Mobile Sources Emissions to Ambient Air Quality: Case Study on the Baseline Road, Greater Colombo, Sri Lanka

H.B.U. Nishajanthani
Department of Civil Engineering
Faculty of Engineering Technology
The Open University of Sri Lanka
Nugegoda, Sri Lanka
udeshikanisha@gmail.com

B.C.L. Athapattu
Department of Civil Engineering
Faculty of Engineering Technology
The Open University of Sri Lanka
Nugegoda, Sri Lanka
bcliy@ou.ac.lk

H.D.S. Premasiri
Environmental Studies and Services Division
National Building Research Organisation, Sri Lanka
Sarath_nbro@yahoo.com

S. Karunaratne
Department of Civil Engineering
Sri Lanka Institute of Information Technology, Malabe, Sri Lanka
shiromi.k@sliit.lk

***Abstract*— Understanding air quality near roads is important for mitigating urban air pollution and safeguarding public health. Empirical evidence has shown that vehicular emissions significantly contribute to elevated air pollution levels in near-road environments, as indicated by monitoring data collected predominantly during short-term campaigns worldwide. This study evaluates the contribution of vehicular emissions to near-road ambient air quality ($PM_{2.5}$, CO, and NO_2) in a significant segment of Baseline Road, of the Colombo metropolitan area, Sri Lanka. using the AERMOD view dispersion model. AERMOD was validated using monitored data for CO, NO_2, and $PM_{2.5}$. The results show that CO has a fractional bias (FB) of 0.421, a normalized mean square error (NMSE) of 0.294, a factor of two (FAC2) of 0.652, and a correlation coefficient (R) of 0.5. For $PM_{2.5}$, the FB is 1.858, the NMSE is 32.865, the FAC2 is 0.037, and the correlation coefficient (R) is 0.376. NO_2 has an FB of 0.727, while NMSE of 0.954, a FAC2 of 0.467, and a low correlation coefficient (R) of -0.407. The simulated results were under-predicted because only the exhaust emissions of vehicles were considered for the study. The maximum contribution of CO (>83%), $PM_{2.5}$ (10%) and NO_2 (77%) was observed near road junctions. However, the maximum concentrations of pollutants were below the ambient air quality standards stipulated by the Central Environmental Authority of Sri Lanka.**

Keywords: Air Quality, Vehicular Emissions, Dispersion Modelling, Air Pollution

I. Introduction

Emissions from motor vehicle fleets have considerably impacted air quality, increasing public health and climate threats. This is significant in urban areas in developing and underdeveloped countries, where traffic impacts are observed concerning pollution and congestion [1]. Several studies have linked adverse health outcomes with exposure to mobile source emissions [2], [3], [4], [5]. Accordingly, heart diseases, respiratory illnesses, and cancer are considered the most common health effects due to poor air quality [6].

Diesel engines power vehicles, including trucks, buses, trains, ships, and off-road industrial vehicles, such as excavation machinery and mining equipment. Gasoline is the fuel used by a large proportion of cars. Fuel combustion burns hydrocarbons in oxygen, producing carbon dioxide and water, but it is rarely complete, releasing unburnt hydrocarbons and carbon monoxide (CO) into the atmosphere [5]. Impurities in the fuel lead to the emission of oxides of Sulphur (SOx) and particulate matter (PM). There are three types of vehicular emissions: exhaust emissions emitted from the vehicle exhaust tailpipe, evaporation emissions from various locations throughout the fuel delivery and storage system, and non-exhaust emissions such as brake and tire wear [7]. Main roads and intersections often experience higher levels of pollutants due to proximity to heavy traffic flow. This results in localized pollution hotspots where pollutant concentrations can exceed air quality standards. Therefore, it is essential to be concerned about traffic-related emissions because of their proximity to many people in urban areas.

The dispersion of air pollutants depends primarily on meteorological conditions such as wind speed and direction, rainfall, temperature, atmospheric stability, relative humidity, pressure, global horizontal radiation, and cloud cover [8]. In addition, surface roughness (the number of projections above the ground level, obstructions, mountains, buildings, trees, etc.) and source configurations are other parameters that influence air pollutant dispersions. Wind and relative humidity are the most essential meteorological parameters that affect the behaviour of air pollutants [8].

The impact of vehicular emissions on the atmosphere was observed during the COVID–19 pandemic and the related lockdown period in 2020. Due to travel restrictions during the pandemic, the air quality index (AQI) decreased by 7.80% [9]. The levels of SO_2, $PM_{2.5}$, PM_{10}, NO_2, and CO air pollutant decreased by 6.76%, 5.93%, 13.66%, 24.67%, and 4.58%, respectively. Consequently, vehicular emissions significantly impact air quality compared to other anthropogenic emissions [5], [10], [11]. Especially in developing countries, poor traffic management and development problems, such as a rapid increase in vehicles, result in traffic congestion compared to developed countries [9].

