Factors Affecting Air Quality at Urban Parking Area: Case Study of Motorcycle Emissions Inside Institute of Technology of Cambodia (ITC)

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Abstract: Motorcycle emissions represent a significant yet underexplored source of urban air pollution in Phnom Penh, Cambodia. This study investigates the impact of motorcycle emissions at the Institute of Technology of Cambodia (ITC) through real-time monitoring of particulate matter (PM), traffic volume counts, and regression analysis. Results show that peak PM0.3 concentrations reached 23.6 million particles/m³ in the morning, while PM_{10} concentrations peaked at 58,202 particles/m³ in the evening both strongly associated with high motorcycle traffic volumes ($r = 0.58$ for PM0.3). Meteorological factors also played a role, with wind speed ($\beta = -0.47$) and humidity ($\beta = -0.70$) significantly affecting PM dispersion. Moreover, older motorcycles, with an average odometer reading of 219,386 km, were found to disproportionately contribute to emissions. These findings underscore serious public health concerns, particularly during peak commuting hours in enclosed or semi-enclosed parking environments. Based on the results, this study recommends the implementation of mandatory motorcycle emissions testing, the promotion of electric motorcycle adoption, and the expansion of localized air quality monitoring networks. By providing data-driven evidence on the relationship between traffic composition and pollutant exposure, this research contributes to ongoing efforts to improve urban air quality and promote sustainable transport planning in Southeast Asian cities.

***Keywords*:** Motorcycle Emissions, Particulate Matter, Urban Air Quality, Parking Areas, Traffic Pollution, Phnom Penh

1. INTRODUCTION

Air pollution is a significant public health concern in urban areas worldwide, and Phnom Penh, Cambodia, is no exception, as noted by Sokharavuth et al. (2023). The city's rapid development and population growth have led to increased vehicle traffic, significantly contributing to the deterioration of air quality. According to recent reports, motorcycles represent over 80% of registered vehicles in urban areas, with more than 3 million registered in Phnom Penh alone, as reported by Long (2023). These vehicles emit large amounts of particulate matter (PM) and other harmful pollutants, worsening air quality and posing serious health risks to the population, as demonstrated by Beddows and Harrison (2021) and Woo et al. (2022). The widespread use of outdated motorcycle technology and the lack of emissions control regulations further exacerbate the problem, making it imperative to assess their impact on urban air quality, as highlighted by Alimo et al. (2024) and Zhang et al. (2024). The rapidly expanding motorbike fleet in Cambodian cities is a major source of air pollution, particularly in Phnom Penh, but the extent of its impact has not been fully measured. The information currently available is insufficient to determine the precise role that motorbikes and other vehicle types play in Cambodia's air pollution levels. Despite the dominance of motorcycles in Cambodia's transportation sector, research on their emissions and specific contributions to air pollution remains limited. Most existing studies focus on larger vehicles, creating a knowledge gap that hampers the development of effective mitigation policies.

Particulate matter (PM) is a significant air contaminant, especially in metropolitan areas where vehicle emissions, including those from motorcycles, contribute to deteriorating air quality. According to Roșca et al. (2023) and Wang et al. (2024), PM concentrations vary based on traffic density, vehicle types, and local meteorological conditions. The health concerns of PM exposure are highlighted by its association with cardiovascular and respiratory disorders, as defined by Thangavel et al. (2022). According to the World Health Organization (2016), exposure to contaminated air kills about 7 million people annually, with ambient air pollution accounting for 4.2 million fatalities in low- and middle-income nations in particular.

Particularly in confined locations like parking areas where emissions build, research shows that motorbikes are major emitters of PM, nitrogen oxides (NOx), and carbon monoxide (CO), especially Borhani et al. (2021) and Hassani and Hosseini (2016). Poor ventilation in these areas exacerbates pollution, posing health risks to individuals nearby, as highlighted by Thangavel et al. (2022). The role of traffic density and peak hours in aggravating pollution has also been noted, with motorcycle-dominated areas exhibiting high PM levels, as reported by Chatzidiakou et al. (2019) and Wang et al. (2023). Localized studies using portable air quality monitors and fixed monitoring stations have demonstrated the effectiveness of these measurement techniques in assessing PM levels, as shown by Hernández-Gordillo et al. (2021) and Munir et al. (2022). The influence of climatic variables, including wind velocity, temperature, and humidity, on PM concentrations is extensively documented. Elevated wind speeds facilitate pollutant dispersion, whereas humidity affects particulate deposition, as indicated by Alaran et al. (2024) and Birim et al. (2023). These findings underscore the need for targeted air quality management strategies, particularly in areas with high motorcycle emissions.

