Estimation and ground validation of CO Concentration dispersion modelling in five different road types in Makassar City

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Abstract. Climate change and worsening urban air quality remain critical global challenges, with transport-related emissions contributing substantially to atmospheric pollution. This study aims to examine carbon monoxide (CO) concentration values obtained from motor vehicle emission load dispersion modeling, alongside direct measurement values, in Makassar City. Direct measurements were conducted at 30 locations on different road types (6/2D, 4/2D, 4/1UD, 2/2UD, 2/1UD) to determine vehicle volume and CO concentrations. CO emission loads were calculated using the Tier 2 methodology in accordance with Ministry of Environment Regulation No. 12 of 2010, and subsequently simulated using dispersion modeling software. The findings indicated that the 6/2D type had the highest emission loads, correlating with elevated traffic volume. A comparison of CO concentration values between direct measurements and emission load modeling revealed that direct measurements ranged from 229 to 1,684 μg/m³, whereas dispersion model results ranged from 275 to 1,320 μg/m³, demonstrating a similar distribution pattern across all road types. The Paired sampel T-Test produced a significant value of 0.45 ($p > 0.05$), indicating no meaningful difference between measured and modeled concentrations. The findings demonstrate that the dispersion model effectively represents the distribution pattern of CO concentrations attributable to traffic activities across different road types in Makassar City. This research provides essential scientific support for urban air pollution control strategies and contributes to achieving ustainable Development Goal (SDG) 13 related to climate change mitigation.

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1 Introduction

Air pollution arises from the generation and dissemination of many contaminants in the atmosphere. This process adversely affects the environment and human health in metropolitan areas, mostly because of increased traffic, industrial activity, and residential energy consumption [1]. Among the numerous forms of pollution, motor vehicles represent a significant contributor in developing nations [2, 3]. This aligns with the annual increase in vehicle numbers, as private vehicles remain the predominant mode of mobility for the town. This phenomenon is also observed in Makassar, a metropolitan city outside Java, Indonesia, which has experienced a 34.39% growth (from 905,074 to 1,216,338 automobiles) over a five-year period (2020-2024) [4].

Numerous hazardous exhaust emissions, including nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and microscopic particles (particulate matter) like PM2.5 and PM10, are produced by internal combustion engines in gasoline and diesel-powered motor vehicles [5, 6]. Carbon monoxide (CO) is a primary indication of pollution, especially in Jakarta, Indonesia, where it accounts for 93% of road traffic emissions [7]. Carbon monoxide (CO) is a colorless, odorless, and tasteless gas, typically present in the atmosphere at around 0.1 ppm; thus, an environment contaminated by CO is imperceptible to the human eye. The primary source of carbon monoxide (CO) gas is vehicle emissions, particularly from gasoline engines, and its prevalence in urban regions is marked by significant traffic congestion. The dispersion of carbon monoxide from engine exhaust will influence the ambient air quality along roadways and extend to broader regions, so affecting human health. Elevated concentrations of carbon monoxide (CO) in ambient air are breathed in through the respiratory system, entering the lungs and binding to hemoglobin in the bloodstream to form carboxyhemoglobin (COHb). The affinity of carbon monoxide (CO) for hemoglobin (Hb) is 240 times greater than that of CO for oxygen (O2). Elevated levels of carbon monoxide in the blood (HbCO) will manifest symptoms, such as dizziness at HbCO 10%, nausea and dyspnea at HbCO 20%, impaired vision and diminished concentration at HbCO 30%, unconsciousness and coma at HbCO 40-50%, and potentially fatal outcomes if exposure persists [8].

