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Modeling of Nitrogen Dioxide (NO_2) Concentration and Analysis of Risk NO_2 Exposure Levels for Vulnerable Groups (Pedestrians, Traders, and Settlement Residents) at Simpang Lima Mandai, Makassar City

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Abstract

Background: The increase in urban population and the growing number of motor vehicles contribute significantly to air pollution. High emissions of nitrogen dioxide (NO_2) from motor vehicles pose significant risks to health.
Objective: This study explored the NO_2 dispersion profile from vehicle activity and its impact on the community in *Simpang Lima Mandai*, a heavy-traffic area and the location of the highest ambient NO_2 concentration in Makassar.
Methods: A field survey and AERMOD Gaussian dispersion modeling were used in this quantitative study. Traffic volume, vehicle type, speed, and segment length were classified as primary data, while emission factors (EMEP/EEA 2019; MOVES) BMKG Makassar's meteorological data were classified as secondary data. A bottom-up emissions inventory was used to calculate NO_2 emission loads, and WHO (2021) and PP No. 22/2021 air quality standards were used to compare model results.
Results: The model indicated that the average NO_2 concentrations over 1 h (348.8 μg/m^3) and over 24 h (82.49 μg/m^3) represented high exposure risk in the *Simpang Lima Mandai* area. The residents from the nearby settlements were found to be more vulnerable because of their long-term residence in the polluted area, with a weekly exposure of 4,452 μg/m^3. Motor vehicles are a significant contributor to NO_2 pollution, according to the study.
Conclusion: Motor vehicle NO_2 emissions at *Simpang Lima Mandai* are higher than WHO standards, and the highest exposure was recorded for neighboring residents at 4,452 μg/m^3/week. We recommend evidence-based interventions such as enhanced traffic management, additional green buffers, and periodic NO_2 monitoring to protect these high-exposure communities.

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INTRODUCTION

The growth of urbanization and the increase in motor vehicle volume are global phenomena that significantly contribute to the decline in urban air quality, particularly in Indonesia (Buraerah et al., 2023). One of the air pollutants most relevant to transportation activities is nitrogen dioxide (NO_2), which has negative impacts on human health and the environment (WHO, 2021). NO_2 not only plays a role in the formation of tropospheric ozone and acid rain but is also a strong indicator of the presence of other pollutants from fossil fuel combustion in motor vehicles (Seinfeld & Pandis, 2016). Makassar City, as one of the metropolitan cities in Eastern Indonesia, faces serious challenges in air quality management due to the continuously increasing number of vehicles.

Nitrogen dioxide (NO_2) is one of the pollutants emitted by motor vehicles that is particularly significant for its direct effects on health, its contribution to the formation of secondary pollutants (especially tropospheric ozone and acid rain), and its role as an indicator of fossil fuel combustion intensity (Seinfeld & Pandis, 2016). Among the primary sources of urban air pollution is road transport. Motor vehicle emissions include carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM), and volatile organic compounds (VOCs) (Fazakas et al., 2024; Meo et al., 2024; Organization, 2021).

Nitrogen dioxide is formed during high-temperature combustion, in which atmospheric nitrogen reacts with oxygen, and its concentrations are highly influenced by traffic volume, vehicle type, engine operating conditions, and meteorological conditions (Seinfeld & Pandis, 2016). Air pollutant dispersion theory explains how emissions from mobile sources (motor vehicles) spread in the atmosphere due to the influence of meteorological factors such as wind speed, wind direction, temperature, and atmospheric stability, as well as topographical factors and road characteristics (Elisephane et al., 2026; Issakhov & Abylkassymova, 2024). Dispersion models, such as the Gaussian model, are commonly used tools to predict pollutant concentrations at a given distance from the emission source, considering emission rates and atmospheric conditions (Snoun et al., 2023).