Motorcycles are a prevalent form of transportation in many urban areas, as highlighted by Marquet and Miralles-Guasch (2016) and Wigan (2002). Motorcycles dominate the streets of numerous cities throughout the world, with sales totaling 60.1 million units in 2019. As explained by Guerra (2019), motorbikes are popular because they are economical, safe, comfortable, and allow for point-to-point mobility. Numerous studies have highlighted the significant contribution of motorbike emissions to urban air pollution, as documented by

Hassani and Hosseini (2016), Kim Oanh et al. (2012) and Talla et al. (2018). For instance, Liang (2019) and Mahalana et al. (2022) proved that motorbikes are responsible for a significant share of particulate matter and nitrogen oxides in the urban atmosphere. A study on motorbike emissions indicates that they contribute to a specific percentage of total vehicular emissions in campus areas, emphasizing the need for targeted air quality management strategies, as noted by Paidi et al. (2022) and Rahmadani et al. (2024). Furthermore, emissions from older motorbikes have been shown to be higher compared to newer motorbikes, as demonstrated by Tsai et al. (2017), exacerbating air quality issues in densely populated regions.

Motorcycle emissions considerably contribute to urban air pollution by emitting fine particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), and polycyclic aromatic hydrocarbons (PAHs), all of which pose serious health risks. Studies indicate that exposure to motorcycle emissions increases the likelihood of respiratory diseases, cardiovascular conditions, and even lung cancer due to high concentrations of lung deposited surface area (LDSA) particles during rush hours, as demonstrated by Chang et al. (2021). A study in an urban tunnel in Taipei found that motorcycles emit high levels of CO and CO_2, which negatively impact respiratory and cardiovascular health, as documented by Ting et al. (2023). Additionally, research on motorcycle gasoline engines confirms that emissions contain toxic pollutants contributing to acute respiratory diseases and allergies, as observed by Dimitrov et al. (2020). Long-term exposure is linked to carcinogenicity and mutagenicity, with high-mileage motorcycles producing significantly more toxic emissions, as emphasized by Lin et al. (2019). Poor maintenance further exacerbates emissions, leading to deteriorating air quality and heightened health risks, as reported by Odunlami et al. (2018).

Despite growing research on motorbike air pollution and health, significant gaps remain, especially in Southeast Asia like Cambodia. Most studies focus on developed countries or urban areas, limiting tailored interventions for local issues. The impact of motorbike emissions on educational institutions is particularly overlooked; while urban air quality is well examined, the effects on students and staff at universities need further exploration. More research is necessary to link air quality with health outcomes and clarify exposure effects. Additionally, understanding emission profiles, especially of older motorbikes in developing countries, is limited. Addressing these gaps is critical for designing effective health policies and initiatives to fight air pollution. The purpose of this study is to evaluate how motorbike emissions affect the quality of the air by measuring particulate matter (PM0.3–PM10.0) concentrations at ITC across different time periods. It examines motorcycle traffic volume patterns and their connection to PM levels while examining how meteorological variables like temperature, humidity, and wind speed affect the dispersion of pollutants. The study assesses the connection between motorbike emissions and deterioration of the air quality using statistical regression analysis. Based on these findings, it proposes air quality management strategies, including emission control policies and alternative transportation solutions, to mitigate motorcycle-related pollution. This investigation offers useful insights for politicians, urban planners, and environmental authorities looking to enhance air quality in motorcycle-dominated metropolitan areas.

2. METHODS AND MATERIALS

2.1 Study Area

This study was conducted at the Institute of Technology of Cambodia (ITC), a major academic institution in Phnom Penh with high levels of daily motorcycle traffic. The campus includes multiple parking zones and access roads where motorcycles constitute the majority of vehicles. The main entry and motorcycle ticketing stations were selected as key observation points, as they experience concentrated traffic volumes during peak hours. This setting allows for focused observation of motorcycle-related emissions in a controlled environment, minimizing interference from other vehicle types. With approximately 2,850 motorcycle parking spaces, ITC serves as a representative microcosm of Phnom Penh’s broader motorcycle-dominated urban landscape.

Furthermore, ITC serves as a small-scale version of Phnom Penh’s broader urban transportation challenges, where motorcycles dominate as a primary mode of commuting. The campus environment facilitates structured data collection, including the monitoring of entry and exit points and controlled air quality assessments. Additionally, the availability of cooperative administration and a research-oriented environment enhances the feasibility of conducting extensive monitoring campaigns. The study's findings have larger significance for understanding urban air pollution dynamics and developing policies to reduce emissions in similar high-density motorcycle usage locations.

