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Coupled MOVES–AERMOD modeling and field validation of carbon monoxide dispersion from motorcycle-dominated traffic at a complex five-leg urban intersection in Makassar, Indonesia

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ABSTRACT

Urban intersections are major hotspots of traffic-related carbon monoxide (CO) pollution in rapidly growing cities. However, integrated emission–dispersion modeling studies with field validation remain limited in developing urban regions, particularly in Eastern Indonesia. This study aimed to simulate and validate CO dispersion at the Mandai Five-Leg Intersection, Makassar, using an integrated MOVES–AERMOD framework. Traffic data were collected through 12-hour classified traffic surveys and grouped into motorcycles, passenger vehicles, and heavy-duty vehicles. Vehicular CO emissions were estimated using emission factors derived from the Motor Vehicle Emission Simulator (MOVES3), while atmospheric dispersion was simulated using AERMOD with site-specific meteorological data obtained from BMKG Region IV Makassar. Model performance was evaluated using field measurements at monitoring locations and statistical indicators including mean bias (MB), root mean square error (RMSE), and coefficient of determination (R^2). The results showed that peak traffic occurred during the evening period (17:00–18:00 WITA), with motorcycle volume reaching 5,080 veh/h. Motorcycles were identified as the dominant emission source, contributing 39,457.06 g/h of CO emissions. AERMOD simulations produced maximum CO concentrations of 83.2 $\mu g/m^3$ for the 1-hour averaging period and 12.1 $\mu g/m^3$ for the 24-hour averaging period near the intersection center. Validation results demonstrated strong agreement between observed and simulated concentrations (MB = 3.8 $\mu g/m^3$, RMSE = 4.40 $\mu g/m^3$, $R^2 = 0.92$). The study confirms that the integrated MOVES–AERMOD framework can reliably represent traffic-related CO dispersion and provides useful support for urban air quality management in rapidly urbanizing tropical cities.

Keywords: carbon monoxide, MOVES, AERMOD, traffic emission, urban intersection, air quality modeling.

INTRODUCTION

Urban air pollution caused by traffic emissions has become one of the most critical environmental challenges in rapidly developing cities, particularly in Southeast Asia where motorization rates continue to increase significantly. Carbon monoxide (CO), as one of the primary pollutants emitted from incomplete combustion of fossil fuels, is closely associated with vehicular activity and is strongly influenced by traffic density, fleet composition, and driving behavior. In urban transportation corridors, intersections often represent localized pollution hotspots due to repeated vehicle acceleration–deceleration cycles and congestion-induced emission amplification (Choudhary and Gokhale, 2019; Chen et al., 2022). These conditions make intersection-scale air quality assessment essential for understanding real-world exposure patterns in urban environments.

Previous studies have demonstrated that vehicular emissions are highly sensitive to traffic composition and operational conditions. In particular, motorcycle-dominated traffic systems, which are common in many developing cities, tend to generate substantial CO emissions due to inefficient combustion under stop-and-go conditions (Both et al., 2013; Rahma et al., 2025). Similarly, studies in urban transport corridors have shown that congestion significantly increases emission intensity and near-road pollutant accumulation (Choudhary and Gokhale, 2019; Li et al., 2023). These findings indicate that traffic characteristics, especially fleet composition and congestion patterns, play a dominant role in shaping urban air pollution profiles.

In addition to traffic activity, meteorological conditions are widely recognized as key determinants of pollutant dispersion in urban environments. Wind speed, wind direction, and atmospheric stability directly influence pollutant transport, dilution, and accumulation processes. Studies using atmospheric dispersion models have confirmed that meteorological variability significantly affects model accuracy and pollutant concentration distribution (Afzali et al., 2017; Kumar et al., 2017). AERMOD, as a widely used regulatory dispersion model, has been applied in various urban environments and has demonstrated reliable performance when supported by accurate meteorological and emission inputs (Askariyeh et al., 2017; Eslamidoost et al., 2023).

Urban morphology further modifies pollutant dispersion by influencing airflow patterns and creating localized turbulence zones. Road geometry, building configuration, and surface roughness can alter wind flow and reduce dispersion efficiency, particularly in complex intersections (Finlayson-Pitts and Pitts, 2000; Tee et al., 2020). In such environments, pollutant accumulation tends to be highly heterogeneous, with elevated concentrations occurring in zones of restricted airflow. These characteristics highlight the need for integrated modeling approaches that consider both emission sources and micro-scale atmospheric behavior.

Recent advancements in emission and dispersion modeling have increasingly focused on integrating traffic activity data with atmospheric models to improve prediction accuracy. The MOVES emission model has been widely used for estimating vehicle-specific emissions under varying traffic conditions, while AERMOD is commonly applied for simulating pollutant dispersion in urban environments. Studies have shown that coupling emission inventories with dispersion models improves the reliability of air quality assessments, particularly in complex traffic systems (Lei et al., 2024; Park et al., 2023). However, most existing studies still rely on generalized traffic assumptions or limited field validation, which reduces their applicability to heterogeneous urban intersections in developing countries.

In the context of Indonesian cities, rapid urbanization and increasing vehicle ownership have intensified traffic congestion and air pollution problems, particularly in major metropolitan areas such as Makassar. Previous studies have highlighted that urban transportation corridors in Indonesia are characterized by high motorcycle dependency and complex traffic dynamics, which significantly contribute to local air pollution levels (Surya et al., 2020; Santoso et al., 2020). However, detailed intersection-scale analyses that integrate real traffic data, emission modeling, and dispersion simulation remain limited. This gap restricts the understanding of localized pollutant behavior in highly dynamic urban intersections.

Therefore, the research gap identified in this study lies in the lack of integrated, field-validated modeling frameworks that combine localized traffic characterization, emission estimation, and atmospheric dispersion analysis at complex urban intersections dominated by motorcycle traffic. The significance of this study is its contribution to improving the methodological integration of MOVES and AERMOD models under real-world tropical urban conditions, providing more accurate representation of near-road CO dispersion patterns. The aim of this study is to evaluate carbon monoxide emission and dispersion from motorcycle-dominated traffic at a complex five-leg urban intersection in Makassar using a coupled MOVES–AERMOD modeling framework validated with field measurements.

