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ANALYSIS OF DIESEL LIGHT-DUTY VEHICLE EMISSION ON PENGAYOMAN STREET IN MAKASSAR CITY

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Abstract

This study aims to analyze the emissions of diesel-fueled light vehicles in 14 segments of Jalan Pengayoman, Makassar City, namely segments A to N. The first stage is to analyze the emissions of light vehicles using two methods, namely the IPCC Tier 2 method and the Metropolitan Traffic Emissions Inventory Model method. The second stage is to conduct a statistical test of RMSE for the results of both methods. The results of the analysis of vehicle emissions at the morning peak from both methods in 14 segments of each CO2 emission between 0.539kg–5.64 kg, NOx between 0.005kg–0.05 kg, CO 0.004kg–0.04 kg, SO2 0.0006–0.06 kg, PM10 0.0008kg–0.008 kg, and HC 0.0008–0.008 kg. Vehicle emissions during the afternoon peak from both methods in 14 segments show CO_2 emissions of 0.318–5.64 kg, NOx of 0.003–0.05 kg, CO of 0.0024–0.04 kg, SO_2 of 0.0004–0.06 kg, PM10 of 0.0005–0.08 kg, and HC of 0.0002–0.03 kg. The highest emissions during the morning and afternoon peak hours were found in segment K. The dominant pollutants produced by diesel-fueled light vehicles were CO_2 and NOx. Vehicle emissions increased between the morning and afternoon peak hours in segments E, F, L, J, and I, ranging from 9% to 67%. The results of the IPCC Tier 2 emission RMSE test and The Metropolitan Traffic Emissions Inventory Model during the morning and afternoon peak hours produced figures ranging from 0.003 to 0.069. It can be concluded that the results of the IPCC Tier 2 emission calculations and the Metropolitan Traffic Emissions Inventory Model are not dissimilar. This study illustrates the importance of analyzing and evaluating emissions from diesel-powered light vehicles and developing more effective emission calculation methods.
Keywords: Diesel Light-duty Vehicle; emission; IPCC Tier-2 ; Metropolitan Traffic Emissions Inventory Model ; RMSE

Introduction

Urban air pollution remains a critical environmental issue with substantial impacts on public health worldwide (Bikis, 2023). The World Health Organization estimates that more than seven million premature deaths occur annually due to air pollution exposure, with approximately 90% of the global population breathing air that exceeds recommended guideline values, particularly in low- and middle-income countries (World Health Organization, n.d.). Major sources of urban air pollution include residential activities, industrial processes, power generation, and transportation, with emissions from road traffic recognized as one of the dominant contributors (Harrison et al., 2021; Piracha and Chaudhary, 2022)

Emissions from diesel- and gasoline-powered vehicles release a wide range of pollutants, including carbon dioxide (CO_2), nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), sulfur dioxide (SO_2), and particulate matter (PM_{10}), all of which pose significant environmental and health risks. Exposure to pollutants from light-duty vehicles has been associated with cardiovascular, respiratory, and cognitive disorders(Kostenidou et al., 2021). Although diesel engines are widely used due to their high efficiency and performance, their extensive application has contributed to increased air and noise pollution (Jamali et al., 2019). CO_2 plays a central role in global climate change (Samreen et al., 2021), NOx contributes to acid rain and photochemical smog formation (Lasek and Lajnert, 2022), CO reduces oxygen transport in the bloodstream (Mattiuzzi and Lippi, 2020), PM_{10} penetrates deeply into the respiratory tract and lungs (Bodor et al., 2022), SO_2 irritates the respiratory system (Susetyo et al., 2024), and long-term exposure to hydrocarbons has been linked to increased risks of cancer and neurological disorders (Alao et al., 2025). The rapid growth in passenger vehicle ownership over the past decade has further intensified urban traffic congestion and associated emission levels (Rahman et al., 2021).

In Indonesia, Makassar City has experienced substantial growth in motorized vehicles, with annual increases of approximately 10–11%, alongside a population of 1.47 million in 2023 (Statistics of Makassar Municipality, 2024). The city faces persistent congestion along several major road corridors, including Pengayoman Street, a commercial arterial characterized by high traffic volumes and extensive roadside parking activity (Basri Said and Syafey, 2021; Wahyuni et al., 2023). These conditions make Pengayoman Street a representative urban corridor for evaluating traffic-related emissions and their environmental implications.

A variety of emission estimation models have been developed to quantify road transport emissions, such as PHEM, IVE, COPERT, and HBEFA(Thana Singam et al., 2024). Driving cycle analysis is commonly employed to represent real-world traffic conditions and to assess vehicle emissions and performance (Gebisa et al., 2021). This study applies the IPCC Tier 2 methodology and Metropolitan Traffic Emissions Inventory Model to estimate emissions from light-duty diesel vehicles. Previous studies have investigated emissions from light-duty diesel vehicles under laboratory and on-road conditions (Grange et al., 2019; Singh et al., 2022; Valverde et al., 2019); however, localized and segment-level analyses for urban corridors in Makassar City remain limited.