Figure 1. Motorcycle parking area at Institute of Technology of Cambodia

2.2 Data Collection

The initial data collection, and further measurements of particulate matter (PM) concentrations are scheduled to be conducted at motorcycle ticket stations on the ITC campus during three separate sessions on December 4, 2024. The parking lot will have a measurement station with a particle counter for PM0.3, PM0.5, PM1.0, PM3.0, PM5.0, and PM10.0 pollutants. Data will be collected from ticket motorcycles by measuring emissions during idle and peak hours, focusing on all models. A social survey of 50 samples will be conducted among students, staff, and faculty to gather information on motorcycle usage patterns, maintenance habits, and emissions awareness. The combined analysis of emission data and survey responses will identify key factors contributing to pollution, considering variables such as engine size, year of manufacture, and fuel type. Furthermore, usage patterns-including mileage and frequency of use will be evaluated to explain their impact on overall emissions and provide recommendations for reducing motorcycle emissions within the campus.

Traffic counts will be undertaken at various times during the morning peak hours (MP), off-peak hours (OP), and evening peak hours (EP) to measure motorcycle traffic volume. Trained study assistants will record video footage at specific campus sites to ensure reliable monitoring throughout peak hours (7-9 am, 4-6 pm) and non-peak hours (11-1 pm). From recordings taken by EZVIZ BC2 cameras mounted on light poles at three separate locations within the ticket zones, the volumes of each type of motorcycle will be manually retrieved. The cameras were strategically positioned to capture all traffic movements. The wooden table in the foreground is of standard height, approximately 71 to 76 cm and 90 to 120 cm wide. This height is suitable for comfortable use while standing or sitting, allowing easy access to equipment. The table's surface is sturdy enough to support devices, providing a stable platform for measurements and observations related to air quality. The data collected will be evaluated to determine the association between motorcycle traffic flow and air pollution levels. These 1-min traffic volumes were recorded because they match with measurement data of air pollution (i.e., 1-min intervals); thus, allowing more sophisticated analyses (e.g., regression modeling, comparative statistics).

The Y09-310AC/DC portable laser particle counter will be utilized to measure air pollution levels, specifically focusing on particulate matter (PM) concentrations in various environments, including motorcycle parking areas and ticket stations on the ITC campus. This sensor, capable of detecting airborne particles across six size channels (0.3, 0.5, 1.0, 3.0, 5.0, and 10.0 micrometers) and operating at a flow rate of 28.3 liters per minute, it will record PM concentrations every minute on December 4th, 2024: from 6:55 a.m. to 9:06 a.m., 10:50 a.m. to 1:27 p.m., and 4:00 p.m. to 6:10 p.m.

The collected data will be processed in Microsoft Excel and python to average PM concentrations for each session, allowing for comparisons of air quality conditions throughout the day and leading to a better understanding of how motorbike emissions affect local air quality. As noted by Arslan and Toltar (2023), Birim *et al*. (2023) and Istiana *et al*. (2023), meteorological elements such as wind speed, relative humidity (RH), and temperature (T) can have a considerable impact on micro air quality assessments; for this reason, it is crucial to monitor these parameters. To guarantee a precise link with pollution levels, these measurements were made at the same sites and during the same times as the air quality monitoring.

Regression analyses will be conducted to identify significant predictors of health outcomes based on exposure to air pollution. Reducing the sum of the squared discrepancies (residuals) between the values predicted by the linear model and the observed values is the main objective of OLS regression. The OLS regression equation's generic form is:

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon \quad (1)$$

Where,

y	: is the dependent variable,
$x_1,\ x_2,\ \ldots,x_n$	: are the independent variables,
β_o	: is the intercept,
$\beta_1,\ \beta_2, \ldots,\ \beta_n$	: are the coefficients for each independent variable,
ε	: is the error term

The coefficients (*β*) are determined using the least squares criterion to minimize the sum of squared residuals:

$$\text{Minimize } \sum(y_i - \hat{y}_i)^2 \quad (2)$$

In an OLS regression model, each coefficient represents the predicted change in the dependent variable as a one-unit increase in the linked independent variable, with all other variables held constant. The R-squared number shows the proportion of variance in the dependent variable that can be explained by the independent variables, with values closer to one suggesting a good fit. Hypothesis tests, such as t-tests, determine whether the coefficients are significantly different from zero, indicating a meaningful relationship between the independent and dependent variables.