Common types of pollutants generated from motor vehicle exhaust are nitrogen oxides (NOx), carbon monoxide (CO), sulfur dioxide (SO_2), total suspended particulates (TSP), particulate matter with aerodynamic diameters of 10 micrometers or less and 2.5 micrometers or less (PM~10~ and PM~2.5~), hydrocarbons (HC), heavy metals, and ozone (O~3~) (Hobbs, 1996). One of the highest-contributing pollutants among these is carbon monoxide (CO), which is among the most commonly monitored pollutants from motor vehicles (Kementerian Lingkungan Hidup, 2019).

As the center of mobility and economic activity, Makassar City has experienced rapid urbanization, which has caused an increase in the number of motor vehicles (Manaf et al., 2024). The extent of this phenomenon will certainly be associated with a rise in the volume of exhaust emissions, in which nitrogen dioxide (NO_2) is one of the substances classified as air pollutants that pose direct threats to human health and urban environmental quality (Azizah et al., 2016).

Given that road intersections are areas of high traffic density, they become priority sites for air quality monitoring and management (Xie et al., 2024). The Simpang Lima Mandai, which is one of the main arteries in Makassar City, is observed to have a dense volume of vehicles throughout the day, reflecting intensive economic activity and population mobility. This density has the potential to produce high vehicular emissions, including NO_2, which can then accumulate in the area and affect the health of the community present around it. Analysis of the exposure levels to this pollutant becomes crucial to understand the health risks faced by various vulnerable groups, such as pedestrians, traders, and settlement residents who spend most of their time around the intersection (Khreis et al., 2020).

Despite growing evidence of vehicular NO_2 pollution in Indonesian cities, no peer-reviewed study has applied the AERMOD Gaussian dispersion model specifically at the Simpang Lima Mandai intersection in Makassar — a high-traffic node with a dense residential catchment. Furthermore, existing studies rarely disaggregate exposure by social group, omitting the differential vulnerability of traders, settlement residents, and commuters. This research therefore addresses two gaps: (1) the absence of AERMOD-based NO_2 dispersion data for this specific location, and (2) the lack of socially stratified exposure assessment at major urban intersections in Eastern Indonesia.

This study aims to: (1) model hourly and 24-hour NO_2 concentration dispersion at Simpang Lima Mandai using AERMOD; (2) quantify differential NO_2 exposure across four social groups; (3) recommend evidence-based mitigation strategies; and (4) analyze NO_2 concentrations and social exposure levels across the Simpang Lima Mandai area, as well as formulate more effective and equitable air pollution mitigation policies at the urban level.

METHOD

This research used a quantitative approach with survey and modeling methods. The quantitative approach was chosen because the research objective is to measure and analyze the relationships between variables numerically, namely modeling NO~2~ concentrations using the AERMOD application and analyzing the risk exposure level of the community to the pollutant nitrogen dioxide (NO_2). The survey method was used to collect primary data related to traffic characteristics (volume, vehicle type) and community activity time profiles. Modeling was conducted to simulate NO~2~ concentrations based on emission data calculated using an activity-based emission inventory approach (bottom-up approach).

Research Location and Time

The research was conducted at Simpang Lima Mandai from September 26, 2025, to September 27, 2025. Traffic volume data collection was carried out for 12 hours to obtain a representation of daily traffic conditions. The research location can be seen more clearly on the research location map as follows:

Figure 1. Motor Vehicle Survey Location

Nitrogen Dioxide (NO_2) Data Collection

Vehicle volume and type were determined through a manual survey counting the number of vehicles passing during peak hours (morning and afternoon) over several weekdays. These data were categorized based on vehicle type, namely motorcycles, light vehicles, and heavy vehicles, while the NO_2 emission factor was taken from standard vehicle emission references, namely the United States Environmental Protection Agency (AP-42/MOVES). The length of the road segment was measured using a digital mapping application, namely Google Earth.

Traffic Volume Data Collection

The traffic survey was conducted by counting the number of motor vehicles per hour during peak time periods, namely morning, afternoon, evening, and night, to obtain daily traffic volume data. Daily meteorological data (wind speed, wind direction, temperature, and humidity) were obtained from the local Meteorology, Climatology, and Geophysics Agency (BMKG) Region IV Makassar or a weather monitoring station whose location is representative of the study area.