The dispersion pattern of CO pollutants from motor vehicles can be predicted to geographically and temporally predict the locations with the highest pollution levels surrounding mobile sources on roads. This methodology enables dispersion modeling to characterize dispersion patterns in regions lacking monitoring instruments. In Indonesia, specifically in the city of Makassar, research on carbon monoxide gas dispersion models from motor vehicles remains inadequate. Most prior research have concentrated on presenting pollutant concentration levels derived from dispersion modeling outcomes without confirming the observational data and model simulation findings [9]. This study will examine these factors by comparing CO dispersion data from emission load models with field data. This research aims to deliver a more thorough understanding of air pollution dispersion resulting from transportation activities in urban environments and to serve as a scientific foundation for developing motor vehicle emission control strategies, thereby contributing to the attainment of the Sustainable Development Goals (SDGs), specifically goal 13 concerning climate change mitigation efforts.

 https://doi.org/10.1051/e3sconf/202568204004

2 Method

2.1 Research Locations

This study was conducted at 30 road locations throughout each sub-district in Makassar City, by monitoring the volume of motor vehicle activity at these sites, in accordance with SNI 19-7119.6-2005 regarding sampling sites for ambient air quality assessment. Primary data collection, specifically vehicle volume and air quality test results, was executed across 15 working days commencing on Tuesday, February 25, 2025. The specifics of the research sites for each measurement point are presented in Table 1.

Table 1. Research Location and Road Characteristics

Type of Road	Segment	Sampling Road's Name	Width of Roads (m)	Length of Roads (km)
6/2 D	1	St. Veteran Utara	19.2	1.4
	2	St. Metro Tj. Bunga	19.5	1.1
	3	St. Poros Makassar-Maros	19.3	1.0
	4	St. Bumi Tamalanrea Permai	18.0	1.0
	5	St. Boulevard	27.0	1.2
	6	St. Urip Sumoharjo	11.1	0.9
	7	St. Urip Sumoharjo	20.0	0.8
	8	St. Letjen Hertasning	16.5	0.9
4/2 D	9	St. Satando	6.6	0.7
	10	St. HOS Cokroaminoto	23.1	0.3
	11	St. Metro Tj. Bunga	16.7	1.1
	12	St. Metro Tj. Bunga	16.6	1.0
	13	St. Kima I	14.6	1.4
	14	St. Dr. Ratulangi	14.6	1.5
	15	St. Aroeppala	12.1	1.0
4/1 UD	16	St. Masjid Raya	13.3	1.2
	17	St. Ps. Terong	14.1	1.2
	18	St. G. Bawakaraeng	14.4	1.6
2/2 UD	19	St. Sabutung	6.0	1.3
	20	St. Sunu	8.5	0.8
	21	St. Teuku Umar Raya	8.9	0.9
	22	St. Niaga Daya Ruko	11.6	0.4
	23	St. Toddopuli Raya Timur	4.0	1.0
	24	St. Antang Raya	7.5	0.9
	25	St. Borong Raya	7.2	1.1
	26	St. Rajawali	11.2	0.9
2/1 UD	27	St. Sulawesi	9.4	1.1
	28	St. Penghibur	8.6	0.8
	29	St. Penghibur	10.0	0.8
	30	St. Landak Lama	8.6	0.4