2.3 Data Analysis

The analysis will correlate traffic volume data with air quality indices, including particulate matter (PM0.3 to PM10.0), temperature (T), wind speed, and relative humidity (RH), which can significantly impact micro air quality measurements, as reported by Kirešová and Guzan (2022); Paraschiv and Paraschiv (2019), therefore, monitoring these parameters is essential. These measurements were obtained at the same locations and times as the air quality monitoring to achieve a precise correlation with pollution levels. These pollutants will be monitored using calibrated air quality sensors strategically placed at the same locations where traffic counts are recorded. This double data collection approach will facilitate a comprehensive understanding of how differences in motorbike traffic contribute to variations in air pollution. Furthermore, statistical methods such as multivariate regression will be employed to identify patterns and potential causal relationships. The study aims to separate the effect of motorcycle traffic on air quality by adjusting for confounding factors like weather.

3. RESULTS

3.1 Descriptive Statistics

The table 1 provides a comprehensive summary of ticket traffic volume, air pollution exposure levels, and environmental conditions across three key time intervals (7–9 am, 11 am–1 pm, and 4–6 pm), as well as cumulative data for the full day (7 am–6 pm). During the morning peak (7–9 am), vehicle entrance volume was highest (20.58 vehicles/hour), while the afternoon period (4–6 pm) recorded the highest number of vehicles exits (13.82 vehicles/hour). Very few entries or exits were recorded during the midday period, reflecting lower traffic activity. The cumulative average vehicle entrance and exit rates over the day were 0.91 and 0.79 vehicles/hour, respectively. Environmental conditions varied by time interval. The highest average temperature was observed at midday (29.65°C), while the morning period had the lowest (27.08°C). Wind speeds were also highest during the 11 am–1 pm interval (5.78 m/s), decreasing to 2.48 m/s in the afternoon, which could influence particulate dispersion. Humidity remained high throughout the day, with the peak recorded during the afternoon (87.01%).

Air pollution data, measured in particle counts per hour, reveal that PM concentrations were highest in the early morning for smaller particles such as PM 0.3 (23.57×10^6 particles) and PM 0.5 (12.41×10^6 particles). The midday period (11 am–1 pm) showed a significant drop across all particle sizes. Daily averages indicate that the highest cumulative counts were for PM 0.3 (65.67×10^6) and PM 0.5 (55.18×10^6), with total particle concentration reaching 75.66×10^6 particles. The corresponding daily average for total particle mass was 5.07×10^{-5} g. These findings suggest elevated exposure levels in the morning hours, potentially due to peak traffic and atmospheric conditions conducive to particulate accumulation. Overall, the data highlight clear diurnal patterns in both traffic and pollution levels, emphasizing the importance of time-specific strategies for air quality management in high-exposure environments such as parking areas or transit terminals.

Figure 2 presents the correlation matrix illustrating the relationships between traffic variables, environmental conditions, and particulate matter (PM) concentrations across various particle sizes. The analysis reveals strong positive correlations among different PM sizes, with coefficients exceeding 0.9 between PM 0.3, PM 0.5, PM 1.0, and PM total, indicating that fine and ultrafine particles tend to rise and fall together across the dataset. Notably, PM total and mass PM total are also highly correlated ($r = 0.99$), confirming consistency between particle count and mass concentration measurements. In terms of environmental variables, temperature shows a moderate positive correlation with PM concentrations (e.g., $r = 0.51$ with PM 0.3), suggesting that warmer conditions may facilitate particle suspension or formation. Humidity, on the other hand, shows weaker correlations with PM sizes, though it is slightly positive ($r \approx$ 0.20–0.30), potentially influencing particle agglomeration or deposition. Wind speed demonstrates a consistently negative correlation with all PM variables (e.g., $r = -0.70$ with PM 0.3), indicating its role in dispersing airborne pollutants and reducing local particle concentrations.