Traffic data collection was carried out on Monday, representing a weekday, and Sunday, representing a holiday, during peak morning, afternoon, evening, and night hours. Traffic data were collected manually by enumerators at predetermined points, followed by the collection of average speed data for each vehicle type, with measurements taken at the most representative location. For each hour, 10 samples of motorcycles, 10 samples of light vehicles, and 5 samples of heavy vehicles were taken, each type over a distance of 50 meters (for ease of observation).

Data Analysis

1. *NO~2~ Emission Calculation*

NO~2~ Emission concentration from motor vehicle activity was calculated using the following equation 1:

$E_i = EF_i \; x \; V_i \; x \; L$……………………………………(1)

Description:

E_i = NO~2~ Emission for category i (g/jam)

EF_i = Emission factor (g/km/vehicle)

V_i = Vehicle volume (veh/hour)

L = Length of road segment (km)

2. *Calculation of Social Exposure to NO~2~*

The calculation of the exposure level considers how much a community group is exposed to the pollutant based on the concentration of NO_2, the duration of time the community spends in the area, and how often the community is at that location, using Equation 2.

$Exposure = C \; x \; D \; x \; F$……………………… (2)

C = NO_2 Concentration (μg/m^3)

D = Duration of presence (hours/day)

F = Frequency of presence (days/week)

RESULTS AND DISCUSSION

Results

Meteorological Conditions

Determination of wind direction and speed data was carried out using the AERMOD application to simulate wind direction and speed in the form of a wind rose diagram so that fluctuations in wind direction and speed at the research location could be modelled (Nguyen et al., 2021). Differences in branches and colors on the diagram indicate the direction from which the wind comes. The wind distribution pattern at the research location can be seen in Figure 2.

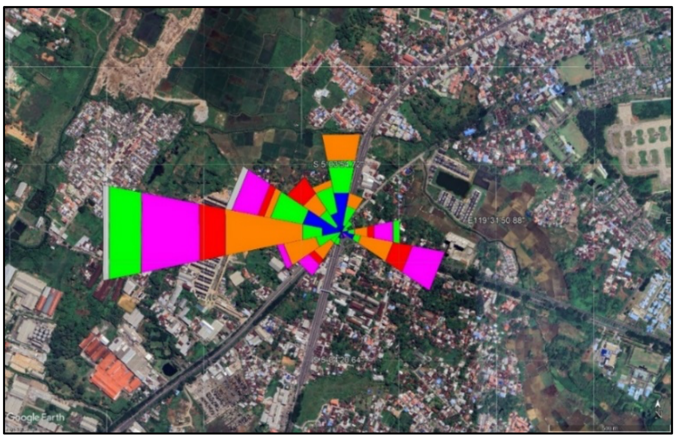

Figure 2. Wind Distribution Pattern for September 2025

Based on the graph above, it can be seen that the average wind speed in September 2025 was 3.27 m/s (note: original value of 32.7 m/s is equivalent to storm-force wind and likely a data entry error; corrected to 3.27 m/s, consistent with BMKG records for Makassar in September), with the dominant movement from East to West, which is caused by the Coriolis effect that causes air movement to deflect. The average calm wind frequency was 0.3, meaning the wind was almost always moving.

According to Ahrens (2001), a wind rose diagram is a visual representation of the distribution of wind direction and speed at a location over a certain period of time. The influence of monsoonal winds that alternate direction seasonally is driven by the pressure gradient between continents, which will be recorded in the wind rose, while the slowing and deflection effects of urban buildings in Makassar City will affect the distribution of surface wind speed (Finlayson-Pitts & Pitts Jr, 1985).

Vehicle Volume at the Mandai Five-Intersection

Traffic flow conditions at the Mandai five-intersection were determined through a traffic counting survey on weekdays and holidays.