Sri Lanka is a low-income and developing country that struggles with poor air quality due to increasing pollution levels. Due to the fast growth in motor vehicles and increased industrial emissions over the last few years, air quality issues in Sri Lanka are worsening daily [10], [12]. The major cities of Sri Lanka, such as Colombo, with populations exceeding 5 million, are becoming saturated with industries and commercial activities. This results in a shift in population, thus increasing the number of vehicles in urban areas [10].

According to the daily variation of pollutant levels in Sri Lanka, some base-level pollutant levels and two high-level peaks occur in the morning and evening, respectively [12]. This is due to vehicular emissions during school and office hours in the morning and evenings. Based on the base level, pollutant emissions within the area are calculated considering the contribution of sources such as vehicles, domestic, commercial, and industrial emissions. Although several studies have been conducted in Sri Lanka to monitor ambient air quality levels [12], [13], [14], there is a lack of quantification of the levels of pollutants from different sources that contribute to Sri Lanka's air quality levels. Most studies focus on vehicular emissions and have considered monitored results in fewer locations [15], [16], [17]. Thus, it is essential to study the differences in pollutant contributions from different sources of emissions carefully to identify their impacts.

However, due to limited resources, air quality monitoring is not done continuously in Sri Lanka. As Sri Lanka is still in its early stages of development, funding facilities are not available to improve infrastructure, such as air quality monitoring points, to buy relevant equipment, or to educate technical people. This is a common scenario seen primarily in developing and underdeveloped countries. As such, the general consideration of using dispersion models to assess the contribution of sources to air quality levels in Sri Lanka is lacking and should be highlighted. The results will help understand pollutant levels and their effects on future commercial and residential buildings near roads in urban and peri-urban areas. The outcome will open doors for more research in health, environment, economics, etc. The knowledge gained through this research will be significant for future urban planning and policy-making development.

The study of the dispersion of pollutants released by automobiles was carried out on one of the main arterial roads within the Greater Colombo area, the 'Baseline Road'. The baseline road is 8 km long and runs from north to south through the eastern end of Colombo. The Baseline Road connects many roads and serves as the gateway to Colombo. As a result, daily traffic is comparatively high compared to other roadways. Furthermore, the study area contains different types of land use, such as commercial, residential, and sensitive areas, making it well-suited for vehicular emission studies. Therefore, the baseline road was selected as the emission source to assess the dispersion of vehicular emissions.

The objectives of this study are to evaluate the contribution of vehicular emissions to near-road $PM_{2.5}$, CO, and NO_2 concentration levels, use the air dispersion model to assess $PM_{2.5}$, CO, and NO_2 dispersion patterns, and identify concentration hotspots of these air pollutants near high traffic areas.

II. Literature Review

Various near-road dispersion models have been developed to assess the population's exposure to traffic-related emissions [18]. Some of these models are CAL3QHCR [19] and CALINE4 [20], ADMS [21], RLINE [22] and AERMOD [18]. The American Meteorological Society and the United States Environmental Protection Agency (EPA) have developed a regulatory model (AERMOD) for point source air dispersion and a ground-level air quality assessment model applicable to line and area sources. A study has compared CAL3QHCR and AERMOD using the predicted pollutant concentration results obtained near a highway in the USA [23]. The results have shown that the predictions of the CAL3QHCR model at the edge of the road for crosswind conditions were not dependent on atmospheric stability. However, AERMOD has anticipated a broader range of concentrations across unstable to stable atmospheric conditions in contrast to CAL3QHCR. CALINE4, CAL3QHCR and AERMOD for near-road PM2.5 showed a relative equivalent between CALINE4 and CAL3QHCR with the observed concentration [24]. Since AERMOD underestimated $PM_{2.5}$ concentrations, the EPA has recommended using either AERMOD or CAL3QHCR for highway and intersection projects [25]. Out of the reviewed results, the AERMOD model, the preferred model by the US EPA for near-field applications, was selected to estimate the dispersion of pollutant emissions from area sources within the Colombo metropolitan region.

The American Meteorological Society/ EPA Regulatory Model Improvement Committee Regulatory Model (AERMOD) is a Gaussian dispersion model. It contains potentially improved algorithms for plume rise and buoyancy and for computing vertical profiles of wind, turbulence, and temperature [26], [27]. AERMOD can be used in flat or complex terrain scenarios. Two preprocessors, AERMET and AERMAP, are required to run the model.