Table 1. Summary of Ticket Traffic and Air Pollution Exposure Data Across Time Intervals

Time		7 am-9 am		11 am-1 pm		4 pm-6 pm		7am-6pm	
Samples		N=120 min		N=120 min		N=120 min		N=360 min	
Items	Unit per hour	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ticket traffic data									
Dam	vehicle	1	0	0	0	0	0	0.31	0.47
Dpm	vehicle	0	0	0	0	1	0	0.31	0.46
Entrance	vehicle	20.58	17.06	6.44	7.39	2.43	2.63	0.91	0.48
Exits	vehicle	2.08	5.03	8.07	12.18	13.82	11.05	0.79	0.53
Air pollution exposure data									
Temperature	(ºC)	27.08	0.58	29.65	0.29	29.5	0.35	28.80	1.24
Wind Speed	(m/s)	2.59	0.37	5.78	0.73	2.48	0.43	1.37	0.15
Humidity	(%)	84.3	0.54	84.19	0.39	87.01	2.39	1.70	0.004
Ticket traffic data									
PM 0.3	particle	23.57×10^6	4.38×10^6	14.96×10^6	3.43×10^6	19.68×10^6	3.69×10^6	65.67	4.49
PM 0.5	particle	12.41×10^6	3.08×10^6	7.24×10^6	2.63×10^6	10.16×10^6	3.44×10^6	55.18	5.16
PM 1.0	particle	1.34×10^6	0.51×10^6	0.92×10^6	0.62×10^6	1.47×10^6	0.95×10^6	2.70	0.03
PM 3.0	particle	0.25×10^6	0.12×10^6	0.21×10^6	0.17×10^6	0.37×10^6	0.27×10^6	2.59	0.04
PM 5.0	particle	0.04×10^6	0.03×10^6	0.05×10^6	0.05×10^6	0.09×10^6	0.07×10^6	2.46	0.06
PM 10.0	particle	0.03×10^6	0.03×10^6	0.04×10^6	0.04×10^6	0.06×10^6	0.05×10^6	2.43	0.07
PM total	particle	37.67×10^6	7.83×10^6	23.43×10^6	6.76×10^6	31.85×10^6	8.26×10^6	73.64	5.76
Mass total	(g)	3.99×10^{-5}	2.93×10^{-5}	4.48×10^{-5}	3.95×10^{-5}	6.93×10^{-5}	5.22×10^{-5}	5.07×10^{-5}	4.29×10^{-5}

Regarding traffic activity, vehicle entrances and exits are weakly to moderately correlated with PM levels. For example, entrance data is positively associated with PM 0.3 (r = 0.28) and PM 1.0 (r = 0.24), supporting the notion that traffic inflows contribute to short-term spikes in particle concentration. Conversely, dam (morning dummy variable) shows a moderate positive correlation with PM 0.3 (r = 0.50) and PM 0.5 (r = 0.40), reinforcing earlier findings that morning hours exhibit the highest pollution peaks due to traffic surges and stagnant conditions. These results underscore the complex interplay between meteorological factors, traffic dynamics, and particulate pollution. They emphasize the importance of considering both environmental and human-induced variables when evaluating exposure risks and planning mitigation strategies in urban transportation environments.

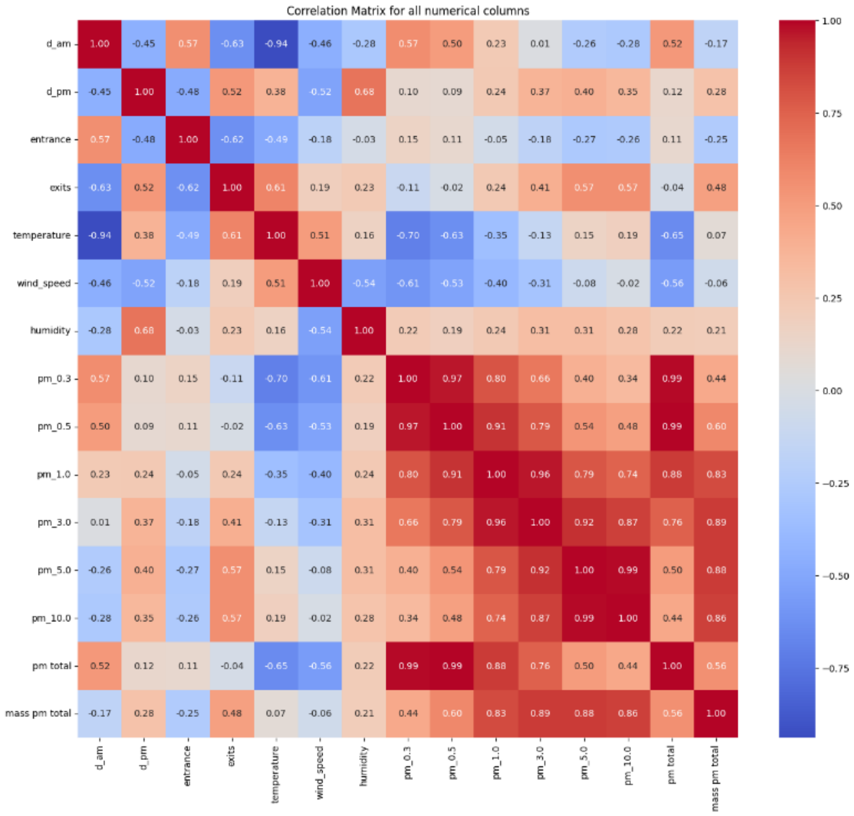

Figure 2 Correlation matrix of Environmental Factors and Particulate Matter (PM) Size

