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Simulation of $PM_{2.5}$ Concentrations around the Proposed Yangon Outer Ring Road (Eastern Section) in Myanmar Using CALINE 4 Model

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ABSTRACT

An increase in traffic volume has resulted in the deterioration of environmental quality and human health in Yangon as well as in the surrounding areas that are connected to the city via several road links. The Yangon Outer Ring Road Construction (YORR) (Eastern Section) is a priority project for solving traffic-related problems. This study aimed to simulate the current levels of $PM_{2.5}$ concentration around the proposed YORR (Eastern Section) area using the CALINE 4 model and to evaluate the model's performance. Air quality measurements of $PM_{2.5}$ were carried out in five townships around the proposed road construction area-for one week at each monitoring location-from January 24th to March 2nd, 2021 using the Haz-Scanner Environmental Perimeter Air Station. When compared to the ambient air quality guidelines of Myanmar, the International Finance Corporation, and the World Health Organization, the observed $PM_{2.5}$ concentrations were found to be usually high at all locations, except in Kyauktan township. Statistical analysis indicated that the CALINE 4 model performed satisfactorily with a coefficient of determination of 0.85-0.90, fractional bias of 0.03-0.50, and normalized mean square error of 0.001-0.100. It is crucial that mitigation measures, including policies regarding the use of low PM emission vehicles and road-side barriers, be implemented by regulatory authorities during and after the YORR construction.

1. INTRODUCTION

Rapid growth in traffic volume has resulted in deterioration of environmental quality and human health. Evidently, an increase in traffic volume-as a result of a newly constructed roads-is an additional source of particulate matter (PM) in the surrounding environment of the new roads (Chuang et al., 2020). PM exposure leads to a risk of developing diseases and health conditions, such as nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, and increased respiratory symptoms such as coughing or difficulty breathing, and premature death in people with existing heart or lung diseases (Kim et al., 2015). Particulate matter that is 2.5 μm or smaller in size ($PM_{2.5}$) not only causes health problems but also seriously affects the chemical processes in the atmosphere and influences climate change (Kumar et al., 2010).

The development of roads for transportation plays an important role in a country's economic growth as it facilitates a continuous supply of goods and services. The proposed Yangon Outer Ring Road Construction (YORR) (Eastern Section) has a total length of approximately 49 km, including a 1.28 km-long bridge across the Bago River and frontage roads; it is approximately 20 km from the downtown area and is a priority project for solving traffic problems (JICA, 2015). The project site is located near five townships: Hlegu, East Dagon, Dagon Seikkan, Thanlyin, and Kyauttan. In view of sustainable development goals, such projects must focus on the environment, including air quality.

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Several air quality models have been developed to evaluate roadside air quality (Gokhale and Khare, 2004). However, several of these models are complex, given the poor availability of meteorological and traffic data. The modified general finite line source model of particulates, as well as CALINE 3 and CAL3QHC models have been used to evaluate vehicle-derived airborne particulate mass emissions (Gokhale and Raokhande, 2008). Other models that have been widely used to evaluate the dispersion of air pollutants at roadsides (Ghanshyam, 2018) include a series of California Line Source Dispersion Models. CALINE 4 is the most recent version in the CALINE series, which has been used extensively worldwide and is claimed to perform better than other line source models (Dhyani et al., 2013; Goud et al., 2015; Muneeswaran and Chandrasekaran, 2015; Sharma et al., 2013).

In view of the proven negative effects of new road construction on air quality, forecasting $PM_{2.5}$ concentration is important to control air pollution in the study area, as no such research has been conducted to date. The objective of this study was to simulate the current levels of $PM_{2.5}$ concentration in the proposed YORR (Eastern Section) area using the CALINE 4 model. Overall, this study aimed to lay the foundation for further research into the impacts of the YORR (Eastern Section) on the $PM_{2.5}$ concentrations.

2. METHODOLOGY

2.1 Study area

The Yangon Outer Ring Road (YORR) (Eastern Section) project in Yangon-a former capital city and now the biggest commercial center of Myanmar-was chosen as the study area. Based on the 2014 census, the total population of the five townships in the YORR project area was approximately 1,039,328 (city population, 2022). The climate of Yangon is mainly characterized by tropical monsoon (Weatherbase, 2022). The main contributors of $PM_{2.5}$ in the study area include traffic, domestic fuel consumption, industrial activities, and natural dust. Air quality was monitored at one location in each of the five townships, represented as Point-1, Point-2, Point-3, Point-4, and Point-5. A map of the study area with the air quality monitoring locations is presented in Figure 1.