Therefore, this study aims to analyze emissions from light-duty diesel vehicles along Pengayoman Street, Makassar City, using a dual-method approach based on the IPCC Tier 2 methodology and Metropolitan Traffic Emissions Inventory (MARNI) Model. The novelty of this research lies in its comparative evaluation of both methods across 14 micro-segmented urban road sections, supported by RMSE statistical validation and detailed segment-level emission profiling. The findings are expected to provide scientifically robust evidence to support urban air quality management, contribute to improved emission estimation practices, and inform the development of stricter emission standards and inspection–maintenance policies for light-duty diesel vehicles in Indonesia.

Methodology

Data Collection

This study uses quantitative and descriptive methods to describe light-duty diesel vehicle emissions on Pengayoman Street in Makassar City. The study began with observations to collect the necessary primary and secondary data. Primary data consisted of vehicle volume, driving cycle data, and test vehicle data. Secondary data consists of standard vehicle emission factor data for Indonesia. Vehicle volume is determined directly through surveys conducted on the road using video cameras and then calculated. Driving cycle data was collected by tracking along Pengayoman Street using a test vehicle and Garmin 78s GPS.

Research location

This study was conducted on Pengayoman Street, located in Makassar City, South Sulawesi, Indonesia. The data collection location on Pengayoman Street was divided into 14 segments, namely segments A to N. The first traffic direction is segment A to segment H. The second traffic direction is segment N to segment I. The highest distance at the research location was in segment L, which was 0.362 km. Figure 1 shows the location map of this study. The distance traveled in each segment on Pengayoman Street can be seen in Figure 2 .This research was conducted on Monday (weekday), September 10, 2024, and data collection was carried out for 1 hour during each peak hour interval in the morning (7 a.m. – 8 a.m.) and peak hour interval in the afternoon (5 p.m. – 6 p.m.).

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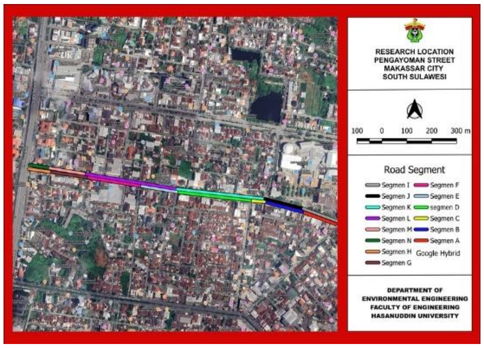

Fig 1. Research Location

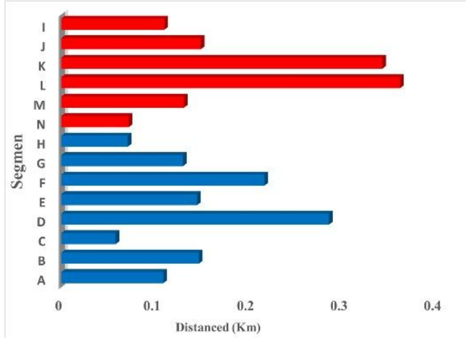

Fig 2. Distance

Test vehicle

Vehicle test data was collected by conducting a survey at gas station 74.902.25 located on Pengayoman Street. The test vehicle used in this study was a Mitsubishi Pajero Sport Dakar 4x2 Ultimate (2021). This vehicle has an 8-speed automatic transmission. It is powered by a 2442 cc diesel engine. It uses diesel fuel. This vehicle is the most dominant light diesel vehicle found at gas stations 74.902.25 so it was chosen as the test vehicle. Figure 3 shows the test vehicle used in this study.

Fig 3. Test Vehicle

Emission factor

Vehicle emission factors (EFs) are mathematical relationships that estimate the amount of a pollutant released based on the activity responsible for the emission. Emissions parameters are substantially affected by variables including vehicle type, engine age and maintenance, fuel type and composition, in addition to driver behavior and travel speed (Geldenhuys et al., 2022). This study uses Indonesian standard emission factors based on (Minister Of The Environment, 2010), which can be seen in Table 1.

TABLE I. VEHICLE EXHAUST EMISSION FACTORS FOR METROPOLITAN AND LARGE CITIES IN INDONESIA BASED ON VEHICLE CATEGORY

Pollutant	Vehicle Category
	Diesel Car
CO (gr/km)	2.8
HC (gr/km)	0.2
NOx (gr/km)	3.5
PM10 (gr/km)	0.53
CO2 (gr/kg fuel)	3172
SO2 (gr/km)	0.44

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Data Analysis

Tier 2 Method

The 2006 IPCC technique consists of three tiers: Tier 1 utilizes default data, Tier 2 incorporates some location-specific data, and Tier 3 integrates comprehensive location-specific data (The Intergovernmental Panel on Climate Change, 2006). The Tier 2 method is adopted in (Minister Of The Environment, 2010)and can be calculated using (1) and (2), as follows:

$$Ea = \sum_{b=1,c=1}^{n,m} (VKT_{b,c} \times FE_{a,b,c} \times 10^{-6}) \quad (1)$$

$$VKT_{b,I} = Q_{b,i} \times l_i \quad (2)$$

Where:

Ea: Total emissions for pollutant a (Kg)

VKTb,c: Total length of travel for category b motor vehicles using fuel type c (km)

FEa,b,c: Emission factor (g/km)

