levels surpass WHO standards in numerous areas of the city (deSouza, 2020).

This study's objective was to quantify vehicular emission concentrations along urban roads using Argwings Kodhek road in Hurlingham, Nairobi, Kenya as a case study. The study adopted AERMOD dispersion software to model the diffusion of the CO and PM2.5 pollutants into the atmosphere at the road's periphery and within the abutting zones, 500 meters from the road. 0

2. Literature Survey

Atmospheric dispersion modelling entails the performance of mathematical simulations by computer programs to establish how air pollutants disperse into the ambient atmosphere (Khan & Quamrul, 2021). A dispersion model estimates emission concentration levels at any point in space and time dependent on the prevalent environmental conditions. Atmospheric processes influence the dispersion of emissions of gases into the abutting zones. Atmospheric dispersion modelling entails the performance of mathematical simulations by computer programs to establish how air pollutants disperse into the ambient atmosphere. A dispersion model estimates emission concentration levels at any point in space and time dependent on the prevalent environmental conditions. Dispersion models are therefore significant in the determination of the spatial and time distribution of pollutants from the emission source. Since the mid-1900s, traffic simulation systems have been in use. The rapid advancement of information technology, especially in numerical computing techniques combined with powerful computers, has significantly contributed to the development of modern computational methods used in traffic engineering. (Madziel, 2023). Traffic Emission models consist of computer programs encoded with traffic pollutant dispersion equations that use algorithms to estimate the downwind ambient concentration of vehicular emissions.

In Delhi, India, exhaust emissions, particulate matter and volatile organic compounds were estimated for the period from 1991 to 2020. (Nagpure et al., 2015) used the VAPI model (Vehicular Air Pollution Inventory) in the assessment of Carbon Monoxide (CO), Carbon Dioxide (CO2), Hydrocarbons (HC), PM10, and NOx emanating from the tailpipe by taking into consideration vehicle technologies, vehicle age and other parameters. Also assessed were non-exhaust emissions like tire attrition, road-dust particles and evaporative emissions from the crankcase and brake wear. Future vehicle fleet projections were calculated using an econometric model calibrated to the country's per capita income and GDP. Following these projections, the Vehicle Air Pollution Inventory (VAPI) model was employed to analyze emission trends. The study revealed a substantial increase in emissions from 1991 to 2011, followed by a notable decline in PM10 levels from 2011 onward, attributed to the adoption of clean fuel technologies within the city. However, from 2011 to 2020, emissions of hydrocarbons (HC), carbon dioxide (CO_2), carbon monoxide (CO), mobile source air toxics (MSATs), nitrogen oxides (NO_x), and PM10 displayed a steady upward trend.

(Peterside & Utang, 2011) conducted a study on the spatio-temporal variations in motorized traffic emissions in Port Harcourt, Nigeria. Utilizing four sampling points, traffic data were collected during morning peak, afternoon off-peak, and evening peak periods. Simultaneously, emissions of carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and hydrocarbons (HC) were measured using a Testo 350XL emission analyzer, which also recorded ambient temperature, wind speed, and wind direction. The findings indicated that rapid population growth has spurred an increase in vehicular traffic, predisposed the city to traffic-related pollution.

In 2016, Ramboll Environ appointed by the African Development Bank (AfD) implemented a pilot scheme in five pre-selected capitals with current transport projects at the time with an aim of capacity building in emission monitoring for the governments of the selected cities (AfD, 2017). NO2, SO2, PM2.5 and PM10 emissions were measured in the cities of Rabat, Morocco, Abidjan, Cote d'Ivoire, Dar Es Salaam, Tanzania Yaoundé, Cameroun), and Lusaka, Zambia (AfD, 2017). The methodology employed included vehicle volume sampling using camera video recorders; measurement of meteorological parameters (temperature, humidity, pressure, and wind speed & direction); and measurement of traffic emissions using micro-sensors (cairmet systems). ADMS-Roads (Atmospheric Dispersion Modelling System) and COPERT 5 software were used to model the emission dispersions.

Liang et al., (2023) examined the various methods and models employed in studying the dispersion of pollutants emitted by urban vehicles. The research explored mechanism research methods and modelling approaches in pollutant dispersion simulation. Mechanism Research Methods included field measurements that involved collecting real-world data on emission levels, wind tunnel experiments which involved simulating environmental conditions to observe dispersion behaviours and numerical simulations which involved utilizing computational models to predict dispersion trends. The modeling approaches studied were divided into box models and Gaussian models. Box Models included STREET, CPBM, AURORA, and PBM whereas Gaussian Models covered CALINE, HIWAY, OSPM, CALPUFF, RLINE, the ADMS series, EPISODE, CityChem, SIRANE, and MUNICH. Liang et al. further noted that despite substantial advancements in understanding atmospheric pollutant dispersion, notable gaps persist, particularly regarding the specific impacts of urban vehicles. Many previous studies focused on localized environments, such as individual streets or blocks. In contrast, analyses of broader urban areas often simplified the built environment, frequently lacking detailed building data. To enhance the understanding of urban vehicle pollutant dispersion, (Liang et al.) proposed future research aimed to improve modelling techniques to better account for low-wind scenarios and the complexities of urban environments.

AERMOD is used by the United States Environmental Protection Agency (US EPA) in monitoring compliance with environmental regulation programs. AERMOD is used in the prediction of tracer concentrations from point, area, or volume source emissions in a stable and convective environment (Masoud, Shekarrizfard, & Hatzopoulou, 2016). AERMOD uses two methods in the simulation of line-type sources by representing the line as a protracted area or as a series of volume sources uniformly spread out along the span of the line (Snoun, Krichen, & Cherif, 2023). AERMOD predicts emission concentrations near the surface (approximately 0.5 meters, 3.5m and 9.5m above the surface (Askariyeh, Sri, Suriya, Josias, & Qi, 2017).

