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Research Article

Spatio-temporal patterns of air quality on commuter lane of the sub-urban area of Yogyakarta, Indonesia

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ABSTRACT

Yogyakarta, a city based on culture, education, and tourism, has different commuting activities from other industrialized cities in Indonesia. On the other hand, the city is also dominated by motorcycles, like most cities in Indonesia and Southeast Asia. The movement of commuters by motorcycle affects the instantaneous air quality. In this paper, the results of an investigation of the spatio-temporal pattern of air quality of commuter routes in the suburbs of Yogyakarta are presented. Data were collected through observation by measuring five air quality parameters and vehicle intensity in 10 commuter routes in Yogyakarta. Data were analyzed using GIS analysis using average nearest neighbour, statistical analysis using simple linear regression, and matching analysis referring to The World Air Quality Index and Vianney and Erfianto (2023), supported by descriptive analysis. There are three critical findings from this study. First, air quality varies spatially and temporally, with differences among commuter routes and travel times. Second, the relationship between passing vehicle intensity and air quality is unique. Some positively correlate with linear, exponential, logarithmic, or polynomial relationship properties. Third, poor air quality tends to be found on main routes with high vehicle intensity. In summary, this study provides new insights into air quality patterns concerning commuter traffic in motorcycle-dominated cities in Indonesia.

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INTRODUCTION

Approaching a quarter of a century after the turn of the millennium, the world's population increasingly lives in urban areas. Data from the Population Reference Bureau shows that by 2023, 57% live in urban area [1]. With more and more people living in urban areas, urbanization has become a crucial contemporary issue in which urban transportation plays a fundamental role. The availability of good transportation facilities has proven to significantly impact the progress of cities and the welfare of residents of various cities in the world. However, urban transportation has also long been proven to be one of the factors responsible for degrading the environmental quality of urban areas, especially air pollution. This is a consequence of the increasing use of multi-modal transportation in terms of type and number [2], [3]. Studies conducted in China [4], [5] and Africa [6] prove that transportation activities impact urban air pollution. On the other hand, transportation improvements have been shown to reduce pollution levels in many cities of developed countries through innovations in green transportation modes [7] – [9] as well as mobility restrictions during the COVID-19 pandemic [10], [11].

There is a commuter zone in the city's spatial structure, especially in models that refer to the ecological approach. This zone is found in the suburbs or the outer part of the city as a link between where people live outside the city and their activities in the city [12], [13]. This area is crossed by many commuters from the hinterland and satellite areas to the inner city. In many Southeast Asian cities, this commuter zone is heavily populated by motorcycle users, as is the case in Indonesia [14], [15]; Vietnam [16], as well as Thailand [17]. High vehicle intensity in commuter zones has an impact on worsening air quality as a study conducted in Solo, Indonesia [18]; Hanoi, Vietnam [19], [20]; Bangkok, Thailand [21]; and Lagos, Nigeria [22]. Poor air quality is also detrimental to commuters' health. This issue has received much attention in previous studies in Vietnam [23] – [25], China [26]; India [27], [28]; and Taiwan [29], [30].

The problem is how much impact the flow of commuters has on the instantaneous air quality felt by commuters in these commuting zones has not been sufficiently addressed in previous literature. Previous studies in the past decade have mainly focused on the exposure to air pollutants among commuters and its impact on their health or the effect of private vehicle shifts to public transport and motorcycle to electric motorcycle conversions on air quality in urban areas [31] – [33]. Therefore, previous studies have not included analysis and discussion on the relationship between commuting activities in motorcycle-dominated cities. This indicates a scientific gap that needs to be addressed by further studies.

Yogyakarta is a city based on education, culture, and tourism. Like most cities in Indonesia, Yogyakarta also has commuter zones. However, the commuting pattern in this city is relatively different from those large industrial-based cities. For example, commuting patterns in Jakarta and Surabaya are based on BPS data [34], [36], [37] dominated by certain lines. Meanwhile, the condition in Bandung is relatively similar to Yogyakarta, where there is no dominance of certain commuter lines [35]. Besides being related to the activities of the population and the distribution of activity centers within the city, commuting patterns may also be associated with the geographical conditions of the city itself. The non-coastal morphology of Bandung and Yogyakarta allows for an even flow of commuters from all sides. In Yogyakarta, residents from the hinterland and satellite cities who commute to the city for education or employment in the public service sector come from all directions. This specific pattern also needs further evaluation to determine its influence on the instantaneous air quality pattern during commuter transportation activities.

In this paper, we describe the spatio-temporal air quality pattern in Yogyakarta's commuter zone. In this regard, there are three more specific objectives in this paper. First, to evaluate the variability of commuter characteristics in Yogyakarta commuter lines. Second, to assess the spatio-temporal pattern of air quality on the various commuter routes. Last, consider the influence of commuting activities on the instantaneous air quality in Yogyakarta's commuter routes. This study emphasizes the impact of commuting activities on instantaneous air quality, which has never been discussed before in various international publications. As such, this study offers new insights into the influence of commuting activities on instantaneous air quality. This study also provides alternative information on the air quality of suburban areas concerning commuter traffic using private vehicles.

MATERIALS AND METHODS

Research Methods

This study employs a geography approach, namely a spatial approach. This study also implements geography themes to analyze the problem, including location, place, human-environment interaction, movement, region, and landform. The subjects in this study are commuter routes in Yogyakarta City. The object of the research is the instantaneous air quality that occurs due to the influence of commuter activities.

The data in this study are primary data, collected through observation. Observations were conducted at ten points which are the main route of commuters in Yogyakarta City, including: Magelang Street, Palagan Street, Kaliurang Street, Solo Street, Wonosari Street, Imogiri Timur Street, Parangtritis Street, Bantul Street, Wates Street, and Godean Street. The intensity of vehicles passing every minute was measured at each location, consisting of motorcycles, cars, and total vehicles. Instantaneous air quality measurements were also taken, along with the vehicle intensity measurement. Air quality variables include PM2.5, PM10, CO_2, TVOC, and HCHO.

According to Zimakowska-Laskowska & Laskowski [80], CO_2 is one type of pollutant produced by transport. The Environmental Protection Agency of the United States (2024) also explains that burning fossil fuels like gasoline and diesel releases carbon dioxide, a greenhouse gas, into the atmosphere. Meanwhile, the International Energy Agency [82] explains that motorised transport on land, sea and air remains dependent on internal combustion engines that generally run-on fossil fuels. Transport accounts for more than a third of CO_2 emissions from end-use sectors.

Observations at each location were conducted in the morning, afternoon, and evening to determine the temporal variation of air quality to commuting activities. Morning measurements were taken at 06:00-08:00, afternoon measurements at 12:00-14:00, and evening measurements at 16:00-18:00. The assumption made in this study is that the morning and evening are the peaks of commuting activity where in the morning there is a flow from the hinterland to the city and in the evening, there is a reverse flow. The midday measurement is intended as a comparison between the two busy times. Air quality and vehicle intensity were measured ten times at each measurement time. Thus, at each measurement location, there are 300 data points throughout the day, consisting of the results of morning, afternoon, and evening measurements. Air quality measurements were carried out with Particle Counter HTI HT 9600 instruments for PM2.5 and PM10 and a JLDG air quality tester for CO_2, TVOC, and HCHO measurements.