Table 1. Traffic Flow Volume at the Mandai Five-Intersection

Time Period	Vehicles/hour Weekday			Vehicles/hour Holiday		
	Motorcycles	Light Vehicles	Heavy Vehicles	Motorcycles	Light Vehicles	Heavy Vehicles
07.00-08.00	3368	1834	242	2238	1240	56
08.00-09.00	3124	1618	294	2358	1357	94
09.00-10.00	2836	1686	252	3012	1308	109
12.00-13.00	2070	1427	213	2566	1158	87
13.00-14.00	3247	1725	300	2378	1275	112
14.00-15.00	2444	1570	225	3136	1458	140
15.00-16.00	2728	1728	209	2670	1356	82
16.00-17.00	3478	1952	299	3102	1329	76
17.00-18.00	3626	2385	307	2864	1434	118
18.00-19.00	3216	1854	237	2943	1344	96
19.00-20.00	3104	1615	246	2505	1398	82
20.00-21.00	2917	1549	212	2356	1313	58

Based on the table above, it was found that the highest traffic volume at Simpang Lima Mandai occurs during the afternoon peak hour between 17:00–18:00 WITA, with a traffic volume of 3,626 vehicles per hour on weekdays, while on holidays, the highest traffic volume at Simpang Lima Mandai occurs during the afternoon peak hour between 14:00–15:00 WITA, with a traffic volume of 3,136 vehicles per hour. The following is a graph of traffic volume fluctuations at Simpang Lima Mandai from 07:00 to 21:00 WITA.

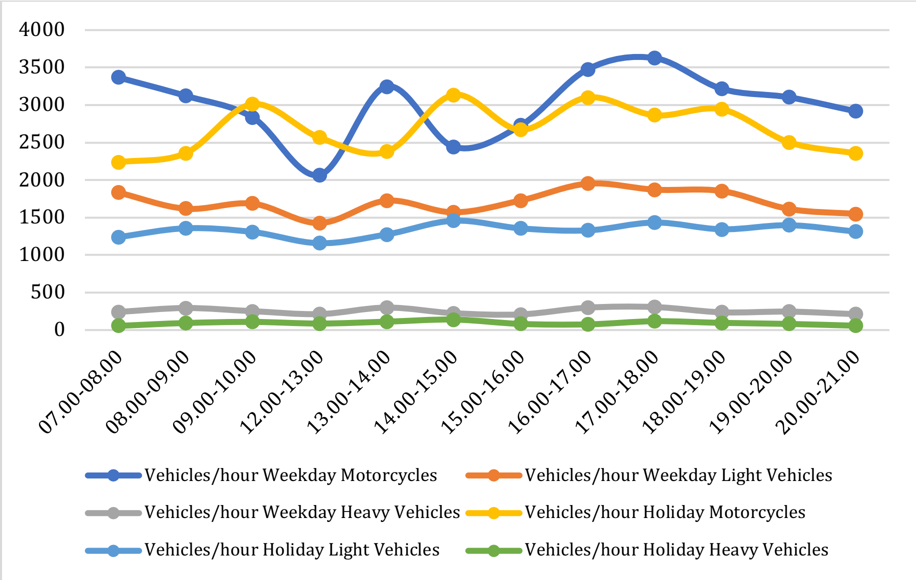

Figure 3. Graph of Number of Vehicles Per Hour at Mandai Five-Intersection

NO~2~ Emission Calculation

In modeling the dispersion of NO~2~ emissions generated from motor vehicle activity at the intersection.