MATERIALS AND METHOD

Study area

This study was conducted at the Mandai Five-Leg Intersection in Makassar City, South Sulawesi, Indonesia (5°05′13″ S; 119°32′18″ E), which represents a high-traffic urban intersection dominated by motorcycles, passenger vehicles, and freight transportation. The study area consists of five connected road segments forming a signalized intersection with multidirectional traffic flow and frequent stop-and-go vehicle movement. A 2 × 2 km modeling domain centered on the intersection was established for the dispersion simulation. Terrain elevation data with 30 m spatial resolution were obtained from the shuttle radar topography mission (SRTM) to characterize surface topography within the modeling area, which was generally classified as flat urban terrain. Meteorological data for 26–27 September 2025, including wind speed, wind direction, temperature, and atmospheric conditions, were obtained from BMKG Region IV Makassar and processed using the AERMET preprocessor before being incorporated into the AERMOD dispersion model. The spatial layout of the study area, roadway geometry, and monitoring locations are presented in Figure 1.

Research framework

This study applied a reproducible four-stage framework consisting of traffic data collection, emission estimation, dispersion modeling, and model validation. Traffic volume data were collected through hourly classified traffic counts at the Mandai Five-Leg Intersection (Figure 2) and grouped into motorcycles, gasoline passenger cars, diesel passenger cars, light-duty trucks, and heavy-duty trucks. Vehicular CO emissions were estimated using MOVES3 emission factors (EPA, 2021; EPA, 2023) by multiplying hourly traffic volume (veh/h) by the corresponding emission factor (g/km) assuming a representative travel distance of 1 km, and the results were converted into g/s for AERMOD input. Dispersion modeling was performed using AERMOD by representing roadway emissions as line sources along the five road segments within a 2 × 2 km modeling domain. Meteorological data including wind speed, wind direction, temperature, and atmospheric stability were obtained from BMKG Region IV Makassar and processed using AERMET, while terrain characteristics were derived from SRTM 30 m elevation data and classified as flat urban terrain. Model validation was conducted by comparing simulated and observed CO concentrations at monitoring locations around the intersection using the coefficient of determination (R^2), mean bias (MB), and root mean square error (RMSE). The overall research workflow consisting of traffic counting, MOVES3 emission estimation, AERMOD simulation, and field validation is presented in Figure 2.

Traffic volume survey and vehicle classification

Traffic volume data were collected at the Mandai Five-Leg Intersection through manual classified traffic counting conducted for 12 hours per day (07:00–21:00 WITA) during 26–27

Figure 1. Location of the Mandai Five-Leg intersection and vehicular traffic survey points in Makassar City, Indonesia

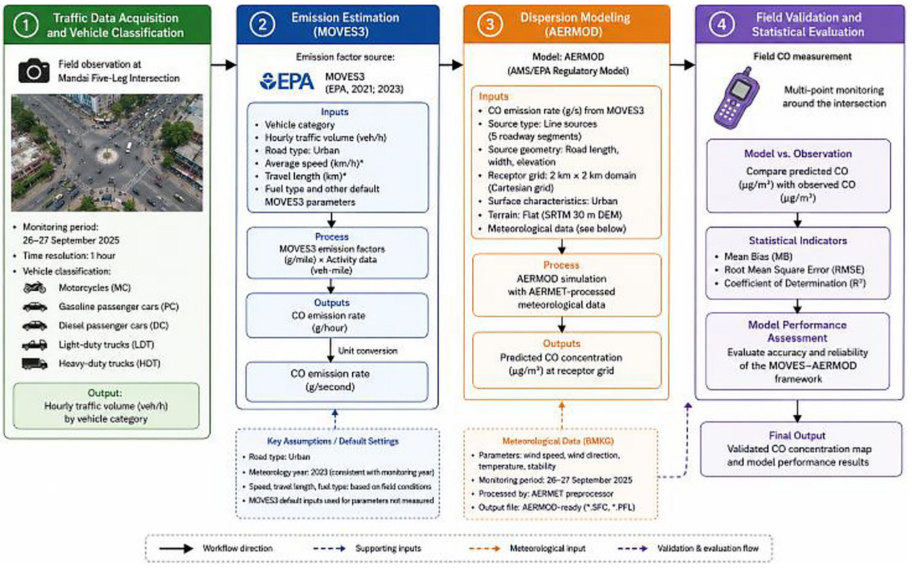

Figure 2. Research framework of the integrated MOVES-AERMOD modelling and field validation

September 2025 to capture daily traffic variation. Traffic observations were supported by an Android-based digital multi-counter application (Figure 3), and vehicles were classified into five categories consisting of motorcycles, gasoline passenger cars, diesel passenger cars, light-duty trucks, and heavy-duty trucks. Observers were positioned at each approach of the five-leg intersection, and multiple trained observers were assigned to minimize counting errors and overlapping records. Traffic counts were recorded in real time and expressed as hourly traffic volume (veh/h) for each vehicle category. The collected data were cross-checked during field observations and subsequently aggregated to obtain total hourly traffic volume for each vehicle category. The highest hourly traffic volume observed during the monitoring period was selected as the representative traffic condition for vehicular emission estimation and AERMOD dispersion modeling. The overall workflow consisting of field observation, vehicle classification, hourly counting, data verification, aggregation, and peak-hour selection is illustrated in Figure 3.

Figure 3. Android-based digital multi-counter application used for traffic volume survey at the Mandai Five-Leg intersection

Meteorological data collection

Meteorological data used for atmospheric dispersion modeling were obtained from BMKG Region IV Makassar for the monitoring period of 26–27 September 2025 and included hourly wind speed (m/s), wind direction (°), ambient temperature (°C), and other atmospheric variables required for AERMOD simulation. Surface observations were collected from the BMKG Makassar meteorological station located nearest to the Mandai Five-Leg Intersection, which was characterized as an urban transportation corridor with mixed roadway and commercial land use. The collected meteorological data were checked for consistency and completeness before processing. Wind characteristics were analyzed using WRPLOT View software to generate wind rose diagrams and identify dominant wind direction and airflow patterns, which indicated prevailing wind movement from east to west during the monitoring period. The average observed wind speed was 3.27 m/s. The validated meteorological dataset was subsequently processed using the AERMET meteorological preprocessor to generate atmospheric boundary layer parameters required for AERMOD simulation, including friction velocity, Monin–Obukhov length, convective velocity scale, mixing height, and atmospheric stability class. The processed outputs were then formatted according to AERMOD input requirements and incorporated into the atmospheric dispersion modeling framework.