AERMAP is a terrain preprocessor that characterizes the terrain and generates receptor grids, discrete receptors, and elevation for AERMOD [28]. Accordingly, AERMET calculates the hourly boundary layer parameters, such as Monin-Obukhov length, convective velocity scale, temperature scale, mixing height and surface heat flux, which are necessary meteorological data for running AERMOD [28]. The model includes improved algorithms for treating receptors on all types of terrain from the surface up to and above the plume height, treating building wake effects, and computing vertical profiles of wind, turbulence, and temperature [26]. To date, AERMOD has already been used to model air quality near roadways, other transportation sources, and ground-level sources for regulatory applications by EPA and other federal and state agencies [26]. The impending costs associated with other software are relatively high.

III. Methodology

A. Study area

The study was carried out on one of the main arterial roads (Baseline Road) within the greater Colombo, the commercial capital of Sri Lanka. The map of Sri Lanka and the study area considered are shown in Figure 1. The metro area population of Colombo in 2021 is 619,000. Colombo is situated in a lowland region, and the climate conditions are typically hot and humid, with two main monsoons and two inter-monsoon periods. The climate experienced during the 12 months in Sri Lanka can be characterized by four seasons. The first inter-monsoon is from March to April, the South-West monsoon is from May to September, the second inter-monsoon is from October to November, and the North-East monsoon is from December to February.

B. Model Selection

AERMOD View 9.9.5 (Lake Environmental), a US EPA-approved steady-state Gaussian plume model for near-field applications (<50 km), was selected for this study. Its selection was based on its regulatory acceptance, cost-effectiveness compared to alternatives like CALPUFF and ADMS, and practical features. These include flexibility in handling both flat and complex terrain, user-friendly input file preparation, and the ability to visualize results in Google Earth. The model utilizes the AERMET and AERMAP pre-processors for meteorological and terrain data, respectively.