Qb, i: Number of category b vehicles on road section i

l, i: Length of road section i

Metropolitan Traffic Emissions Inventory Model

Metropolitan Traffic Emissions Inventory model consists of a set of mathematical models designed to forecast the emissions produced by vehicles in motion on the road (Aly, 2015). The Metropolitan Traffic Emissions Inventory (MARNI) model is derived from vehicle volume (N), emission factors (EF), average speed distribution parameters (DC), and travel time (TT) (Aly, 2021), as illustrated in equation (3).

$$EV^t = N \times FEt,p \times DCt,p \ TTt,p \quad (3)$$

RMSE Test

RMSE (Root Mean Square Error) is commonly utilized to assess the accuracy of a recommender system (Wang and Lu, 2018). The formula for RMSE is presented in equation (4)

$$RMSE = \sqrt{\frac{\sum_{n=1}^{N}(\hat{r}_n - r_n)^2}{N}} \quad (4)$$

$\hat{r}_n$ denotes the predicted rating;

r_n signifies the actual rating in the testing dataset;

N represents the quantity of rating prediction pairs between the testing data and the prediction outcome.

The Results

Vehicle Volume

In the analysis of weekday morning peak hours, segment G exhibits the highest vehicle volume, recording 48 cars per hour, while segment I shows the lowest count at 16 vehicles per hour. Examination of weekday afternoon peak hours reveals that section F experiences the highest vehicle volume, recorded at 48 cars per hour, whereas segment H shows the lowest volume at 12 vehicles per hour. The increase in vehicle volume during morning and afternoon peak hours in segments E, L, J, and I ranged from 40% to 67%. The data reveals a decline in vehicle volume from the morning to the afternoon peak hours across segments A, B, G, H, and M, with reductions noted between 10% and 70%. The volume of vehicles in each segment is affected by the commercial activities taking place on Pengayoman Street in Makassar City. Figure 4 illustrates the number of light-duty diesel vehicles documented during the peak morning and afternoon periods on weekdays.

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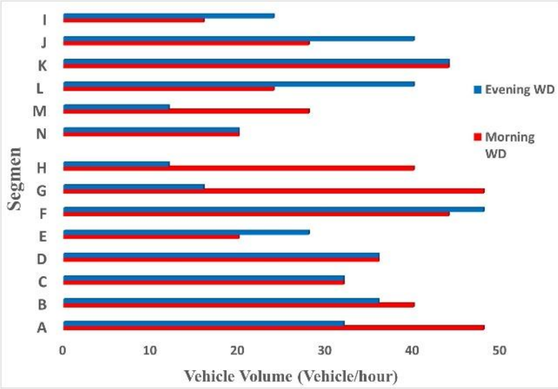

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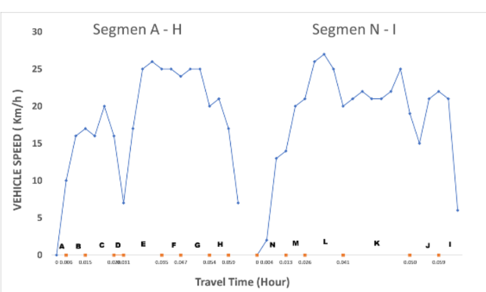
Fig 4. Vehicle Volume

Driving Cycle

During the morning rush hour on weekdays, the highest speed in the A–H segment was recorded in segment D at 26 km/h, while in the N–I segment, the highest speed occurred in segment L at 27 km/h. Figure 5 shows the driving cycle of a light-duty diesel vehicle during the morning rush hour. During the afternoon rush hour, the highest speed in the A–H direction decreased and occurred in segment E at 23 km/h, while in the N–I direction it remained in segment L at a speed of 25 km/h. Figure 7 shows the driving cycle of a light-duty diesel vehicle during the afternoon rush hour. Travel time in the A–H direction increases from 0.059 hours during morning rush hour to 0.070 hours during afternoon rush hour, while in the N–I direction it increases from 0.059 hours to 0.068 hours. This increase in travel time indicates traffic congestion during the afternoon rush hour in both directions.

The results of the driving cycle frequency distribution show that on the Pengayoman road section, vehicles operate at speeds ranging from 0–15 km/h and 16–30 km/h. During the morning rush hour, the majority of vehicles travel at speeds of 16–30 km/h with a frequency of 50–100%, with the maximum travel time occurring in segment K at 0.01444 hours. Figure 6 shows the frequency distribution of the driving cycle during the morning rush hour. Conversely, during the afternoon rush hour, vehicles are dominated by low speeds of 0–15 km/h with a frequency of 50–100%, and the maximum travel time occurs in segment L at 0.0247 hours. Figure 8 shows the frequency distribution of the Driving Cycle during the afternoon peak hours. Vehicle speed fluctuations are influenced by roadside parking activities that cause traffic congestion. Overall, the decrease in speed and increase in travel time indicate that congestion levels are higher during the afternoon rush hour compared to the morning rush hour.