Estimation of vehicular CO emissions

Vehicular CO emissions were estimated using vehicle-specific emission factors obtained from the Motor Vehicle Emission Simulator (MOVES3) developed by the United States Environmental Protection Agency (EPA, 2021; EPA, 2023). Hourly classified traffic volume data collected at the Mandai Five-Leg Intersection during the monitoring period were used as activity data and grouped into five vehicle categories: motorcycles, gasoline passenger vehicles, diesel passenger vehicles, light-duty trucks, and heavy-duty trucks. Total hourly CO emissions were calculated by multiplying the hourly traffic volume of each vehicle category by its corresponding CO emission factor using Equation 1:

$$E_{CO} = \sum_{i=1}^{n} (V_i \times FE_{CO,i}) \tag{1}$$

where: E_{CO} is the total CO emission rate (g/h), V_i is the traffic volume for vehicle category i(veh/h), and $FE_{CO,i}$ is the CO emission factor for vehicle category i(g/km).

The emission factors used in this study were 7.767 g/km for motorcycles, 0.631 g/km for gasoline passenger vehicles, 0.751 g/km for diesel passenger vehicles, 0.969 g/km for light-duty trucks, and 0.915 g/km for heavy-duty trucks. A representative roadway length of 1 km was applied for all traffic corridors to standardize emission estimation. The calculated emissions expressed in grams per hour (g/h) were subsequently converted into grams per second (g/s) and incorporated as line-source emission inputs in the AERMOD dispersion model according to the roadway geometry of the Mandai Five-Leg Intersection.

Atmospheric dispersion modeling using AERMOD

Atmospheric dispersion of vehicular CO emissions was simulated using the American Meteorological Society/United States Environmental Protection Agency Regulatory Model (AERMOD). Vehicular emissions estimated from the MOVES3 framework were represented as line-source emissions distributed along the roadway segments forming the Mandai Five-Leg Intersection, where each road segment was defined as an individual emission source. The AERMOD simulation incorporated four primary inputs consisting of vehicular emission rates, meteorological data processed using AERMET, roadway geometry, and terrain characteristics. Meteorological inputs included wind speed, wind direction, ambient temperature, atmospheric stability, friction velocity, and boundary layer parameters obtained from AERMET preprocessing. The modeling domain covered a 2 × 2 km area centered on the intersection, and a Cartesian receptor grid was applied to estimate ambient CO concentrations across the study area. Traffic-related emissions were assigned as near-surface emission sources consistent with roadway emission characteristics, while terrain conditions were classified as relatively flat based on SRTM elevation data. Simulations were performed for 1-hour and 24-hour averaging periods to evaluate short-term and daily pollutant dispersion conditions. The resulting concentration distributions were visualized as contour maps to identify pollutant accumulation zones and near-road exposure patterns, and the simulated concentrations were subsequently compared with field measurements to evaluate model performance and reproducibility of the integrated MOVES–AERMOD framework.

Field measurement and model validation

Field measurements of ambient CO concentrations were conducted at five monitoring locations surrounding the Mandai Five-Leg Intersection to validate the integrated MOVES–AERMOD modeling framework. Monitoring points were selected based on roadway geometry, traffic intensity, and prevailing wind direction to represent different traffic exposure conditions within the study area. Ambient CO concentrations were measured using a portable CO monitoring instrument positioned at roadside locations at breathing-zone height during the monitoring period. The instrument was inspected and calibrated prior to field measurements to ensure data consistency. Observed CO concentrations were compared with AERMOD-simulated concentrations at the corresponding monitoring locations and averaging periods. Model performance was evaluated using MB, RMSE, and the coefficient of determination (R^2). MB was calculated using Equation 2:

$$MB = \frac{\sum(C_{model} - C_{obs})}{n} \tag{2}$$

The root mean square error (RMSE) was calculated using Equation 3:

$$RMSE = \sqrt{\frac{\sum(C_{model} - C_{obs})^2}{n}} \tag{3}$$

where: C_{model} is the modeled CO concentration, C_{obs} is the observed CO concentration, and n is the number of monitoring points.

The validation procedure was used to evaluate the accuracy and reproducibility of the MOVES–AERMOD framework for simulating traffic-related CO dispersion under urban traffic and meteorological conditions.

Data analysis

All traffic, meteorological, vehicular emission, and ambient CO concentration data collected during the study were processed and analyzed quantitatively using Python version 3.11 with the pandas, numpy, matplotlib, and scikit-learn libraries. Traffic volume, meteorological observations, emission inventory data, and field measurements were temporally aligned according to the monitoring schedule, while missing data were treated using linear interpolation and potential outliers were evaluated using the interquartile range (IQR) method. Descriptive statistical analyses including mean, minimum, maximum, and standard deviation were calculated for traffic activity, meteorological parameters, emission rates, and CO concentrations. Temporal traffic and pollutant variations were visualized using time-series analysis, while spatial CO dispersion was simulated using the AERMOD atmospheric dispersion model with meteorological inputs processed through AERMET and vehicular emissions estimated from the MOVES3 framework. Model performance was evaluated by comparing modeled and observed CO concentrations using the coefficient of determination (R^2), MB, and RMSE, while residual analysis was additionally performed to identify systematic prediction errors. All analyses were conducted within the same spatial domain centered on the Mandai Five-Leg Intersection to ensure consistency and reproducibility of the integrated traffic emission and dispersion modeling framework.

Data availability and reproducibility

All traffic, meteorological, emission inventory, field measurement, and atmospheric dispersion modeling data generated in this study were systematically documented to ensure transparency and reproducibility of the integrated MOVES–AERMOD framework. The archived datasets included hourly classified traffic counts, meteorological observations obtained from BMKG Region IV Makassar, MOVES3-based emission factor tables, hourly vehicular emission calculations, AERMET preprocessing outputs, AERMOD configuration and simulation files, receptor-grid settings, and observed ambient CO concentrations measured at field monitoring locations. Wind rose outputs generated using WRPLOT View, spatial concentration contour maps, and statistical validation results including MB, RMSE, and coefficient of determination (R^2) were also documented. All data processing, statistical analyses, visualization procedures, and model evaluation workflows were conducted using reproducible Python-based computational scripts. The compiled datasets, processing workflows, and modeling configurations can be made available by the corresponding author upon reasonable request for academic and non-commercial research purposes.

