Regional Case Study

Emission Inventory Estimation and Dispersion Model Study using AERMOD And CALINE4 From Transportation On Road

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Abstract :

Urban air pollution has escalated due to increased vehicular traffic, necessitating accurate emission inventories and dispersion models. This study estimates emission loads and models pollutant dispersion using AERMOD and CALINE4, focusing on Semarang City's transportation sector. Emission inventories were derived using the Tier 2 method, considering various vehicle categories and kilometers traveled. AERMOD and CALINE4 were employed to simulate the dispersion of NOx, SO_2, PM_{10}, HC, and CO. Emission data from January to December 2017 were collected, focusing on different vehicle types and road categories. AERMOD and CALINE4 models were utilized to predict pollutant concentrations, incorporating meteorological data and vehicle emission factors. The analysis revealed that motorcycles were the largest contributors to emissions, producing significant amounts of CO and HC. AERMOD results indicated high pollutant concentrations in Central Semarang, while CALINE4 estimated notable CO levels on Perintis Kemerdekaan Road. Both models showed variability due to atmospheric conditions, with wind speed and direction significantly affecting pollutant dispersion.The study underscores the critical role of emission inventories in air quality management, highlighting the need for targeted interventions to mitigate pollution from road transportation. Accurate modeling aids policymakers in developing effective strategies to improve urban air quality and public health.

Keywords: Emission Inventory; AERMOD; CALINE4; transportation; dispersion Model

1. Introduction

The rapid growth of urban populations and the corresponding increase in vehicular traffic have exacerbated the air pollution problem. Emissions from road transportation are among the primary contributions to ambient air pollution in many cities worldwide (Eggleston and Buendia 2006). These emissions include exhaust gases from internal combustion engines, tire and brake wear particles, and road dust resuspension which is a mixture of hundreds of gases and aerosols. Pollutants emitted by motorized vehicles include carbon monoxide (CO), nitrogen oxide (NOx), hydrocarbons (HC), sulphur dioxide (SO_2), lead (Pb), and carbon dioxide (CO_2). According to the US Environmental Protection Agency (EPA), each gallon of gasoline will produce carbon emissions of 8.8 kg/CO_2/gallon or the equivalent of 2.3 kg CO_2/liter. If in one big city there are 8 million motorbikes, and if each one consumes 1 litter of petrol/day, it will produce carbon emissions of 18.4 thousand tons of CO_2/day just from motorbikes alone (Kleinberg 2021). The pollutants released have both local and regional effects, influencing air quality and posing health risks to the urban population. Numerous studies have demonstrated that both short-term and long-term exposure to fine particulate matter in the atmosphere, such as nitrogen oxides (Nox) and sulphur dioxide (SO_2), are significantly linked to higher rates of mortality and illness (Gibson, Kundu et al. 2013). Exposure to air pollutants, especially fine particulate matter (PM2.5), is strongly associated with respiratory and cardiovascular diseases. PM2.5 can penetrate deep into the lungs and enter the bloodstream, causing inflammation and exacerbating conditions such as asthma, bronchitis, and chronic obstructive pulmonary disease (COPD) (Pope & Dockery, 2006). Long-term exposure increases the risk of heart attacks, strokes, and hypertension (Brook, Rajagopalan et al. 2010).