In 2023, air quality in Nairobi City, Kenya, was modeled using remote sensing imagery from Google Earth via Landsat 5 TM, Landsat 8 OLI, and Landsat 7 ETM+ (Meltus & Karanja, 2024). The study focused on sampling traffic hotspots, green spaces, residential areas, and industrial zones, utilizing Air Pollution Indices to assess air quality levels. Results indicated elevated emission levels across the city, leading to a recommendation for developing a customized Air Quality Index specific to Kenya. Further, Matara et al., 2024 used the AERMOD model to simulate vehicular emissions, including particulate matter ($PM_{2.5}$), carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter (PM_{10}), and total volatile organic compounds (TVOCs), quantifying the expressway's contribution to overall ambient air quality. Findings indicated that concentrations of these pollutants remained within the limits established by the National Environmental Management Authority (NEMA) for both observed and modeled data.

In an earlier study in 2003, air quality in Nairobi was assessed by measuring the hourly average concentrations of NO_x and ozone at a location intersecting University Way and Uhuru Highway, utilizing chemiluminescent techniques. Particulate matter (PM_{10}) was analyzed using a stacked filter unit air sampler equipped with nucleopore filters of 0.4 mm pore size for fine particulates, while trace elements in coarse particulates were examined with an Energy Dispersion X-ray Fluorescent (EDXRF) method using 8.0 mm pore size filters. Vehicle density at the sampling site was monitored using automatic counters (Odhiambo, A., C., & J., 2010).

3. Methodology

a) Study Area

The study focused on Argwings Kodhek Road, Hurlingham between Ring Road Kilimani Intersection and Valley Road roundabout in Nairobi, Kenya. The modelling adopted a buffer zone of 500 meters. Nairobi's terrain ranges from 1512m to approximately 1868m above sea level. The terrain in the study area, along Argwings Kodhek Road between Yaya Centre and Valley Road, is generally gentle, with an average slope of 2.1% and a maximum slope of 9.7% [Google Earth Pro, 2024].

b) AERMOD Atmospheric dispersion modelling

The AERMOD model, a Gaussian plume model, is widely recognized for its reliability in predicting pollutant concentrations across various scenarios and meteorological conditions (US EPA, 2004; Matacchiera et al., 2019; Snoun et al., 2023).It assumes a Gaussian distribution of pollutant concentrations, with the highest levels at the plume's center and decreasing progressively toward its edges. Due to their ability to balance computational efficiency with acceptable accuracy, Gaussian models are frequently employed in air quality modeling (Shorshani, Shekarrizfard, & Hatzopoulou, 2017). In this study, AERMOD, grounded in the Gaussian dispersion principle, was used to model CO and PM2.5 emission concentrations.

AERMOD operates with two key preprocessors: AERMET, which incorporates meteorological and surface feature data, and AERMAP, which accounts for topographical influences (Kumar et al., 2017; Prasad et al., 2024). Essential emission source data—including stack characteristics, pollutant emission rates, and receptor locations defining the modeling domain—were collected. Pollutant concentrations at each receptor were recorded at specified intervals, and the highest concentrations at ground level under worst-case meteorological conditions were visualized as contours or points on a grid. The model estimated CO and $PM_{2.5}$ concentrations both upwind and downwind, providing a comprehensive view of ground-level pollutant distribution. Figure 1 below outlines the adopted methodology.

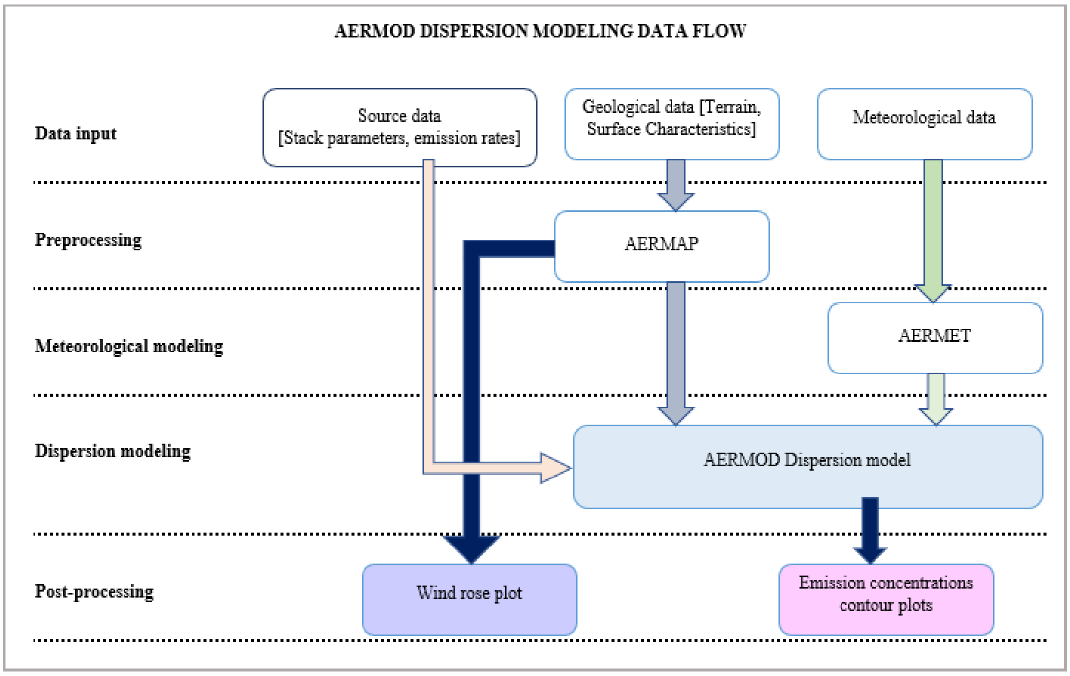

Figure 1: AERMOD modelling methodology schematic diagram.

c) Meterological Data Input (AERMET)

Temperature, humidity, solar radiation, wind direction, wind speed, and other atmospheric parameters are among the meteorological data that must be prepared in an Excel file for AERMOD. Meteorological data was collected from the nearest station that represented the weather conditions in the study area and is presented in Table 1.