RESULTS AND DISCUSSION

Meteorological characteristics and wind pattern analysis

Meteorological conditions play an important role in controlling the transport, dilution, and accumulation of traffic-related air pollutants in urban environments. In this study, meteorological data obtained from BMKG Region IV Makassar were processed using WRPLOT View to evaluate local wind characteristics during the monitoring period, and the resulting wind rose diagram is presented in Figure 4. The analysis showed that the dominant airflow moved from the eastern sector toward the western part of the study area, indicating that pollutant transport at the Mandai Five-Leg Intersection was primarily controlled by easterly wind circulation. The average wind speed during the observation period was approximately 3.27 m/s, while calm conditions occurred only in a small proportion of observations, indicating relatively continuous atmospheric movement throughout the monitoring period. According to Ahrens (2019), wind rose analysis is widely used to evaluate atmospheric circulation and pollutant transport pathways in urban environments.

The observed meteorological conditions indicate that pollutant dispersion at the study area was moderately effective; however, the complex five-leg intersection geometry and high traffic density likely contributed to localized pollutant accumulation, particularly during congestion periods. Similar findings were reported by Choudhary and Gokhale (2019), who found that interrupted traffic flow and repeated acceleration–deceleration cycles at urban intersections increase pollutant accumulation. Likewise, Chen et al. (2022) reported that congestion conditions can intensify near-road CO concentrations because low-speed traffic operation increases emissions while reducing pollutant dispersion efficiency. The dominant east-to-west wind pattern observed in this study is also consistent with regional atmospheric circulation in South Sulawesi and previous observations reported by Assegaf and Jayadipraja (2015) and Surya et al. (2020).

Meteorological conditions are also important for determining the reliability of atmospheric dispersion modeling. Previous studies demonstrated that meteorological inputs strongly influence AERMOD simulation accuracy, particularly in urban transportation corridors with fluctuating emission intensity. Afzali et al. (2017) reported that integrating meteorological forecasting systems with dispersion models improves pollutant prediction reliability, while Kumar et al. (2017) emphasized the importance of atmospheric stability and wind variability in reducing simulation

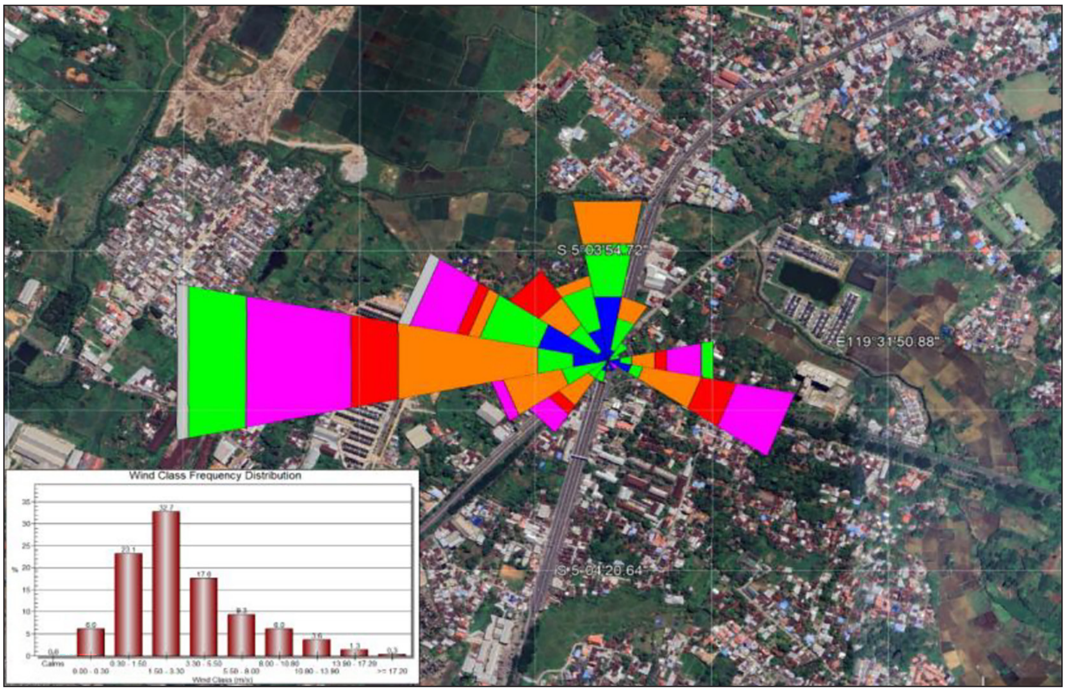

Figure 4. Wind rose pattern during the study period at the Mandai Five-Leg intersection

uncertainty. In addition to meteorological conditions, urban morphology such as buildings, road geometry, and roadside structures may also influence airflow turbulence and pollutant accumulation. Similar observations were described by Finlayson-Pitts and Pitts (2000) and Tee et al. (2020), who highlighted that urban canopy structures can modify near-surface airflow and create heterogeneous pollutant dispersion patterns.

The relatively flat topography surrounding the Mandai Five-Leg Intersection likely supported horizontal pollutant transport without major terrain-induced airflow obstruction. However, near-road pollutant concentrations may still remain high because vehicular emissions are continuously released at low atmospheric heights near traffic corridors. Demirarslan (2025) demonstrated that traffic density and roadway geometry remain dominant factors influencing near-road pollutant concentrations in urban-scale simulations, while Askariyeh et al. (2017) reported that AERMOD performs effectively when accurate traffic and meteorological data are incorporated into the model. These findings indicate that the Mandai Five-Leg Intersection represents a dynamic urban environment where pollutant dispersion is controlled by the interaction between traffic activity, atmospheric circulation, and roadway configuration.