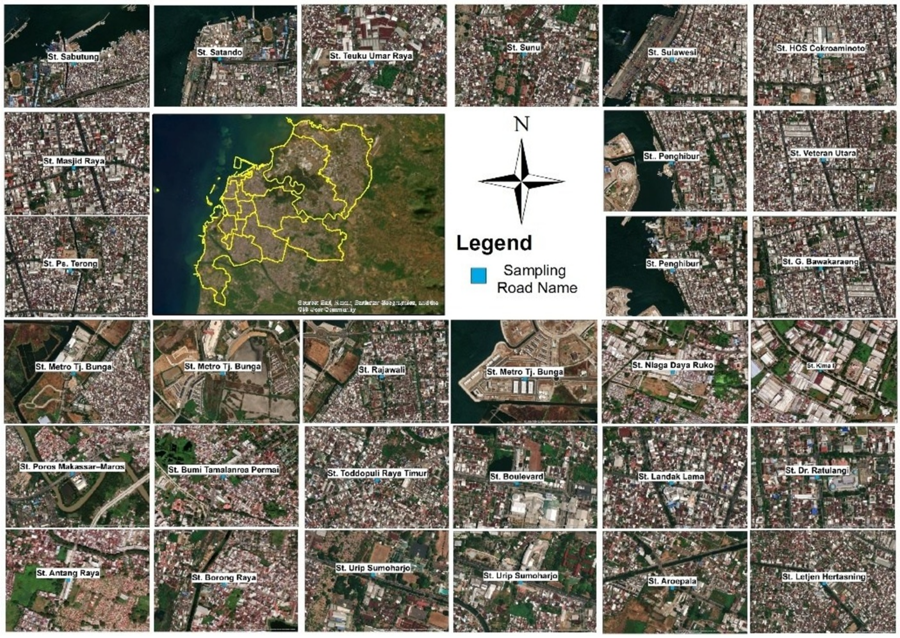


Fig. 1. Location of measurement points in Makassar City

2.2 Ground Measurement

This study utilizes primary data comprising vehicle volume data, collected via observation using a traffic counter, categorized into three vehicle types: motorcycles (MC), light vehicles (LV), and heavy vehicles (HV). Observations were conducted every 15 minutes and consolidated into 1 hour during the daylight peak period. Meanwhile, ambient air quality data for carbon monoxide (CO) was collected by impinger measurements throughout a one-hour daytime period and subsequently analyzed for absorbance using a spectrophotometer, following the protocols outlined in the Andalas University Air Quality Laboratory Module (2018). The equation employed is as follows in equation 1 [10].

$$(\gamma + 0.0099/0.07979) \times V \times T \times 760\text{mmHg} \times BM \times 106 \;/\; (Q \times t \times P \times 298\text{ K} \times 24.45\text{ L/mol}) \qquad (1)$$

Description:
V: Final solution volume
γ: Absorbance value
BM: Molecular weight of CO (gr/mol)
P: Barometric pressure (mmHg)
106: Conversion from grams to µg

2.3 Dispersion Model

Carbon monoxide (CO) dispersion modeling was performed using the AERMOD (American Meteorological Society/Environmental Protection Agency Regulatory Model) developed by the USEPA. This model is used to simulate the dispersion of pollutants from motor vehicle emissions based on meteorological and topographical conditions in Makassar City. This model was chosen because it has the ability to describe pollutant dispersion patterns from various sources, including line sources such as motor vehicle emissions on urban roads.

CO emission data were calculated using the Tier 2 method in accordance with Minister of Environment Regulation No. 12 of 2010 "Implementation of Air Pollution Control in Regions," taking into account the number and type of vehicles (motorcycles, light vehicles, and heavy vehicles), vehicle kilometers traveled (VKT), and each vehicle's emission factor (g/km) [11]. The emission factors used in this study are presented in Table 2. Meanwhile, the emission rate (g/s) was then calculated and used as the primary input to the model [11]. The formulas applied in this calculation are provided in Equations (2) and (3) below.

Table 2. Emissions Factors Based on Vehicle Category

Vehicle Category	Motorcycle	Gasoline Passenger Car	Diesel Passenger Car	Bus	Truck
CO (g/km)	14	40	2.8	11	8.4

To calculate the emission load of each vehicle, use the following formula:

$$VKT_{j,line} = \sum_{i=1}^{n} Q_{ji} \cdot I_j \quad (2)$$

$$E_{cji} = VKT_{ji} \cdot \frac{EF_{cj}(100-C)}{100} \quad (3)$$

Description:
$VKT_{j,line}$: Vehicle Kilometer Traveled (distance ctualan) for vehicle category j on road section I calculated as the source of the line (km/hour)
Q_{ji}: Vehicle volume in category j on road section I (vehicles/hour)
I_j: Length of road section I (km)
E_{cji}: Pollutant emissions c for vehicles in category j on road section I (g/hour)
EF_{cj}: Emission factor (g/km)
C: Emission control equipment efficiency (%)
C: 0, if no emission control equipment is installed

The modeling was conducted in three main stages: (1) AERMET, to process meteorological data (cloud cover, air temperature, humidity, air pressure, wind direction, velocity, precipitation, and solar radiation) from the Copernicus Climate Data Store (CDS) using the website https://cds.climate.copernicus.eu; (2) AERMAP, to process topographic data from a 30-m resolution Digital Elevation Model (DEM); and (3) AERMOD, to run dispersion simulations with a line source 1.5 m above ground level.