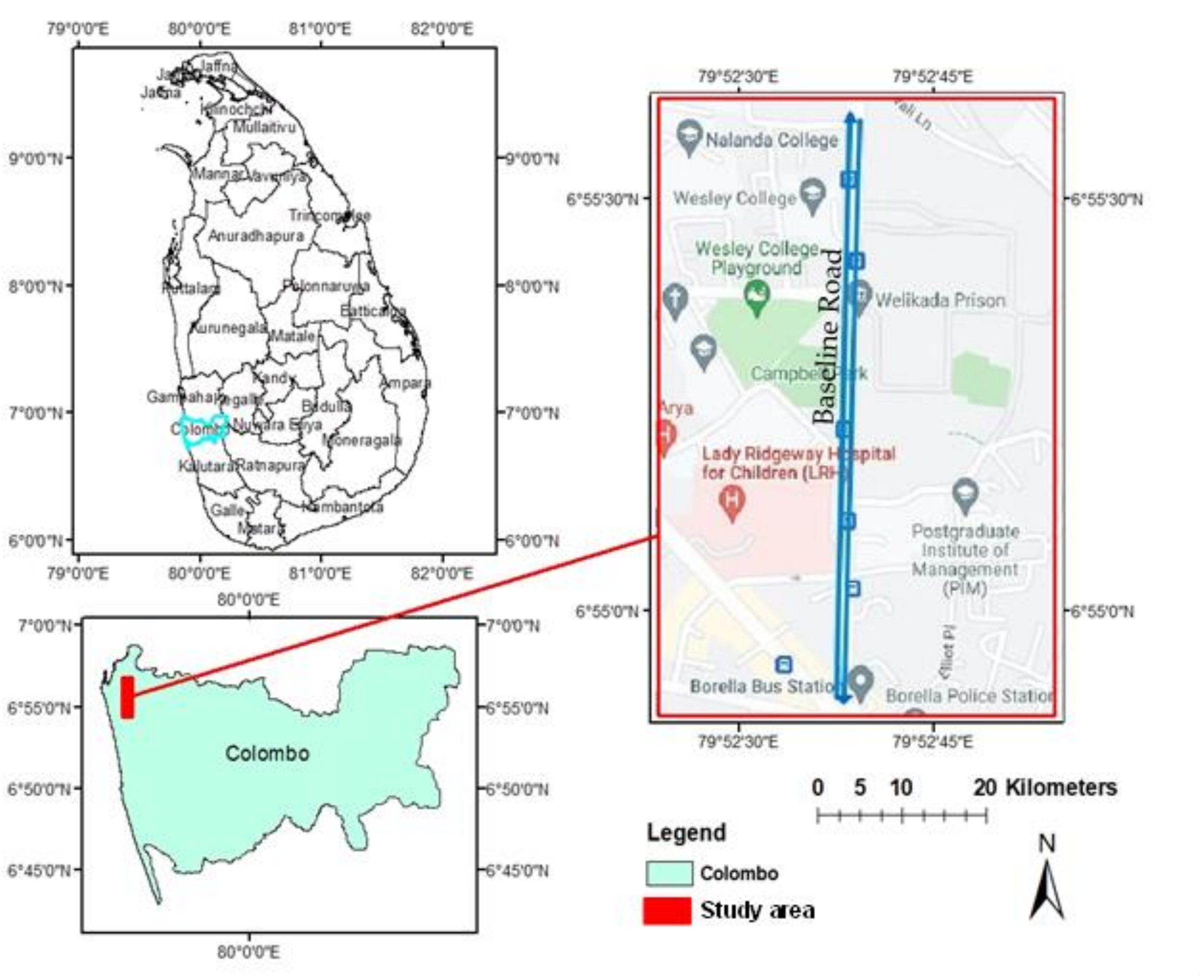

Figure 1. Map of Sri Lanka with the location of Colombo city where the Baseline Road is located.