Traffic characteristics and vehicular activity

Traffic activity at the Mandai Five-Leg Intersection showed significant temporal variation associated with commuting patterns, commercial activities, and regional transportation connectivity. Hourly traffic volume for each vehicle category is presented in Table 1, while temporal traffic fluctuations during the observation period are illustrated in Figure 5. The results indicate that motorcycles were the dominant vehicle type throughout the monitoring period, followed by gasoline passenger cars. Peak traffic conditions occurred during the evening period (17:00–18:00 WITA), when motorcycle traffic volume reached 5,080 veh/h, while gasoline passenger cars, diesel passenger cars, light-duty trucks, and heavy-duty trucks reached 2,132, 422, 326, and 59 veh/h, respectively. These findings indicate a strong dependence on private motorized transportation, particularly motorcycles, within the Makassar urban transportation system.

The temporal traffic pattern showed increased vehicle activity during afternoon and evening periods, corresponding to commuting and commercial activities. Similar traffic characteristics have been widely reported in rapidly urbanizing Southeast Asian cities where motorcycle dominance and congestion are common urban transportation features (Both et al., 2013). Rapid urban growth and increasing socio-economic activities in Makassar have also intensified transportation demand and traffic congestion within major urban corridors (Surya et al., 2020). The operational complexity of the five-leg intersection, including traffic interruptions, turning movements, and stop-and-go driving conditions, likely increased fuel consumption and vehicular emission intensity. Similar observations were reported by

Table 1. Hourly traffic volume at the Mandai Five-Leg intersection

Time period	Observation time	Motorcycles	Gasoline passenger cars	Diesel passenger cars	Light-duty trucks	Heavy-duty trucks
Morning	07:00–08:00	2970	1427	285	293	28
	08:00–09:00	3524	1618	324	304	56
	09:00–10:00	2836	1686	337	210	30
Afternoon	12:00–13:00	4368	2025	415	311	59
	13:00–14:00	3647	1734	347	213	32
	14:00–15:00	2444	1870	374	242	36
Evening	15:00–16:00	2728	2028	416	296	46
	16:00–17:00	3878	1952	390	217	37
	17:00–18:00	5080	2132	422	326	37
Night	18:00–19:00	4716	1833	387	237	36
	19:00–20:00	3606	1715	383	226	34
	20:00–21:00	3217	1549	350	198	23
Maximum value		5080	2132	422	326	59

Choudhary and Gokhale (2019) and Chen et al. (2022), who found that congestion and repeated acceleration–deceleration cycles significantly increase on-road vehicle emissions.

The dominance of motorcycles has important implications for urban air quality because motorcycles generally produce relatively high CO emissions under congested traffic conditions. According to the MOVES3 emission inventory framework (EPA, 2021), gasoline-powered motorcycles generate elevated CO emissions due to incomplete combustion during low-speed operation and idling conditions. Similar findings were reported by Rahma et al. (2025), who identified motorcycles and gasoline-powered vehicles as major contributors to urban CO pollution in developing cities. In addition to traffic volume, fleet composition and vehicle operational characteristics strongly influence urban emission dynamics and pollutant accumulation patterns (Li et al., 2023). Liu et al. (2018) further explained that gasoline combustion remains one of the primary sources of urban carbon monoxide emissions.

Accurate traffic characterization is essential for improving the reliability of emission estimation and atmospheric dispersion modeling. Previous studies demonstrated that traffic activity, vehicle-specific operating conditions, and traffic speed significantly influence MOVES-based emission inventories and dispersion model performance (Lei et al., 2024; Park et al., 2023). The extremely high motorcycle traffic volume observed during peak-hour conditions also indicates a substantial risk of localized roadside pollutant accumulation because traffic density and congestion strongly affect near-road pollutant concentrations (Khreis et al., 2020; Yirdaw et al., 2024). These findings are consistent with broader transportation trends in developing countries, where rapid urbanization and increasing private vehicle ownership contribute to worsening urban air pollution (Piracha and Chaudhary, 2022). Therefore, the traffic characteristics identified in this study provide important input for the integrated MOVES–AERMOD framework and highlight the need for sustainable traffic management strategies in Makassar City, as also emphasized by Rodrigues and da Costa (2026).

Estimation of vehicular CO emissions

Vehicular CO emissions at the Mandai Five-Leg Intersection were estimated by combining hourly traffic activity data with vehicle-specific emission factors derived from the MOVES3 model. The calculated emission rates for each vehicle category are presented in Table 2. The emission inventory was developed using the highest observed hourly traffic volume to represent peak traffic conditions at the intersection. The results indicate that motorcycles were the dominant source of CO emissions, producing approximately 39,457.06 g/h (0.4567 g/s), which was substantially higher than gasoline passenger cars (1,345.96 g/h), diesel passenger cars (317.02 g/h), light-duty trucks (315.80 g/h), and heavy-duty trucks (53.54 g/h). These findings show that