Data analysis was conducted using statistical analysis, matching analysis, and descriptive analysis. Statistical analysis was carried out using simple linear regression to see the effect of the number of vehicles passing through the commuter zone as an independent variable on instantaneous air quality as the dependent variable. Air quality consists of several parameters: PM 2.5, PM 10, CO_2, TVOC, and HCHO. The linear regression model used is formulated as follows.

$$Y = a + bX \qquad (1)$$

X represents the number of vehicles travelling in each commuter zone in the measurement period, Y represents the air quality at the same time as the vehicle measurement, a is the intercept, and b is the regression coefficient that shows the impact of vehicles on air quality. The formula for a and b are as follows.

$$a = \frac{(\sum Y)(\sum X^2)-(\sum X)(\sum XY)}{n\sum X^2-(\sum X)^2} \text{ and } b = \frac{n\sum XY-(\sum X)(\sum Y)}{n\sum X^2-(\sum X)^2} \qquad (2)$$

Descriptive analysis supported statistical analysis to clarify, sharpen, and provide additional descriptions of qualitative aspects. Data presentation with descriptive statistics using a summary statistics table and boxplot is used to support descriptive analysis. Furthermore, matching analysis was used for air quality categorization. PM parameters refer to The World Air Quality Index Project [38], using the Instant Air Quality Index (AQI converted directly from the 1-hour readings. Air quality categorization based on The World Air Quality Index Project [38], includes the categories of Good (0-50), Moderate (51-100), Unhealthy for Sensitive Groups (101-150), Unhealthy (151-200), Very Unhealthy (201-300), Hazardous (>300). Meanwhile, the parameters CO_2, TVOC and HCHO refer to the classification used by Vianney Augusta & Erfianto [39], which consists of five categories namely Excellent, Good Quality, Mild Pollution, Mediocre Pollution and Serious Pollution.

Research Area

This study was conducted in the commuter zone of Yogyakarta city. Referring to Rodrigue [12], based on The Burgess Urban Land Use Model and the Sector and Nuclei Urban Land Use Representations theory, commuter zones are located in suburban areas. Therefore, this study focused on these areas. Sample locations for measurements were purposively determined at points before entering the city center (Figure 1). There were 10 points used as observation locations, as shown in Table 1.

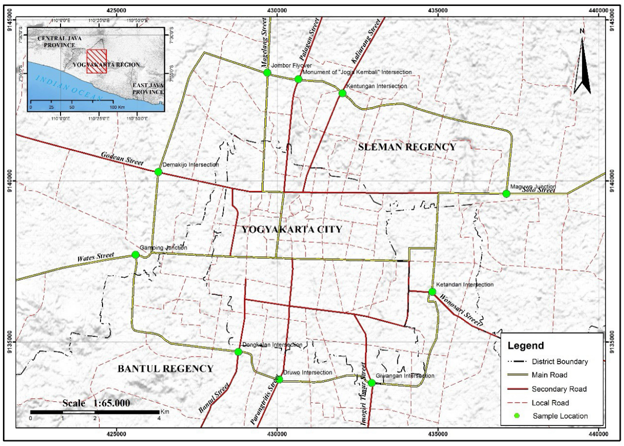

Figure 1. The Study Area

The research area is geomorphologically included in the landforms of the footplain to the fluviovolcanic plain of Merapi Volcano. The area is composed of the lithology of Young Merapi volcanic activity product with a high infiltration rate [40] – [42]. Yogyakarta City is the center of the Yogyakarta Special Region (locally known as Daerah Istimewa Yogyakarta or DIY), a relatively narrow area with complex landform characteristics [43].

RESULT AND DISCUSSION

The characteristics of commuting movement in the commuter lane of Yogyakarta

Commuting is the dominating transportation activity in the local scale spatial structure of the urban area. In terms of transportation modes, various road transportation modes tend to serve transportation at short distances in this local area [12]. Among the various modes of road transportation used in commuting activities in urban areas, motorcycles are the most widely used. Data from the Transportation Office of Yogyakarta Special Region [44] shows that in 2020, the total number of vehicles registered in DIY was 1,576,153 units. Of these, 86% were motorcycles. This high percentage of motorcycles is relatively stable in the five years between 2016-2020. Meanwhile, data from the Yogyakarta City Government [45] shows that in 2022, the number of motorcycles in Yogyakarta City reached 85% of all registered vehicles of 576,016 units.

By looking at the number of motorcycles in Yogyakarta City and other areas in Special Region of Yogyakarta as a hinterland, the typology of transportation modes and cities for the Yogyakarta region is motorcycle cities. Guerra & Duranton

Table 1. Location of the Measurement of Air Quality and Vehicle Intensity

No	Commuter lane	Location	Coordinate
1	Magelang Street	Jombor Flyover	429962, 9143359
2	Godean Street	Demakijo Intersection	426309, 9140276
3	Wates Street	Gamping Junction	425598, 9137705
4	Bantul Street	Dongkelan Intersection	428796, 9134692
5	Parangtritis Street	Druwo Intersection	430065, 9133831
6	Imogiri Timur Street	Giwangan Intersection	432947, 9133725
7	Wonosari Street	Ketandan Intersection	434832, 9136555
8	Solo Street	Maguwo Junction	437133, 9139599
9	Kaliurang Street	Kentungan Intersection	432035, 9142719
10	Palagan Street	Monument of “Jogja Kembali” Intersection	430664, 9143155

Source: Data analysis (2024)

[46] explain that motorcycle cities are dominated by motorcycles that sometimes uneasy and dangerous coexistence with other motorized vehicles. With three-quarters of the global two-wheeled vehicle fleet in Asia, Asian cities tiny to medium-sized cities, such as Taipei, Ho Chi Minh City, and Hanoi, are examples of this typology. In Indonesia, Surakarta is cited as a concrete example of this typology [18, 46]. Given the dominance of motorcycles in many Indonesian cities, motorcycle cities are a common typology for Indonesian cities, including Jakarta and Bandung [14], as well as Yogyakarta.

This study examines the movement of commuters during weekdays. Commuting activities in Yogyakarta during weekdays occur mainly in the morning and evening. This is related to the time of commuting to and from work, where commuters from various hinterland areas enter the sub-urban and CBD areas in the morning and then move back out of the city in the evening. In this study, we conducted 300 observations of commuter movements, with details in each of the 10 locations, we conducted three observations representing the morning, afternoon, and evening sessions, where ten observations were made in each session.

The study results show that the intensity of motorcycles passing within one minute is always more than cars. This was applicable at all points and all observation sessions. The highest average intensity of motorcycles in the morning was found on Parangtritis Street, while the lowest was on Godean Street. This is reasonable given that Parangtritis Street is an important route from the Bantul hinterland. At the same time, Godean Street comes from a less extensive hinterland, and there are many route options from the hinterland of Godean to the city. The highest maximum intensity in the morning session is found on Wonosari Street, while the lowest minimum intensity is again found on Godean Street.

In the Afternoon Session, the highest averages are found on Palagan Street and Kaliurang Street. Both roads are next to each other, which drain commuters from the same hinterland. The lowest average was found on Wates Street. This finding is interesting because Wates Street is a highway that connects Yogyakarta City to Yogyakarta International Airport and Central Java Province. Still, the intensity of motorcycles during the day is not high, whereas it is very high in the morning. This suggests that commuter activity on this road is relatively focused in the morning. Commuters come from relatively distant areas of Kulon Progo Regency.

The same condition as on Wates Street is also found on Magelang Street and Solo Street. These three roads connect Yogyakarta with other big cities and provinces. Magelang Street is a national road that connects Yogyakarta, the capital city of the Yogyakarta Special Region, with Semarang City, the capital city of Central Java Province. Meanwhile, Solo Street connects Yogyakarta with Surakarta City in Central Java Province. In the morning, the intensity of vehicles is very high, but in the afternoon, it drops drastically, which is related to the commuters' relatively distant areas of origin. The condition is very different from Palagan Street and Kaliurang Street, which are residential zones extend northward from Yogyakarta City.