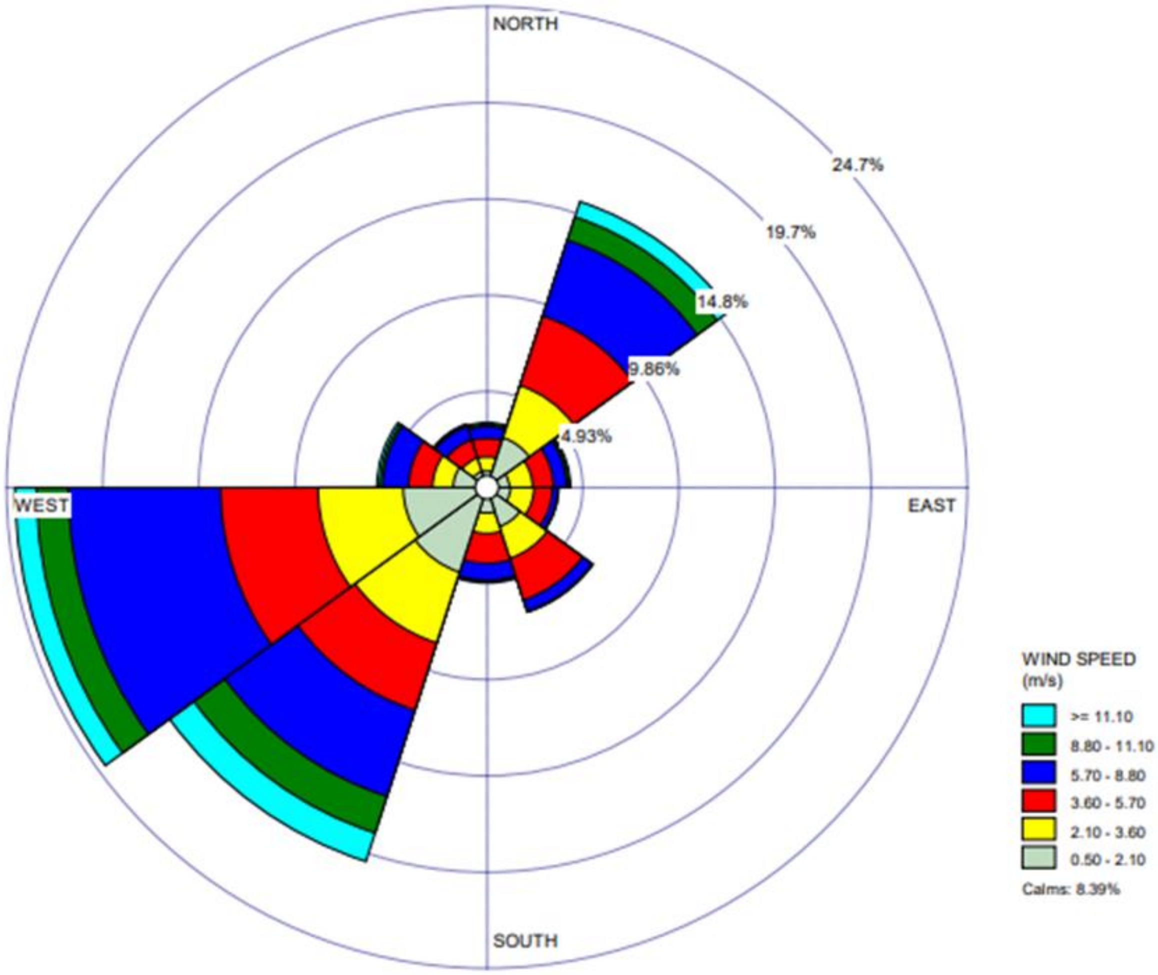

Figure 2. Annual wind rose plot for the year 2021

C. Meteorological data

Meteorological data were collected from the Colombo Meteorology Department (Station number 43466), the nearest weather station. Data on wind speed, wind direction, temperature readings, humidity, precipitation, and ceiling height were prepared in a spreadsheet and processed by AERMET to generate meteorological input for AERMOD. According to the wind rose diagram in Figure 2, the dominant wind direction is south-west 25% of the time with wind speed ranges of 0.5–2.1 m/s, 2.1 m / s, 2.1 to 3.6 m/s, 3.6 to 5.7 m/s and 5.7 to 8.8 m/s. However, 8.39 % of the time, the wind is calm. According to the frequency distribution of the wind stability classes, the atmosphere was primarily unstable within the data period from 0.5m/s to 8.8 m/s (21.3%, 21.5%). This facilitates the dispersion of pollutants due to the turbulence generated by the instability. Atmospheric instability mixes pollutants, enabling wide dispersion.

D. Source data

The type of vehicles selected for this study were motorcycles (MCL), three-wheelers (TWL), cars (CAR), vans (VAN), medium passenger buses (MBU), large passenger buses (LBU) and medium goods vehicles (MG1). Medium-good vehicles include lorries and trucks with two axles. Vehicular emissions were considered as volume source emissions in this study. The source parameters required for volume source emission modelling are coordinates of the source, release height (m), source width (m), initial vertical dimensions (m), and source emission rate in g/s [26].

For this study, only the average operating speed was considered, even though the emission quantity varies with various aspects of vehicle operation, including idle, cruise, acceleration, and deceleration. Significant emission levels are present at junction stops since a sharp acceleration is followed in each vehicle stop. However, this study does not consider emission fluctuation at signalized and unsignalized junctions.

The AADT count and emission factors for each type of vehicle were used to calculate the vehicular emission rates required to run the AERMOD model. Hourly traffic counts at Borella junction and Senanayake junction of Baseline Road for the 23rd of July 2021 were gathered from the Department of Transport and Logistics Management of the University of Moratuwa in Sri Lanka. Since the unavailability of the data set for the Orugodawatta junction for 2021, the AADT count was calculated using the traffic count on the 7th of July, 2016. The Orugodawatta junction data set was obtained from the Road Development Authority, Sri Lanka, to calculate the annual average daily traffic count. The road networks are considered at the Orugodawatta junction and the Borella junction. For computing the monthly expansion factors, the average vehicular speed count was recorded by inserting coordinates of the chosen route using a GPS built for calculating travel time and distance every 15 minutes.

Table 1 presents the monthly variation factors of traffic count, determined through speed variation for each month. The emission rates for each vehicle type were derived using Equation 1.

$$Emission\ rate(E) = \frac{FE\ .\ N}{A\ .\ c} \quad (1)$$

Where,
E = Emission rate in (g/ (s-m^2))
FE = Factor Emission (g km^{-1})
N = number of average vehicles per day
A = Track width (km)
c = Unit conversion factor 86400000000 (days km^2 m^{-2} s)

TABLE I. MONTHLY VARIATION FACTORS OF TRAFFIC COUNT CALCULATED USING SPEED VARIATION DURING EACH MONTH

Month	Monthly variation factor
January	21.66%
February	22.22%
March	27.54%
April	17.39%
May	15.94%
June	15.94%
July	0.00%
August	20.77%
September	23.19%
October	24.64%
November	26.52%
December	31.88%
January	21.66%

E. Terrain data

The site's topographical effects were addressed by employing the software's flat and elevated terrain option, which obtained contour lines with a resolution of ~90 m from the Shuttle Radar Topography Mission (SRTM3) database maintained by the US National Geospatial-Intelligence Agency (NGA).

F. Receptors

Receptor heights were considered 1.5m except for three discrete receptor locations (3m) selected for monitoring the background air quality levels. The uniform Cartesian grid was used to create a mesh of 441 receptors and interesting receptors. Google Earth Pro was used to obtain road geometries, including the coordinates of the road configurations. Distance from the road section to the selected receptors was 55m, 65m and 160m for L1, L2 and L3, respectively.

G. Monitoring data

Air samples were collected from selected locations as per the methods stipulated in National Ambient Air Quality Standards on a one (01) hour basis for nitrogen dioxide (NO_2) and carbon monoxide (CO), and for Particulate Matter ($PM_{2.5}$) analysis was 24 hours. Table 2 shows the testing methods used for the analysis of air quality samples.