Based on government regulation number 41 of 1999 and also the commitment of the Indonesian government at the G20 meeting to reduce the level of greenhouse gas emissions, it is necessary to carry out inventory activities of sources of air pollution or what is called an emissions inventory. Creating accurate emission inventories is a critical step in air quality management. An emission inventory quantifies the number of pollutants release into the atmosphere from various sources over a specified period. For road transportation, this involves calculating emissions based on vehicle types, fuel usage, driving conditions, and other factors. Emission inventories provide the data needed for air quality modelling and regulatory assessments. On top of that, accurate emission inventories are essential for air quality modelling. Emission inventories help identify major sources of pollution, enabling targeted interventions. For example, inventories can pinpoint high-emission industries or traffic hotspot, guiding effort to reduce emission from these sources (Benson 1988). In addition to estimating the quantity of air pollutants produced, predicting their distribution is also crucial. Analysing pollutant distribution models is one of the most important aspects of air quality analysis. This analysis establishes a correlation between the released emissions, the distribution of pollutant concentrations, and the affected areas. The American Meteorological Society and the U.S. Environmental Protection Agency Regulatory Model (AERMOD) are commonly used models for predicting how pollutants disperse. AERMOD focuses on short-range air pollution dispersion from different sources such as point, line area, and volume sources using a steady-state Gaussian plume dispersion model (Perry et al., 2005). The California Line Source Dispersion Model (CALINE) is a tool for evaluating the impact of vehicle emissions and is specifically made to predict roadside pollution and meteorological conditions (Yura, Kear et al. 2007). The CALINE algorithms for dispersion and transport were first developed using a revised version of a Gaussian point source plume model(Benson 1992). Models such as AERMOD and CALINE4 depend on emission inventory data to simulate pollution scenarios and evaluate the impact of emissions on air quality (Seinfeld and Pandis 2016). Furthermore, by providing detailed information on pollutant sources and levels, emission inventories aid in health risk assessments and the development of strategies to safeguard public health. Understanding the sources of pollutants assists in formulating measures to reduce exposure and mitigate health impacts (Zhu et al., 2012).

Some comparative studies have evaluated the performance of AERMOD and CALINE in pollutant dispersion modelling. Benson (1979) conducted a foundational study using CALINE4 to predict CO concentrations near roadways. The study validated the model's performance with observed data, demonstrating its accuracy in estimating near-road pollutant concentrations. Subsequent research has further refined CALINE4's application, integrating more detailed traffic data and enhancing its predictive capabilities. Additionally, a study by Zhu et al. (2012) compared the predictions of AERMOD and CALINE4 with observed air quality data in a major Chinese city. The study found that both models provided reasonable estimates of Nox and PM concentrations, with AERMOD showing slightly better performance in complex urban terrains.

In this paper, an experiment was carried out to calculate the air pollutant emission load and the distribution of air pollutant gas emissions and greenhouse gases from the road transportation sector including Nox, SO2, HC, CO, dan PM10. This study aims to provide a comprehensive understanding of the impact of road transportation emissions on air quality the result will highlight areas with high pollutant concentrations and potential health risk, informing policymakers and regulatory agencies in developing targeted air quality management strategies

2. Data and Methods

2.1. Study Area

The research conducted in Semarang city, covered transportation sector of the research area in several roads, including Tembalang toll road, perintis kemerdekaan road, setiabudi road, and East Ngesrep road yang merupakan kategori jalan yang berbeda, including highway primary arterial road, secondary arterial road, and collector road. Table (1) summarizing the selected roads and their classifications has been incorporated to support the research and provide a structured overview of the study area. Furthermore, Figure (1) represent of the study area is presented to visually depict the location and distribution of the selected roads. The table and map emphasize the diversity of road types and their strategic roles within the transportation network, providing a comprehensive basis for the analysis conducted in this study.

Figure 1. Selected Road Sections in Semarang through Google Earth Pro

Table 1. Selected road sections in Semarang

No	Name	Category
1	Tembalang Toll Road	Highway
2	Perintis Kemerdekaan Road	Primary Arterial Road
3	Setiabudi Road	Secondary Arterial Road
4	East Ngesrep V Road	Collector road

2.2. Emission Inventory Estimation

The sources of pollution inventoried are mobile sources originating from transportation. The emissions inventoried in this experiment are NOx, SO2, PM10, HC, and CO2. To calculate emissions from transportation, the tier 2 method is used, namely using emission factors based on vehicle kilometers traveled (VKT). The data used for the inventory refers to pollutants produced by on-road transportation in the city of Semarang on January 1 2017-December 31 2017. The types of vehicles included in this research are divided into trucks, buses, motorbikes, cars, gasoline-based car, and diesel-based car. The fraction between passenger cars fueled by petrol and diesel based on previous research conducted is 97% and 3% (Buanawati, Huboyo et al. 2017). The emission inventory estimation is presented in Table 2

Table 2. VKT average odometer readings per vehicle type

Category	Unit	Average VKT (km/year)
Bus	3,271	43,435
Truck	78,448	10,115
Gasoline based car	219,291	15,330
Solar based car	6,782	15,330
Motorcycle	1,252,196	14,600