Magelang Street, a national arterial road, tends to have a stable motorcycle intensity. The measurement results in the morning show a relatively stable intensity. In the morning when it is crowded, in the afternoon when it is quiet, and in the evening when it is crowded, the intensity is relatively stable from 10 observations made in one session. Different conditions were found at Palagan Street in the afternoon session and Imogiri Timur Street in the evening session, which showed high outliers. This means that among the ten observations in one session, there are very high motorcycle intensity events, while the other data is relatively stable (Figure 2). Overall, motorcycle movements in areas with many settlements show relatively stable conditions. This is demonstrated by the average intensity of motorcycles per minute in the morning, afternoon, and evening sessions, which are relatively not significantly different. Meanwhile, highways such as Magelang Street, Solo Street, and Wates Street, connecting routes to other cities, show significant average differences between the three sessions, with a decrease in intensity in the afternoon (Table 2).

Different findings were found for car traffic behaviour. In the morning, the highest average number of passing cars was found on Solo Street, while the lowest was on Godean Street and Wonosari Street. This is because Solo Street is the main road to Adisutjipto Airport in the east of Yogyakarta, and the main road connects Yogyakarta with Surakarta. Meanwhile, Godean Street is not a connecting road with other major cities, comes from a less extensive hinterland, and has many route options to avoid congestion in the morning. The highest maximum intensity of cars in one minute for the morning session is on Solo Street and Palagan Street. In contrast, the lowest minimum intensity occurs in Godean Street, Wonosari Street, and Imogiri Timur Street.

In the Afternoon Session, the highest averages are found on Palagan Street and Solo Street. Palagan Street is the route to the densely populated residential zone in the city's north. Meanwhile, Solo Street also still has the highest average car intensity during the day. Interestingly, the lowest average is found on Kaliurang Street. This finding is interesting because Kaliurang Street carries commuters from the same hinterland as Palagan Street. In the morning, the intensity of cars on these two roads is the same, but during the afternoon session, the intensity of cars on Kaliurang Street is relatively low, while Palagan Street remains high.

The change in car intensity between morning and afternoon is generally relatively small. In other words, the number of cars travelling in the morning and afternoon is relatively the same. This is the case in the majority of observation locations. However, there are anomalies at specific locations where car intensity drops or increases drastically. Although still showing the highest intensity in the afternoon, Solo Street experienced a significant decrease in intensity compared to the morning. Meanwhile, Godean Street, Bantul Street, and Imogiri Timur Street experienced a significant increase in the afternoon session (Table 2). Godean Street, Bantul Street, and Imogiri Timur Street are not connecting roads between cities but from densely populated hinterlands. The high intensity of cars in the afternoon session could be due to non-local traffic, or there is another possibility that car users tend to travel indifferent sessions to avoid congestion caused by the large number of motorcycles in the morning.

Compared to the average intensity of cars in the afternoon session, the average number of vehicles in the evening session increased at all observation points, except at Bantul Street, where it decreased. This decrease in the average intensity of cars on Bantul Street is still within reasonable limits because it does not show a significant difference. Compared to the morning session, the average intensity of vehicles in the evening shows an upward trend. Substantial increases are found in Kaliurang Street, Imogiri Timur Street, and Godean Street, all three routes to densely populated hinterlands, not inter-city roads. This indicates that the high intensity of cars in the evening comes from local commuters who share the road with motorcycle commuters.

The average intensity of passing cars is relatively same at eight observation points: Magelang Street, Kaliurang Street, Wonosari Street, Imogiri Timur Street, Parangtritis Street, Bantul Street, Wates Street, and Godean Street. This indicates that the commuters' return time is the same and spread evenly across the commuter routes in Yogyakarta City. Meanwhile, Palagan Street and Solo Street again show the highest average intensity of cars. The intensity of vehicles along the nine commuter routes in Yogyakarta City generally indicates a relatively stable condition. This can be seen through the average intensity of cars passing per minute in the morning, afternoon, and evening sessions, which is not significantly different. Only Solo Street, a national road and the route to the airport show a significant difference in average between the three sessions, with a decrease in intensity occurring in the afternoon. See Figure 2.

Spatio-temporal pattern of air quality on the commuter lanes of Yogyakarta

In this study, we measured ambient air quality at all observation sites and the intensity of vehicles passing by in one minute. Like the vehicle intensity measurements, air quality measurements were also taken at ten commuter lanes. Three measurement sessions were conducted at each location: morning, afternoon, and evening. In each session, ten measurements were taken. Thus, the total data collected from the study area was 300, with 100 data for the morning, afternoon, and evening sessions.

Five air quality parameters are measured in this study, namely PM2.5, PM 10, CO_2, TVOC, and HCHO. Particulate matter (PM) are particles consist of in the air, including dust, soot, dirt, smoke, and liquid droplets. PM2.5 is known to be the biggest threat from air pollution, among other types of pollutants. Li et al. [47] explained that PM2.5 is the most consistent and robust predictor of mortality based on long-term study findings. Huang et al. [48] also explained that PM is one of the most critical environmental problems in most world regions. One source of PM2.5 is transportation. The study conducted in China by Yu et al. [49] showed that transportation density and road network structure in urban transportation play an essential role in PM2.5 concentrations. A study conducted by C. Li & Managi[84] found that in the United States, 6.17 billion kilometres (km) per km2 on-road transportation increase is associated with a 1-µg/m3 county-level PM2.5 concentration increase. On this basis, they recommended county-level policies that consider the temporal and spatial variability of the relationship to mitigate PM2.5 from road transport.

In addition to PM2.5, PM10 is a pollutant source that has received much attention. PM10 has a diameter of 10 micrometers, making it coarser than PM2.5. Sloss & Smith [50] explain that PM10 and PM2.5 arise from natural and human sources. Potential sources of human activities include coal-fired power plants, industry, and road transportation. Given the crucial position of PM in air pollution, as well as the role of road transportation as one of the primary sources of PM, PM parameters, both PM2.5 and PM10, are used as the indicators of air quality in commuter routes in this study.