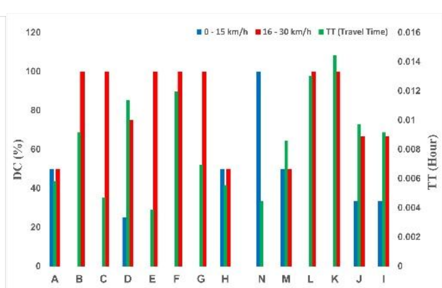


Fig 5. DC Morning Fig 6. Freq DC Morning

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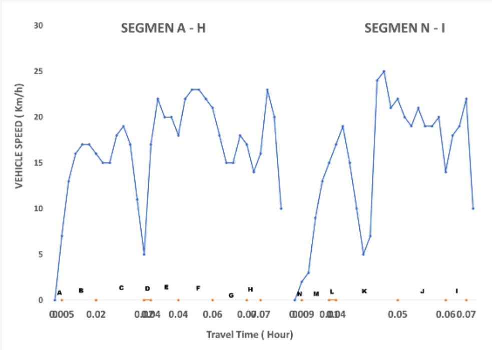

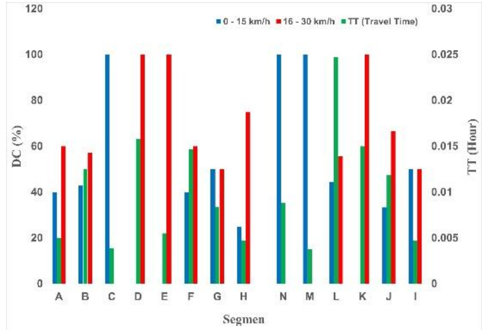

Fig 7. DC Afternoon Fig 8. Freq DC Afternoon

Vehicle Kilometer Traveled (VKT)

The highest total vehicle kilometers traveled (VKT) during weekday morning rush hours was 15.092 km in segment K, whereas the lowest total VKT was 1.44 km in segment N. The maximum total VKT during the afternoon rush hour occurs in segment K at 15.092 km, while the minimum total VKT is recorded in segment H at 0.852 km. The total vehicle kilometers traveled (VKT) exhibits an increase ranging from 9% to 67% during the morning and afternoon peak hours across segments E, F, L, J, and I. During the morning and afternoon peak hours, a reduction in total Vehicle Kilometers Traveled (VKT) was noted in segments A, B, G, H, and M, with decreases varying between 10% and 70%. During both the morning and afternoon rush hours, Segment K had the highest VKT value. This was because it traveled a longer distance than the other 13 segments, and there were many cars on the road during these times. During the morning rush hour, segment N had the lowest VKT values, and during the afternoon rush hour, segment H had the lowest values. Segments N and H show that people don't travel very far on Pengayoman Street, which is why the VKT readings are lower. The distance traveled and the number of vehicles are two important things that affect VKT values. Figure 9 depicts the graph of total vehicle kilometers traveled (VKT) for light-duty diesel vehicles during weekday morning and afternoon peak periods on Pengayoman Street.

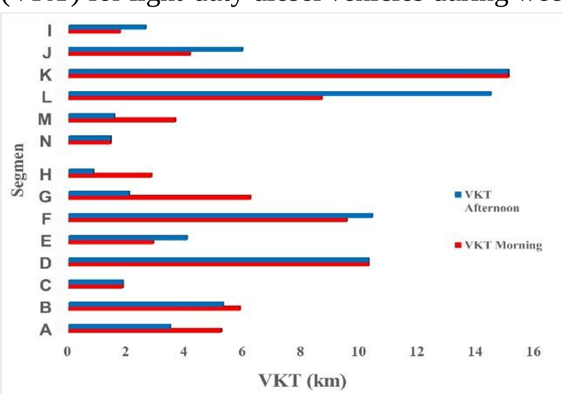

Fig 9. Vehicle Kilometer Traveled

Emissions based on IPCC Tier 2

Segment K exhibited the greatest emissions, totaling 5.64 kg of CO_2, 0.05 kg of NOx, 0.04 kg of CO, 0.006 kg of SO_2, 0.008 kg of PM10, and 0.003 kg of HC, respectively. Segment N had the lowest emissions, with total CO_2, NOx, CO, SO_2, PM10, and HC emissions measuring 0.539 kg, 0.005 kg, 0.004 kg, 0.0006 kg, 0.0008 kg, and 0.0003 kg, respectively. Figure 10 illustrates the outcomes of diesel emission calculations for light-duty vehicles during morning peak hours, utilizing the IPCC Tier 2 methodology. Segment K exhibited the greatest emissions, totaling 5.64 kg of CO_2, 0.05 kg of NOx, 0.04 kg of CO, 0.006 kg of SO_2, 0.008 kg of PM10, and 0.003 kg of HC, respectively. Segment H had the least emissions. The total emissions of CO_2, NOx, CO, SO_2, PM10, and HC were 0.3189 kg, 0.003 kg, 0.0024 kg, 0.0004 kg, 0.0005 kg, and 0.0002 kg, respectively. Figure 11 illustrates the outcomes of emissions calculations from light-duty diesel vehicles during the afternoon peak hour, utilizing the

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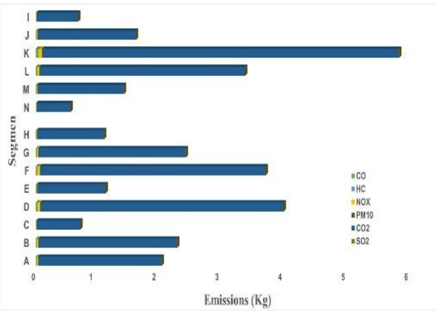
IPCC Tier 2 methodology. During the morning and afternoon peak hours, Segment K had the highest emissions because its VKT values were also high during those times. Segment N had the least emissions during the morning rush hour, and segment H had the least emissions during the afternoon rush hour. This was because their VKT values were so low.