Table 1: Meteorological data (Source _ Wilson Airport Station – July and August 2021)

	JULY 2021			AUGUST 2021		
Temperature °F	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**
Max temperature	79	71.16	64	86	74.16	59
Avg Temperature	66.25	63	60.21	70.22	64.67	58.85
Min Temperature	59	56.03	52	59	56.58	50
Dew Point °F	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**
Dew Point	59	53.46	43	63		
Precipitation	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**
Rainfall	0.00	0.00	0.00	0.00	0.00	0.00
Wind (mph)	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**
Wind	81	5.09	0	23	5.22	0
Gust Wind	0	0	0	0	0	0

AERMET preprocessors, which is encompassed in AERMOD, was used to create weather data by using atmospheric conditions. The AERMET output data was presented in a windrose.

d) Terrain Information input (AERMAP)

AERMAP, a pre-processor in AERMOD software utilizes digital elevation data to process the information required to simulate topographical characteristics, such as hills, valleys, and buildings, to ascertain how these features impacted the spread of pollutants. AERMAP analyzed topography data to calculate hill heights and elevations for sources and receptors. The output was represented in an AERMAP's pre-processed DEM file.

e) Characteristics of the source

Details regarding the sources of emissions, such as the type of source (e.g., volume source, area source for roads, or point source), the rate at which pollutants are released, and the physical characteristics (e.g., stack height, diameter, exhaust gas type, and velocity) were determined and utilized as input parameters in the AERMOD simulations.

f) Atmospheric Stability

In AERMOD air dispersion modelling, atmospheric stability is crucial for understanding how pollutants emitted from a source disperse in the atmosphere. AERMOD uses stability classes, which range from extremely unstable to very stable, to categorize atmospheric conditions based on temperature changes. Unstable conditions encourage significant vertical mixing and distribution of pollutants, whereas stable conditions restrict vertical movement, causing pollutants to accumulate close to the ground. The model often utilizes the Pasquill-Gifford stability categories, based on empirical observations, to define these stability classes. Dispersion tends to be least effective during stable atmospheric conditions (E and F), which typically occur at night. By incorporating stability classes into its dispersion calculations, AERMOD improves the precision of predicting pollutant concentrations at downwind receptors, supporting regulatory compliance and environmental assessments. Table 2 summarizes the six stability classes.

Table 2: Atmospheric Stability Classification

Class	Stability Class	Atmospheric Condition	Frequency
A	Very stable	Calm wind, clear skies, and hot day conditions	13.5
B	Moderately unstable	Clear skies, daytime conditions	4.6
C	Unstable	Moderate wind, slightly overcast daytime conditions	28.4
D	Neutral	High winds or cloudy day and night conditions	0.0
E	Stable	Moderate wind, slightly overcast night-time condition	26.6
F	Very stable	Low winds, clear skies, cold night-time conditions	8.5

g) Grid of Receptors

A grid of sites (receptors) was established within a buffer zone of 500m from Argwings Kodhek road within which the CO and $PM_{2.5}$ pollutant concentrations were determined as shown in Figure 2.

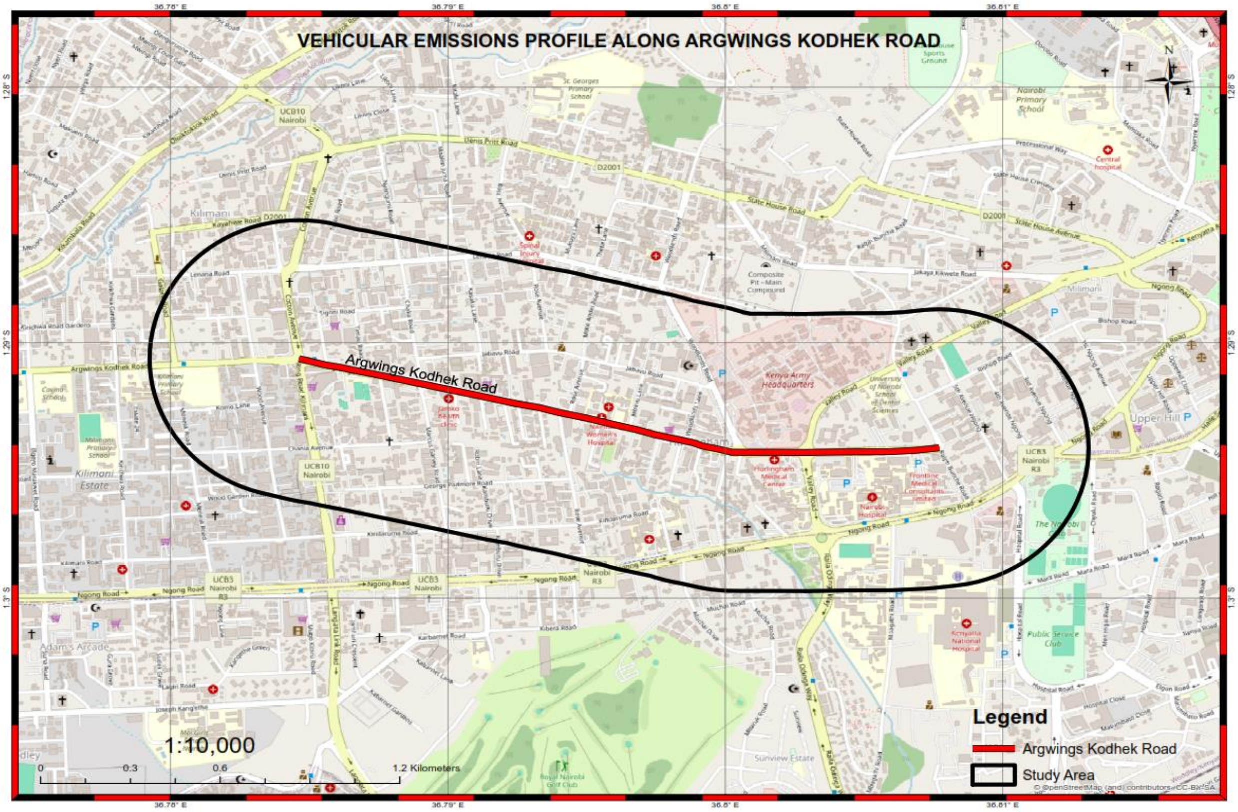

Figure 2: Receptor grids within Study area

h) AERMOD simulation run

Output from AERMAP and AERMET was AERMOD simulates the dispersion of pollutants in the atmosphere and determines concentrations at each receptor location using the source data, digital elevation model, and meteorological information provided. Pollutant concentration values of CO

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and PM2.5 at various receptors for the 1-hour, 24-hour, 1-month, and annual periods generated and presented in the form of shape files, contour lines and colour ramp maps. The color ramp maps provide statistical summaries of findings of the maximum concentrations of the CO and $PM_{2.5}$ emissions from the road and the degree of to which the pollution spread within the 500m buffer area.

