Dispersion Modeling of SO_2 and NO_X from Transportation Sources Using Gaussian Model on Krikilan Highway, Driyorejo, Gresik

Wanda Anggraeni[1,*], Rachmanu Eko Handriyono[2]
[1,2] Environmental Engineering Department, Faculty of Civil Engineering and Planning
Institut Teknologi Adhi Tama Surabaya

Email: [1,*]wandaanggraeni812@gmail.com, [2]handriyono.rachmanu@gmail.com

DOI: https://doi.org/10.31284/j.jtm.2024.v5i2.5441
Received 29 April 2024; Received in revised 25 January 2024; Accepted 16 May 2024; Available online 31 July 2024

Abstract

The emissions from transportation sources contribute to 70% of air pollutants. The increase in the number of vehicles results in traffic density and the production of pollutants. This research was conducted on Krikilan Highway on Mondays and Sundays during peak morning and afternoon hours for one month. Direct measurements were taken at distances of 0 m and receptors at 200 m, 400 m, and 800 m. The objective of this study is to assess the ambient air quality status, determine the results of direct measurements, Gaussian modeling, and the dispersion of SO_2 and NO_x gases generated by vehicles on the road. The ambient air quality measurements on Krikilan Highway, Driyorejo Subdistrict, showed the highest concentrations for SO_2 at 34.03 $\mu g/m^3$ and NOx at 120.41 $\mu g/m^3$ on Sundays. The Gaussian model calculations on Krikilan Highway, Driyorejo Subdistrict, revealed the highest concentrations for SO_2 at 0.00000262 $\mu g/m^3$ and NO_x at 0.0000787 $\mu g/m^3$ at a receptor distance of 200 m on Mondays. The ambient air concentrations of SO_2 and NO_x on Krikilan Highway, Driyorejo, using Gaussian model calculations and measurements, complied with the standards set by Regulation No. 22 of 2021. The Index of Agreement (IOA) validation for SO_2 and NO_x concentrations yielded a value of 0.97.

Keywords: *Vehicle Emissions, Gaussian Model, NO_x, SO_2, IOA validation*

1. Introduction

The increase in the number of vehicles can lead to traffic congestion and result in exhaust emissions that contribute to air pollution [1]. The data obtained from the Central Statistics Agency of East Java Province indicates an annual increase in the number of vehicles in Gresik Regency. The number of vehicles reached 725,077 in 2018, increased to 779,277 in 2019, and reached 808,609 in 2020. This increase reflects the community's need for transportation, considering that transportation is a basic necessity [2]. More than 70% of vehicle emissions contribute to air pollution in Indonesia [3]. Motor vehicles contain harmful components that can pose risks to human health and the environment. Some harmful substances in vehicles include lead (Pb) reaching nearly 100%, suspended particulate matter (total particulate) reaching 13.44%, hydrocarbons ranging from 71 to 89%, NO_x ranging from 34 to 73%, and some carbon monoxide emissions released into the air. Sulfur dioxide (SO_2) is an air pollutant produced by the combustion of petroleum, coal, and other sulfate-producing processes. SO_2 has a pungent odor and is colorless [4]. Motor vehicles and industries are sources of nitrogen oxide emissions [5]. According to the National Ambient Air Quality Standards (NAAQS) issued by the EPA, motor vehicles are the largest contributors to NO_x gas emissions. This research aims to assess ambient concentrations, calculate concentration values, and determine the dispersion patterns of SO_2 and NO_x gases generated by vehicles on Krikilan Highway, Driyorejo District.

Sulfur dioxide (SO_2) is produced through the combustion processes of coal, petroleum, and other sulfate-containing processes [6]. Sulfur dioxide gas has a pungent odor, is colorless, and is non-flammable in the air; moreover, it can enter the human body through inhalation via the nose or mouth [7]. Almost 99% of SO_2 gas in the atmosphere originates from human and industrial activities, occurring when SO_2 gas and solutions undergo oxidation from combustion emissions and volcanic eruptions. Fuels and lubricants often contain sulfur, but the primary source of SO_2 gas is the combustion of fuels with sulfur content. The presence of SO_2 gas can lead to the occurrence of acid rain with a tendency toward low acidity, indicated by pH values below 7. The main cause of this phenomenon is a 15% increase in the level of SO_2, primarily originating from motor vehicle and industrial emissions [8].