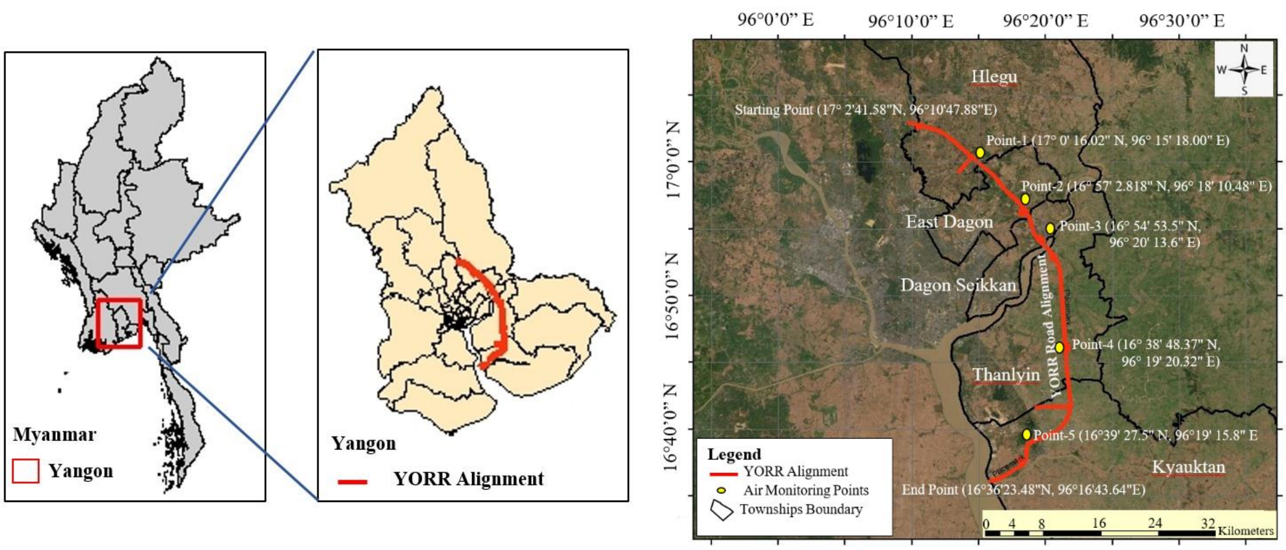


Figure 1. Map of Yangon Outer Ring Road (Eastern section) showing the air quality monitoring locations (location of YORR (Eastern section) in Yangon is shown in the top panel)

2.2 Data collection

$PM_{2.5}$ measurements were carried out from January 24th to March 2nd, 2021, at the five locations surrounding the proposed road construction area (Table 1) using the portable wireless Haz-Scanner Environmental Perimeter Air Station (HAZS-CANNER™ EPAS). The Haz-Scanner is equipped with a variety of gas, $PM_{2.5}$, temperature, and humidity sensors, which can detect different variables ranging from 1 to 20,000 $\mu g/m^3$. The $PM_{2.5}$ sensor is equipped with a high-precision laser sensor that detects the number and diameter of particles through the laser scattering method, and accurately calculates the $PM_{2.5}$ concentration. An anemometer (Vantage Pro2 Console) was installed on top of the monitoring station (2.5 m above ground level) and connected to HAZSCANNER™ EPAS instrument. Due to limited availability of instruments, simultaneous monitoring at all five locations could not be performed. In addition, the weekly variability and long-range transport events were not considered.

2.3 CALINE 4 model

CALINE 4 is a Gaussian dispersion model specifically used to simulate the level of air pollution adjacent to roadways by estimating the vehicular pollutant concentration at source receptor distances of tens to hundreds of meters (Pournazeri et al., 2013).

The CALRoads View model Version 6.2.5 form of CALINE 4, developed by Lakes Environmental Software, Canada in 2008, was used for this study (Mishra, 2016).

Table 1. Air quality monitoring locations and schedule

Location	Description	Monitoring date
Point-1	Hlegu Township (~0.8 km from centerline of road alignment)	24-30 January 2021
Point-2	East Dagon Township (~0.24 km from centerline of road alignment)	31 January - 6 Febuary 2021
Point-3	Dagon SeikKan Township, (~1.9 km from centerline of road alignment)	7-13 Febuary 2021
Point-4	Thanlyin Township, (~0.7 km from centerline of road alignment)	15-21 Febuary 2021
Point-5	Kyaut Tan Township, (~0.51 km from centerline of road alignment)	23 Febuary - 1 March 2021

2.3.1 Inputs for CALINE 4 model

"Multirun" was chosen as the CALINE 4 model run type to calculate the eight-hourly average $PM_{2.5}$ concentration at the receptor points - because of the time limitations - to observe the fluctuations during different periods of the day. The five monitoring points were set as discrete receptor points.

The important input variables required for the CALINE 4 model included traffic volume (number of vehicles per hour), meteorological parameters (wind speed, wind direction, ambient temperature, mixing height, and stability class), composite emission factors (CEFs), road geometry (road width, median width, and road elevation), type of terrain (rural or urban), background concentration of pollutants (ppm or $\mu g/m^3$), and pre-identified receptor locations along the road alignment (Dhyani et al., 2013). The input parameters used in the model are listed in Table 2.

Meteorological data of the observation periods, including wind direction, wind speed, and temperature at the monitoring stations, were obtained through on-site measurements. The CALINE 4 model cannot predict input wind speeds of less than 1 m/s and automatically selects a speed of 0.5 m/s as the default value (Dhyani and Sharma, 2017).