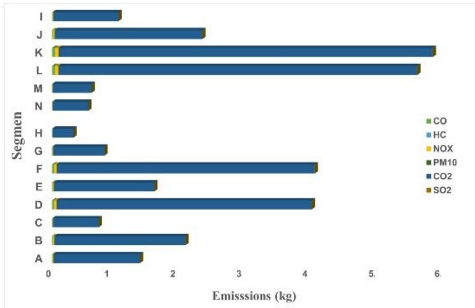


Fig 10 . Morning Emission based Tier 2 Fig 11. Afternoon Emission based Tier 2

Emissions Based On Metropolitan Traffic Emissions Inventory Model

Metropolitan Traffic Emissions Inventory Model demonstrates that emissions from diesel light-duty cars depend on the driving cycle. The results of the The Metropolitan Traffic Emissions Inventory Model emissions calculations show the same results as the IPCC Tier 2 calculations. During the morning rush hour, Segment K has the highest emissions at velocities ranging from 16 to 30 km/h. The cumulative emissions of CO_2, NOx, CO, SO_2, PM10, and HC in segment K at a velocity range of 16–30 km/h are 5,648 kg, 0.052 kg, 0.042 kg, 0.006 kg, 0.007 kg, and 0.003 kg, respectively. The minimal emissions were observed in segment N within a speed range of 0–15 km/h. Figure 12 illustrates the results of diesel light-duty vehicle emissions assessments performed during morning peak hours, employing the Metropolitan Traffic Emissions Inventory Model. During the afternoon rush hour, the peak emissions occurred in segment K within the speed range of 16–30 km/h. The emissions of total CO_2, NOx, CO, SO_2, PM10, and HC in segment K at the 16–30 km/h interval were 5,648 kg, 0.052 kg, 0.042 kg, 0.006 kg, 0.007 kg, and 0.003 kg, respectively. The minimal emissions were observed in segment H at velocities ranging from 0 to 15 km/h. In the morning peak hours, emissions are predominantly generated by vehicles operating at speeds between 16 and 30 km/h, with total average emissions of CO_2, NOx, CO, SO_2, PM10, and HC amounting to 1,950 kg, 0.018 kg, 0.014 kg, 0.002 kg, 0.0027 kg, and 0.001 kg, respectively. Figure 13 illustrates the outcomes of diesel light-duty vehicle emissions computations during the afternoon peak hour, derived from the MODEL Metropolitan Traffic Emissions Inventory. During the afternoon peak hours, predominant emissions occurred when cars traveled at speeds ranging from 0 to 15 km/h, with average emissions of CO_2, NOx, CO, SO_2, PM10, and HC totaling 0.806 kg, 0.007 kg, 0.006 kg, 0.0009 kg, 0.0011 kg, and 0.0004 kg, respectively. The driving cycle of the vehicle substantially affects the emissions generated. A high frequency of speed intervals and journey durations will result in elevated emissions at certain speed intervals. A reduced frequency of speed intervals and travel duration will result in diminished emissions generated at that speed interval. The reduction in vehicle speed results in heightened emissions in segments E, F, L, J, and I. The rise in emissions is attributable to the reduction in speed and the augmentation in the quantity of cars in these segments.

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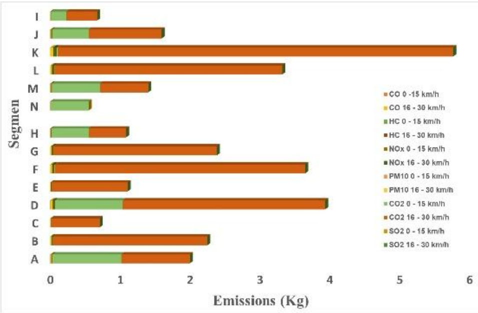

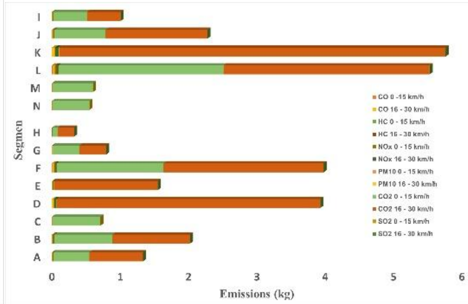

Fig 12. Morning emissions Marni Model Fig 13. Afternoon emissions Marni Model

Comparison of peak emissions in the morning and afternoon

Diesel light-duty cars generate the highest emissions of CO_2 and NOx. This outcome is attributable to the elevated emission factors of diesel light-duty cars, including CO_2 and NOx. The minimal emissions generated by diesel light-duty cars are hydrocarbons (HC) and sulfur dioxide (SO_2). This outcome is attributable to the minimal emission factors of hydrocarbons (HC) and sulfur dioxide (SO_2) from diesel light-duty cars. Vehicle emissions escalated by 9–67% during morning and afternoon peak hours in segments E, F, L, J, and I. Emission levels in segments A, B, G, H, and M decreased by 10–70% during morning and afternoon peak hours.