2.3. AERMOD

AERMOD is a reliable steady-state plume model utilized to showcase adherence to environmental regulatory programs. It utilizes meteorological data (e.gg., wind speed, wind direction, temperature, and atmospheric stability. This model is highly versatile and can be applied to diverse source types such as point, area, and volume sources, in both stable and convective atmospheric states. The model employs Monin-obhukov similarity theory to scale the winds and turbulence vertically (Cimorelli et al., 2005). The model used in this research is the ISCST3 model. . The advantage of AERMOD over other software is its ability to predict ground level concentration (GLC) due to the influence of PBL (Natsir, Pambarep et al. 2017).

2.4. CALINE4

CALINE4 model represents a line source by using a series of finite-length elements, each positioned perpendicular to the wind. In order to enhance computational efficiency, the length of each element is determined based on its distance from the receptor of interest (Heist, Isakov et al. 2013). This particular model is utilized for predicting air pollution levels within 500m of roadways and was created by the California Department of Transportation. This model is effective in estimating the concentration of pollutant near highway and urban street, providing valuable insight into the impact of traffic emission on air quality. The model accounts for various atmospheric conditions and employs a gaussian plume approach to predict pollutant concentrations at receptor locations. The CALINE4 model in this experiment was used to estimate the distribution of carbon monoxide (CO) pollutants with the data used being wind direction and standard deviation of wind direction, temperature and wind speed, mixing height, and atmospheric stability.

2.5. Dispersion Modelling

Modeling air quality is important for determining how pollutants are distributed in different areas (Popoola, Jimoda et al. 2023). AERMOD was used to calculate the levels of each identified pollutant at ground level and to forecast how air quality would change within a 15-kilometer radius from the source of the pollutants. Several techniques are used to simulate the distribution of pollutants. The Gaussian model is considered the most appropriate for systematically describing the three-dimensional pattern of emission distribution. The distribution pattern of pollutants on a flat plane across the wind direction (crosswind) and vertically will follow a normal (Gauss) distribution. As we move away from the center of the burst, the concentration of pollutants will decrease, and the plume shape will be wider in the vertical direction and in the direction of the crosswind. Creating a dispersion model starts from creating a windrose, importing a base map, setting up a pathway, running ISCST3, and reading the results

2.6. Source Pathway

The source pathway is a crucial aspect of pollution modeling. It identifies information on the number of emission sources and pollutants specified (Popoola, Jimoda et al. 2023). Source pathways are created using polygon icon for each sub-district and complete with base elevation, release height, and emission rate data in g/s.

2.7. Receptor Pathway

In this experiment, the receptor pathway is used to determine the impact of air quality, including pollutant distribution area and emission source in certain areas (Popoola, Jimoda et al. 2023). The receptor used is the Uniform Cartesian Grid (UCART1) type by clicking on the Uniform Cartesian Grid icon and dragging it to the edge of the map until the window is automatically filled.

2.8. Meteorology Pathaway

The condition of the atmosphere in a specific area to be modeled was established to factor in the distribution of air pollution impacts (Popoola, Jimoda et al. 2023). The data for this experiment were obtained from the Meteorological, Climatological, and Geophysical Agency with a reference anemometer height of 10 m and processed using Microsoft Excel.

2.9. Data Validation

The data validation process is carried out to analyze the working system and see the level of accuracy of the AERMOD software. The simulation of pollutant dispersion results then compared with the data from measurements of ambient air pollutant concentration on the highway. The measurement data used in simulation validation is the CO value because it is the easiest to measure. This equation is used to calculate the percentage of error produced in the simulation validation. The data validation process is carried out to analyze the working system and see the level of accuracy of the AERMOD software. Then compare the simulation results of pollutant dispersion with data from measurements of ambient air pollutant concentrations on the highway. The measurement data used in simulation validation is the CO value because it is the easiest to measure. The following equation (1) is used to find out what percentage of error is produced