Table 2. Input parameters used in the CALINE 4 model

No	Input data	Units	Source
1	Meteorological data		
	- Wind direction	Degree	On-site measurement
	- Wind speed	m/s	On-site measurement
	- Atmospheric stability class (Pasquill (P-G) stability class)	A (1) to G (7)	Based on on-site measurement of wind speed
	- Wind degree standard deviation	Degree	Based on on-site measurement of wind direction
	- Mixing height	Meters (m)	Benson, 1984 (recommended value)
	- Temperature	°C	On-site measurement
2	Road link information		
	- Link type	At-grade	Physically observed
	- Link height (at-great option assumes roadway to be at ground level)	Meters (m)	
	- Mixing zone width (carriage width+3 on both sides)	Meters (m)	Google map
	- Link geometry Beginning (17° 2'41.58" N, 96°10'47.88" E) and Ending coordinates (16°36'23.48" N, 96°16'43.64" E)	-	Google map

Table 2. Input parameters used in the CALINE 4 model (cont.)

No	Input data	Units	Source
3	Road link activity		
	- Hourly traffic volume	vehicles/h	Calculated based on the secondary data with the assumed percent fraction for the existing road networks JICA, 2015 MJTD, 2016
	- Composite emission factor	g/vehicle-km	JICA, 2016 ARAI, 2008 for $PM_{2.5}$
4	Background concentration	µg/m^3	Calculated based on on-site measurement of wind direction and observed concentrations at the nearest monitoring points

Hourly atmospheric stability classes in the study area, which were based on the Pasquill-Gifford classification, were estimated using wind speed, incoming solar radiation, and cloud cover (daytime and night-time) (Turner, 1994). The study area was either sunny or slightly cloudy during the monitoring period. Typically, the temperature fluctuated between 30 and 38°C during the daytime; the amount of incoming solar radiation was assumed to be moderate. Clear skies and a temperature drop to 16°C were recorded at night-time (Weather Spark, 2022). According to the classification of Pasquill-Gifford, atmospheric stability in the study area was classified as A (extremely unstable) at daytime and F (moderately stable) at night-time. The wind degree standard deviation of the horizontal wind direction (σθ) was based on the atmospheric stability classification (NRC, 1980). The meteorological parameters used in the CALINE 4 model are presented in Table 3.

Table 3. Meteorological parameters used in CALINE 4 model

Townships (monitoring Points)	Temperature (°C)		Wind speed (m/s)		Predominant wind direction	Predominant atmospheric stability class	
	Max	Min	Max	Min		Daytime	Nighttime
Hlegu (Point-1)	37.3	18.3	5	0	*NNE	A	F
East Dagon (Point-2)	36.9	17.2	2	0	*NE	A	F
Dagon Seikkan (Point-3)	35.9	16.9	4	0	*E	A	F
Thanlyin (Point-4)	36.2	19.5	7	0	*S	A	F
Kyauk Tan (Point-5)	37.6	17.3	2	0	*SE	A	F

*NNE- North East, *NE- North East, E-East, S- South, SE-South East

The mixing height was set to 1,000 m, except for very severe nocturnal inversions; this is the recommended value for all normal atmospheric occurrences (Benson, 1984; Chen et al., 2008; USEPA, 1995). Mixing height rarely affects the predicted concentration, especially under perpendicular wind conditions (Sahlodin et al., 2007). Some studies have reported negligible effects of mixing height on the predicted concentrations (Batterman et al., 2010; El-Fadel et al., 2000).

Road link information: The road geometry, used as the input parameter for the model, was obtained from the YORR project information. Based on physical observations, all road link types for the existing road networks were at-grade. Therefore, all road links were assumed to be zero.

The mixing zone was considered to be an area of uniform emissions and turbulence. Mixing zone width is defined as the width of the travelled way (traffic lanes not including shoulders) plus 3 m (horizontal dispersion adjustment) on each side. Google Map measurements were applied to the carriageway width of the roads.

Road link activity: Hourly traffic volumes were taken from a study conducted at the Bago and Yangon-Thanlyin bridges in 2013 (JICA, 2015) to obtain hourly distribution factors. Subsequently, the hourly traffic volume (vehicles/h) recorded in 2015 on Than Lyin-Thilawa and Thilawa roads near the study area (MJTD, 2016) were used to calculate the hourly traffic volume based on hourly traffic volume distribution factors (vehicles/h) obtained from a previous study

(JICA, 2015). Furthermore, the total traffic volume in the study area for 2021 was calculated using future annual average daily traffic formula (Horowitz, 1999; Dixon, 2004). The traffic volumes in the vicinity of the monitoring points were obtained using mass balance and after adjusting the percentage fraction based on the location and direction of the roads in the existing road networks in each township.

The CEF represented the source strength by the average emission rate of all vehicle types in the local vehicle kilometer (g/v-km). The weighted emission factor was obtained based on the vehicle distribution by type, age, and operation mode. Information on the distribution of vehicle types was collected from the Bago River Bridge EIA report (JICA, 2016). $PM_{2.5}$ emission factors for different vehicle types were obtained from the Automotive Research Association of India, assuming a similar traffic pattern in developing countries (ARAI, 2008). The evaluated average CEFs for different vehicle types were used in the CALINE 4 model for simulations.