Comparison of the Metropolitan Traffic Emissions Inventory Model and IPCC Tier 2 using RMSE analysis

The RMSE test results for the parameters CO, HC, NOx, PM10, CO2, and SO2 during the morning peak hour vary from 0.003 to 0.037. The RMSE test results for the parameters CO, HC, NOx, PM10, CO2, and SO2 during afternoon peak hours vary from 0.003 to 0.069. In the RMSE statistical test, the results range from 0 to infinity, with values approaching 0 indicating a minimal difference between the two computation techniques. The RMSE test results for morning and afternoon peak hours indicate values approaching zero. The IPCC Tier 2 and Metropolitan Traffic Emissions Inventory Model yield equivalent emission calculations, allowing for the use of either technique to assess emission levels. Table 2 displays the RMSE test results for IPCC Tier 2 emission estimates and the Metropolitan Traffic Emissions Inventory Model.

TABLE I. RMSE TEST RESULTS FOR IPCC TIER 2 AND METROPOLITAN TRAFFIC EMISSIONS INVENTORY MODEL FROM 14 SEGMENTS OF PENGAYOMAN STREET

Polutant	RMSE Test between IPCC Tier 2 and Metropolitan Traffic Emissions Inventory Model	
	Morning Value	Afternoon Value
CO	0.037	0.031
HC	0.006	0.009
NOx	0.020	0.069
PM10	0.008	0.038
CO2	0.003	0.003
SO2	0.007	0.020

The comprehensive analysis of vehicle volume, driving cycle characteristics, vehicle kilometers traveled (VKT), and emission estimates reveals a strong interdependence between traffic dynamics and pollutant generation along Pengayoman Street. The spatial variability observed across the 14 segments highlights how localized traffic conditions, road geometry, and roadside activities substantially influence emission levels. Segments with higher vehicle volumes and longer travel distances consistently exhibited elevated emission outputs, confirming the critical role of traffic density and movement intensity in shaping urban air quality. In particular, the pronounced dominance of segment K across multiple indicators—vehicle volume, VKT, travel time, and emission magnitude—demonstrates how specific road segments can function as emission hotspots within urban corridors.

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The analysis of driving cycles further underscores the importance of speed distribution in emission formation. During morning peak hours, vehicles predominantly operated within the 16–30 km/h speed range, whereas afternoon peak conditions were characterized by a higher frequency of low-speed operations (0–15 km/h). This shift reflects worsening congestion levels in the afternoon, which is corroborated by increased travel times in both traffic directions. The prevalence of low-speed driving, frequent deceleration, and stop-and-go conditions significantly amplifies emission rates, particularly for NOx and particulate matter. These findings align with established literature indicating that congested traffic regimes tend to produce disproportionately higher emissions per kilometer traveled due to inefficient engine operation and increased idling periods.

Vehicle Kilometer Traveled (VKT) emerged as a decisive parameter influencing emission magnitude. Segments E, F, L, J, and I experienced notable increases in VKT between morning and afternoon peak hours, corresponding to increased vehicle activity and prolonged travel durations. Conversely, reductions in VKT observed in segments A, B, G, H, and M suggest shifts in traffic flow patterns, possibly influenced by temporal changes in commercial activity and driver route selection. The consistent identification of segment K as the highest VKT contributor in both peak periods confirms that road length combined with high vehicle density exerts a compounding effect on total emissions.

Emission estimates derived from the IPCC Tier 2 methodology demonstrate that carbon dioxide (CO_2) and nitrogen oxides (NOx) are the predominant pollutants emitted by diesel-powered light-duty vehicles along Pengayoman Street. This dominance reflects the combustion characteristics of diesel engines, which inherently produce higher CO_2 emissions due to fuel carbon content and elevated NOx emissions due to high combustion temperatures. In contrast, hydrocarbons (HC) and sulfur dioxide (SO_2) were consistently recorded at lower levels, attributable to relatively low emission factors and improved fuel quality standards. The marked variability in emissions across segments further emphasizes the influence of traffic conditions rather than uniform vehicle characteristics alone.

The Metropolitan Traffic Emissions Inventory Model results closely mirror those obtained through the IPCC Tier 2 approach, while offering additional insights into the role of driving cycles. The model reveals that emissions peak at specific speed intervals depending on traffic conditions, with morning emissions concentrated at moderate speeds (16–30 km/h) and afternoon emissions shifting toward lower speeds (0–15 km/h). This dynamic illustrates the sensitivity of emission outputs to speed fluctuations and reinforces the necessity of incorporating driving cycle data into urban emission inventories. The results confirm that emission formation is not solely dependent on traffic volume but also on operational driving behavior.