$$\%\, error = \frac{C.ambient - C.model}{C\ ambient} \times 100\% \qquad (1)$$

C ambient : ambient air concentration
C model : modelled air concentration

3. Result and Discussion

3.1. Emission Calculation

The transportation sector emissions calculation is calculated based on the distance traveled by each vehicle or Vehicle Kilometers Traveled (VKT). The calculation of total source emissions is obtained from multiplying the number of vehicles and the average kilometers traveled per year for each vehicle category and then multiplying by the emission factor. The emission load value can be seen in the figure. It can be seen that the main contribution to air pollutant and greenhouse gas emissions is motorbikes. This is caused by the number of motorbikes amounting to 1,252,196 or 80% of the total number of motorized vehicles in Semarang. On the other hand, diesel-based cars are the smallest contributor to emissions because they are the smallest among the other categories. Gasoline vehicles rank second in terms of emissions, totaling 219,291 units. Trucks come in third, contributing 78,448 units to emissions. In terms of geographical area, Pedurungan District is the largest emitter in the transportation sector, while Tugu District is the smallest, largely due to differences in population density.

Table 3. Total Emission Burden Based on Vehicle Type in Semarang City, 2017

Category	Unit	Emission load (tons/year)				
		CO	HC	NOx	PM10	SO2
Bus	3.271	1,563	183	1,691	199	132
Truck	78.448	6.665	1,428	14,045	1,111	651

Gasoline based car	219.291	134.469	13,447	6,723	34	87
Diesel based car	6.782	291	21	364	55	46
Motorcycle	1.252.196	255.948,86	107.864,16	5.301,80	4.387,69	146,26
Total		398.937,35	122.944,87	28.124,83	5.786,23	1.062,21

3.1.1. NOx

NO is non-irritating and harmless, but at normal ambient air concentrations NO can oxidize to the more toxic NO_2 (Jawwad and Mahendra 2023). The dominant source of NOx emissions was derived primarily from trucks, accounting for 14,045 tonnes/year or 50.02% of all emissions in the transportation sector. This was followed by gasoline-fueled cars at 23.91% and motorcycles at 18.85% of the entire presentation emissions, the source of the total NOx emission load can be seen in figure (2)

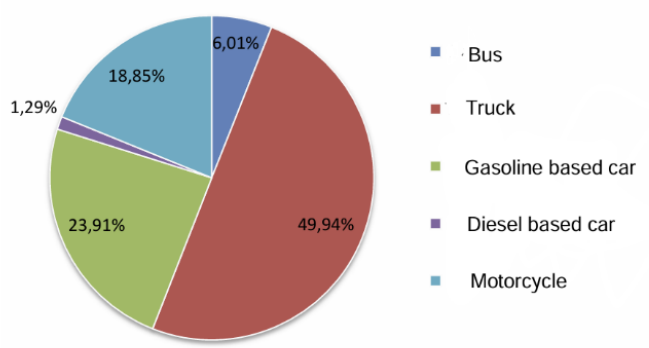

Figure 2. NOx emission load from transportation sector in Semarang 2017

3.1.2. SO2

Exposure to SO_2 gas has harmful effects on respiratory health even at low exposure concentrations. Long-term exposure to SO_2 in ambient air can significantly increase the risk of developing type 2 diabetes in Asians aged 30-50 years (Jawwad and Mahendra 2023). SO_2 pollution produced from transportation reached 1,062.21 tons/year with trucks as the main contributor producing 651 tons/year or 61% of the total SO_2 emissions produced. Furthermore, motorcycles are in second place with 13.76% and buses contribute 12.43% of total emissions. Diesel based cars are the smallest contributor with a total of 4.33% of total emissions. According to (Hodijah, Amin et al. 2014) the sulfur content in diesel (0.2156%) is greater than premium (0.015%). And the specific gravity of diesel fuel (838 g/l) is greater than premium (735 g/l), this condition influences the emission factor value. Therefore, the emission factor for diesel fuel vehicles is greater than for gasoline-based car for SO_2 pollutants. This causes diesel trucks to become the main contributors to SO_2 production. For the contribution SO_2 can be seen in figure (3)