The background concentrations for each simulation were estimated according to the hourly concentrations observed at the nearest monitoring points. Based on the wind directions and distance between the two points, the background concentrations at the receptor location were assumed to be 70% and 50% of the observed concentration at the nearest monitoring points for dominant and non-dominant wind directions, respectively. For example, at Point-4, the predominant wind direction during the observation period was from the south, and the closest observation location was point-5, which was situated 12.6 km away at the south-south-west region of Point-4. Therefore, the background concentrations at Point-4 were assumed to be 70% and 50% of the observed concentrations at Point-5 for the dominant and nondominant wind directions, respectively.

Five simulation domains were set up to represent the emission sources from the existing road networks in each of the five townships located near the new YORR alignment. As the CALRoads View Model could be used for a maximum of 62 links, domains were set up considering this limitation.

Model performance evaluation was conducted by regression analysis of observed and simulated $PM_{2.5}$ concentrations, including coefficient of determination (r^2), normalized mean square error (NMSE), and fractional bias (FB), as recommended by the U.S. Environmental Protection Agency (Hanna et al., 1993).

3. RESULTS AND DISCUSSION

3.1 Meteorological results

Wind rose diagrams displaying the distribution of wind directions and wind speeds for each township are presented in Figure 2.

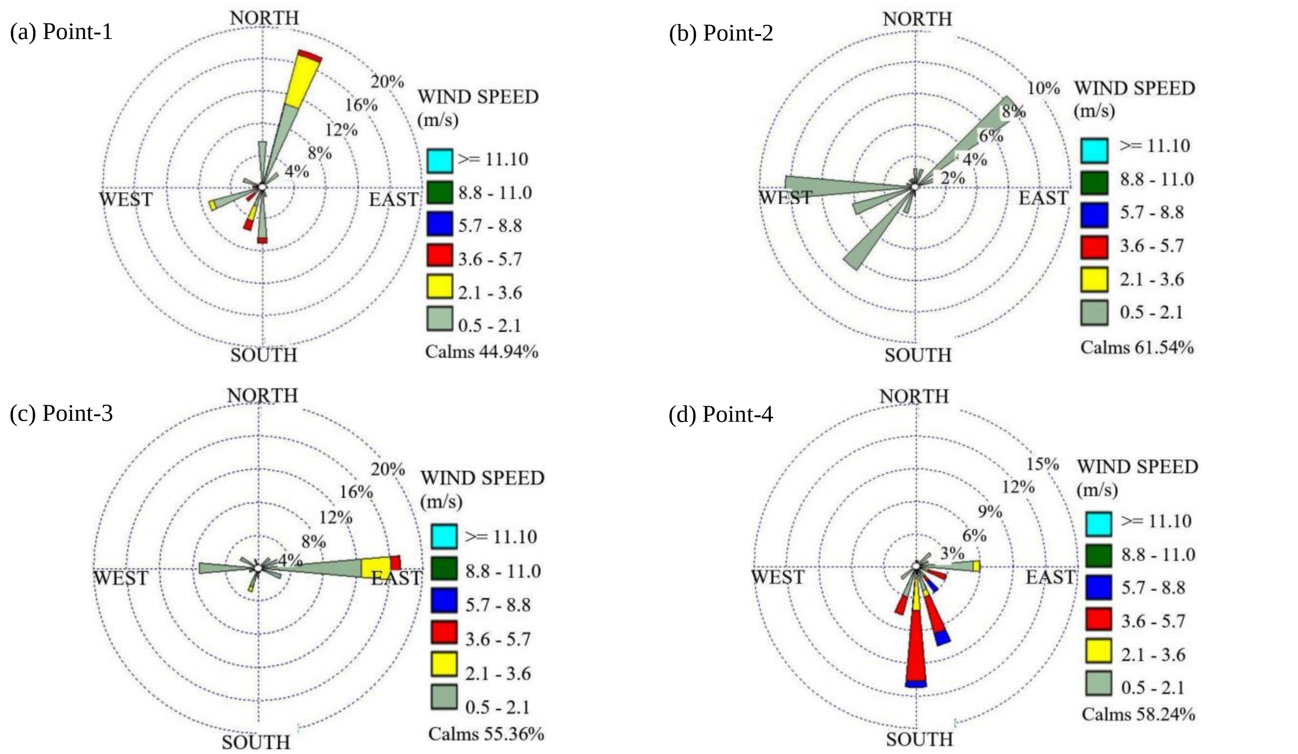


Figure 2. Wind directions and wind speeds at each monitoring station during the respective monitoring periods

(e) Point-5

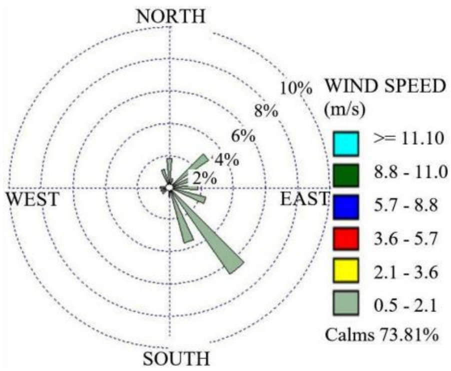


Figure 2. Wind directions and wind speeds at each monitoring station during the respective monitoring periods (cont.)