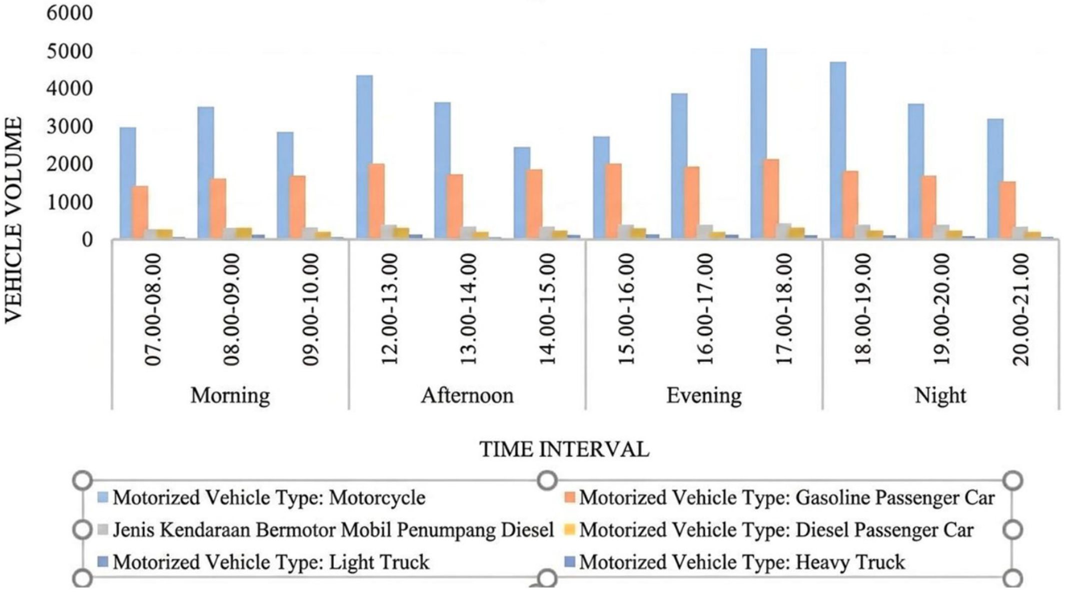

Figure 5. Hourly traffic volume fluctuation at the Mandai Five-Leg intersection

Table 2. Estimated carbon monoxide (CO) emissions from vehicular sources

No.	Vehicle category	Traffic volume (veh/h)	Travel length (km)	CO emission factor (g/km)	Estimated CO emission (g/h)	CO emission rate (g/s)
1	Motorcycles	5080	1.0	7.767	39457.06	0.4567
2	Gasoline passenger cars	2132	1.0	0.631	1345.96	0.0156
3	Diesel passenger cars	422	1.0	0.751	317.02	0.0037
4	Light-duty trucks	326	1.0	0.969	315.80	0.0037
5	Heavy-duty trucks	58.5	1.0	0.915	53.54	0.0006

Note: MOVES3 Vehicle Operation Emission Factors (EPA, 2021).

traffic-related CO emissions at the study area were strongly influenced by motorcycle activity and gasoline-powered vehicles.

The high contribution of motorcycles to total CO emissions is associated with both their large traffic volume and relatively high CO emission factors under congested traffic conditions. Repeated acceleration–deceleration cycles, idling, and unstable engine loads during stop-and-go traffic conditions increase incomplete fuel combustion and consequently elevate CO formation. Similar findings were reported by Choudhary and Gokhale (2019) and Chen et al. (2022), who demonstrated that traffic congestion significantly increases vehicular emissions in urban transportation corridors. Motorcycle-dominated transportation systems have also been identified as major contributors to urban CO pollution in developing cities such as Jakarta and other Southeast Asian metropolitan areas (Both et al., 2013; Rahma et al., 2025). Although heavy-duty vehicles generally have higher fuel consumption, their contribution to total CO emissions in this study remained relatively low due to their smaller traffic frequency, which is consistent with the findings reported by Liu et al. (2018) and Li et al. (2023).

The estimated emission inventory demonstrates the applicability of the MOVES3 framework for evaluating urban vehicular emissions when combined with localized traffic activity data. Previous studies reported that MOVES-based approaches provide reliable emission estimation for heterogeneous urban traffic systems, particularly when vehicle operating conditions and traffic dynamics are incorporated into the analysis (Lei et al., 2024; Park et al., 2023). The high CO emission intensity identified at the Mandai Five-Leg Intersection also reflects broader urban environmental challenges associated with rapid urbanization and increasing transportation demand in Makassar City (Surya et al., 2020). In addition, transportation-related emissions contribute to worsening urban air quality and increased environmental health risks in rapidly developing metropolitan regions (Piracha and Chaudhary, 2022). Therefore, the emission characteristics identified in this study highlight the importance of sustainable traffic management and emission reduction strategies for improving urban air quality.

Spatial dispersion of CO concentration using AERMOD

The spatial distribution of CO concentrations at the Mandai Five-Leg Intersection was simulated using the AERMOD atmospheric dispersion model based on observed traffic emissions and local meteorological conditions. The resulting concentration contours for the 1-hour and 24-hour averaging periods are presented in Figures 6 and 7, respectively. The simulation results showed that the maximum predicted CO concentration for the 1-hour averaging period reached 83.2 µg/m³ near the central intersection area, while the 24-hour average concentration decreased to 12.1 µg/m³ due to atmospheric dilution and temporal averaging effects. The concentration contours followed the roadway orientation, indicating that vehicular traffic was the dominant source controlling ambient CO distribution within the study area.

Higher pollutant accumulation was consistently observed near the central intersection and roadway segments characterized by heavy traffic flow, idling, and repeated acceleration–deceleration activity. Similar near-road pollutant behavior has been reported by Askariyeh et al. (2017), who demonstrated that AERMOD effectively reproduces pollutant accumulation patterns in congested roadway environments. Choudhary and Gokhale (2019) also reported that traffic interruption and congestion significantly increase near-road pollutant