A direct comparison between morning and afternoon peak emissions indicates a clear temporal pattern in pollutant generation. In several segments, emissions increased by as much as 67% during the afternoon peak, driven by congestion-induced speed reductions and increased travel times. However, the observed emission decreases in selected segments suggest that traffic redistribution and reduced vehicle activity during certain periods can effectively mitigate emission levels. These contrasting trends highlight the complexity of urban traffic systems and the importance of targeted, segment-specific emission mitigation strategies.

The RMSE-based statistical comparison between the IPCC Tier 2 and Metropolitan Traffic Emissions Inventory Model provides strong validation for the consistency and reliability of both methods. RMSE values approaching zero across all pollutants during both peak periods indicate minimal deviation between the two estimation approaches. Notably, CO_2 exhibited the lowest RMSE values, reflecting high methodological agreement in estimating fuel-based emissions. Slightly higher RMSE values for NOx and PM10 during afternoon peak hours may be attributed to the increased sensitivity of these pollutants to speed variations and congestion effects. Nevertheless, the overall RMSE results confirm that both models are suitable for urban emission assessments and can be interchangeably applied depending on data availability and analytical objectives.

Overall, the findings demonstrate that diesel light-duty vehicle emissions on Pengayoman Street are strongly influenced by traffic volume, speed distribution, and road segment characteristics. The integration of micro-segment analysis with dual emission estimation methods provides a robust framework for understanding localized emission behavior in urban environments. These results underscore the urgency of implementing traffic management measures,

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parking control policies, and emission reduction strategies in high-impact segments such as segment K. Furthermore, the methodological consistency observed between IPCC Tier 2 and the Metropolitan Traffic Emissions Inventory Model supports their broader application in urban air quality planning and policy development, particularly in rapidly growing cities like Makassar.

Discussion

The results of this study provide strong empirical confirmation that emissions generated by diesel-powered light-duty vehicles along Pengayoman Street are highly sensitive to localized traffic characteristics, particularly vehicle volume, average operating speed, and congestion intensity. This finding corroborates a growing body of literature emphasizing that traffic-related emissions are spatially heterogeneous and strongly influenced by micro-scale traffic dynamics rather than uniform corridor-level conditions (Harrison et al., 2021; Zhang et al., 2022; Bigazzi & Rouleau, 2017). The persistently high emission levels observed in segment K during both morning and afternoon peak hours further indicate that road segments with longer travel distances, high traffic density, and recurrent congestion function as critical urban emission hotspots. Similar hotspot phenomena have been reported in studies conducted in dense urban corridors across Asia and Europe, where emissions tend to cluster spatially due to cumulative traffic interactions and road geometry constraints (Thana Singam et al., 2024; Chen et al., 2020; Wang et al., 2021).

These findings imply that city-wide emission inventories relying solely on aggregated traffic indicators may significantly underestimate pollution concentrations at the micro-spatial level. Previous research has shown that coarse spatial resolution in emission inventories can obscure localized exposure risks and misinform mitigation strategies, particularly in rapidly urbanizing cities (Karagulian et al., 2018; de Nazelle et al., 2020; Smit et al., 2019). Therefore, the segment-based analytical approach adopted in this study enhances the accuracy of urban emission assessments by capturing intra-corridor variability that is often overlooked in conventional models.

The dominance of CO_2 and NOx emissions across all observed road segments aligns closely with the well-documented combustion characteristics of diesel engines reported in earlier studies (Jamali et al., 2019; Valverde et al., 2019; Fontaras et al., 2018). Diesel engines are characterized by higher compression ratios and thermal efficiency, which contribute to increased CO_2 emissions per kilometer traveled, while elevated combustion temperatures favor the formation of nitrogen oxides (NOx). Numerous studies have confirmed that NOx emissions from diesel vehicles remain a critical challenge in urban air quality management, even under increasingly stringent emission standards (Carslaw et al., 2019; Degraeuwe & Weiss, 2017; Jonson et al., 2020).

Conversely, the relatively low levels of hydrocarbon (HC) and sulfur dioxide (SO_2) emissions observed in this study likely reflect improvements in fuel quality, the widespread adoption of low-sulfur diesel, and advancements in exhaust after-treatment technologies such as diesel oxidation catalysts and particulate filters. These trends are consistent with findings from other developing countries that have implemented progressive fuel quality regulations over the past decade (Guo et al., 2021; Timmers & Achten, 2016; Liu et al., 2020). As such, the results suggest that future policy interventions in urban corridors dominated by diesel vehicles should prioritize CO_2 and NOx mitigation to achieve the greatest air quality and climate co-benefits.

Analysis of driving cycles further reveals that emission generation is not solely dependent on traffic volume but is strongly mediated by vehicle operating conditions. The observed shift from moderate-speed dominance (16–30 km/h) during morning peak hours to low-speed dominance (0–15 km/h) in the afternoon reflects worsening congestion and increased stop-and-go traffic patterns. Such conditions have been consistently shown to exacerbate emissions, particularly NOx and particulate matter, due to incomplete combustion, frequent acceleration–deceleration events, and prolonged idling durations (Gebisa et al., 2021; Singh et al., 2022; Barth et al., 2017). These findings reinforce the argument that traffic flow optimization strategies—such as signal coordination and congestion management—may be more immediately effective in reducing emissions than vehicle technology upgrades alone (Rakha et al., 2018; Ahn & Rakha, 2019).