4. Results & Discussion

1) AERMAP Meteorological Output

The terrain in the study link [Argwings Kodhek between Yaya Centre and Valley Road] was classified as gentle with an average slope of 2.1% and a maximum slope of 9.7%. Information about the emission sources, including the type of source (point source, area source for Roads, volume source), the emission rate of pollutants and associated physical parameters (stack height, diameter, type of exhaust gas, and velocity) was used for modelling the terrain and surface of the study area. The topography of the study area domain processed by AERMAP is illustrated in figure 3.

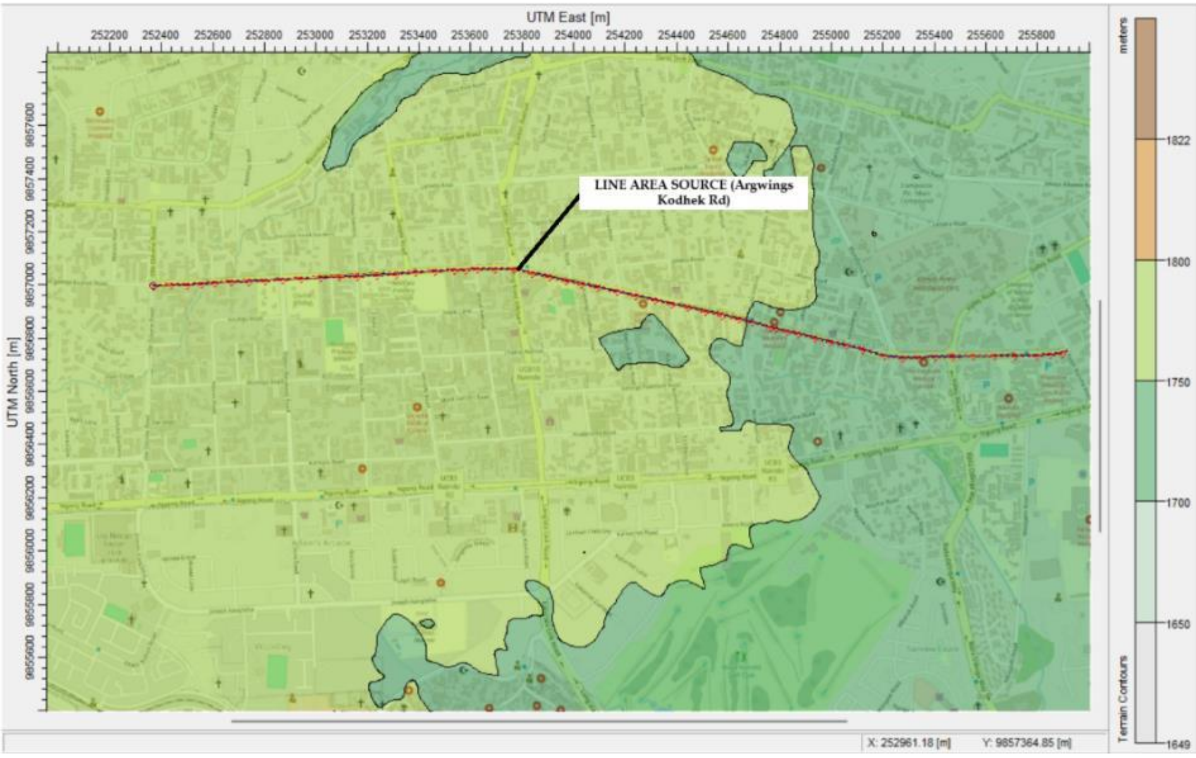

Figure 3: Terrain of Study Area_ Pre-processed DEM file in AERMAP

2) AERMET Meteorological Output

The prevailing wind direction is north easterly with an annual probability of up to 11.10 m/s and a minimum windspeed of 0.50m/The annual wind rose processed by AERMET is shown in Figure 4.

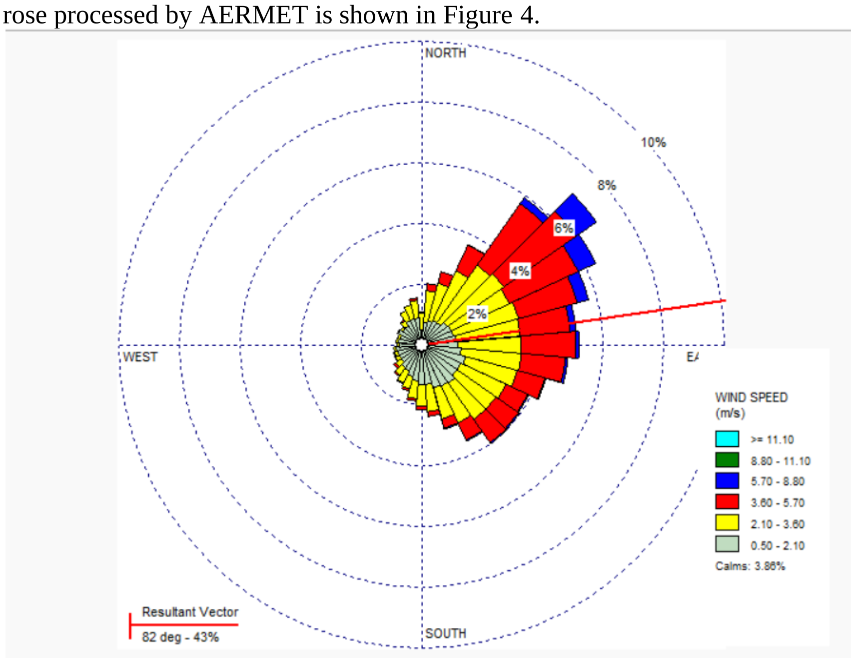

Figure 4: AERMET Windrose Diagram (January 2018 to December 2022)