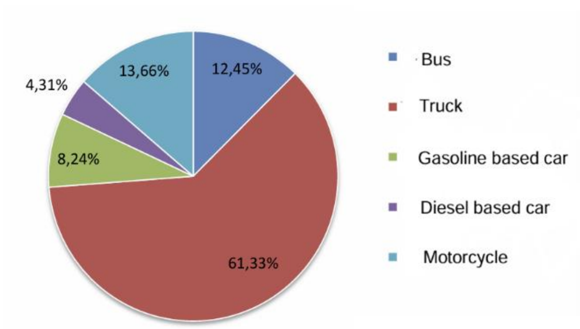

Figure 3. SO2 emission load from transportation sector in Semarang 2017

3.1.3. HC

Estimated HC emissions reach 12,997 tonnes/year with motorbikes as the main contributor of 106,918 tonnes/year or 88% of all hydrocarbon emissions from the transportation sector. This is because the population of motor vehicle types is much larger than other types of vehicles, reaching 1,241,197 units in 2017. More HC emissions are produced from vehicles that burn gasoline. This is in line with Purwanto's statement (2015), that gasoline is a hydrocarbon compound (HC), so any HC found in vehicle exhaust gas indicates the presence of unburned gasoline and is wasted with the combustion residue. The contribution of HC to emission of air can be seen in figure (4)

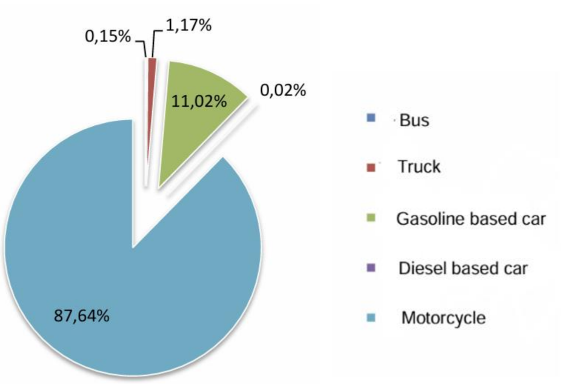

Figure 4. HC emission load from transportation sector in Semarang 2017

3.1.4. PM10

The value of PM10 emissions produced from the transportation sector reached 5,747.68 tonnes/year with motorbikes as the main producer then trucks with percentages of 76% and 19% respectively. Diesel engine combustion produces the most particulates because diesel fuel contains a lot of residues with high C levels. The emission load is impacted by both emission factors and the distance travelled by each vehicle (VKT) as well as the quantity of vehicles. Semarang has the highest VKT for motorcycles, which is 18,121,476,200 km/year. This is what causes more PM10 emissions in Semarang City to be produced from motor vehicles. PM 10 is known to increase death rates from heart and respiratory diseases (Gunawan, Ruslinda et al. 2018).

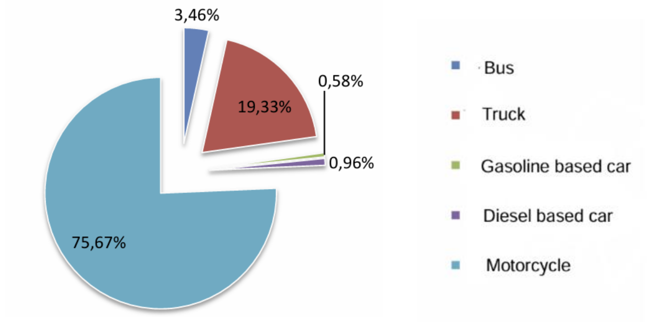

Figure 5. PM10 emission load from transportation sector in Semarang 2017

3.1.5. CO

The estimated CO emissions from the transportation sector reached 396,689.16 tons/year, where motor vehicles were the main contributor, namely 253,700.67 tons/year, followed by gasoline-fuelled passenger cars with a contribution reaching 134,469.12 tons/year. Diesel based cars are the smallest contributor to CO emissions with a total of 0.07% of the total percentage. High CO emissions are influenced by traffic density. The correlation between the number of vehicles and CO concentration (R = 0.701) indicates a linear relationship between an increase in the number of vehicles and an increase in CO concentration at the study site (Natsir, Pambarep et al. 2017). According to (Zhai, Frey et al. 2006), it is known that CO emissions increase as speed decreases. An increase in the amount of CO beyond 10 ppm can result in the concentration of carboxyhemoglobin (COHb) in the blood reaching 2% which will cause asymptomatic, which is a disease where the patient does not realize any symptoms (Natsir, Pambarep et al. 2017). Load is not only influenced by emission factors, but also the length of travel for each vehicle (VKT) and the number of vehicles. In Semarang, the largest VKT value is for motorcycles which reaches 18,121,476,200 km/year. This is what causes more PM10 emissions in Semarang City to be produced from motor vehicles.