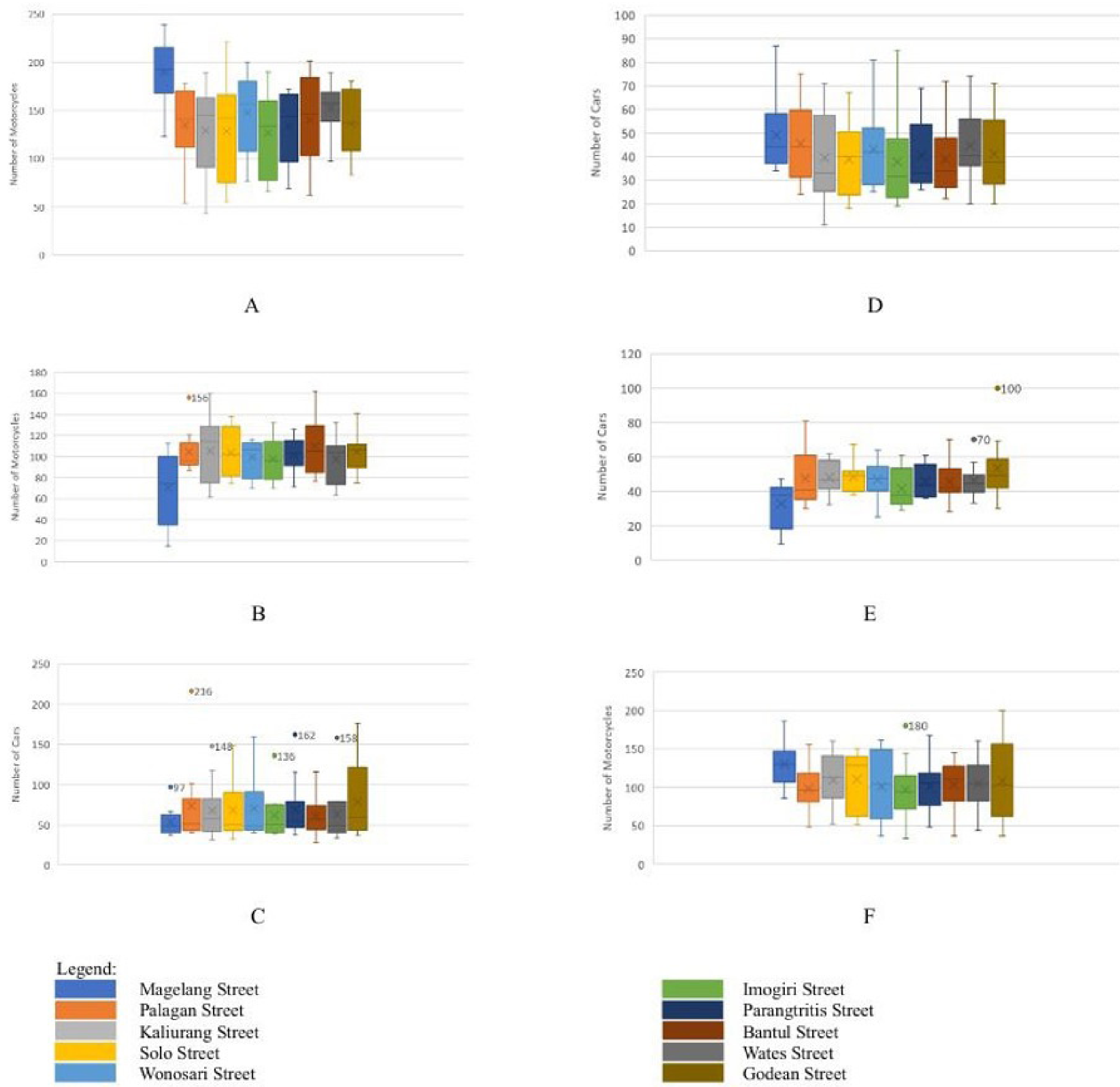

Figure 2. Boxplot for motorcycle and car intensity in the study area. (A) motorcycle in the morning, (B) motorcycle in the afternoon, (C) motorcycle in the evening, (D) car in the morning, (E) car in the afternoon, (F) car in the evening.

Other parameters used are CO_2, TVOC, and HCHO. After the COVID-19 pandemic, there was an increase in CO_2 from transportation, 72% of which was generated from road transportation [51]. He et al. [52] explained that volatile organic compounds, or VOCs, are commonly considered the major types of pollutants in urban air pollution. In road transportation, benzene is a source of VOCs from vehicles, including leaded gasoline, which still exists. Formaldehyde, or HCHO, is particularly influential in the troposphere, where traffic and transportation are essential anthropogenic sources [53].

The measurement results show that air quality conditions vary among locations and sessions. PM2.5 measurements show that PM2.5 concentrations tend to be higher in the morning and evening than the afternoon session. Measurements at 10 locations show that the average PM2.5 in the morning session is always higher than the afternoon session except at Kaliurang Street and Parangtritis Street. On Kaliurang Street, PM 2.5 in the afternoon is slightly higher than in the morning. Meanwhile, on Parangtritis Street, PM2.5 in the afternoon increased significantly compared to the morning. In the evening session, the average PM2.5 increased again compared to the afternoon, except on Palagan Street and Parangtritis Street. This pattern of increasing and decreasing PM2.5 concentrations between morning, afternoon and evening is thought to be related to commuter activities that are busier in the morning and evening than during the afternoon.

Maximum PM2.5 concentrations in the morning occur on Godean Street, which tends to be narrow and congested with motor vehicles. In the afternoon, the maximum con-

Table 2. Summary of statistical data on the intensity of motorcycles and cars in the study area in the morning, afternoon, and evening

Location	Parameters	Motorcycles			Cars		
		Morning	Afternoon	Evening	Morning	Afternoon	Evening
Magelang Street (Jombor Flyover)	N	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	151,6	99,1	113,0	48,4	41,0	45,6
	Median	143,0	109,0	105,5	45,5	40,5	43,5
	Stdev	25,3	26,2	33,2	8,9	10,7	8,1
	Max	217,0	125,0	200,0	67,0	57,0	63,0
	Min	134,0	38,0	86,0	37,0	18,0	37,0
Palagan Street (Monument of Jogja Kembali Intersection)	N	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	144,3	115,2	150,6	62,2	62,4	65,4
	Median	153,0	123,5	153,5	58,5	65,5	68,5
	Stdev	20,2	39,6	22,8	10,5	22,5	11,1
	Max	170,0	162,0	180,0	87,0	100,0	76,0
	Min	111,0	15,0	93,0	54,0	9,0	37,0
Kaliurang Street (Kentungan Intersection)	N	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	164,9	115,4	133,5	38,7	31,1	44,1
	Median	173,0	114,0	133,0	38,5	30,5	40,5
	Stdev	22,0	37,2	19,0	6,9	7,9	19,4
	Max	189,0	160,0	162,0	47,0	48,0	97,0
	Min	135,0	25,0	108,0	30,0	17,0	28,0
	N	10,0	10,0	10,0	10,0	10,0	10,0
Solo Street (Maguwo Junction)	N	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	174,1	89,9	95,0	70,1	58,3	73,4
	Median	168,5	92,5	96,5	71,0	57,5	65,5
	Stdev	19,0	17,2	29,5	10,4	11,8	37,9
	Max	215,0	120,0	135,0	85,0	81,0	176,0
	Min	156,0	63,0	50,0	46,0	37,0	41,0
Wonosari Street (Ketandan Intersection)	N	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	96,5	103,2	54,1	26,5	40,1	128,0
	Median	81,5	107,5	46,0	26,5	39,5	136,5
	Stdev	53,8	17,3	31,6	5,6	6,5	46,4
	Max	239,0	129,0	140,0	34,0	49,0	216,0
	Min	54,0	71,0	33,0	18,0	32,0	55,0
Imogiri Timur Street (Giwangan Intersection)	N	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	103,5	103,8	57,2	28,7	44,7	120,6
	Median	103,0	107,5	50,5	28,0	44,0	116,5
	Stdev	32,0	21,4	19,8	6,3	9,6	32,9
	Max	176,0	129,0	112,0	42,0	58,0	159,0
	Min	66,0	73,0	46,0	20,0	29,0	67,0

Parangtritis Street (Druwo Intersection)	N	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	177,2	87,3	117,2	47,0	46,9	48,9
	Median	180,5	88,5	116,0	47,0	46,0	47,0
	Stdev	29,5	13,7	19,5	9,3	5,0	7,2
	Max	221,0	104,0	158,0	60,0	58,0	64,0
	Min	139,0	61,0	87,0	34,0	41,0	40,0
Bantul Street (Dongkelan Intersection)	N	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	163,7	107,8	128,0	35,1	47,2	45,8
	Median	164,0	104,5	120,0	34,0	46,5	42,5
	Stdev	21,2	15,9	28,9	8,5	6,4	9,2
	Max	194,0	138,0	186,0	48,0	58,0	59,0
	Min	125,0	87,0	99,0	23,0	38,0	33,0
Wates Street (Gamping Junction)	N	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	148,6	74,3	99,8	37,1	41,8	48,0
	Median	152,5	72,5	94,0	37,0	40,5	47,5
	Stdev	37,7	9,7	17,8	8,3	6,5	5,0
	Max	201,0	95,0	144,0	51,0	57,0	55,0
	Min	83,0	61,0	86,0	26,0	36,0	39,0
Street (Demakijo Intersection)	N	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	95,4	98,4	114,5	25,0	42,3	49,8
	Median	99,5	101,0	110,5	24,0	41,5	46,0
	Stdev	37,3	12,7	17,7	8,8	5,8	9,8
	Max	160,0	120,0	150,0	42,0	53,0	71,0
	Min	43,0	75,0	89,0	11,0	34,0	41,0