The model results, in the form of a spatial distribution of CO2 concentration (µg/m³), were visualized as an isoconcentration map using GIS. Validation was performed by comparing the model results with field measurements at 30 points using a Paired Sample T-Test to assess the model's suitability to actual conditions.

3 Result

3.1 Traffic Volume

The result of the vehicle count at 30 measurement stations indicates variations in vehicle numbers across different road types in Makassar City, as shown as Figure 2. Typically, highways classified as 6/2 D type (six lanes in two directions with a median) exhibit the largest vehicular volume across all vehicle categories compared to other road classifications, with a range of 400-7,748 units for motorcars (MC), 408-2,864 units for light vehicles (LV), and 0-228 units for heavy vehicles (HV). Motorcycles (Motorcycle/MC) predominate in all high-connectivity traffic zones, with the exception of Jalan Metro Tanjung. Nevertheless, no large trucks traverse this road. This road type possesses the greatest MC and LV values (7,748 units and 3,144 units) among the 30 other locations, specifically at Jalan Urip Sumoharjo, directly in front of Mall Nipah Makassar. This thoroughfare serves as both a retail district and a primary conduit for urban transportation. A similar condition was documented by previous research, which analyzed emissions along Urip Sumoharjo Road and found that high traffic density and continuous vehicle flow significantly increased pollutant emissions [12].

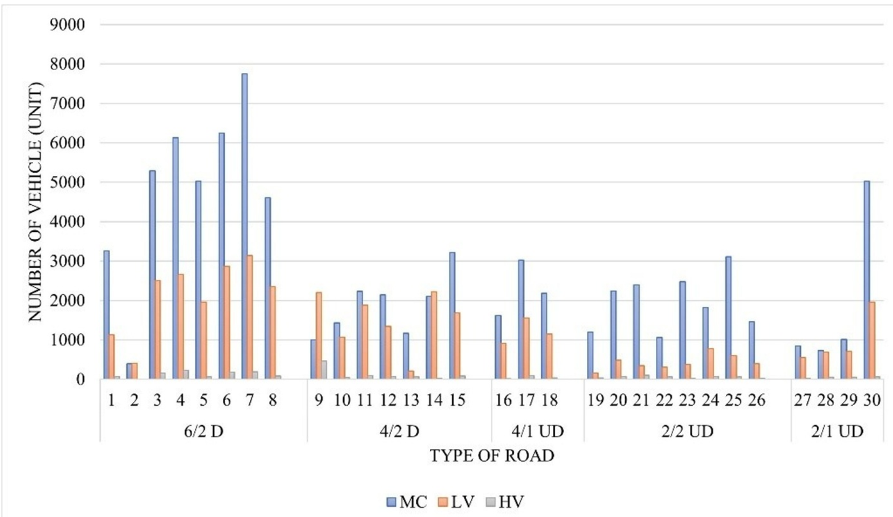


Fig. 2. Distribution of vehicle volume based on road type in Makassar City

In contrast, on 2/1 UD and 2/2 UD roads (two lanes in one direction or two directions without a median), vehicle volume is generally reduced. This condition is typically observed on local roads or minor collector roads with limited capacities and local service roles, exemplified by type 2/1 UD roads, particularly Jalan Sabutung adjacent to Paotere Port in Makassar, accommodating a total of 1,196 motorcycles (MC), 160 light vehicles (LV), and 32 heavy vehicles (HV). For Type 2/2 UD roads, including Sulawesi Street in the Makassar Port area and Penghibur Street near Losari Beach, the values are below 850 units for each vehicle category. Meanwhile, the vehicle count on 4/2 D and 4/1 UD roads is modest, indicative of a combination of secondary arterial and major collector road classifications. Certain thoroughfares, such St. Dr. Ratulangi, particularly in proximity to Mall Ratu Indah Makassar, and St. Masjid Raya, exhibit considerable traffic flow since they function as collector roads linking the city center to commercial zones.