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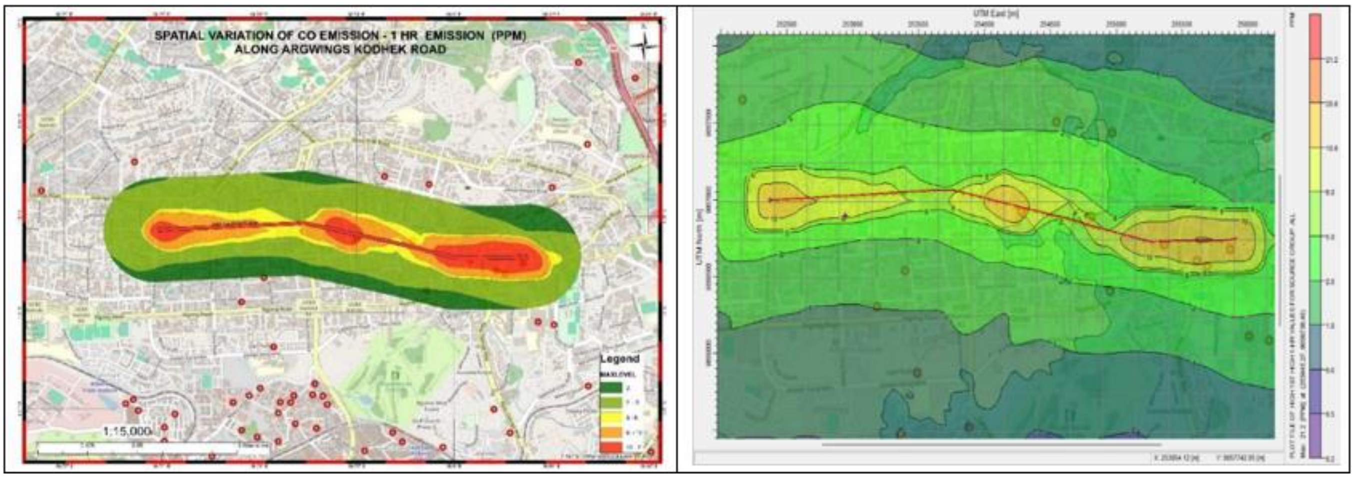
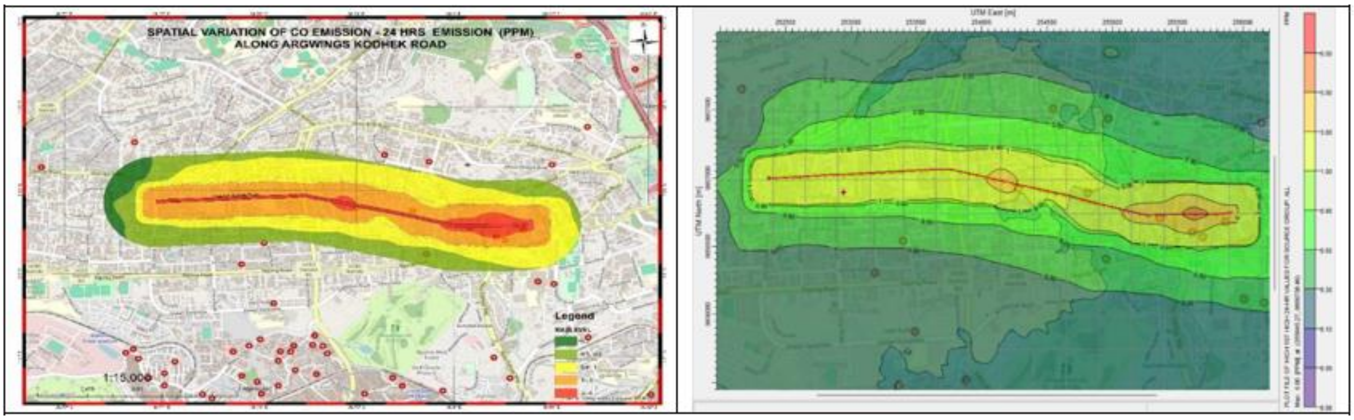
3) Concentration Distribution of Carbon Monoxide, CO