Source: Data analysis (2024)

centration occurs on Parangtritis Street, which is the route to the beach, allowing local non-commuter transportation activities. In the evening, the maximum concentration occurs on Parangtritis Street. The maximum PM2.5 concentration is even higher than at other points and shows an extreme increase compared to the morning and afternoon. The minimum PM2.5 concentration in the morning occurred on Kaliurang Street, in the afternoon on Solo Street, and in the evening also on Solo Street. The minimum PM2.5 concentration in the evening at Wonosari Street is still the highest compared to the other nine measurement locations. The minimum measured number even has a significant difference compared to other locations. This shows that PM2.5 concentrations on Wonosari Street are high in the evening. According to C. Li & Managi [84], PM2.5 mainly comes from combustion emissions, although road transport is not a major source and contributes little to PM2.5. Meanwhile, Z. Li et al.[87] explained that heavy traffic activities are an important source of PM2.5, in addition to energy production and biomass burning. This answers why, during heavy traffic in the morning and evening, PM2.5 concentrations are higher than during the afternoon.

PM10 measurements show similar results to PM2.5. PM10 concentrations tended to be higher in the morning and evening than in the afternoon at almost all measurement points, except at Kaliurang Street and Parangtritis Street. In general, PM10 concentrations were high in the morning, then decreased in the afternoon and increased again in the evening. This can be seen from the average PM10 value, where there is a decrease in PM10 concentration during the afternoon, which then increases in the evening at eight observation points. Meanwhile, two other points, Kaliurang Street and Parangtritis Street, experienced an increase in PM10 concentrations during the afternoon and decreased in the evening. During the afternoon, the increase in PM10 concentration on Kaliurang Street was not much different from the morning and then it decreased again in the evening. While on Parangtritis Street, there was a significant increase in PM10 during the afternoon and then decreased significantly in the evening.

Maximum PM10 concentrations in the morning also occur on Godean Street, which is related to the characteristics of the street, which tends to be narrower and denser with vehicles. During the afternoon, the maximum PM10 concentration occurs on Parangtritis Street. These maximum concentrations significantly different from the other measurement locations and showed extreme increases and decreases between morning, afternoon, and evening. The maximum PM10 concentration in the evening occurred on Wonosari Street, a route that connects the activity centre with the densely populated residential areas to the east of the city and the commuters' regions of origin further away in Gunungkidul Regency. The minimum PM10 concentration in the morning was found on Imogiri Timur Street, while in the afternoon and evening was found on Solo Street. Although the minimum PM10 concentration in the morning was found on Imogiri Timur Street, the average PM10 concentration from the point was the second highest. This shows that PM 10 concentration in Imogiri Timur Street does tend to be high.

PM10 concentrations are associated with exhaust gases from motorised vehicles, both cars and motorcycles. Harrison et al. [86] explains that vehicle exhaust emissions account for an average of 32% of PM10, especially during winter. Findings from a study in Jakarta, Indonesia, even show that PM 2.5 and PM 10 are mostly emitted from the road transport and industrial combustion sectors, each contributing around 43%-46%. Heavy vehicles are still the highest contributor to PM 2.5 emissions in the transport sector [90]. This validates the findings in our study that PM10 concentrations are higher in the morning and evening when more vehicles pass by. However, PM10, larger than 2.5 μm, does not stay in the air for long, and its spatial impact is usually limited because it tends to settle on the ground in the opposite direction of the emission source (EPA, 2018).

The CO_2 measurement results also show that this parameter tends to be higher in the morning and evening than in the afternoon, although the difference is insignificant. Measurements at 10 locations show that the average CO_2 in the morning is always higher than in the afternoon, except on Wonosari Street and Wates Street. On both streets, the CO_2 concentration in the afternoon was slightly higher than in the morning. In the evening, the average of CO_2 concentration increased again in almost all measurement locations except Bantul Street. Unlike the other measurement locations, in Bantul Street, the CO_2 concentration decreased in the evening. This condition shows the possibility that the pattern of increasing and decreasing CO_2 concentrations in the morning, afternoon, and evening are related to commuter activities, which tend to be busy in the morning and evening. This is related to the commuters' departure and return hours.

Maximum CO_2 concentrations in the morning session occurred on Kaliurang Street, which connects the CBD with residential areas in the north of Yogyakarta City. Traffic conditions in the morning on Kaliurang Street tend to be congested with motorized vehicles, so the CO_2 figures obtained are the highest compared to other places. Maximum CO_2 concentrations during the afternoon occurred on Wates Street and was the highest value compared to all measurement locations in the morning, afternoon, and evening. In the evening, maximum CO_2 concentrations occurred on Imogiri Timur Street. Minimum CO_2 concentrations in the morning were found on Wonosari Street and Bantul Street. During the afternoon, minimum CO_2 concentrations are relatively uniform in almost all measurement locations. Meanwhile, minimum CO_2 concentrations in the evening were found on Magelang Street and Parangtritis Street. However, there is no significant difference between the afternoon minimum CO_2 concentrations at all measurement locations.

Total Volatile Organic Compounds (TVOC) measurement results did not show significant differences in the morning, afternoon, and evening sessions. In the morning and evening, the average TVOC concentrations also tended to be higher than in the afternoon session, except on Wonosari Street, Bantul Street, and Parangtritis Street. On Wonosari Street, average TVOC concentration in the afternoon was higher than in the morning. Meanwhile, on Bantul Street and Parangtritis Street, average TVOC concentration in the afternoon was higher than in the evening. The highest average TVOC concentration in the morning was found on Kaliurang Street, in the afternoon on Wates Street and in the evening on Imogiri Timur Street. Maximum TVOC concentrations in the morning, afternoon, and evening were found on these three roads. Meanwhile, minimum TVOC concentration in the morning was found on Imogiri Timur Street, in the afternoon on Palagan Street, and in the evening on Parangtritis Street.

HCHO measurements at the 10 locations show highly variable conditions. As with other air quality parameters, HCHO concentrations tended to be high in the morning and evening. An exciting finding was found at Parangtritis Street and Bantul Street, where there was no significant difference in measurement results between the morning, afternoon, and evening sessions. HCHO concentrations tended to remain constant throughout the day. The highest average concentration of HCHO in the morning occurred on Kaliurang Street, which is congested with motorized vehicles; in the afternoon, it was on Wates Street; and in the evening, it was on Imogiri Timur Street. The highest maximum concentration in the morning was found on Kaliurang Street, in the afternoon on Bantul Street, and in the afternoon on Imogiri Timur Street. The minimum HCHO concentration in the morning was found in six locations: Magelang Street, Palagan Street, Wonosari Street, Imogiri Street, Parangtritis Street, and Bantul Street. While in the afternoon, it showed a minimum value in all measurement locations. In the evening, there are four locations: Magelang Street, Palagan Street, Parangtritis Street, and Bantul Street. Based on all measurements, it is concluded that there is minimal influence during the day, and even in some locations, there is no increase. A summary of the air quality measurement data in the study area is shown in Table 3.