3.2 Estimation of Emission Load from Motor Vehicles

The three figures (3, 4, and 5) below illustrate the substantial variation in CO emission loads across different road types and vehicle categories in Makassar City. The 6/2D type exhibits the greatest emission levels, correlating with the substantial traffic flow on thoroughfares such as St. Urip Sumoharjo, St. Boulevard, and St. Veteran Utara, which serve as primary routes for vehicular travel in the city center. The average overall emission load on this type of route varies from 0.28 to 18.75 g/s, predominantly attributed to light vehicles (LV) and motorcycles (MC), specifically 4.85-26.04 g/s and 1.71-24.1 g/s, respectively. The conditions suggest that elevated traffic intensity, particularly from private vehicles, directly escalates overall CO emissions in metropolitan environments. On type 4/2 D roads, emission load values are moderate, with an average range of 0.24 to 15.42 g/s. In contrast, roads devoid of medians, specifically types 4/1 UD, 2/2 UD, and 2/1 UD, exhibit diminished emission loads, with mean values spanning from 0.13-11.40 g/s, 0.11-7.03 g/s, and 0.08-6.41 g/s for each individual road type. This trend suggests that roadways lacking medians and having fewer lanes exhibit reduced vehicle volumes, leading to diminished emission loads. Nonetheless, several areas, such St. Pasar Terong (S17) and St. Gunung Bawakareng (S18), continue to exhibit relatively elevated emission levels due to their function as primary conduits to the central hub of activity. Moreover, these roadways are predominantly occupied by motorbikes in comparison to other vehicles.

The formulas applied in this calculation are provided in Equations (2) and (3) below.

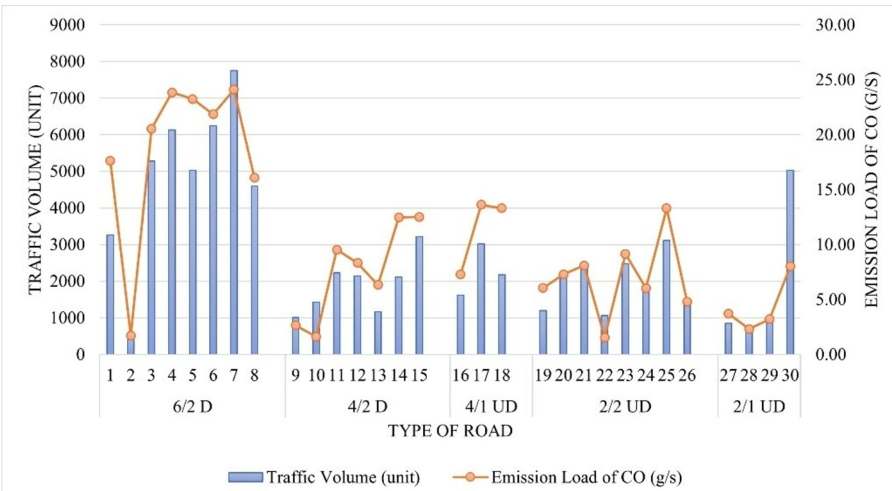


Fig. 3. Distribution of vehicle volume and emission load for MC vehicle types in Makassar City

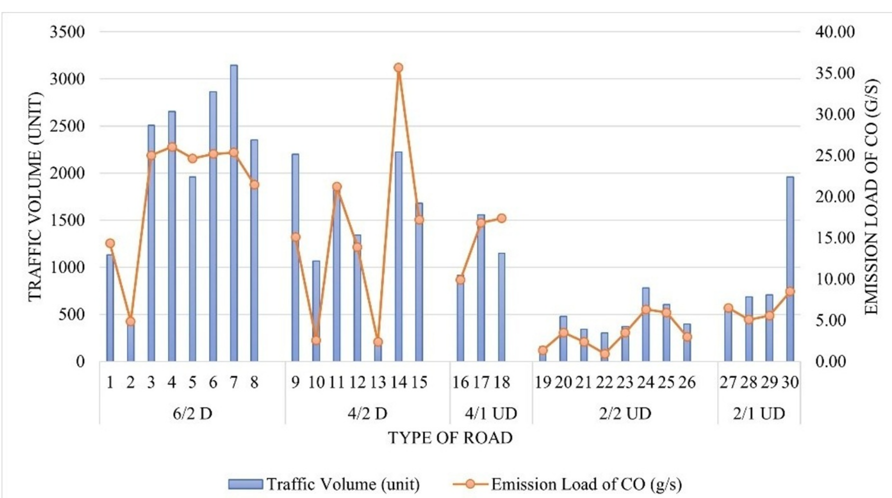


Fig. 4. Distribution of vehicle volume and emission load for LV vehicle types in Makassar City