TABLE II. MONTHLY TESTING METHODS USED TO DETERMINE THE CONCENTRATION LEVELS OF EACH POLLUTANT

Parameter	Testing Method	Instrumentation
NO_2	ASTM D 1607 - 91, 2011, Griess – Saltzman Reaction Method	Standard Personal Air Samplers UV – Visible Spectrophotometer
CO	ASTM D 3162 – 12, 2012 non-dispersive infrared Spectrometric method	Riken Keiki CO Detector Model - CO-7
PM_{10} and $PM_{2.5}$	ASTM D 4096 - 82, 2017 High-Volume Sampling and Gravimetric Analysis	High Volume Sampler with size-selective sample inlet SHIMADZU AUW120D Analytical balance

H. Statistical analysis

Statistical indices are used to analyze the dependability between AERMOD simulated results and monitored results. The statistical parameters considered are given in equations 2 to 4.

FB = (((C_0)̅-(C_P)̅))/(0.5 ((C_0)̅+(C_P)̅)) (2)
NMSE = (〖(C_0-C_P)〗 ^2)̅/(C_0 C_P) (3)
Fac2= 0.5 < Co /Cp < 2 (4)

FB, NMSE, R, Co and Cp are fractional bias, normalized mean square error, correlation coefficient, and observed and predicted concentration, respectively. The correlation coefficient (R) was calculated using IBM SPSS Statistics 26 software. The over-bar sign stands for average.

IV. RESULTS AND DISCUSSION

A. Model Performance Evaluation

Comparing estimated model concentrations with measured air quality data determines the model's accuracy. Therefore, comparing observed concentrations to model predictions is the best way to validate the output of air dispersion modelling. Accordingly, Figure 3 shows the contribution of vehicular emissions to the ambient air quality levels, and the statistical parameters for the monitored and predicted results are calculated and presented in Table 3.

In location L1, simulated concentrations varied from 829.0713 µg/m³ in January, 829.9361 µg/m³ in March, 654.4319 µg/m³ in July, to 826.155 µg/m³ in October. The contribution of vehicles to CO pollution remains consistently high at 83% in all months for location L1 except in July. In location L2, the monitored concentration and simulated concentrations follow a similar trend to L1, with the highest contribution of vehicles being 85%. Similar results were observed in several studies in India, Chile and Iran [11]. Location L3 shows lower concentrations than L1 and L2, with simulated concentrations ranging from 276.0773 µg/m³ in January to 275.0271 µg/m³ in