Nitrogen is the predominant gas in the Earth's atmosphere, constituting 80% of the total atmospheric air volume [9]. If its concentration exceeds a certain limit, it can be harmful. The increase in nitrogen content in the air occurs very rapidly. This is due to fossil fuels, waste, and industrial emissions on Earth. Sunlight can influence the concentration of NO_x in the air. The quantity and rate of NO_x formation from nitrogen compounds depend on their bonds. Heterocyclic compounds such as pyridine, piperidine, quinoline can be found in oils, cyclic chains, and open chains, nitrogen compounds that produce NO gas.

2. Methods

Gaussian Model

The Gaussian dispersion equation is used to determine the spread of pollution [10], [11].

1. Emission loads
   Calculation of the emission loads at the observation point is necessary to determine the concentration of emitted gases from the transportation source. The formula for calculating the emission loads is as follows:
   $$Q = n \times EF \times smp \quad (1)$$
   Where Q is the emission rate (mass/distance.time); n is the number of vehicles; EF is the emission factor (mass/unit, unit = vehicles/mile); and smp is the passenger car equivalent unit. To convert vehicle types to passenger car units, the conversion from MKJI (1997) is used, where a light vehicle is equivalent to a passenger car with a value of 1; heavy vehicles are equivalent to 1.3; and motorcycles are equivalent to 0.4.
2. Meteorological Factors
   $$\sigma z = cx^d + f \quad (2)$$
   $$\sigma y = ax^{0,894} \quad (3)$$
   σz = pollutant dispersion coefficient in the z-direction (m); σy = pollutant dispersion coefficient in the y-direction (m); x = distance from the emission point (m); c, d, f = constant values for vertical dispersion coefficients.
3. Prediction of Pollutant Concentrations
   Road transportation emissions use a line source pattern [12]. The air dispersion model for a line source is used to calculate pollutant concentrations resulting from traffic density. This approach involves measuring emissions from the source and calculating their dispersion based on the distance from the road where the emission source is located. The pollutant dispersion model for a line source utilizes the following formula:
   $$C = \frac{Q.\,X}{2\pi\, u\, \sigma y\, \sigma z} \exp exp \left(\frac{-y^2}{2\,\sigma y^2}\right) \exp exp \left(\frac{-H^2}{2\,\sigma z^2}\right)$$

(4)

Model Validation

Performance presentation of the model, verification, calibration, and development can be aided by model validation. The use of the Index of Agreement (IOA) is employed to assess the extent to which the model aligns with field measurement results. IOA interprets better than modeling results, providing meaningful magnitudes and values [13], [14]. Moreover, IOA is sensitive to differences between observed and predicted concentrations. The IOA equation can be utilized for calculating data validation, and its formula is as follows: [15].

$$d = 1 - \frac{(Cpred - Cobs)^2}{((Cpred - Cobs) + (C\,obs - Cobs))^2} \quad (5)$$

where C_pred is the calculated concentration; C_obs is the measured concentration; C_pred_bar is the average calculated concentration; C_obs_bar is the average measured concentration. Index Of Agreement (IOA) validation is divided into four categories: very good ($d = 1$); good ($0.8 \leq d < 1$); fair ($0.7 \leq d < 0.8$); and poor ($d < 0.7$).

This study was conducted on Krikilan Highway, Driyorejo District, and the selection of the study location was based on the number of vehicles passing through the Krikilan Highway area. In this study, the saturation degree indicating the number of vehicles also served as an indicator in determining the study location. The preliminary test results on Krikilan Highway indicated a saturation degree of 1.38, falling into the category of service level F, meaning that traffic flow is impeded, and the speed is low [16]. The saturation degree is defined as the total number of vehicles (per hour) divided by the road capacity. If the saturation degree exceeds 0.8, the road is considered to be in poor condition due to experiencing congestion.