Table 3. Summary of statistical data on the air quality measurement in the study area

Location	Parameters	PM2.5			PM10			CO_2			TVOC			HCHO		
		M	A	E	M	A	E	M	A	E	M	A	E	M	A	E
Magelang street	N	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	35,2	19,0	30,8	48,7	24,7	44,1	685,2	409,1	485,9	0,3	0,0	0,1	0,1	0,0	0,0
	Median	35,5	19,5	30,5	49,5	24,0	44,0	710,5	391,0	409,5	0,3	0,0	0,0	0,1	0,0	0,0
	Stdev	7,6	4,1	8,3	10,5	5,8	11,8	107,9	42,3	118,5	0,1	0,0	0,1	0,0	0,0	0,0
	Max	50,0	24,0	44,0	69,0	31,0	62,0	766,0	520,0	664,0	0,4	0,1	0,3	0,1	0,0	0,1
	Min	20,0	9,0	12,0	29,0	11,0	17,0	400,0	385,0	385,0	0,0	0,0	0,0	0,0	0,0	0,0
Palagan Street	N	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	30,1	22,5	21,9	42,1	29,7	33,6	731,1	410,6	643,6	0,4	0,0	0,3	0,1	0,0	0,0
	Median	30,0	24,0	14,5	41,0	32,5	19,5	775,5	392,0	661,5	0,4	0,0	0,3	0,1	0,0	0,0
	Stdev	3,0	6,9	11,6	4,8	9,4	23,4	127,7	47,3	181,7	0,1	0,0	0,2	0,0	0,0	0,0
	Max	35,0	30,0	41,0	49,0	38,0	85,0	833,0	541,0	861,0	0,5	0,2	0,6	0,1	0,0	0,1
	Min	26,0	7,0	13,0	36,0	9,0	17,0	387,0	385,0	386,0	0,0	0,0	0,0	0,0	0,0	0,0
Kaliurang Street	N	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	16,3	17,8	20,2	22,1	25,5	22,2	833,6	445,7	646,0	0,5	0,1	0,2	0,1	0,0	0,0
	Median	16,0	14,0	20,5	21,0	19,0	22,5	905,0	407,5	611,0	0,6	0,0	0,2	0,1	0,0	0,0
	Stdev	2,9	8,9	4,9	3,8	14,1	4,4	162,2	68,6	133,2	0,2	0,1	0,2	0,1	0,0	0,0
	Max	22,0	33,0	29,0	30,0	48,0	28,0	922,0	541,0	822,0	0,7	0,2	0,5	0,3	0,0	0,1
	Min	12,0	8,0	10,0	16,0	9,0	15,0	412,0	385,0	454,0	0,0	0,0	0,0	0,0	0,0	0,0
Solo Street	N	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	20,9	9,3	22,1	27,4	13,0	31,3	485,3	435,9	507,6	0,1	0,1	0,1	0,0	0,0	0,0
	Median	21,0	6,5	22,0	27,0	9,0	31,5	480,5	424,5	524,0	0,1	0,0	0,1	0,0	0,0	0,0
	Stdev	5,2	5,8	9,0	6,6	8,6	13,1	62,9	52,7	74,3	0,1	0,0	0,1	0,0	0,0	0,0
	Max	29,0	20,0	44,0	39,0	27,0	63,0	585,0	551,0	597,0	0,2	0,2	0,2	0,0	0,0	0,0
	Min	13,0	4,0	9,0	17,0	5,0	13,0	403,0	385,0	401,0	0,0	0,0	0,0	0,0	0,0	0,0
Wonosari Street	N	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	44,2	9,3	64,6	62,0	12,6	95,9	404,7	433,0	635,6	0,0	0,1	0,3	0,0	0,0	0,0
	Median	43,0	9,5	53,0	58,5	12,0	75,5	399,5	414,0	610,0	0,0	0,0	0,2	0,0	0,0	0,0
	Stdev	6,1	1,6	56,9	8,6	2,4	87,5	19,7	56,3	115,5	0,0	0,2	0,1	0,0	0,0	0,0
	Max	60,0	12,0	222,0	81,0	16,0	338,0	441,0	539,0	760,0	0,1	0,6	0,4	0,0	0,0	0,1
	Min	39,0	7,0	28,0	54,0	9,0	41,0	385,0	385,0	461,0	0,0	0,0	0,1	0,0	0,0	0,0
Imogiri Timur Street	N	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	50,0	11,2	17,3	64,4	21,0	25,2	461,6	420,1	957,9	0,1	0,0	0,8	0,0	0,0	0,1
	Median	50,0	8,0	15,0	69,5	13,0	22,0	470,5	403,5	952,5	0,1	0,0	0,7	0,0	0,0	0,2
	Stdev	16,7	7,1	6,1	29,1	16,7	9,2	56,4	44,7	216,2	0,1	0,0	0,4	0,0	0,0	0,1
	Max	75,0	30,0	27,0	103,0	57,0	41,0	538,0	524,0	1183,0	0,2	0,1	1,3	0,0	0,0	0,2
	Min	28,0	7,0	10,0	10,0	10,0	14,0	393,0	385,0	455,0	0,0	0,0	0,1	0,0	0,0	0,0
Parangtritis Street	N	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	30,7	71,9	42,3	44,4	109,3	59,3	514,8	409,1	481,7	0,0	0,0	0,0	0,0	0,0	0,0
	Median	31,0	38,5	49,5	45,0	51,0	69,5	482,5	403,5	491,5	0,0	0,0	0,0	0,0	0,0	0,0
	Stdev	3,5	64,6	15,3	5,4	105,1	21,9	99,1	29,0	71,0	0,0	0,0	0,0	0,0	0,0	0,0
	Max	36,0	176,0	60,0	53,0	268,0	84,0	725,0	480,0	577,0	0,0	0,0	0,0	0,0	0,0	0,0
	Min	24,0	5,0	12,0	34,0	7,0	16,0	430,0	385,0	385,0	0,0	0,0	0,0	0,0	0,0	0,0

Bantul Street	N	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	40,0	33,1	42,3	57,1	44,6	59,2	509,2	460,5	451,3	0,0	0,0	0,0	0,0	0,0	0,0
	Median	37,5	34,5	43,5	54,0	47,5	61,5	512,0	453,0	431,5	0,0	0,0	0,0	0,0	0,0	0,0
	Stdev	6,6	10,3	10,3	8,6	13,4	13,9	105,7	53,2	55,6	0,0	0,0	0,0	0,0	0,0	0,0
	Max	53,0	48,0	52,0	73,0	62,0	72,0	648,0	579,0	539,0	0,0	0,0	0,0	0,0	0,0	0,0
	Min	34,0	8,0	18,0	47,0	11,0	25,0	385,0	385,0	392,0	0,0	0,0	0,0	0,0	0,0	0,0
Wates Street	N	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	45,0	21,2	42,5	61,9	29,1	61,9	617,1	687,6	644,4	0,2	0,4	0,2	0,0	0,1	0,0
	Median	38,5	18,0	45,0	56,0	24,0	65,5	582,0	602,0	617,5	0,2	0,2	0,2	0,0	0,0	0,0
	Stdev	17,4	14,0	13,3	18,4	20,0	19,8	93,1	321,5	91,9	0,1	0,6	0,1	0,0	0,1	0,0
	Max	92,0	58,0	57,0	112,0	83,0	83,0	796,0	1521,0	786,0	0,4	2,0	0,4	0,1	0,2	0,1
	Min	35,0	5,0	13,0	51,0	8,0	19,0	524,0	387,0	517,0	0,1	0,0	0,0	0,0	0,0	0,0
Go-dean Street	N	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
	Mean	57,3	19,6	31,3	78,7	27,1	45,8	515,2	570,3	610,6	0,1	0,2	0,2	0,0	0,0	0,0
	Median	47,0	19,0	29,0	66,0	25,5	39,5	523,0	572,5	560,0	0,1	0,2	0,2	0,0	0,0	0,0
	Stdev	37,1	8,5	14,3	46,8	11,5	25,1	83,5	158,2	153,3	0,1	0,2	0,2	0,0	0,0	0,0
	Max	162,0	39,0	68,0	211,0	54,0	113,0	669,0	833,0	900,0	0,3	0,5	0,6	0,1	0,1	0,1
	Min	38,0	5,0	12,0	55,0	8,0	17,0	405,0	386,0	409,0	0,0	0,0	0,0	0,0	0,0	0,0