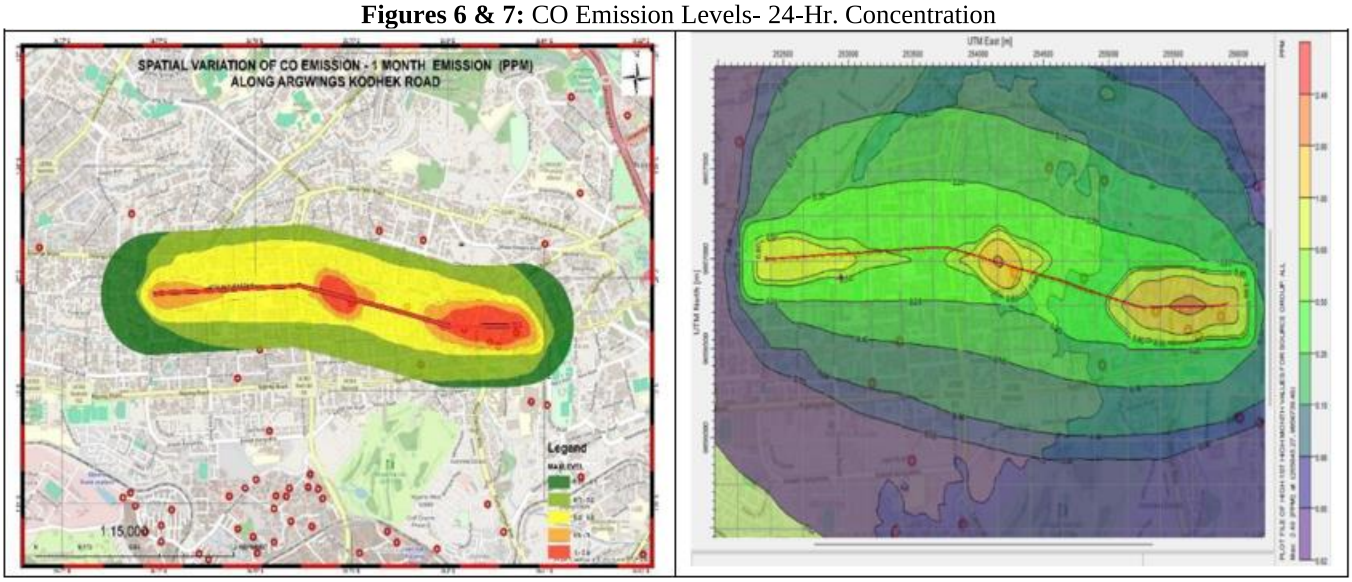
Simulation was undertaken to show concentrations for one hour, twenty-four hours, one day and annually. According to AERMOD's simulation, the carbon monoxide concentration dispersion ranged from 0.02 to 1.79 PPM annually, 0.06 to 6.00 PPM daily, 0.02-2.49 PPM monthly, and 0.2 to 21.2 PPM hourly. At Universal Transverse Mercator (UTM) coordinates 255645.27 m E and 9856738.46 m N, the highest concentration densities were found. The dispersion maps and model forecasts for the maximum one-hour, 24-hour, one-month, and annual concentrations of carbon monoxide are displayed in Figure 4 to Figure 11.



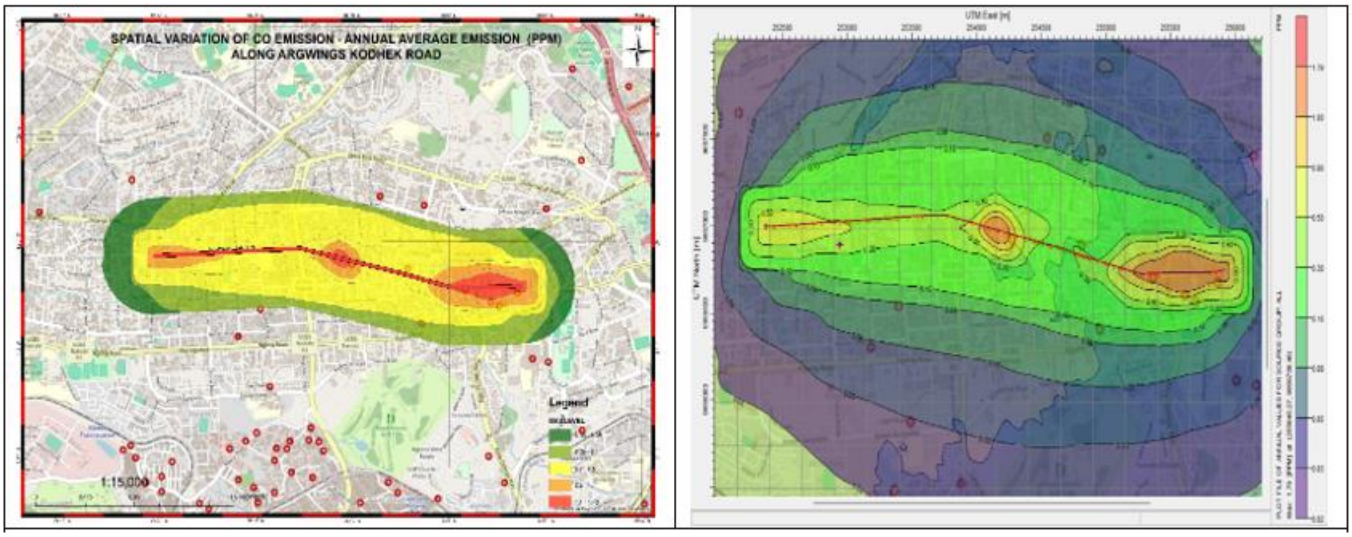
Figures 4 & 5: CO Emission Levels- 1 Hr. Concentration



Figures 6 & 7: CO Emission Levels- 24-Hr. Concentration



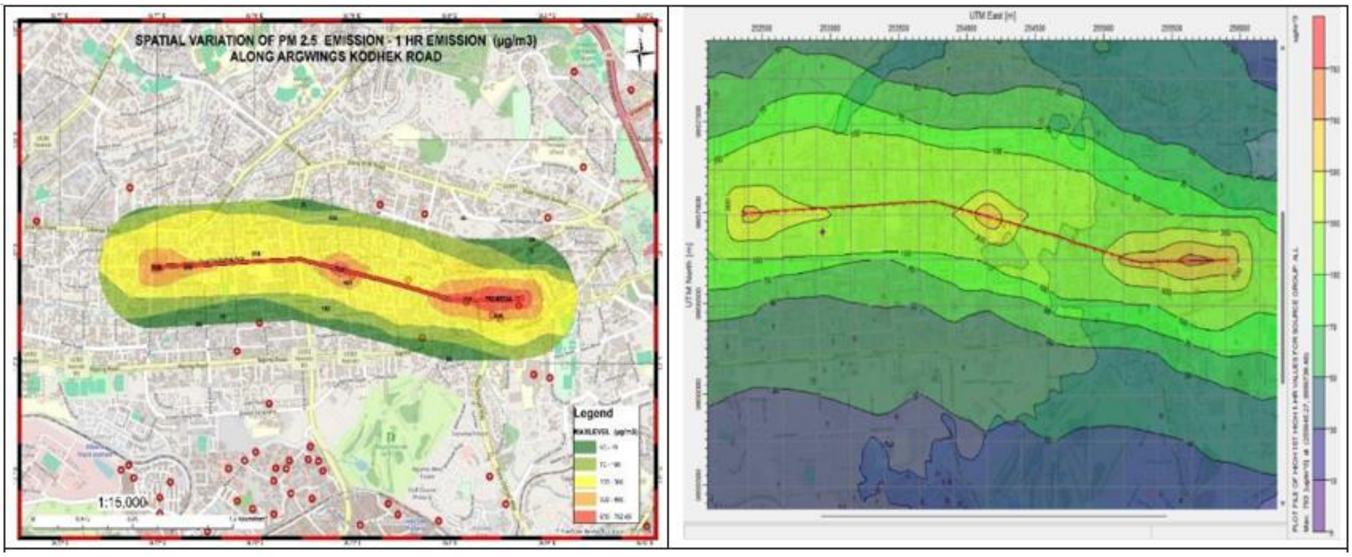
Figures 8 & 9: CO Emission Levels- 1 Month. Concentration