3.2 Observed and simulated results

Based on the hourly $PM_{2.5}$ concentrations observed at each monitoring station for seven days, the maximum concentration observed at Point-1 was 176.76 μg/m^3. This could be due to dust erosion from nearby unpaved roads, vehicular emissions, or domestic fuel consumption. In Myanmar, the ambient air quality standard for the daily average concentrations of $PM_{2.5}$, as prescribed in the National Environmental Quality (Emission) Guidelines, is 25 μg/m^3; this is similar to the value prescribed by the General Environmental Health and Safety Guidelines (ECD, 2015; IFC, 2007). The WHO released the updated air quality guidelines in September 2021, which significantly reduced the maximum allowable safe levels of daily average $PM_{2.5}$ concentration to 15 μg/m^3. In this study, the daily average concentrations of $PM_{2.5}$ were generally higher than the value specified in the new WHO guidelines, except at Point-4 and Point-5 on certain days (Figure 3). The WHO estimates approximately 7 million premature deaths every year due to the effects of air pollution. However, 80% of the deaths attributed to $PM_{2.5}$ exposure can be avoided if countries attain their annual air quality level for $PM_{2.5}$ (WHO, 2021).

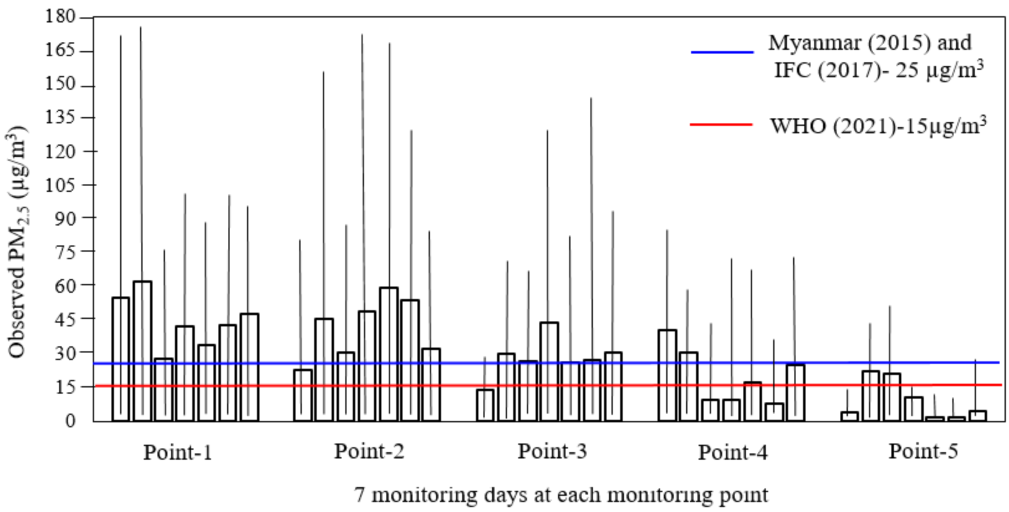


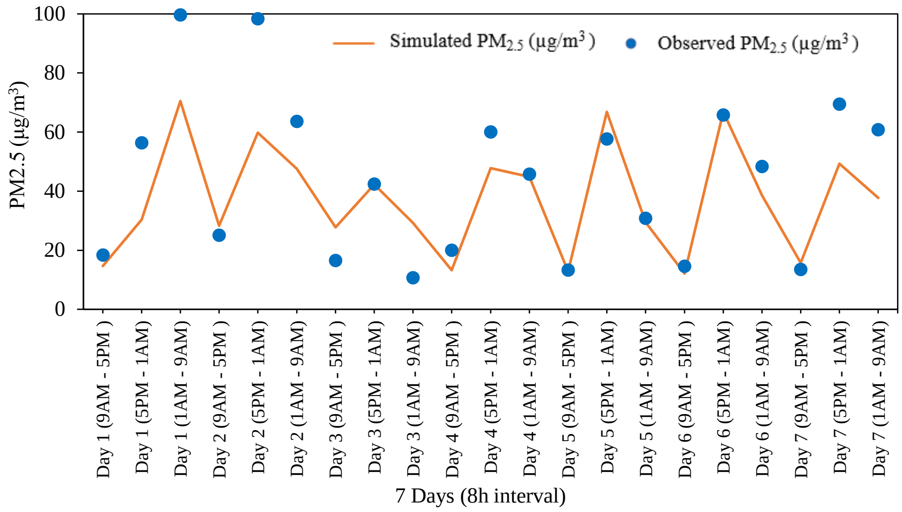
Figure 3. Range and daily average concentrations of $PM_{2.5}$ during the 7-day observation period at all receptor locations