Source: Field Measurements (2024)

The results of the matching analysis between the parameters PM2.5, PM10, CO_2, TVOC and HCHO with air quality categories referring to The World Air Quality Index Project [38] and Vianney Augusta & Erfianto [39] show a variety of air quality categories for each parameter in the morning, afternoon, and evening. The average PM2.5 is relatively uniform across all locations in the morning, afternoon, and evening, which is in the good category. However, several locations fall into the moderate category, including Godean Street in the morning, Parangtritis Street in the afternoon and Wonosari Street in the evening.

In the morning's PM10 parameter, five roads are included in the good category: Magelang Street, Palagan Street, Kaliurang Street, Solo Street, and Parangtritis Street. Five other locations in the moderate category include Wonosari Street, Imogiri Timur Street, Bantul Street, Wates Street, and Godean Street. PM10 conditions in the afternoon session fall into the good category in almost all locations. Still, an anomaly on Parangtritis Street shows that in 10 measurements, three reached >250 ppm and fell into the Unhealthy category for Sensitive Groups on average. Meanwhile, PM10 conditions in the evening session show that there are six locations that fall into the good category, including Magelang Street, Palagan Street, Kaliurang Street, Solo Street, Imogiri Timur Street, and Parangtritis Street; four locations with moderate categories, including Wonosari Street, Parangtritis Street, Bantul Street, and Wates Street.

CO_2 conditions in the morning and evening tend to be more diverse when it compared to the conditions in the afternoon. CO_2 conditions with the Excellent Quality category in the morning are found on Solo Street, Wonosari Street, Imogiri Timur Street, Parangtritis Street, Bantul Street, and Godean Street; Good Quality category is found on Magelang Street, Palagan Street, and Wates Street; while Mild Pollution category in the morning is found on Kaliurang Street. CO_2 conditions in the afternoon show a more uniform category with nine observation points included in the Excellent Quality category, except for Wates Street, which is included in the Good Quality category. Different conditions in each location are also shown in the CO_2 concentration in the evening. The Excellent Quality category is found in four locations: Magelang Street, Solo Street, Parangtritis Street, and Bantul Street. The Good Quality category is found on Palagan Street, Kaliurang Street, Wonosari Street, Wates Street, and Godean Street. In addition to these two categories, a Mild Pollution category is found on Imogiri Timur Street.

There is not too much significant variation in the TVOC parameter. Almost all locations have low TVOC concentrations and are included in the Excellent Quality category. Some locations that fall into the Good Quality category are Palagan Street in the morning and Wates Street in the afternoon. The TVOC concentrations in the Mild Pollution category were found at Kaliurang Street in the morning and Imogiri Timur Street in the evening. Meanwhile, the condition of HCHO in all locations is relatively the same, which is included in the Excellent Quality category.

Influence of commuting activities on the instantaneous air quality

In this section, we present the analysis results of the effect of commuter transportation on instantaneous air quality. We conducted simple linear regression tests between the total number of vehicles and all air quality parameters used in this study, namely PM2.5, PM10, CO_2, HCHO, and TVOC. The test was conducted on all morning, afternoon, and evening data at ten observation locations, which are Yogyakarta commuter lanes.

The analysis shows that the relationship between the number of vehicles passing by in one minute and the instantaneous air quality at that time is entirely positive. Thus, it can be seen that an increase in the number of vehicles passing by affects the ambient air quality, which worsens during that period. Although this relationship is not always significant across all observation locations, this positive relationship shows a clear impact of additional vehicles on worsening air quality.

The relationship between the number of vehicles and various air quality parameters is generally polynomial. This relationship indicates that the impact on air quality is not always steady and linear. This is likely because the exhaust gases from motor vehicles are not the only source of pollutants in this study's air quality parameters. Querol et al. [88] explain that sources of coarse particles (PM2.5 to PM10) include re-suspension of loose soil or road dust, natural dust storms, and different industrial processes. Some minimal non-polynomial relationships were found for PM2.5, PM10, and TVOC. A logarithmic relationship between the number of vehicles and PM2.5 was found on Wates Street in the afternoon and Kaliurang Street in the evening. A linear relationship was found on Parangtritis Street in the evening. In the PM10 parameter, there is an exponential relationship, namely on Magelang Street in the morning. Meanwhile, in the TVOC parameter, there is a logarithmic relationship between Palagan Street and Solo Street in the morning and Wates Street and Bantul Street in the evening.

The most significant relationship between the number of vehicles and PM2.5 in the morning session occurred on Wonosari Street (r2 = 0.8223), the afternoon session on Magelang Street (r2 = 0.8365), the evening session on Wates Street (r2 = 0.5606). In the PM10 parameter, the most significant relationship in the morning session is on Wonosari Street (r2 = 0.7457), in the afternoon session on Magelang Street (r2 = 0.8664), and the evening session on Wates Street (r2 = 0.5443). The CO_2 parameter that has the most significant relationship is found on Magelang Street for the morning session (r2 = 0.8557), Wates Street for the afternoon session (r2 = 0.8105), and Solo Street for the evening session (r2 = 0.5566). For the TVOC parameter, the most significant relationships were found at Imogiri Timur Street (r2 = 0. 8432) for the morning session, Magelang Street (r2 = 0. 5382) for the afternoon session, and Solo Street (r2 = 0.7996) for the evening session. Finally, the most significant relationship on the HCHO parameter occurred on Imogiri Timur Street for the morning session (r2 = 0.8432), Magelang Street for the afternoon session (r2 = 0.5382), and Solo Street (r2 = 0.7996) for the evening session.

Two interesting findings regarding the relationship between the number of passing vehicles and instantaneous air quality exist. First, the nature of the relationship tends to be positive and significant in the morning and afternoon but weakens in the evening. This is likely because, in the evening, there has been an accumulation of pollutants in the atmosphere. Hence, the effect of an increase in the number of vehicles on changes in air quality at that time is only slight. Second, national roads connecting Yogyakarta with other major cities, namely Magelang Street, Wates Street, and Solo Street, appear most frequently as locations with the most significant relationships. This suggests that additional vehicle traffic strongly and positively affects instantaneous air quality on these roads. It seems that their function as national inter-city roads that not only channel commuters from the hinterland causes these roads to be traversed by a variety of vehicles, which in turn influences the worsening of air quality in some of the parameters measured in this study.

There are relationships between vehicle types and air quality parameters. Here, we compare streets with many motorcycles and few cars and streets with fewer motorcycles and more cars. In the study area, there are no motorcycle-only or car-only streets. All streets are dominated by motorcycles, while cars are less in number. With this in mind, we compared two types of streets: those with more motorcycles and fewer cars and those with fewer motorcycles and more cars. The first group of streets is represented by Kaliurang Street, which is passed by 78.4% motorcycles and 21.6% cars. The second group is represented by Wonosari Street, which is passed by 56.6% motorcycles and 43.4% cars.