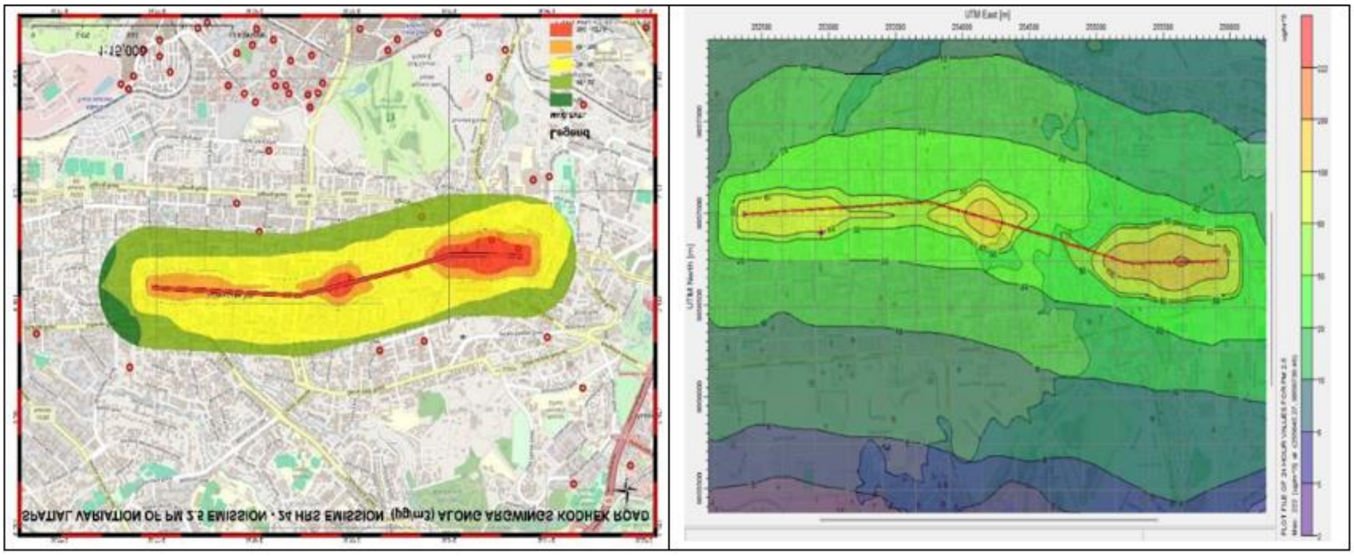
Figures 10 & 11: CO Emission Levels- Annual. Concentration

Concentration Distribution of Particulate Matter PM $_{2.5}$

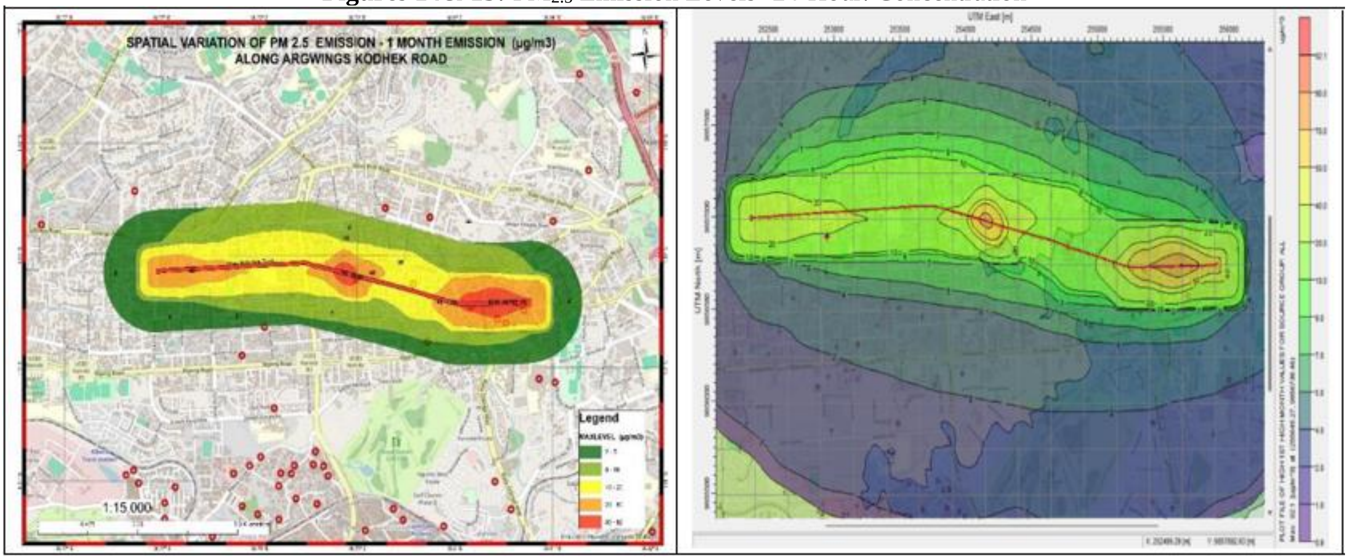
AERMOD simulated that the dispersion of carbon monoxide concentration ranged from 9 to 78 µg/m^3 hourly, 2 to 222µg/m^3 daily, 0.9 to 92.1µg/m^3 monthly and 0.7 to 66.0µg/m^3 annually. The maximum concentrations were at Universal Transverse Mercator (UTM) coordinates 255645.27 m E and 9856738.46m N. Figure 12 to Figure 19 show dispersion maps and model predictions for the maximum 1hr, 24hrs, 1 month and annual concentrations of Particulate Matter with a diameter less than 2.5microns, respectively.