Figure 3 illustrates the temporal variations in particulate matter (PM) concentrations ranging from PM 0.3 to PM 10.0 across three peak traffic intervals: 7–9 AM, 11 AM–1 PM, and 4–6 PM. The data reveal distinct diurnal patterns, with the highest PM levels occurring during the early morning period (7–9 AM), particularly for finer particles such as PM 0.3 and PM 0.5. This peak is likely associated with the morning influx of vehicles, combined with low wind speed and limited atmospheric dispersion. A notable decline in PM levels is observed during the midday period (11 AM–1 PM), which corresponds with reduced traffic volumes and higher wind speeds, aiding in particle dispersion. PM concentrations rise again during the afternoon period (4–6 PM), especially for PM 0.3, PM 1.0, and PM 3.0, aligning with increased traffic activity during evening commutes. Across all time intervals, smaller-sized particles (PM 0.3–1.0) consistently show higher concentrations than larger particles (PM 5.0–10.0), indicating a predominance of ultrafine particulate pollution. This is particularly concerning due to their ability to penetrate deep into the respiratory tract, posing serious health risks. The visualization also suggests that PM levels fluctuate more during the morning and afternoon periods, potentially due to stop-and-go traffic patterns, idling engines, and increased vehicle density. These findings highlight the strong link between traffic patterns and air quality, emphasizing the need for targeted interventions during peak hours to mitigate exposure to harmful particulate matter.

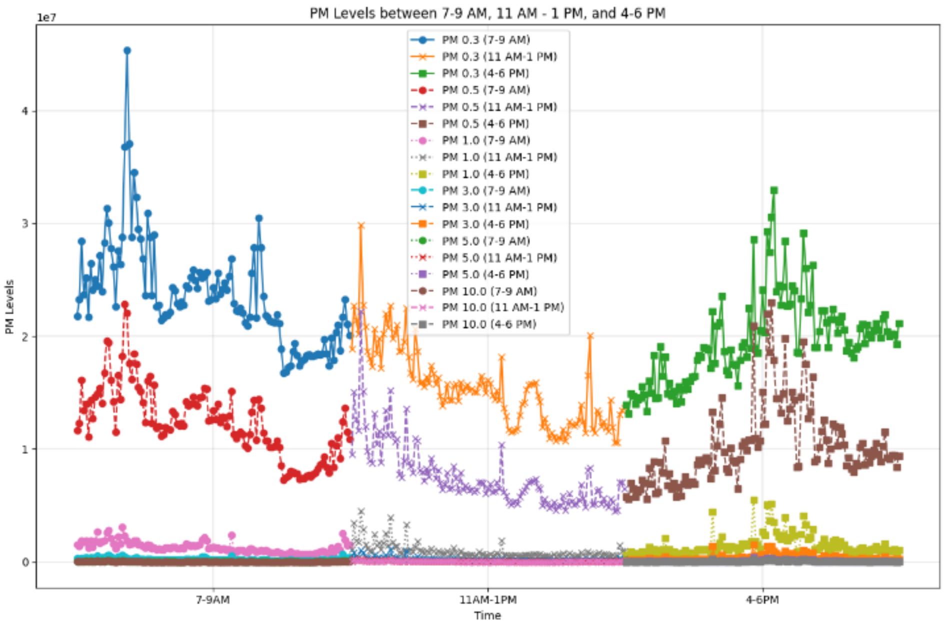

Figure 3. Temporal Variations in PM Levels During Peak Traffic Times

3.2 Usage Patterns

Table 3 presents a summary of key variables related to vehicle attributes and usage patterns, including measures of central tendency (mean), variability (standard deviation), and range (minimum and maximum values). The sample predominantly comprises a young demographic, with an average rider age of 20.88 years, suggesting that motorcycles are a preferred mode of transportation among younger individuals. This preference may be attributed to affordability, ease of use, and practicality for urban commuting. The mean motorcycle cost is 14.17 USD, with a substantial range from 5 to 30 USD and a standard deviation of 5.65, indicating a diverse mix of motorcycle types and features. This variation reflects differing consumer preferences and purchasing capacities within the sample. The average model year of 2017.76, spanning from 2011 to 2024, implies that most motorcycles are relatively modern, aligning with current trends in fuel efficiency and emissions standards. Odometer readings reveal considerable variability, with values ranging from 8,154 km to 776,624 km. The high mean (219,386.2 km) and large standard deviation (235,325.9 km) suggest the inclusion of both extensively used older vehicles and newer models with less mileage.