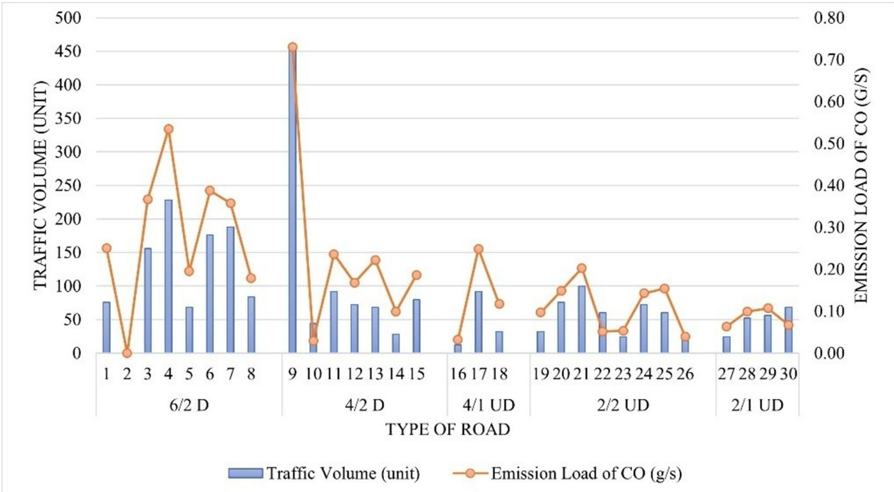
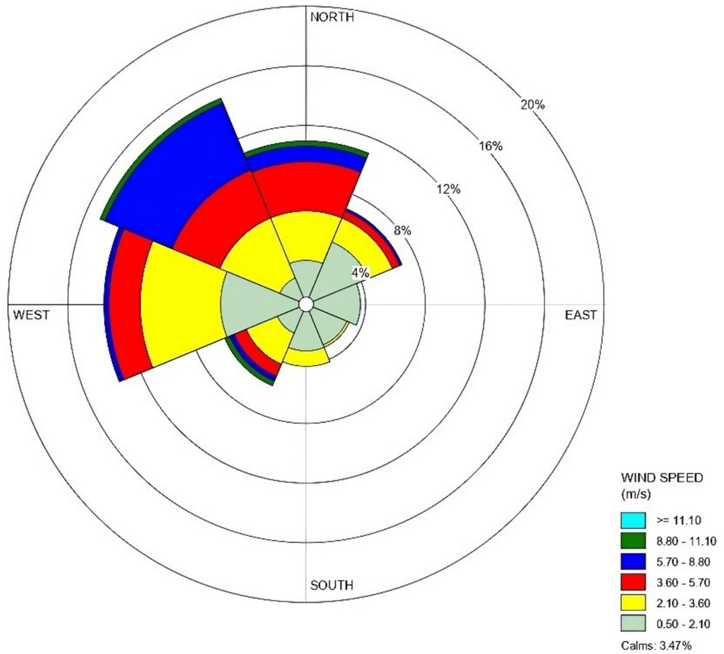


Fig. 5 Distribution of vehicle volume and emission load for HV vehicle types in Makassar City