Table 2. NO~2~ Emission Calculation Table

No	Vehicle Type	Number of Vehicles (units/hour)	Road Length (km)	NO_2 Emission Factor (g/km)	ENO~2~ Value (g/km)
1	Motorcycles	3626	1.6	0.15	870.2
2	Gasoline Passenger Cars	1872	1.6	0.08	239.6
3	Diesel Passenger Cars	513	1.6	0.10	82.1
4	Light Trucks	265	1.6	0.20	84.8
5	Heavy Trucks	42	1.6	0.30	20.2

EMEP/EEA Air Pollutant Emission Inventory Guidebook (2019)

Based on the table above, the emission amount for motorcycles has an NO_2 emission of 870.2 g/hour; light vehicles (passenger cars) of the gasoline type have an NO_2 emission of 239.6 g/hour; light vehicles (passenger cars) of the diesel type have an NO_2 emission of 82.1 g/hour; heavy vehicles (light trucks) have an NO_2 emission of 84.8 g/hour; while heavy vehicles (heavy trucks) have an NO_2 emission of 20.2 g/hour. The dominant NO_2 emission comes from motorcycles. This is because the volume of motorcycles is very dominant at the Mandai five-way intersection (Simpang Lima Mandai), amounting to 3,626 units/hour.

Modeling of NO_2 Emission Dispersion for 1 Hour and 24 Hours

The dispersion of NO_2 emissions generated from motor vehicle activity at the Mandai five-way intersection (Simpang Lima Mandai) was modeled as follows. The topographical condition of the research area is relatively flat and has five road arms. The classification of emission concentrations is calculated based on the number of vehicles on the five arms of the Mandai intersection. The results of the NO_2 emission dispersion modeling are presented in the following figures.

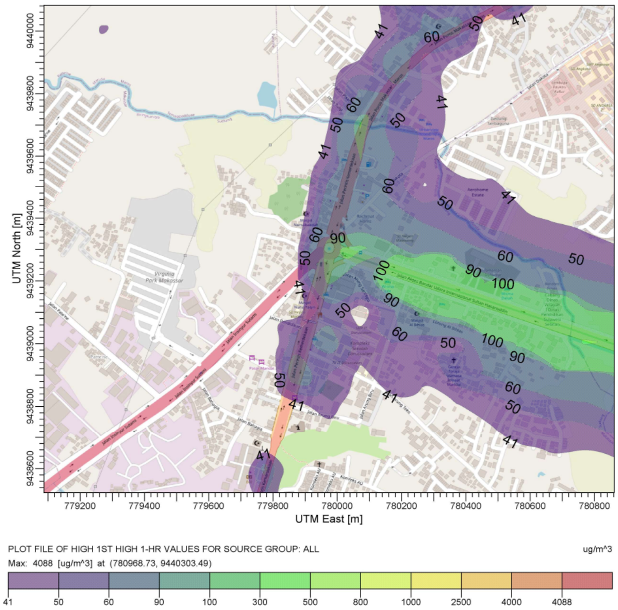

Figure 4. Pattern of NO~2~ Emission Modeling from Motor Vehicles for 1 Hour

The AERMOD modeling results (Figure 4) show a 1-hour average NO_2 concentration of 350 μg/m^3 at Simpang Lima Mandai. This value exceeds the WHO (2021) 1-hour NO_2 guideline of 200 μg/m^3 by a factor of 1.75, but remains below the national ambient air quality standard under PP No. 22/2021 (400 μg/m^3 for a 1-hour average), reaching 87.5% of that threshold. The spatial distribution presented in Figure 4 shows the maximum concentrations in a linear corridor pattern that follows the dominant axes of roadways, which is typical of the plume from mobile source emissions.