This spread may indicate different levels of wear, maintenance needs, and potential environmental impacts related to emissions. Engine size averages 116.80 cc, with a relatively narrow standard deviation of 13.01, and ranges from 50 to 150 cc. This distribution reflects a concentration of motorcycles designed for short to moderate distance travel, balancing performance and fuel economy. The average weekly frequency of motorcycle use is 6.72 times, highlighting motorcycles as a primary mode of daily transport for most participants. This trend is likely driven by convenience, low operating costs, and suitability for short commutes or work-related travel. The observed average urban speed is 41.70 km/h, while the rural speed is higher at 62.20 km/h. This difference reflects typical traffic conditions urban settings with congestion and frequent stops versus rural areas with more open roads. These speed patterns underscore how road environments influence vehicle usage. Furthermore, the average distance traveled per day is 14.21 km, and the mean riding time is 27.28 minutes. These values indicate short-to-medium commutes, consistent with everyday travel needs rather than long-distance use.

Table 3. Statistical Analysis of Vehicle Attributes and Usage Patterns

Variables	mean	Standard deviation	min	max
Age	20.88	2.28	17	28
Cost	14.17	5.65	5	30
Model Year	2017.76	3.20	2011	2024
Odometer (km)	219386.20	235325.90	8154	776624
Engine Size (cc)	116.80	13.01	50	150
Frequency Week	6.72	0.54	5	7
Speed Urban (km/h)	41.70	9.46	20	60
Speed in Rural (km/h)	62.20	12.86	40	90
Distance per day	14.21	8.49	2	32
Minute per day	27.28	15.28	5	65

3.3 Regression Results

Table 4 presents the results of Ordinary Least Squares (OLS) regression analyses examining the influence of environmental and traffic-related factors on particulate matter (PM) concentrations across different particle sizes. The models demonstrate relatively strong explanatory power, with R-squared values ranging from 0.452 (PM 10.0) to 0.750 (PM 0.3). Across all PM sizes, Dpm (afternoon time dummy) shows a consistently significant and positive association with PM concentrations, particularly for PM 0.3 ($\beta = 4.822$, $p < 0.01$), PM 0.5 ($\beta = 3.429$, $p < 0.01$), and PM total ($\beta = 5.275$, $p < 0.01$), confirming that particulate levels tend to rise significantly during afternoon hours. Temperature exhibits a strong and significant negative effect across all PM sizes (e.g., PM total: $\beta = -6.024$, $p < 0.01$), suggesting that higher ambient temperatures may facilitate particle dispersion or reduce emission accumulation. In contrast, wind speed has a significant positive impact on PM 0.3 ($\beta = 12.516$, $p < 0.01$) and PM total ($\beta = 12.804$, $p < 0.01$), possibly indicating that wind contributes to resuspension of particles from road surfaces. Humidity is also a strong positive predictor of PM, especially for smaller sizes like PM 0.3 ($\beta = 823.875$, $p < 0.01$) and PM total ($\beta = 825.846$, $p < 0.01$), implying that moist conditions may increase particle retention in the atmosphere. Traffic-related variables such as vehicle exits are positively and significantly associated with PM

Table 4. OLS Regression Analysis of Environmental Factors and Particulate Matter Levels (N=421)