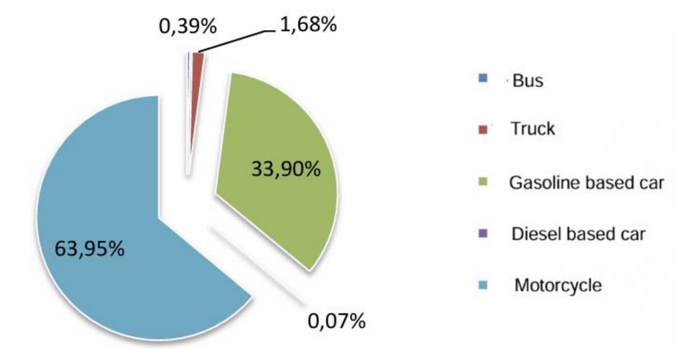

Fig 6. CO emission load from transportation sector in Semarang 2017

3.2. CALINE4 Dispersion Modelling Result

Based on the distribution results, it was found that the highest concentration of CO on East Ngesrep V Road was 11.3 ppm, on Perintis Kemerdekaan Road it was 15.1 ppm, on Setiabudi Road it was 11.6 ppm, and on the Tembalang Toll Road it was 8.2 ppm. The estimates were then compared with the results of direct measurements conducted on these four roads. The highest estimated CO concentration was found to be on Perintis Kemerdekaan at 5,700 µg/Nm3. Meanwhile, based on measurement results, the CO concentration on Jalan Perintis Independen is 4,560 µg/Nm3. Differences in concentration between estimates and measurements can be caused by atmospheric conditions. Estimated conditions that are greater than roadside measurements can cause factors in the form of inaccurate determination of atmospheric stability. Compared with the quality standards of PP Number 41 of 1999, the CO values obtained at the four measurement points do not exceed the established quality standard values.

Table 3. Comparison of CO Distribution Estimation Results Using Caline4 and Results Direct Measurement

Location	Measurement time	time	Estimation result		Result		Difference (%)	Quality standart*
			ppm	**µg/Nm3**	**ppm**	**µg/Nm3**		µg/Nm3
Setiabudi road	February 7th 2018	07.15-08.15	4	4,505	3.23	3,639	23.8	30,000
East Ngesrep road	February 10th 2018	17.00-18.00	2	2,263	3.5	3,959	43.8	30,000
Tembalang Toll Road	February 11st 2018	07.00-08.00	1	1,135	0.58	662	71.4	30,000
Perintis Kemerdekaan Roas	February 7th 2018	16.30-17.30	5	5,700	4	4,560	24.9	30,000