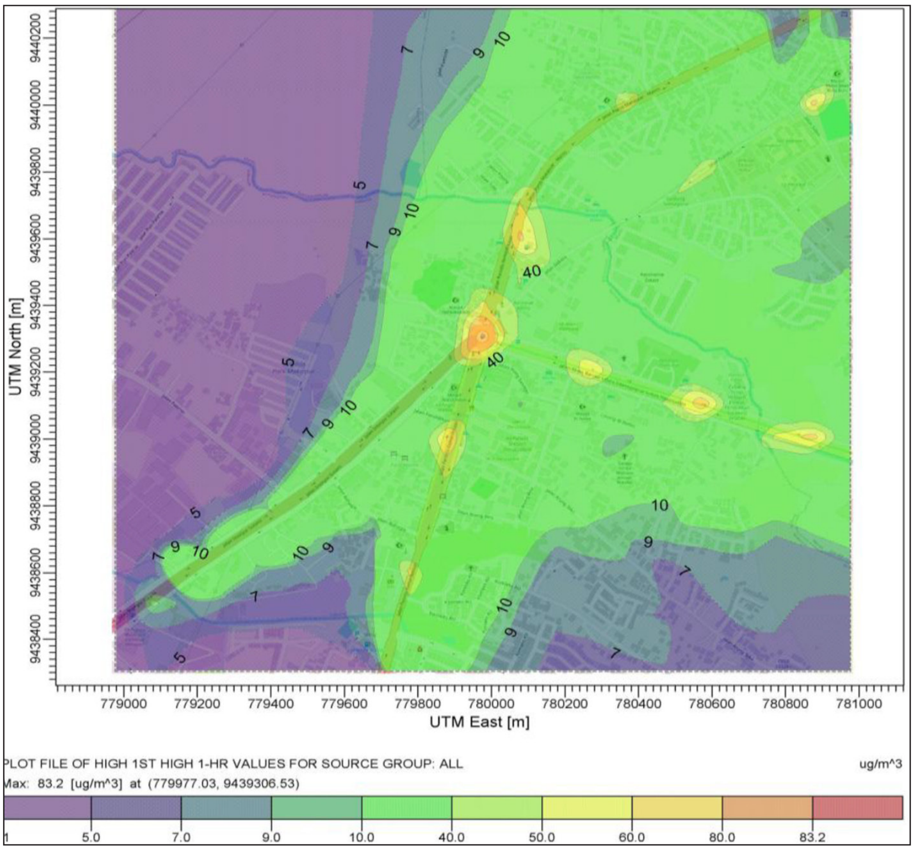

Figure 6. Simulated spatial distribution of CO concentration for the 1-hour averaging period

accumulation due to unstable vehicle movement and increased engine loads. The dominant easterly wind pattern observed during the monitoring period promoted westward pollutant transport, producing asymmetric concentration contours extending along the downwind roadway corridor. Similar relationships between meteorological conditions and pollutant transport were described by Afzali et al. (2017) and Kumar et al. (2017), who emphasized the importance of meteorological inputs in atmospheric dispersion modeling.

Despite relatively moderate wind conditions, pollutant accumulation remained evident near the intersection because of the combined influence of traffic density and urban geometry. Tee et al. (2020) explained that urban intersections can generate localized turbulence and airflow recirculation zones that reduce pollutant dilution efficiency near road surfaces, while Demirarslan (2025) highlighted the importance of roadway geometry and local topography in controlling pollutant dispersion patterns. The concentration distribution identified in this study is also consistent with findings from other rapidly urbanizing cities where transportation activity contributes significantly to roadside air pollution hotspots (Santoso et al., 2020; Surya et al., 2020). Both et al. (2013) further reported that roadside populations in densely populated Southeast Asian cities are frequently exposed to elevated traffic-related pollutant concentrations during peak-hour conditions.

The AERMOD simulation results demonstrate the importance of integrating localized traffic activity and meteorological data into urban air quality assessment. Previous studies showed that traffic congestion, fleet composition, and real-time traffic dynamics strongly influence pollutant dispersion and roadside exposure intensity (Li et al., 2023; Chen et al., 2022). Although the simulated CO concentrations remained below the Indonesian ambient air quality standards specified in Government Regulation No. 22 of 2021, continuous exposure near high-traffic intersections may still pose environmental and public health risks (Piracha and Chaudhary, 2022; Yirdaw et al., 2024). The present study also confirms the applicability of the integrated MOVES–AERMOD framework for evaluating traffic-related air pollution in tropical urban environments, consistent with previous findings reported by Rezaali et al. (2025) and Eslamidoost et al. (2023).

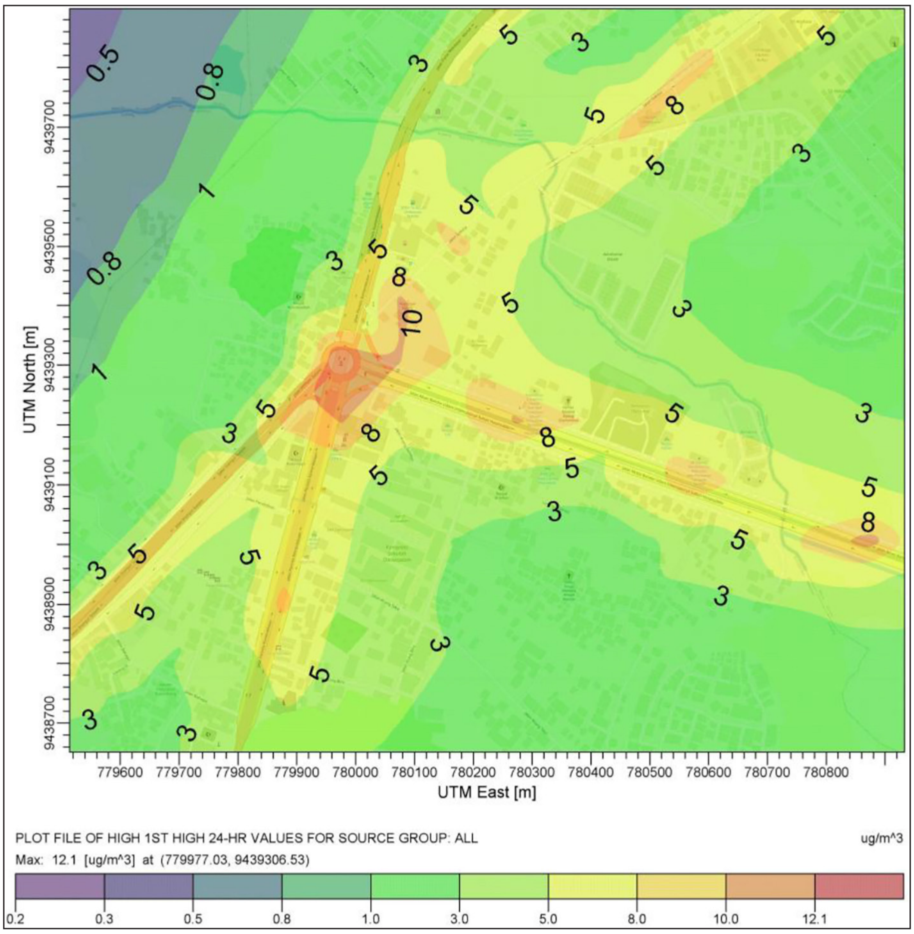

Figure 7. Simulated spatial distribution of CO concentration for the 24-hour averaging period

Model validation and performance evaluation

The reliability of the integrated MOVES–AERMOD framework was evaluated by comparing simulated carbon monoxide (CO) concentrations with field measurements collected at monitoring locations surrounding the Mandai Five-Leg Intersection. The comparison between observed and simulated concentrations is presented in Table 3, while the statistical relationship between both datasets is illustrated in Figure 8. Observed CO concentrations ranged from 38 to 54 µg/m³, whereas simulated concentrations varied between 40 and 60 µg/m³. Overall, the modeled values showed good agreement with field observations, indicating that the integrated framework successfully reproduced the magnitude and spatial distribution of near-road CO concentrations within the study area.