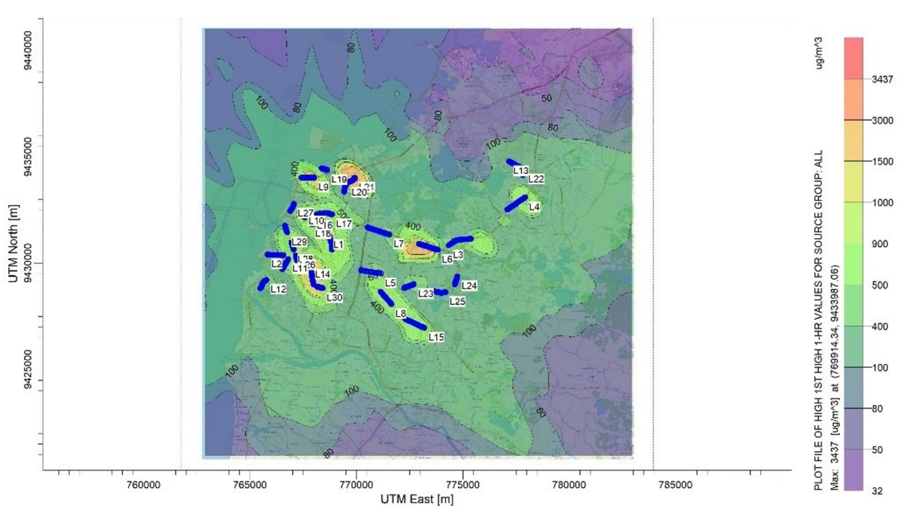
Light vehicles (LV) consistently generate the most emissions across all road types, followed by motorbikes (MC). This indicates that despite the higher quantity of motorbikes, light vehicles generate greater CO emissions per unit due to the emission factors that used in the emission load. Similar findings were also reported by Auliah, who applied the Tier 2 method on collector roads in Makassar and observed that LV and MC contributed the largest portions of emission loads [13]. This supports the emission pattern observed in the present study, where LV and MC categories consistently dominated CO emissions across all road types. These emissions are associated with increased fuel consumption which is caused by an incomplete combustion process in the engine system [3]. Simultaneously, the impact of heavy vehicles (HV) is comparatively minimal across all road types, consistent with their limited presence in urban regions. Moreover, a positive correlation exists between vehicle volume and CO emissions across all road types, whereby an increase in vehicle count corresponds with a rise in total emissions. This relationship is not consistently linear. The maximum vehicle volume (LV) occurs on L7, although the emission load is greater on L14. The vehicle volume on the two roads is similar, with 3,144 units on L7 and 2,224 units on L14. The disparity in the position of the highest emission load can be affected by road characteristics [3, 13, 14] specifically the actual Vehicle Kilometers Traveled (VKT) value of L14 (1.52 km), which exceeds the road length of L7 (0.8 km). The minimum emission load is seen on the shortest road, L12, situated in Pasar Baru Daya Makassar.

3.3 Distribution of CO gas concentration based on the dispersion model

According to the wind rose (Fig. 6), wind speeds are classified into six categories: 0.5–2.1 m/s, 2.1–3.6 m/s, 3.6–5.7 m/s, 5.7–8.8 m/s, 8.8 – 11.1 m/s, and >= 11 m/s. The average dominant wind direction is northwest with a wind speed of 5.7-8.8 m/s. Figure 5. Based on the point at a distance of 0 meters on the map, it is the actual measurement location or assumed emission source point. As the distance from the measurement location or emission source increases, it can be seen that the CO concentration tends to change significantly. Where the CO concentration at sampling points 1-8 will decrease to a radius of 1 km around the location, leading to the prevailing wind direction in the city of Makassar. The measurement model results for each point at a distance of 0 meters from the measurement location of road type 6/2 D can be seen in Figure.



(a) Wind Rose



(b) CO Concentration

Fig. 6. Dispersion Pattern of (a) Wind Rose and (b) CO Concentration in Makassar City