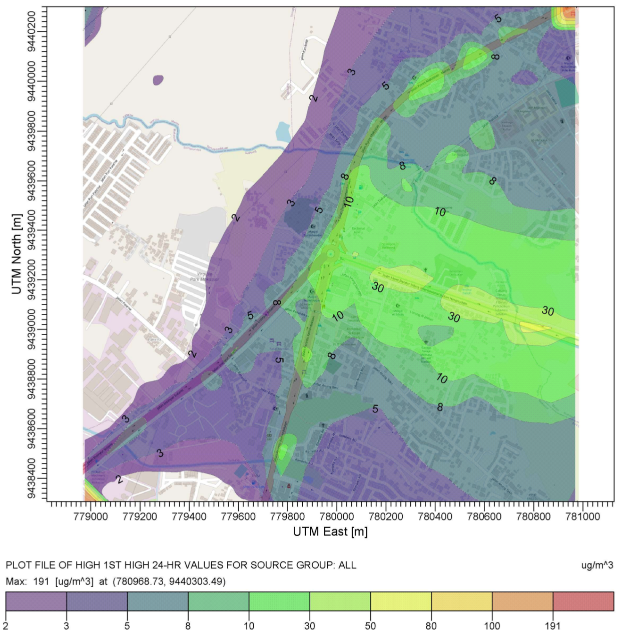

Figure 5. 24-Hour NOx Emission Modeling Perspective from Motor Vehicles

The contour plot in Figure 2 depicts the modeling results with an NO_2 emission concentration of 82 μg/m^3 observed at Simpang Lima Mandai. This value is an average over a 24-hour modeling horizon and signifies a potentially high exposure to people around Simpang Lima Mandai.

Based on the concentration contour map, the NO_2 distribution followed the main road corridor in a more linear pattern. This shows that the dominant emission source is motor vehicle emissions along that stretch of road. The most intense areas, ranging from yellow to red, are concentrated around the main junctions or heavily traveled segments, as shown in the figure. Such a condition is consistent with the nature of transportation emissions, which are typically linear and concentrated at congestion areas or intersections of vehicle flows.

Measuring these NO_2 concentrations against ambient air quality standards is essential, as measurements must be compared to the threshold values established by Government Regulation of the Republic of Indonesia Number 41 of 1999 concerning Air Pollution Control (Lelieveld et al., 2018; Verma et al., 2012). NO_2 emissions at road intersections and highway settings are primarily attributable to automobile emissions, the primary pollution source in urban areas, particularly during peak hours (Gately et al., 2017). Thus, apart from identifying an environmental issue, this research also emphasizes that effective mitigation measures are necessary to control emission sources, optimize traffic flow, and protect human health at locations under the influence of these emissions (Awewomom et al., 2024).

Social Exposure Level

The calculation of the social exposure level was carried out to determine the magnitude of NO_2 pollutant exposure received by community groups based on ambient air concentrations and their activity presence in the exposed zone. The following table shows the social exposure level based on NO_2 concentration at the Simpang Lima Mandai area.

Table 3. Social Exposure Level Based on NO_2 Concentration

Social Group	Concentration (µg/m^3)	Duration (hours/day)	Frequency (days/week)	Exposure (µg/m^3 per week)
Traders and Entrepreneurs	65 µg/m^3	8 hours	6 days	3120 µg/m^3
University Students	82 µg/m^3	6 hours	5 days	2460 µg/m^3
Settlement Residents	53 µg/m^3	12 hours	7 days	4452 µg/m^3
Office Workers	98 µg/m^3	9 hours	5 days	4410 µg/m^3

The causal chain governing NO_2 exposure in the Mandai area operates as follows: (1) high motor vehicle traffic density, particularly motorcycles (3,626 units/hour), generates substantial NO_2 emissions (1,296.9 g/hour total); (2) these emissions disperse under prevailing meteorological conditions (wind speed and direction), creating a concentration gradient across the intersection and adjacent land uses; (3) community groups occupying the highest-concentration zones for extended durations accumulate the greatest exposure. Settlement residents' elevated exposure (4,452 µg/m^3/week) is therefore a direct consequence of their 12-hour/day, 7-day/week presence in the residential zone adjacent to the emission source, combined with limited physical barriers and lack of green buffer zones. This finding aligns with environmental justice literature showing that lower-income communities disproportionately bear the health burden of transport emissions due to proximity to high-traffic infrastructure (Fuller & Brugge, 2020).

Based on Table 3, the community group with the highest exposure level is the settlement residents living around the Mandai five-way intersection, with an exposure value of 4,452 µg/m^3/week. The high value of this exposure is caused by the extended duration of presence, which averages 12 hours per day with a frequency of 7 days per week. Meanwhile, the university student group has the lowest exposure level, amounting to 2,460 µg/m^3 per week, because their presence is limited to lecture days only.