The results of the T-test analysis show statistically significant differences between air quality parameters on Kaliurang Street and Wonosari Street. On PM2.5 and PM10 parameters, Wonosari Street, with more cars, has a worse air quality. Meanwhile, on CO_2, TVOC, and HCHO parameters, Kaliurang Street, dominated by motorcycles, has worse air quality. This shows a difference between streets that are heavily traveled by motorcycles and streets that are pretty heavily traveled by cars.

Discussion

One of the impacts of transportation activities on the environment is pollution caused by various transportation modes. Rodrigue [12] explains that the transportation sector accounts for about a quarter of global CO_2 emissions, of which 74% of CO_2 emissions come from land transportation. This condition shows that land transportation needs much attention as an essential source of atmospheric pollutants. In addition to CO_2, there are various other gases associated with engine combustion inland transportation modes, as well as particulate matter, which is an air pollutant comprising suspended particles in air, one of the primary sources of which is the activity of land transportation modes.

The issue of urban air quality and urban air pollution concerning commuting activities has received much attention from previous authors. Topics related to air pollution and its relationship with commuting activities that have become a trend of discussion in the last decade are commuter exposure to air pollution and its health risks, the effects of transportation on air quality in urban areas, and air quality improvement as a result of the COVID-19 pandemic. Commuter exposure to air pollution is the most discussed topic. This topic has been discussed since five decades ago [54] and continues to be a relevant topic of discussion in the following decades [55] – [58] and has been increasingly discussed in the last decade. Various studies have been conducted in this field, including in Taiwan [29], [30], China [59], U.K. [60], [61], India [61], Ethiopia [62], and Canada [63]. The topic of the effect of COVID-19 on improving air quality due to reduced transportation activity has been widely discussed, including in Russia [64], Canada [10], U.K. [65], France [66], China [67], India [68], and Italy [69].

Meanwhile, studies that address the causal relationship between transportation activities, especially commuting, and urban air quality are relatively undiscussed. Thus, our study provides additional information to fill the scientific gap in this area. In this study, we found that commuting activities affect the instantaneous air quality around commuter routes. By studying Yogyakarta City, which is dominated by the use of private vehicles, especially motorcycles, we found a positive relationship between the level of mobility represented by vehicle intensity and air quality. If the number of vehicles increases, the air quality tends to worsen. The results of 300 observations in 10 locations show that this relationship is not always significant, but all are positive with a polynomial trendline type.

There are several previous studies with topics that are relatively close to our study. Lim et al. [70] , in a study in Seoul, Korea, identified spatial and temporal variations in air quality along bicycle lanes. As expected, the study found that heavy traffic volume affected air pollution levels. This study has similar results in that the spatial and temporal analysis shows a positive influence of urban transportation activities on air pollution. However, this study does not explicitly mention commuting activities. Ferenczi et al. [71] in Budapest, Romania, found the influence of long-distance transportation on air quality, especially on SO2, NO2 and Particulate Matter parameters. Compared to our study, the Budapest study did not highlight commuting activities but long-distance transportation that causes regional-scale air pollution. Meanwhile, Sun et al. [72] also addressed urban air quality in their study of Chinese cities but linked it to public transit use. A comparative analysis with previous studies shows that increased transportation activity does affect worsening air quality. However, studies on the topic within the scope of commuting activities are relatively rare.

In Indonesia, several air quality studies in urban areas related to transportation activities have also been conducted, and they provide a foundation that supports the findings of this study. Several studies related to the influence of motorized vehicles on ambient air quality from [73] – [76], state that differences in time, direction, and volume of passing vehicles affect the concentration of air pollutants. In addition, weather conditions, such as temperature, humidity, and wind speed parameters, also influence the increase in pollutant concentrations. This weather factor is likely why the effect of increasing vehicle intensity on air pollution is not always significant.

Spatially, our findings also show that the correlation between vehicle intensity and air pollution also varies significantly from one location to another. This appears to be highly dependent on the type of vehicle passing through. Commuter lanes with motorcycles will tend to have a more significant relationship between vehicle intensity and air pollution than those with fewer motorcycles and more cars. This is because the type of vehicle passing by affects the emissions load that contributes to the atmosphere. Motorcycles are the most significant contributor to exhaust emissions on the highway compared to other types of vehicles because motorcycles fueled by gasoline have higher exhaust emissions than diesel-fueled vehicles [74], [77] – [79].

The findings of this study show that among the various commuter lanes in Yogyakarta, some routes are of poor quality in the morning and evening due to the large number of vehicles travelling on them. Some commuter routes that need attention include Parangtritis Street and Wonosari Street in the morning, Solo Street in the morning and evening, and Palagan Street and Kaliurang Street in the afternoon and evening. The heavy traffic on these commuter routes positively correlates with poorer air quality. Based on these findings, traffic management is recommended to reduce the amount of vehicle congestion on these routes so that it can impact better air quality. Concretely, the recommended traffic engineering is to divide the number of vehicles on Parangtritis Street by diverting the traffic flow through Bantul Street, which is adjacent to Parangtritis Street, in channelling commuters from the Bantul area. Meanwhile, traffic management on Solo Street and Kaliurang Street is recommended for adaptive traffic timing, which adapts traffic flow to the level of vehicle density during peak hours.

In the context of urban planning, several commuter routes that often experience congestion and high vehicle density are recommended to be built with adequate infrastructure. In concrete terms, Palagan Street has a narrow road section, so it is necessary to expand the road to increase the capacity of commuter vehicles. Wonosari Street, which has a wide road section but relatively high vehicle density intensity, is recommended to be built as a flyover on Magelang Street or an underpass built on Magelang Street and Kaliurang Street.

CONCLUSION

Transportation activities have long been known as one of the primary sources of pollutants in the atmosphere. Here, we have found spatio-temporal air quality patterns in Yogyakarta, Indonesia, whose transportation system is dominated by private vehicles, especially motorcycles. The spatio-temporal pattern of air quality in the commuter route of Yogyakarta city represents the influence of commuters' activities on air quality. There is a relationship between the mobility of commuters and the instantaneous air quality in the commuter routes. Measurements of five air quality parameters in 10 commuter routes show that air quality gets worse spatially on busy roadways that drain many commuters from the hinterland. Temporally, air quality is worse in the morning and evening than the afternoon, which is related to higher mobility during these periods. The number of passing vehicles does have a positive relationship with the increase in pollutants, although it is not always significant.

For evaluation, this study still has limitations. In this study, instantaneous air quality monitoring results from sampling in the morning, afternoon, and evening sessions. Thus, temporally, this study can only compare conditions at these three times. Future studies are highly recommended to conduct measurements throughout the day systematically. This will not only compare conditions between sessions but also illustrate changes in commuter mobility and air quality throughout the day. Moreover, a concrete recommendation for policymakers based on the results of this study is to place ambient air quality monitoring devices on all commuter routes so that drivers can adjust to the pollution level. Also, traffic authorities must make engineering arrangements for traffic flow, especially on Kaliurang Street in the morning.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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ABBREVIATIONS

BPS	Badan Pusat Statistik Republik Indonesia / Indonesian Statistical Agency
CBD	Central Business District
CO_2	Carbon Dioxide
DIY	Daerah Istimewa Yogyakarta / Yogyakarta Special Region
GIS	Geographic Information System
HCHO	Formaldehyde
NO2	Nitrogen Dioxide
PM2.5	Particulate Matter 2.5
PM10	Particulate Matter 10
SO2	Sulfur Dioxide
TVOC	Total Volatile Organic Compounds