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4 Discussion

4.1 Comparison of CO Concentration between Field Measurements and Dispersion Model Results

As shown in Table 3, ground measurements of CO content at 30 observation sites revealed significant heterogeneity across road types in Makassar City. The highest carbon monoxide concentrations were observed on road types 4/1 UD, 4/2D, and 6/2D, particularly at points 18 (St. G. Bawakaraeng), 14 (St. Metro Tanjung Bunga), and 4 (St. Bumi Tamalanrea Permai), with values of 1.664 μg/m³, 1.254 μg/m³, and 1.212 μg/m³, respectively. Conversely, the lowest concentrations were recorded at point 20 (St. Sunu) and point 29 (St. Penghibur), measuring 245 μg/m³ and 384 μg/m³ in road types 2/2UD and 2/1UD. The highest average concentration value was recorded on 4/2D at 803 μg/m³, followed by 6/2D at 756 μg/m³ and 4/1 UD at 739 μg/m³. The concentration levels for road types 2/2 UD and 2/1 UD are diminished, with average values of 644 and 501 μg/m³, respectively, corresponding to the reduced traffic intensity on these road types. Nonetheless, elevated vehicle volume does not inherently indicate high carbon monoxide concentrations, as exemplified by 6/2D highways. This is attributable to road parameters, including road width, which can influence concentration distribution. Hasairin similarly emphasized that although traffic density is a major determinant of CO levels, local environmental factors may modify the resulting concentration patterns. Furthermore, a recent study on NO_2 nowcasting demonstrated that road geometry, particularly street width, length, and betweenness centrality, accounts for more than 80% of the variance in pollutant concentrations across urban corridors, confirming that physical characteristics of the roadway significantly shape spatial pollutant distribution [15].

Table 3. Distribution of CO concentration based on ground measurement and prediction

Type of Road	Code	Ground Measurement	Prediction
6/2 D	1	415	443
	2	601	607
	3	754	659
	4	1,212	1,054
	5	1,001	707
	6	1,071	1,144
	7	808	714
	8	768	719
4/2 D	9	657	712
	10	967	707
	11	1,253	1,181
	12	957	821
	13	659	569
	14	1,145	1,320
	15	229	309
4/1 UD	16	403	412
	17	665	694
	18	1,664	1,110
2/2 UD	19	538	556

Type of	Code	Ground Measurement	Prediction
	20	245	275
	21	634	701
	22	739	576
	23	557	475
	24	1,151	735
	25	965	790
	26	323	548
2/1 UD	27	403	368
	28	450	379
	29	384	381
	30	768	849

The outcomes of the CO dispersion model indicate that the predicted concentration values closely align with the ground measurement findings, exhibiting a comparable distribution pattern across all road types (Table 3). The model results indicated the maximum concentration on the 4/2 UD road type at position 14 (1,320 μg/m³), followed by the 6/2 D road type at point 6 (1,144 μg/m³) and the 4/1 UD road type at point 18 (1,110 μg/m³). Simultaneously, the minimal values were recorded at locations 20 (412 μg/m³) and 27 (368 μg/m³), situated on road types 2/2 UD and 2/1 UD, respectively. According to the statistical analysis, the Paired Sample T-Test showed a significance value of 0.45 ($p > 0.05$). This result indicates that there is no substantial discrepancy between the field-recorded carbon monoxide (CO) concentration and the dispersion model predictions. Hence, it can be statistically inferred that the employed dispersion model effectively represents CO concentration circumstances in the field and demonstrates an appropriate degree of suitability for spatial analysis and air quality forecasting in urban environments. Similarly, Salimi et al. demonstrated that Gaussian Process (GP), based dispersion modeling can accurately reproduce street-level pollutant variability by leveraging roadway geometry, reinforcing that models incorporating road characteristics are capable of reliably capturing real-world pollutant distribution patterns in complex urban settings [15].

5 Conclusion

The results of the study show that CO emission levels and concentrations in Makassar City are greatly influenced by vehicle volume and road type. Roads with types 6/2 D and 4/1 UD had the highest values in both field measurements and modeling results. The CO concentration measured ranged from 229 to 1,684 μg/m³, while the model results ranged from 275 to 1,320 μg/m³, with a consistent distribution pattern. The Paired Sample T-Test results showed a significance value of 0.45 ($p > 0.05$), indicating no significant difference between the measurement results and the model results. Thus, the dispersion model is considered capable of accurately representing the actual CO concentration conditions in the field and can be accepted as a spatial analysis tool for controlling transportation emissions in urban areas.

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