A recent study conducted in seven townships of Yangon City, reported the highest $PM_{2.5}$ concentration observed in the morning (164±52 μg/m^3) followed by the second highest concentration in the evening (100±35 μg/m^3) and the lowest concentrations in the afternoon (31±15 μg/m^3) in the Hlaingtharyar Township (Yi et al., 2018). Another study conducted in Mingaladon, one of the most crowded townships of Yangon, observed the daily average $PM_{2.5}$ concentrations in residential and commercial areas to be 23.60±10.13 μg/m^3 and 33.40±10.64 μg/m^3, respectively. It was observed that 61% of the observed $PM_{2.5}$ concentrations exceeded the previous guideline (25 μg/m^3) of the WHO. Tun et al. (2017) concluded that $PM_{2.5}$ concentration reached its peak between 3:00 and 5:00 am, and after 9:00 pm at traffic congestion locations in Mingaladon Township, Yangon. In this study, 74% of the observed $PM_{2.5}$ concentrations exceeded the new WHO guideline (15 µg/m^3), while 60% of the observed results exceeded the old guideline (25 µg/m^3). Overall, the $PM_{2.5}$ concentrations in the present study were lower than those in other studies conducted in the Yangon area because the townships around the YORR were outside the city and the traffic congestion in downtown area of Yangon was acceptable.

The average of eight-hour interval concentrations of $PM_{2.5}$ at each of the five monitoring stations obtained during the seven monitoring days were compared with the simulated concentrations by the CALINE 4 model (Figure 4).

As shown in Figure 4, the highest eight-hourly average $PM_{2.5}$ concentration was 99.65 µg/m^3 at Point-1 (Hlegu Township). In general, the model slightly underpredicted $PM_{2.5}$. Most of the observed eight-hourly concentrations of $PM_{2.5}$ were close to the simulated results (difference of less than 10 µg/m^3), except at some points during a few monitoring periods. Differences increased with varying wind directions at the monitoring point. For example, wind directions on day-1 (5:00-1:00 am) at Point-1 was from several directions; therefore, the simulated results had a higher difference (26.03 µg/m^3).

(a) Observed and simulated concentration of $PM_{2.5}$ at Hlegu Township- (Point-1)



(b) Observed and simulated concentration of $PM_{2.5}$ at East Dagon Township- (Point- 2)

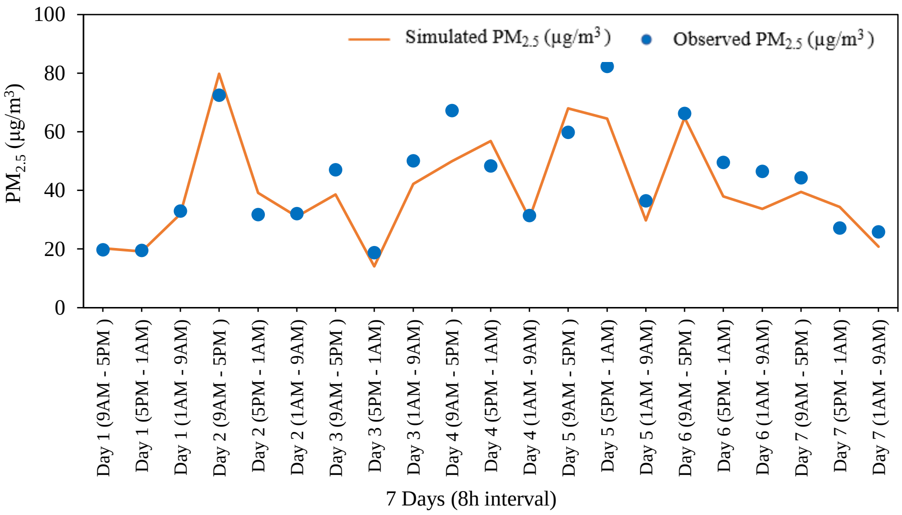
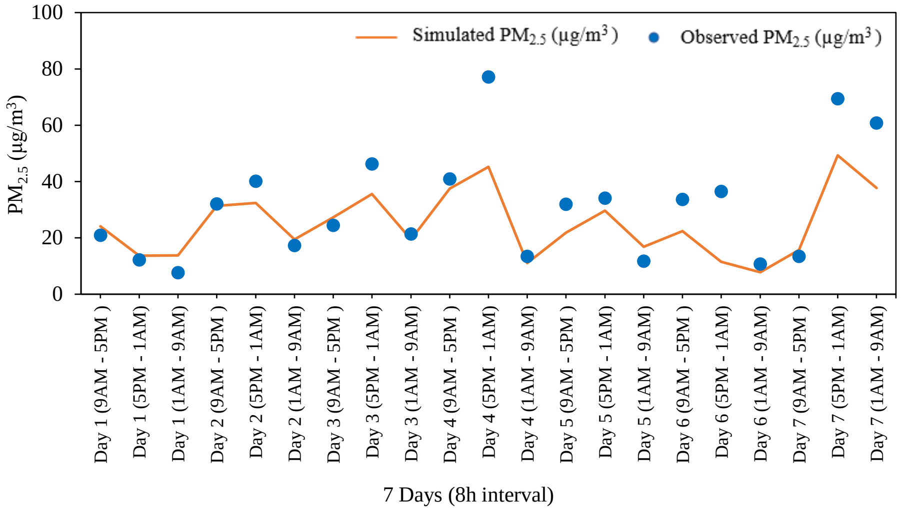
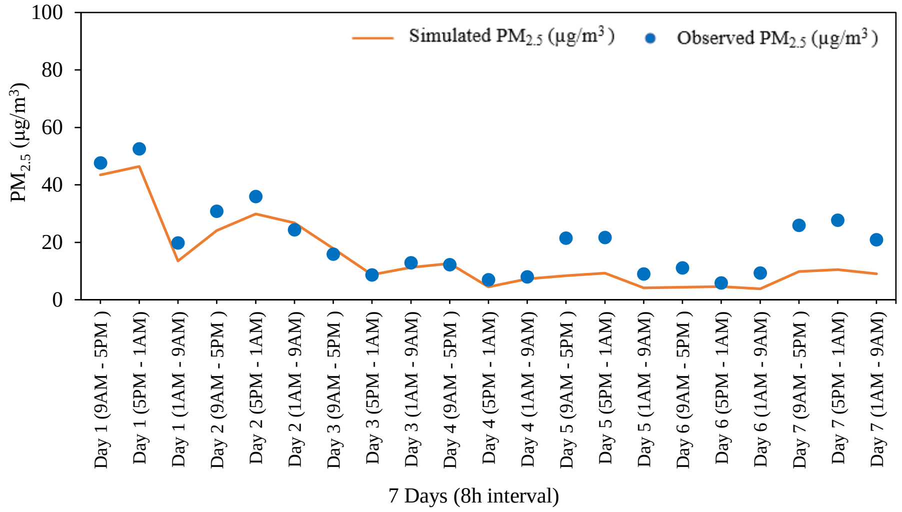