**Ambient Air Quality Standards based on Government Regulation Number 22 of 2021.*

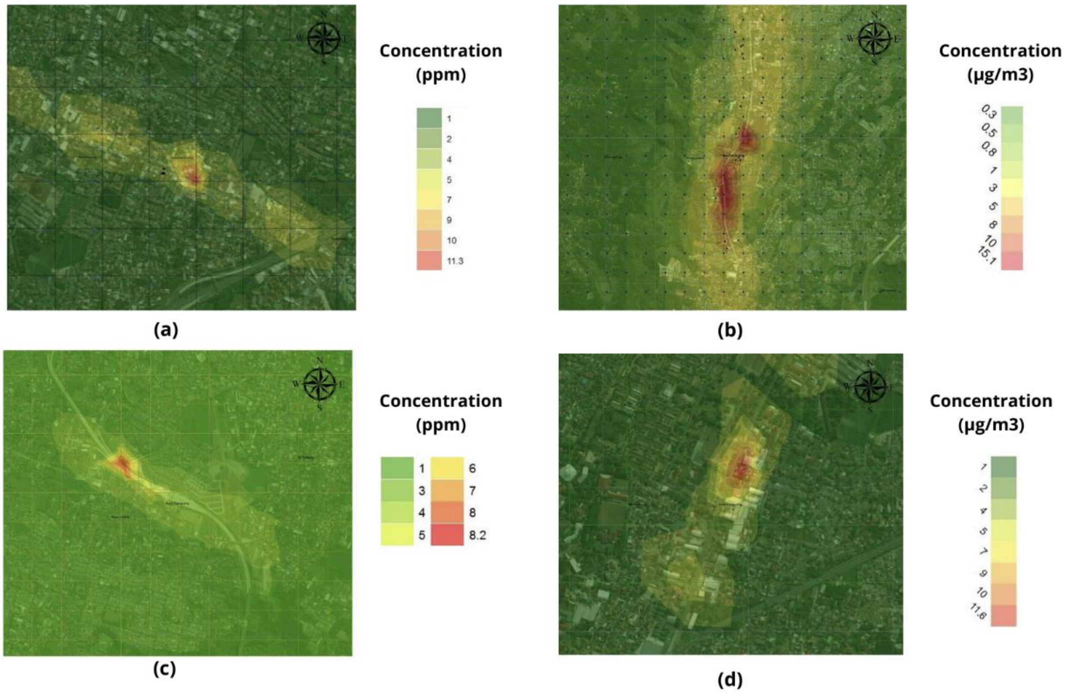

Figure. 7 CO concentration at East Ngesrep V Road (a) Perintis Kemerdekaan Road (b) Tembalang Toll Road (c) Setiabudi Road (d)

3.3. AERMOD Dispersion Modelling Result

The emission results obtained from transportation for the parameters NOX, PM10, SO2, CO, and HC can be seen in the following table. The simulation results using AERMOD are shown on a concentration isopleth map using meteorological data in the form of wind speed, wind direction and air temperature in the period 1 January 2017 to 31 December 2017. Each concentration range is shown in a different color.

Table 4. Concentration values from modeling results with AERMOD in 2017

Polutant	Concentration (24 hours) (µg/m3)	Location	
	Maximum	Coordinate	District
CO	10,397	434630,06 m; 9228265,00 m	Central Semarang
HC	3,155	434630,06 m; 9228265,00 m	Central Semarang
NOx	685	434630,06 m; 9228265,00 m	Central Semarang
PM10	144	434630,06 m; 9228265,00 m	Central Semarang
SO2	25.3	434630,06 m; 9228265,00 m	Central Semarang

The high concentration of pollutants is caused by wind speed and direction. Based on Geiger (1995), the greater the wind speed at a source of exhaust gas, the concentration of exhaust gas in the area itself decreases. If the wind speed is smaller, it is possible that the concentration will remain in the source area.

Table 5. Concentration of Pollutants in Study Location

Sub-District	Emission ton/year

	NOx	PM10	SO2	CO	HC
Mijen	5.52	0,15	0,05	3.00	1.02
Gunungpati	6.90	0.06	0.06	3.76	1.27
Banyumanik	11.65	0.10	0.10	6.34	2.15
Gajahmungkur	4.63	0.04	0.04	2.52	0,85
Semarang Selatan	6.71	0.06	0.06	3.65	1.24
Candisari	4.36	0.04	0.04	2.37	0,80
Tembalang	14.46	0.13	0.13	7.86	2.66
Pedurungan	14.47	0.13	0.13	7.87	2.67
Genuk	8.97	0.08	0.08	4.88	1.65
Gayamsari	5.89	0.05	0.05	3.20	1.09
Semarang Timur	6.48	0.06	0.06	3.52	1.19
Semarang Utara	7.74	0.07	0.07	4.21	1.43
Semarang Tengah	6.76	0.06	0.06	3.68	1.25
Semarang Barat	14.85	0.13	0.13	8.08	2.74
Tugu	2.73	0.02	0.02	1.48	0,50
Ngaliyan	9.41	0.08	0,08	5.12	1.73
Total	13,005	46,769	69.22	178,690	55,681

Line source emissions in each sub-district are searched to obtain total emissions from each sub-district. Total emissions are the sum of area source emissions and line source emissions. Based on research conducted, NOx pollutants from the transportation sector reached 28,078 tons/year. The estimated value of most emissions is produced by trucks with a contribution of 14,045 tonnes/year or 50.02% of all NOx emissions