Statistical evaluation demonstrated strong model performance under complex urban traffic conditions. The coefficient of determination (R^2) reached 0.92, indicating a very strong correlation between observed and simulated concentrations. In addition, the MB value of 3.8 µg/m³ indicated a slight positive bias, while the RMSE value of 4.40 µg/m³ reflected relatively low prediction uncertainty for urban-scale applications. The model consistently produced slightly higher concentrations than field observations, particularly at Point 4, where the simulated concentration reached 60 µg/m³ compared with the observed value of 54 µg/m³. Nevertheless, the overall agreement confirms that the MOVES–AERMOD framework adequately reproduced near-road CO dispersion patterns within the complex five-leg intersection environment.

The slight overestimation observed in this study is consistent with the conservative behavior commonly associated with Gaussian dispersion models. Dresser and Huizer (2011) reported that AERMOD may generate slightly elevated concentration estimates because of conservative assumptions related to atmospheric stability and turbulence parameterization. Similar findings were reported by Askariyeh et al. (2017), who showed that AERMOD can overpredict near-road

Table 3. Comparison between observed and simulated CO concentrations

Monitoring point	Observed CO concentration (μg/m³)	AERMOD-simulated CO concentration (μg/m³)
Point 1	38	40
Point 2	40	42
Point 3	43	50
Point 4	54	60

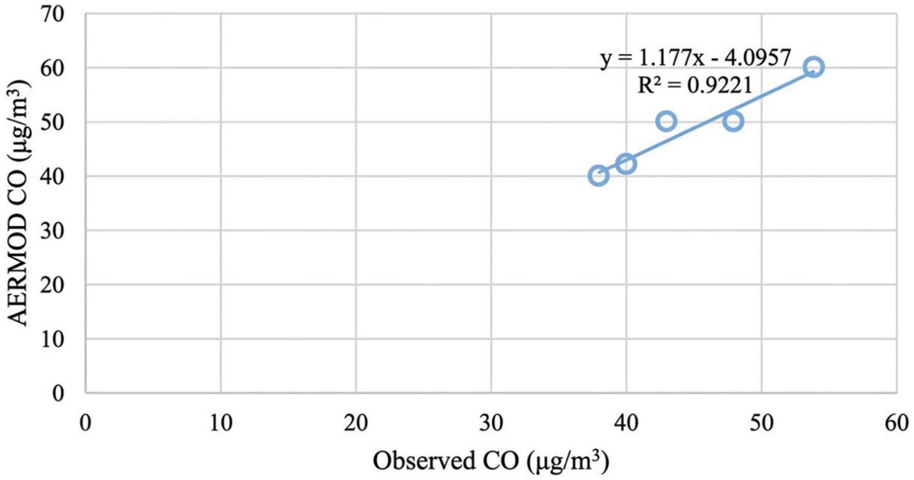

Figure 8. Correlation between observed and simulated CO concentrations

pollutant concentrations under low-wind and congestion-dominated conditions. Additional uncertainty in the present study may also be associated with localized turbulence, short-term traffic fluctuations, and complex airflow interactions generated by the five-leg intersection geometry. Despite these limitations, the model performance obtained in this study is comparable to or better than results reported in previous urban dispersion studies (Haq et al., 2019; Rezaali et al., 2025; Eslamidoost et al., 2023).

The strong agreement between observed and modeled concentrations highlights the importance of integrating localized traffic activity and site-specific emission estimation into atmospheric dispersion modeling. Previous studies demonstrated that real-time traffic monitoring, fleet composition, and localized emission inventories significantly improve urban emission and dispersion predictions (Chen et al., 2022; Li et al., 2023; Lei et al., 2024). In addition, AERMOD has been widely recognized as a reliable dispersion model for evaluating traffic-related air pollution under urban conditions because it incorporates atmospheric stability, terrain characteristics, and surface roughness effects (Nath and Dhal, 2025; Ma et al., 2026). Therefore, the integrated MOVES–AERMOD framework applied in this study provides a reliable approach for assessing traffic-related air pollution and environmental exposure in rapidly developing tropical urban environments.

CONCLUSIONS

The results of this study confirm that the integrated MOVES–AERMOD framework can reliably reproduce traffic-related CO emission and dispersion patterns within the complex environment of the Mandai Five-Leg Intersection. Strong agreement between observed and simulated concentrations ($R^2 = 0.92$, MB = 3.8 μg/m³, RMSE = 4.40 μg/m³) demonstrates that the coupled modeling approach successfully represented the interaction between traffic activity, roadway geometry, and meteorological conditions under real urban traffic environments. The results also revealed that motorcycles were the dominant contributor to CO emissions due to their high traffic volume and operation under congested stop-and-go conditions. Spatial dispersion modeling showed that pollutant accumulation was concentrated near the central intersection area and along major roadway corridors influenced by traffic density and prevailing wind direction. The principal contribution of this study lies in the integration of localized traffic surveys, MOVES3-based emission estimation, AERMOD dispersion modeling, and field-based validation within a tropical developing-city environment, providing a reliable framework for evaluating near-road air pollution at complex urban intersections.

Based on these findings, several recommendations can be proposed to improve urban air quality management in rapidly developing metropolitan areas. Traffic flow optimization and congestion reduction strategies should be prioritized to minimize stop-and-go vehicle operation that increases CO emissions near intersections. Policies focusing on motorcycle emission control, improvement of public transportation systems, and sustainable urban mobility planning are also necessary to reduce traffic-related air pollution exposure. In addition, continuous roadside air quality monitoring and the use of localized emission–dispersion modeling frameworks should be encouraged to support evidence-based environmental management and transportation planning. Future studies are recommended to incorporate real-time traffic data, higher-resolution meteorological simulations, and additional pollutants such as NOx, $PM_{2.5}$, and hydrocarbons to improve the understanding of transportation-related environmental and public health impacts in tropical urban environments.

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