The emission increases observed in segments E, F, L, J, and I during afternoon peak hours further highlight the significant influence of roadside activities and parking behavior on traffic dynamics. Informal on-street parking, curbside loading, and commercial activities along Pengayoman Street contribute to lane obstructions, reduced effective road capacity, and prolonged travel times. Similar dynamics have been documented in other Southeast Asian cities, where mixed land use patterns and weak parking enforcement intensify congestion and localized pollution exposure (Piracha & Chaudhary, 2022; Susilo et al., 2020; Hong et al., 2019). Addressing these issues through improved curbside management and stricter parking regulations could therefore yield substantial emission reductions during peak traffic periods.

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The strong agreement between the IPCC Tier 2 approach and the Metropolitan Traffic Emissions Inventory Model, as indicated by low RMSE values, underscores the methodological robustness of both emission estimation techniques. While IPCC Tier 2 performs well for macro-scale inventories, the slightly higher discrepancies observed for NOx and PM_{10} during afternoon peak hours suggest that models incorporating driving cycle parameters are better suited for capturing speed variability and congestion effects at the micro-scale (Smit et al., 2019; Franco et al., 2013; Ntziachristos & Samaras, 2016). The combined application of both methods, as demonstrated in this study, therefore offers a comprehensive and reliable framework for emission assessment and cross-validation in urban traffic environments.

From a policy standpoint, the findings emphasize the importance of targeted emission mitigation strategies that prioritize high-impact road segments rather than uniform interventions across the entire road network. Segment K, identified as a persistent emission hotspot, should be prioritized for traffic management measures such as signal optimization, access control, and restrictions on roadside parking. Furthermore, promoting the gradual transition toward cleaner vehicle technologies—including electric and hybrid light-duty vehicles—has been widely recognized as an effective long-term strategy for reducing CO_2 and NOx emissions in urban transport systems (Nieuwenhuijsen, 2020; Creutzig et al., 2018; Xue et al., 2021). Enhanced inspection and maintenance programs for diesel vehicles are also critical to ensuring sustained compliance with emission standards and preventing real-world emission deterioration.

In the broader context of urban sustainability, this study underscores the necessity of integrating emission modeling with land-use planning and transportation policy. As Makassar City continues to experience rapid growth in vehicle ownership, localized emission assessments become increasingly important for protecting public health and meeting air quality targets (WHO, 2021; Kumar et al., 2020). The micro-segmented analytical framework applied in this research provides a replicable approach for other rapidly urbanizing cities, enabling evidence-based identification of emission hotspots and prioritization of mitigation measures.

Overall, this discussion highlights that effective urban air quality management requires a holistic understanding of traffic behavior, vehicle technology, and spatial dynamics. By demonstrating consistency between two widely applied emission estimation methods and elucidating the critical role of congestion and driving cycles, this study contributes meaningful insights to the literature on transportation emissions and offers a strong foundation for future methodological refinement and policy-oriented research.

Conclusion

This study analyzes emissions produced by diesel-fueled light vehicles on Pengayoman Street in Makassar City. Data collection on the number of vehicles shows an increase in vehicle volume during the morning rush hour to the afternoon rush hour in segments E, F, L, J, and I, ranging from 40% to 67%. Driving cycle data shows that vehicle speeds during the morning rush hour predominantly range from 16 to 30 km/h, while during the afternoon rush hour, speeds predominantly range from 0 to 15 km/h. This indicates an increase in traffic density during the afternoon rush hour. The results of the VKT value calculation show that the highest VKT values for the morning and afternoon rush hours are in segment K.

The results of emission calculations using the IPCC Tier 2 method and The Metropolitan Traffic Emission Inventory model show no difference. The results of vehicle emission analysis at peak morning hours from both methods on 14 segments show CO2 emissions between 0.539 kg–5.64 kg, NOx between 0.005 kg–0.05 kg, CO 0.004 kg–0.04 kg, SO_2 between 0.0006 kg and 0.06 kg, PM10 between 0.0008 kg and 0.008 kg, and HC between 0.0008 kg and 0.008 kg. Vehicle emissions during the afternoon peak hour from both methods in 14 segments showed CO_2 emissions of 0.318–5.64 kg, NOx of 0.003–0.05 kg, CO of 0.0024–0.04 kg, SO_2 of 0.0004–0.06 kg, PM10 of 0.0005–0.08 kg, and HC of 0.0002–0.03 kg. The highest emissions during the morning and afternoon peak hours were found in segment K.

Research shows that light diesel vehicles are the dominant source of CO_2 and NOx pollutants because these pollutants have the highest emission factor values among light diesel vehicles. Vehicle emissions increase between morning and evening rush hours in segments E, F, L, J, and I in the range of 9–67%. The RMSE test results for emission calculations using IPCC Tier 2 and The Metropolitan Traffic Emissions Inventory Model during morning and afternoon rush hours ranged from 0.003 to 0.069. This shows that the emission calculation results from the two methods are not significantly different. The results of this study provide an overview of the importance of calculating and evaluating emissions from diesel light-duty vehicles and developing more effective emission calculation methods.

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