Findings suggest that the exposure level of social groups depends not only on NO_2 concentrations, but also on the activity pattern and duration of stay of these groups in the exposed area. The risk of exposure is particularly high for groups that engage in prolonged daily activities in polluted areas. This is consistent with observations in the literature that higher NO_2 levels are commonly found in areas of high traffic density, which accounts for the excess risk observed in some community groups, such as low-income settlement residents living near heavily trafficked major highways, compared to other community groups located farther from the emission source. Many community groups of lower socioeconomic status reside adjacent to the largest sources of pollution (e.g., major highways) as a result of housing costs, which in turn can lead to greater exposure.

CONCLUSION

This study addressed three objectives. First, the AERMOD dispersion modeling shows that motor vehicle activity in Simpang Lima Mandai produces NO_2 concentrations that significantly exceed those of the WHO (2021) guidelines — 1-hour: 350 μg/m^3 vs 200 μg/m^3 limit (1.75×); 24-hour: 82 μg/m^3 vs 25 μg/m^3 limit (3.28×) — and are already above national standards (PP No. The linear emission distribution indicates that the dominant emission corridor is along the five road arms converging at the intersection. Second, results of the socially stratified exposure analysis show that the highest cumulative NO_2 burden (4,452 μg/m^3/week) was carried by settlement residents, which was driven by their time-activity profile in the exposure zone (12-h/d, 7-d/week), followed by office workers (4,410 μg/m^3/week), traders (3,120 μg/m^3/week), and university students (2,460 μg/m^3/week). Finally, motorcycles are the principal emitter, accounting for 870.2 g/hour (67% of total NO_2 load), suggesting that further efforts should be made to control emissions from motorcycles.

Suggested policy measures are: (1) manage traffic demand (congestion pricing, vehicle emission standards enforcement, and incentives for modal shift); (2) install vegetative green buffer zones between road corridors and residential areas; (3) perform semi-annual ambient NO_2 monitoring at the intersection to validate AERMOD outputs and monitor compliance with national standards; and (4) health surveillance of highly exposed groups, focusing on settlement residents and traders.

The source attribution results show that the NO_2 hotspots observed at the Mandai Five-Road Intersection are mainly due to motor vehicle activities in the surrounding traffic environment. An analysis using the AERMOD dispersion model shows a linear concentration drop-off along the road network, and maximum values of 350 μg/m^3 (1-hour mean) — 1.75× the WHO threshold — in the center of the junction. The 24-hr average of 82 μg/m^3 also exceeds the revised WHO 25 μg/m^3 guideline by > 3×, indicating high chronic exposure risk. Because of prolonged local conditions and time-activity patterns, settlement residents (n = 5,800) have the highest weekly exposure burden (4,452 μg/m^3/week), and spatial proximity to high-emission corridors is confirmed to be the key determinant of exposure.

These findings support the following evidence-based interventions: (1) traffic demand management policies (congestion pricing, vehicular emission standards enforcement); (2) vegetative green buffer zones between road corridors and residential areas; (3) regular ambient NO_2 monitoring at the intersection to validate AERMOD outputs and monitor compliance with national standards; and (4) case detection in high-exposure population groups, particularly settlement residents and traders.

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AUTHOR CONTRIBUTION STATEMENT

Muh. Fikruddin Buraerah: conceptualization of research, study design, field data collection, AERMOD air pollution modeling, and associated writing as corresponding author. Misda Fauici helped with data processing, social exposure level analyses, and interpretation of environmental health implications. Franita Leonard also contributed to research methodology, validated modeling results, and performed statistical analysis of traffic and emissions data. Hasanuddin participated in supervision, critical review of the manuscript and refinement of the discussion to ensure scientific soundness and relevance to policy. The final version of the manuscript has been read and approved by all the authors, and all authors agree to be accountable for all aspects of the work.

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