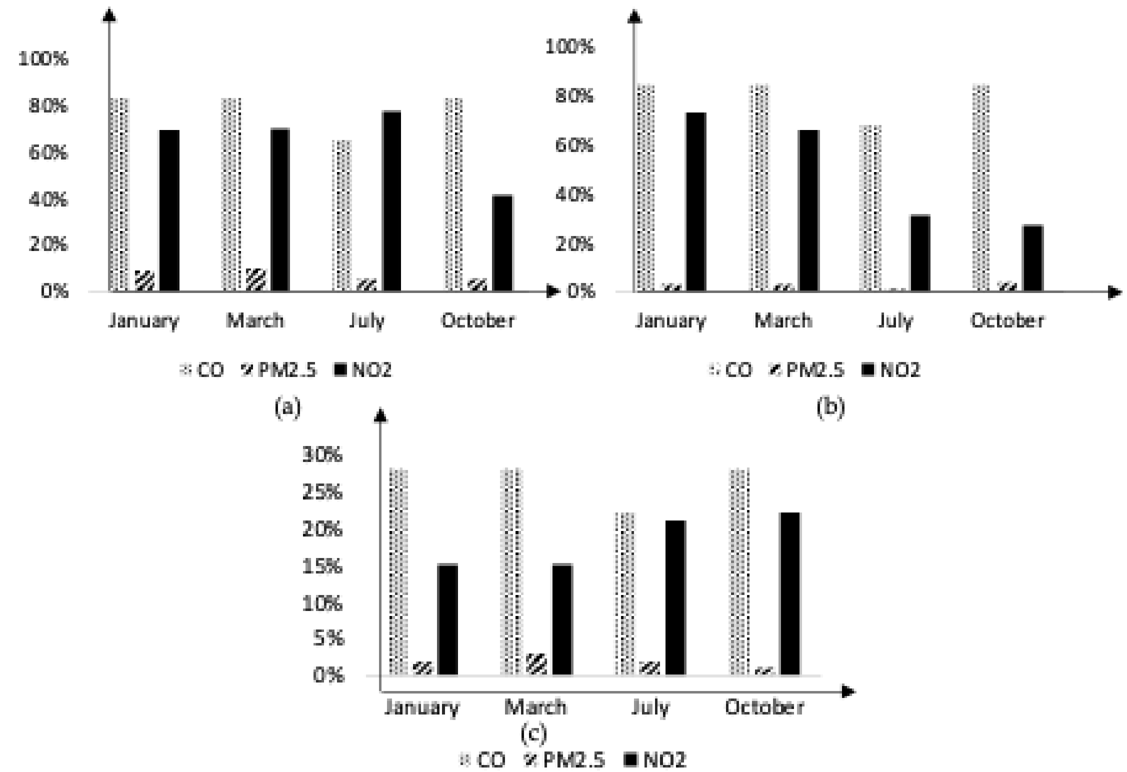

Figure 3. Contribution from vehicular emissions to ambient air quality levels at receptor location (a) L1, (b) L2 and (c) L3

October because the distance between the receptor location (L3) was higher than the other two receptor locations. Vehicle contribution to the CO pollutant level in location L3 is lower, at 28% in all months. The highest contribution was observed near the source. For PM2.5, in location L1, the monitored concentration ranges from 15 µg/m³ in January to 33 µg/m³ in October.

TABLE III. STATISTICAL ANALYSIS OF THE MODEL PERFORMANCE

	FB	NMSE	FAC2	R
CO	0.421	0.294	0.652	0.5
$PM_{2.5}$	1.858	32.865	0.037	0.376
NO_2	0.727	0.954	0.467	-0.407

Simulated concentrations range from 1.34713 µg/m³ in January to 1.59769 µg/m³ in October. Vehicles contribute 9-10% to $PM_{2.5}$ pollution in January and March and 5% in July and October, in location L1. The transportation sector accounted for 8% of the nation's total $PM_{2.5}$ emissions [25]. In location L2, both monitored and simulated concentrations are higher than in L1, but the trend is similar. Vehicle contribution to $PM_{2.5}$ pollution in location L2 is lower, ranging from 1-4% across different months. Location L3 shows the lowest concentrations among the three locations because the distance between the source and the receptor (L3) is comparatively high. Vehicle contribution to $PM_{2.5}$ pollution in location L3 ranges from 1-3% in most months, except for 2% in January.

The monitored concentration ranges from 35 µg/m³ in July to 93 µg/m³ in October for L1. Simulated concentrations range from 26.88012 µg/m³ in July to 37.87077 µg/m³ in October. Vehicle contribution to NO_2 pollution in location L1 is highest in July at 77% and lower in the other months, ranging from 41-70%. In location L2, both monitored and simulated concentrations are lower than in L1, but the trend is similar. Vehicle contribution to NO_2 pollution in location L2 varies across the months, ranging from 27%-73%. Location L3 shows lower concentrations than L1 and L2, with simulated concentrations ranging from 7.98553 µg/m³ in July to 10.00864 µg/m³ in March. Vehicle contribution to NO_2 pollution in location L3 ranges from 15-22% across different months. Similar contribution percentages were observed in India, ranging from 24% to 42% within different states in India, indicating poor agreement. The FAC2 value of 0.467 for NO_2 suggests that approximately 46.7% of the predicted values fall within a factor of 2 of the observed values, indicating moderate agreement.

The R-value measures the linear correlation between the predicted and observed values. The R-value of 0.5 for CO suggests a moderate positive correlation between the predicted and observed values. The R-value of 0.376 for $PM_{2.5}$ indicates a weak positive correlation between the predicted and observed values. The R-value of -0.407 for NO_2 suggests a weak negative correlation between the predicted and observed values.

However, the predicted values were underestimated since only the contribution of each pollutant type from vehicle tailpipe emissions was considered. Many other sources contribute to ambient air quality levels. Therefore, it can be concluded that the model's performance in predicting field data is acceptable.

B. Spatial distribution of pollutant concentration

The spatial distribution patterns of CO, $PM_{2.5}$, and NO_2 within a 1.5 km radius from a point (60 55' 57.79" N, 790 52' 41.44" E) on the baseline were studied to understand the distribution patterns of pollutants and to identify the hotspots where pollutants are highly concentrated. Figure 4 shows the spatial dispersion maps obtained after running the AERMOD dispersion model for CO, $PM_{2.5}$, and NO_2.

Figure 4 (a) shows that the maximum one-hour CO concentration is 1567.84 µg/m^3 (375948.61N, 764516.42 E). The maximum concentrations are observed in the two road junctions. However, according to the ambient air quality standards for CO, the 1-hour maximum concentration level does not exceed the maximum permissible levels stipulated by the Ministry of Environment, Sri Lanka, which is 30,000 µg/m^3 (1 hour).