Table 1. Location Coordinates

No	Location	Coordinates
1	Krikilan Highway (counting location/distance 0 m)	7° 22' 58.00" S - 112° 34' 41.74" E
2	Receptor at a distance of 200 m	7° 23' 2.90" S - 112° 34' 46.54" E
3	Receptor at a distance of 400 m	7° 23' 4.75" S - 112° 34' 52.91" E
4	Receptor at a distance of 800 m	7° 23' 16.73" S - 112° 34' 59.89" E
5	Receptor at a distance of 200 m	7° 22' 58.00" S - 112° 34' 41.74" E

(Source : Google Earth)

The main data consists of air quality measurements on Krikilan Highway at specific points, namely at distances of 0 m, 200 m, 400 m, and 800 m. Additionally, calculations were conducted for the volume of vehicles passing through Krikilan Highway at the initial point of 0 m, using a Traffic Counter. Vehicle volume measurements were conducted for one month on Mondays and Sundays, both in the morning from 06:00 to 09:00 AM and in the afternoon from 04:00 to 07:00 PM. The selection of these days was based on the goal of observing the difference in SO_2 and NO_x concentrations between weekdays. Coordinates for each measurement point have also been established.

3. Results and Discussions

SO_2 and NO_x Emission Loads

The Krikilan area is essentially an industrial zone, which can lead to traffic congestion. The observation of the number of vehicles on Krikilan Highway is conducted by recording using a mobile phone in both directions, as the highway is a two-way road. After observing the traffic volume on Krikilan Highway, calculations will be performed using the Traffic Counter application to determine the number of motorcycles, cars, trucks, buses, public minivans, and pickups passing through the road.

Table 2. The Average Vehicle Volume Over One Month

Day	Motorcycles	Cars	Trucks	Buses	Pickups	Public Minivans

Monday morning	5489	191	220	3	58	20
Monday evening	3104	252	194	2	69	7
Sunday morning	2230	199	68	2	33	11
Sunday evening	1866	343	46	1	37	4

(Source : Calculation, 2023)

Table 2 shows the average vehicle volume passing through the road over one month. The average calculation is done by taking the values for each week, both on Monday mornings and evenings, as well as on Sunday mornings and evenings. During this one-month period, the majority of vehicles passing through are motorcycles.

Table 3. The Average Vehicle Emissions of SO_2 and NOx Over One Month

Day	Motorcycles	Cars	Trucks	Buses	Pickups	Public minivans
			SO_2 emissions (µg/m.s)			
Monday morning	4.88	5.82	65.02	1.09	2.11	0.16
Monday evening	2.76	7.70	57.49	0.81	2.48	0.06
Sunday morning	1.98	6.07	20.01	0.62	1.19	0.09
Sunday evening	1.66	10.47	13.74	0.39	1.35	0.03
			NO_x emissions (µg/m.s)			
Monday morning	176.86	121.76	1403.50	13.97	32.45	11.72
Monday evening	100.03	161.00	1241.05	10.38	38.15	4.03
Sunday morning	71.87	126.82	431.97	7.88	18.33	6.66
Sunday evening	60.12	218.82	296.68	5.01	20.69	2.19

(Source : Calculation, 2023)

Analysis of SO_2 and NO_x Concentrations Using Gaussian Model

Meteorological factors influence the dispersion process of pollutants in the atmosphere. When wind speed increases, pollutant concentrations decrease. This effect is due to the significant impact of wind speed on pollutant dispersion [17], [18]. As a result, pollutant concentrations decrease from the source to the receptor. Wind influences the dispersion of air pollutants; high wind speeds result in smaller pollutant dispersion, and vice versa. This is substantiated by the calculations of the Gaussian Model and direct measurements that overlay with windrose analysis, proving that when wind speed increases, pollutant concentrations decrease.

Table 4. Results of SO_2 and NO_x Concentration Calculations

Day	Receptor Distance (m)	Modeling results SO_2 (µg/m^3)*	Modeling results NO_x (µg/m^3)*	Direct measurements SO_2 (µg/m^3)**	Direct measurements (µg/m^3)**	Baku Mutu SO_2 (µg/m^3) ***	Baku Mutu NO_x (µg/m^3) ***
Monday	0	0	0	23.56	86.54	150	200
	200	0.000002624	0.000078780	20.94	79.02		
	400	0.000000300	0.000008996	10.47	73.37		
	800	0.000000103	0.000003093	2.62	71.49		