Figure 4. Observed and simulated $PM_{2.5}$ concentrations at five monitoring stations during the seven-day observation period

(c) Observed and simulated concentration of $PM_{2.5}$ at Dagon Seikkan Township- (Point-3)



(d) Observed and simulated concentration of $PM_{2.5}$ at Thanlyin Township- (Point-4)



(e) Observed and simulated concentration of $PM_{2.5}$ at Kyauktan Township- (Point-5)

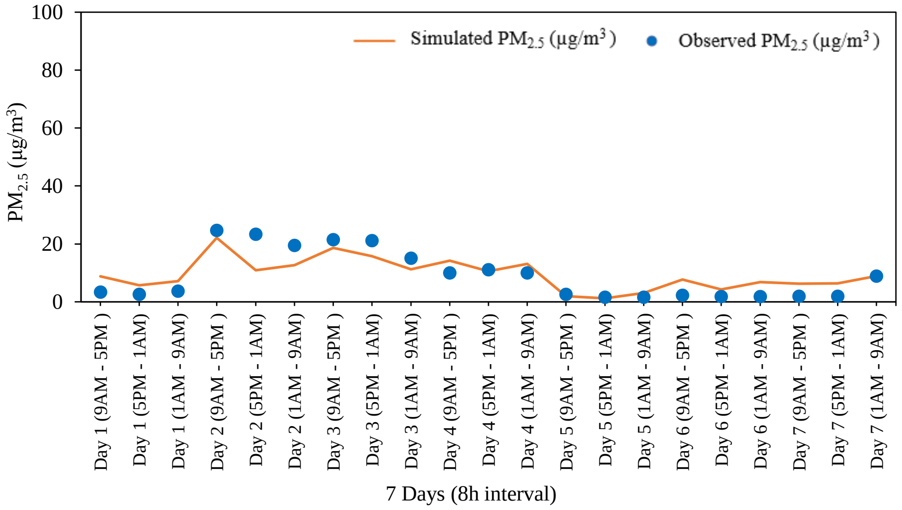


Figure 4. Observed and simulated $PM_{2.5}$ concentrations at five monitoring stations during the seven-day observation period (cont.)

3.3 Performance evaluation of the model

Scatter plots of the observed versus simulated concentrations during the monitoring period are presented in Figure 5.

Performance evaluation parameters, r^2, NMSE, and FB, which are based on the regression analysis of observed and simulated $PM_{2.5}$ concentrations, are shown in Table 4.