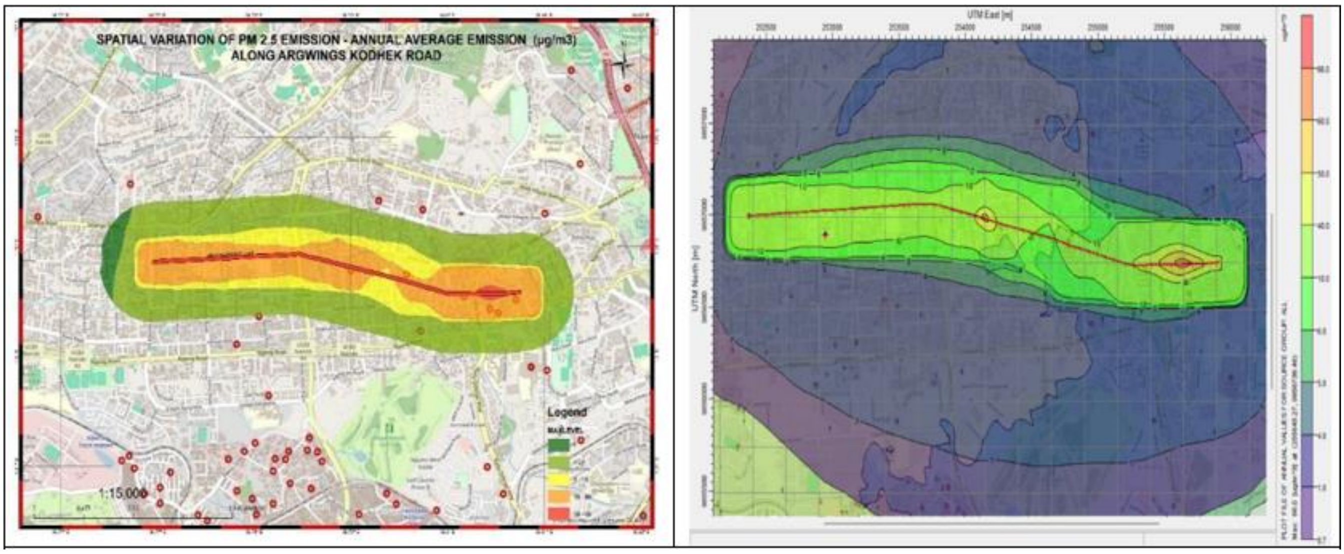
Figures 12 & 13: PM $_{2.5}$ Emission Levels- 1- Hour. Concentration



Figures 14& 15: $PM_{2.5}$ Emission Levels- 24-Hour. Concentration



Figures 16 & 17: PM $_{2.5}$ Emission Levels- 1 Month. Concentration



Figures 18 & 19: PM $_{2.5}$ Emission Levels- Annual. Concentration

5. Conclusion

Simulated spatial distributions in concentrations modelled by AERMOD presented maximum Carbon Monoxide (CO) concentration values of 0.02 to 21.2 PPM and 0.7 to 222 µg/m^3 of Particulate Matter with a diameter less than 2.5microns (PM2.5) with the maximum recording noted at universal transverse Mercator (UTM) coordinate 255645.27m E and

9856738.46m N. Sections of the study road where business centers and intersections are located exhibited higher concentrations of the pollutants. This can be attributed to reduced flows and stop and go conditions at the intersections (major junctions and roundabouts). Whereas the mean CO concentration was within the WHO limits, maximum concentrations exceeded the allowable limits. PM2.5 concentrations exceeded the WHO limits during the varied simulation periods As PM2.5 pollutants can penetrate deep into the lungs and bloodstream, contributing to respiratory and cardiovascular diseases, and even cancer (WHO, 2023), there is need for stringent adoption of stringent measures to curb vehicular pollutant emissions.

This study provides an understanding on the prevailing spatial concentrations of emissions emanating from vehicles along urban roads represented by Argwings Kodhek in this study and its respective abutting zone. This is a contribution to the baseline data required in monitoring air quality along urban roads and updating of emission policies in Kenya.

6. Future Scope

Future research can utilize advanced dispersion modeling techniques to enhance the accuracy of emission impact assessments and expand the range of pollutants studied to include other significant emissions like volatile organic compounds (VOCs) and sulfur dioxide (SO_2).

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Authors Profile

Vane Kerubo Momanyi is a Snr. Civil Engineer Multiscope Consulting Engineers Ltd. She heads the Roads and Transportation department and has extensive experience in the design of various civil infrastructure, supervision of projects and she is skilled in Contract management.

Prof. Sixtus Mwea Kinyua - Snr. Lecturer University of Nairobi

Prof Mwea has an extensive lecturing, research and industrial, experience in Civil Engineering. The teaching areas include geotechnical engineering, pavement design and civil engineering technology. Prof. Mwea has designed and supervised construction a wide range of civil engineering schemes including bridges, roads, buildings and their infrastructure. Additionally, he has been involved in the technical audit of several projects.

Dr. Eng. Osano Simpson Nyambane

Dr. Eng. Osano is the current Head of Department, Civil & Construction Engineering at the University of Nairobi. Dr. Osano has over 11 (eleven) years of lecturing and research experience, both as a Tutorial Fellow, Lecturer and Senior Lecturer, and over Fifteen (15) years extensive experience in civil engineering design, construction works and supervision of projects. He has been involved in the design, tender documentation, project management and supervision of irrigation projects, water projects, runways and roads.