Day	Receptor Distance (m)	Modeling results SO_2 (µg/m^3)*	Modeling results NO_x (µg/m^3)*	Direct measurements SO_2 (µg/m^3)**	Direct measurements (µg/m^3)**	Baku Mutu SO_2 (µg/m^3) ***	NO_x (µg/m^3) ***
Sunday	0	0	0	34.03	120.41		
	200	0.000000296	0.000006511	31.41	86.54		
	400	0.000000280	0.000006153	31.41	94.07		
	800	0.000000152	0.000003338	26.18	90.31		

(Source : *Calculations 2023, *Laboratory ITS Test Results, ***Quality Standards of the Government Regulation of the Republic of Indonesia No. 22 Year 2021)

The Gauss calculation values are smaller compared to direct measurements because in Gauss measurements, the emission factor is considered only motorized vehicles, whereas direct measurements yield higher emission values due to influences from pollutant sources and the research location. The modeling results using the Gauss model and the direct measurements both comply with the quality standards set by the Government Regulation of the Republic of Indonesia No. 22 Year 2021. The values from both modeling and direct measurements are well below the standard limits. Previous research has indicated that direct observation concentrations tend to be higher than Gauss modeling concentrations, attributed to differences in pollutant source activities, monitoring locations, and environmental conditions [19].

(a) Direct Measurement of SO_2 on Monday

(b) Direct Measurement of SO_2 on Sunday

(c) Direct Measurement of NO_x on Monday

(d) Direct Measurement of NO_x on Sunday

Figure 1. Results of overlay measurement of SO_2 and NO_x

Validation of SO_2 and NO_x Modeling Results

This research employs the validation method of the Index of Agreement (IOA) to assess the accuracy of SO_2 and NO_x modeling. IOA is a standard for measuring the level of model prediction error, with values ranging from 0 to 1.

Table 5. Validation results IOA

Day	Receptor Distance (m)	Modeling results SO_2 (μg/m³)*	Modeling results NO_x (μg/m³)*	Direct measurements SO_2 (μg/m³)**	Direct measurements (μg/m³)**	Validation results SO_2	Validation results NO_x
Monday	0	0	0	23.56	86.54		
	200	0.000002624	0.000078780	20.94	79.02		
	400	0.000000300	0.000008996	10.47	73.37		
	800	0.000000103	0.000003093	2.62	71.49		
Sunday	0	0	0	34.03	120.41		
	200	0.000000296	0.000006511	31.41	86.54	0.97	0.97
	400	0.000000280	0.000006153	31.41	94.07		
	800	0.000000152	0.000003338	26.18	90.31		
Total		**0.000003754**	**0.000106870**	**180.61**	**701.76**		
Average		**0.000000469**	**0.000013359**	**22.58**	**87.72**		

(Source: Calculations, 2023)

Previous research indicates that validation using primary data is essential to obtain IOA values approaching conformity [11]. The validation results for SO_2 and NO_x concentrations show a value of 0.97, confirming that the IOA model validity used in this study approaches the perfect value of 1. This result indicates that the model is highly suitable for use. In a similar study using IOA validation, the results show that a validation value of d = 0.8 indicates high confidence in the model, with data obtained from calculations and existing data [20].

4. Conclusions

The research yields the following conclusions:

1. Ambient concentration measurements on Krikilan Highway, Driyorejo District, resulted in the highest values for SO_2 at 34.03 μg/m³ and NO_x at 120.41 μg/m³ on Sundays.
2. The results of the Gauss model calculations on Krikilan Highway, Driyorejo District, yielded the highest concentrations of SO_2 at 0.000002624 μg/m³ and NO_x at 0.000078780 μg/m³ at a receptor distance of 200 meters on Mondays.
3. The model validation for SO_2 and NO_x concentrations resulted in a value of 0.97, indicating that the IOA model validity is close to 1, making it suitable for use.

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How to cite this article:
Wanda Anggraeni, Rachmanu Eko Handriyono. Decision Support to Improve Railway Track Maintenance in Indonesia: *Dispersion Modeling of SO2 and NOX from Transportation Sources Using Gaussian Model on Krikilan Highway, Driyorejo, Gresik* Jurnal Teknologi dan Manajemen. 2024 July; 5(2):151-156. DOI: 10.31284/j.jtm.2024.v5i2.5441