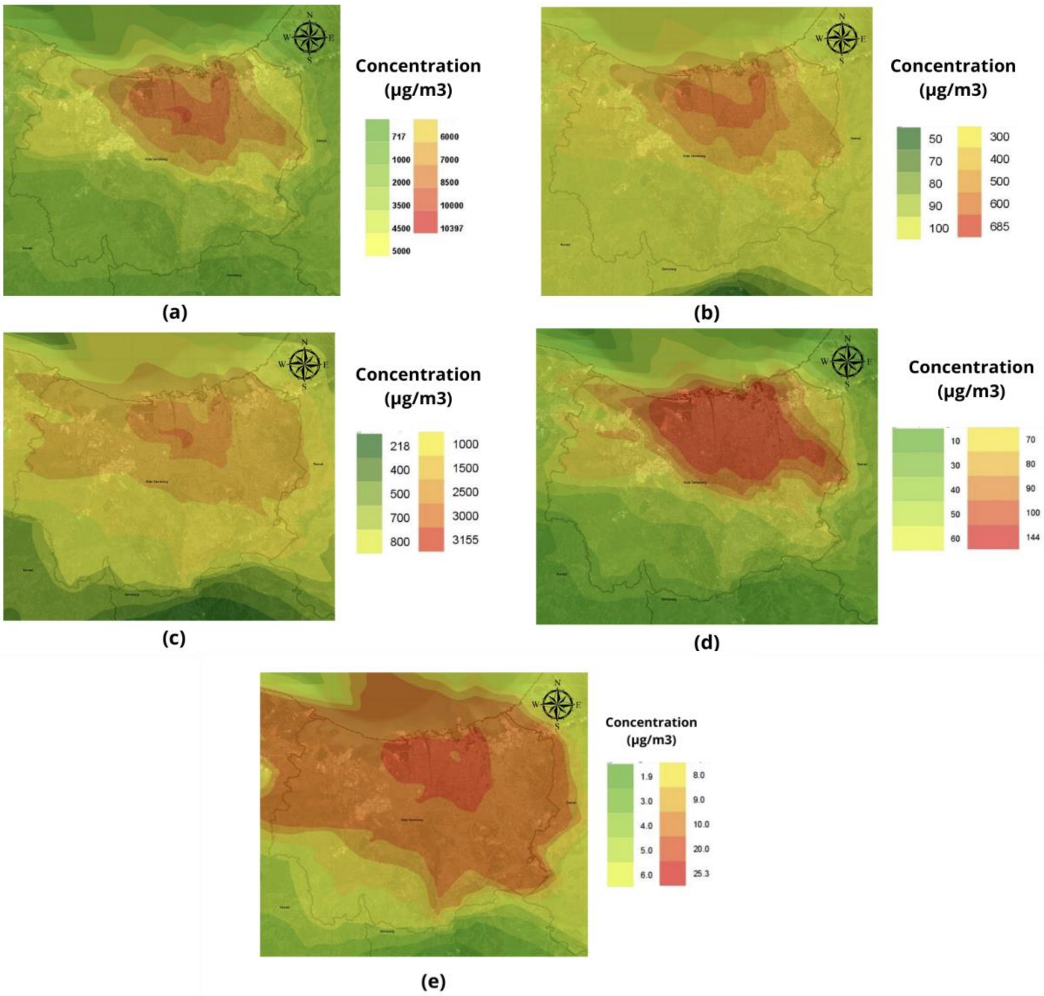

Figure 8. Emission concentration in Semarang 2017 (a) CO (b) NOx (c) HC (d) PM10 (e) SO2

4. Conclusions

Based on modelling made with CALINE4 and AERMOD, CO, HC, NOx, PM10, SO2 emissions resulting from the transportation sector on-road respectively is 398,937 tons/year with the main contributor is a motor vehicle; 122,944 tons/year with the main contributor is a motor vehicle; 28,124 tons/year with the main contributor is a truck vehicle; 5,786 tons/year with the main contributors being motorcycle; 1,062 tons/year with the main contributors being truck vehicle. Pollutant levels in each area can be influenced by several aspects, such as wind direction and speed, temperature, atmospheric stability, and mixing height. The greater the wind speed in an area where the exhaust gas is sourced, the concentration of exhaust gas in that area will decrease, and vice versa

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