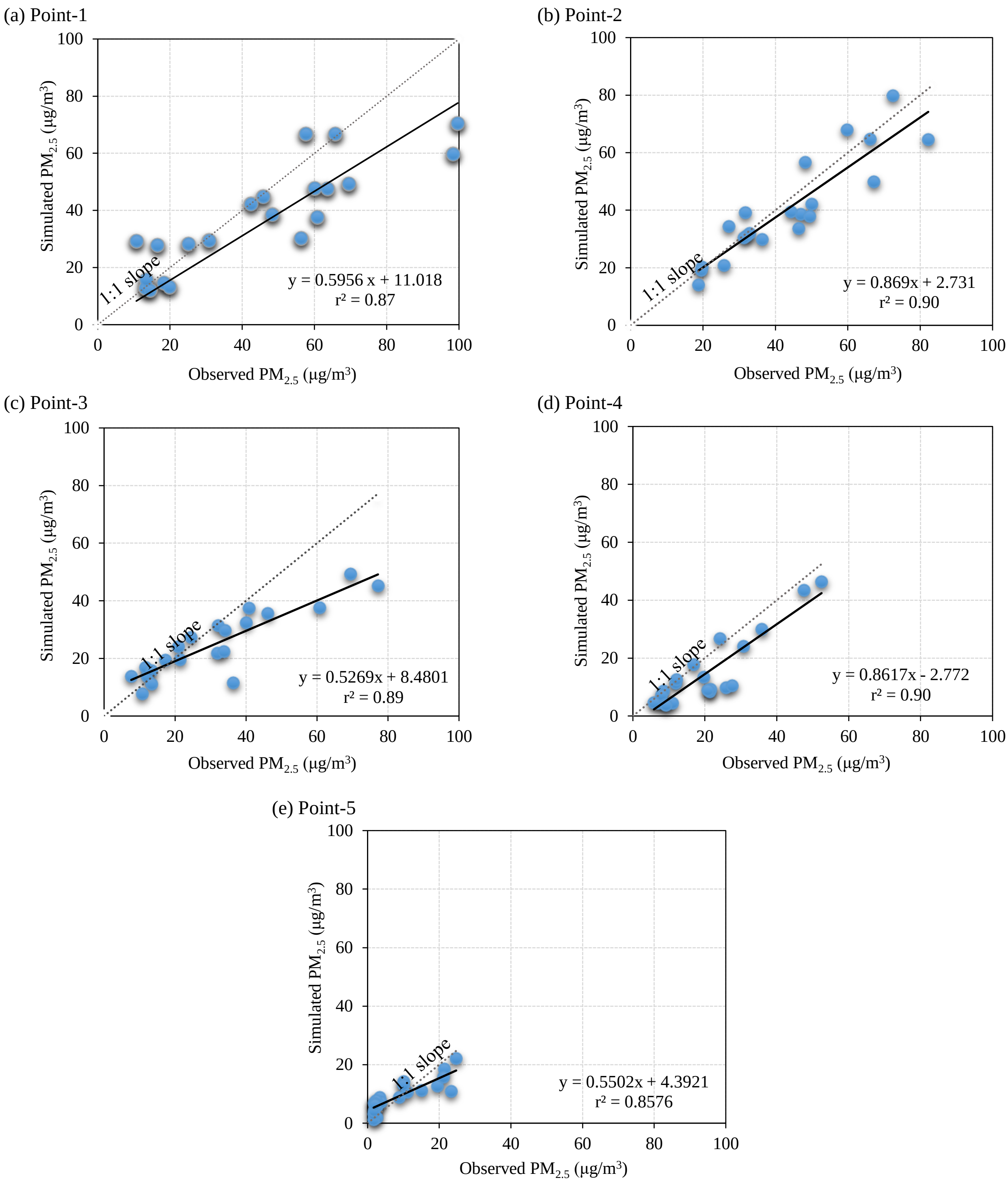


Figure 5. Model performance for 8 h mean concentration at five receptor locations during the seven-day observation period

Correlation between the observed and simulated $PM_{2.5}$ concentrations for all the receptor points was higher than 0.85, which was better than the result obtained by Yu et al. (2021) at 0.51. However, higher values of correlation between the observed and simulated $PM_{2.5}$ concentrations (0.95 and 0.89) with and without background concentrations have been reported in other studies (Chen et al., 2008; Chen et al., 2009). As shown in Table 4, the values of the correlation coefficient, FB, and NMSE were within the acceptance limits. Hence, the CALINE 4 model performed satisfactorily in simulating the $PM_{2.5}$.

Table 4. Model performance evaluation

	Model performance					Acceptance value
	Point-1	Point-2	Point-3	Point-4	Point-5	
Correlation (r^2)	0.8714	0.9020	0.8873	0.9007	0.8576	close to 1
Fractional bias (FB)	0.3760	0.0373	0.5000	0.0442	0.4367	$-0.5<FB<0.5$
Normalized mean square error (NMSE)	0.0287	0.0050	0.0510	0.1038	0.0010	$NMSE\leq 0.5$

The CALINE 4 model can be effectively used to estimate the concentrations of other air pollutants in the YORR (Eastern Section), such as $PM_{2.5}$ CO, and NO_2, and compare with pre-project conditions. This can aid in the vehicular pollution management of new road projects.

4. CONCLUSION

Based on the hourly $PM_{2.5}$ concentrations during the seven days at each monitoring station, the highest concentration observed at Point-1 was 176.76 $\mu g/m^3$. This could be due to dust erosion from nearby unpaved village roads. When compared with the ambient air quality guidelines of Myanmar, International Finance Corporation (IFC), and WHO, $PM_{2.5}$ concentrations were generally high at all locations, except at Point-4 and Point-5 on certain days.

The observed 8-hourly average $PM_{2.5}$ concentrations (for seven days) were compared with the simulated concentrations for all five receptor locations. The slopes of the regression lines between the observed (Y-axis) and simulated concentrations (X-axis) were less than the ideal 1:1 line. Therefore, model slightly underestimated $PM_{2.5}$. Based on statistical analysis, r^2, NMSE, and FB were well within the prescribed limits. Therefore, the performance of the CALINE 4 model was considered acceptable.

Mitigation measures, such as transportation policies regarding the use of low PM emission fuels and roadside barriers, need to be implemented by regulatory authorities.

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