The maximum daily concentration is 4.90 µg/m^3 (375948.61N, 764286.42E). The highest concentration was again found closer to the traffic intersections. However, the permissible levels of $PM_{2.5}$, as per the Ministry of Environment, Sri Lanka, for the daily average are 50µg/m^3, concluding that the maximum $PM_{2.5}$ level is within the acceptable level.

The highest hourly concentration of NO_2 is 75.80 µg/m^3 (375948.61N, 764516.42E), and the maximum concentration was discovered closest to the road junctions. However, according to Sri Lanka's Ministry of Environment, the acceptable amount of NO_2 for an hourly average is 250 µg/m^3. Therefore, the maximum NO_2 level is considered to be within safe limits.

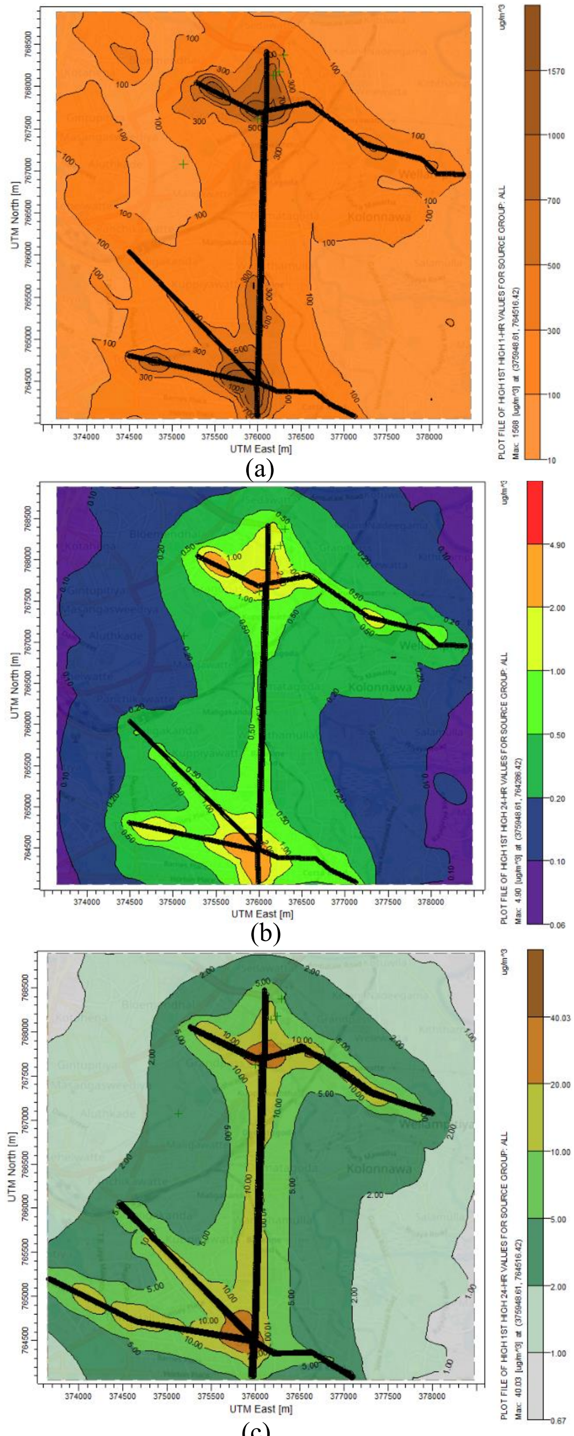

Figure 4. Spatial distribution pattern for (a) hourly average concentration of CO, (b) daily average concentration of PM2.5, and (c) hourly average concentration of NO2

V. CONCLUSION

This study analyses the contribution of pollutants emitted from mobile sources to the ambient air quality levels using the AERMOD dispersion model. The modelled results were compared with the measured data from monitoring locations. Evaluation of the model performance was carried out by using statistical analysis. It was found that AERMOD could provide accurate results for CO, $PM_{2.5}$ and NO_2. As per the results, the highest contribution to the ambient CO and NO_2 levels was from vehicle exhaust emissions. However, in contrast to various urbanized cities worldwide, the maximum pollutant levels resulting from vehicular emissions within the Colombo region were below the air quality standards set forth by the Ministry of Environment in Sri Lanka. When comparing the monitored 24-hour $PM_{2.5}$ with the ambient air quality standard of 50µg/m3, the ambient $PM_{2.5}$ concentration level had reached the permissible limit. This can be due to other background sources like industrial emissions, household activities, and even non-exhaust emissions like brake and tire wear. Therefore, further source apportionment studies are required to identify the possible pollutant-generating sources. Also, the findings from the study can be generalized to many other locations, and they have important implications for epidemiological and other studies.

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