Variable		constant	Dam	Dpm	entrance	exits	temperature	wind speed	humidity	R-square
PM0.3	Coefficient	-643.488	0.991	4.822***	0.122	2.753***	-4.491***	12.516***	823.875***	0.750
	standard error	157.240	1.118	1.014	0.381	0.337	0.297	3.505	153.527	
PM0.5	Coefficient	-331.412	-2.078	3.429***	0.558	4.568***	-5.510***	7.535*	534.732***	0.679
	standard error	204.847	1.456	1.322	0.497	0.439	0.387	4.566	200.011	
PM1.0	Coefficient	1.086***	-0.008*	0.012***	0.004**	0.016***	-0.014***	0.025*	0.814	0.517
	standard error	0.670	0.005	0.004	0.002	0.001	0.001	0.015	0.655	
PM3.0	Coefficient	0.542	-0.010	0.023***	0.007***	0.021***	-0.016***	0.052***	1.348	0.497
	standard error	0.874	0.006	0.006	0.002	0.002	0.002	0.019	0.854	
PM5.0	Coefficient	-3.845	-0.024	0.095***	0.031***	0.073***	-0.047***	0.290***	7.208**	0.478
	standard error	3.079	0.022	0.020	0.007	0.007	0.006	0.069	3.006	
PM10	Coefficient	-4.862	-0.024	0.099***	0.036***	0.081***	-0.049***	0.336***	8.184**	0.452
	standard error	3.487	0.025	0.022	0.008	0.007	0.007	0.078	3.405	
PM total	Coefficient	-595.047**	-0.645	5.275***	0.463	4.524***	-6.024***	12.804***	825.846***	0.707
	standard error	218.535	1.553	1.410	0.530	0.468	0.413	4.871	213.376	
Total mass PM	Coeffient	-0.0005	-4×10^{-5}**	2.887×10^{-5}*	1.251×10^{-5}**	5.185×10^{-5}***	-3.300×10^{-5}***	8.781×10^{-5}	0.001	0.358
	standard error	0.002	1.710×10^{-5}	1.560×10^{-5}	5.850×10^{-6}	5.170×10^{-6}	4.560×10^{-6}	5.380×10^{-5}	0.002	

***Significant at 0.01 level; ** Significant at 0.05 level; * Significant at 0.1 level.

concentrations in almost all models (e.g., PM total: $\beta = 4.524$, $p < 0.01$), highlighting the role of vehicle movement in elevating near-road PM exposure. Entrance shows weaker but still significant positive associations with smaller PM sizes. Interestingly, Dam (morning dummy) is generally insignificant, suggesting that morning periods have less predictive influence when other variables are controlled. Overall, these regression results underscore the multifactorial drivers of air pollution exposure in urban traffic environments. The significant role of afternoon traffic activity, atmospheric conditions (especially temperature and humidity), and vehicular movement on PM levels reinforces the need for time-sensitive and meteorologically informed air quality management strategies.

4. DISCUSSIONS

The findings of this study highlight the major influence of motorcycle traffic on air quality in urban parking lots, particularly at the Institute of Technology of Cambodia (ITC). The Ordinary Least Squares (OLS) regression analysis shows that particulate matter (PM) levels are closely related to traffic patterns, meteorological conditions, and exit activities, revealing critical areas for air pollution prevention.

The analysis indicates that PM concentrations are significantly higher throughout the afternoon (Dpm) and around departure points. PM0.3 ($\beta = 4.822$, $p < 0.01$), PM0.5 ($\beta = 3.429$, $p < 0.01$), and PM10.0 ($\beta = 0.099$, $p < 0.01$) demonstrate the largest increases. This trend correlates to peak motorcycle usage during commuting hours, when emissions build up owing to traffic and idling. The strong positive correlation observed between exit activity and PM levels, specifically for PM0.3 ($\beta = 2.753$, $p < 0.01$) and PM0.5 ($\beta = 4.568$, $p < 0.01$), indicates that motorbikes contribute to localized pollution spikes by emitted the maximum pollutant loads during acceleration. These results are consistent with prior research undertaken in Southeast Asian cities such as Jakarta and Bangkok, where motorbikes have been identified as substantial sources of urban PM emissions, as reported by Kim Oanh *et al*. (2012) and Mahalana *et al*. (2022). The strong correlation between motorcycle entrance rates and PM0.3/PM0.5 levels ($r = 0.576$ and $r = 0.482$, respectively) underscores the role of traffic density in exacerbating pollution, particularly in confined spaces like parking areas. Our analysis further confirms a strong correlation between motorcycle traffic volume and air pollution levels, particularly for fine particulate matter (PM0.3, PM0.5, and PM10.0). The regression results indicate that PM concentrations significantly increase with motorcycle activity, as reflected in PM0.3 ($\beta = 4.822$, $p < 0.01$), PM0.5 ($\beta = 3.429$, $p < 0.01$), and PM10.0 ($\beta = 0.099$, $p < 0.01$). These findings support the conclusion that motorcycles are a dominant source of urban air pollution, particularly in areas with high traffic density. This pattern is consistent with observations in Bangkok, Thailand, where motorcycles contribute up to 60% of total PM emissions, with pollution levels in dense urban zones exceeding those in suburban areas by 50%, according to Lewchalermvongs *et al*. (2024). However, unlike Thailand, which has adopted Euro 4 emission standards for motorcycles, Cambodia lacks strict enforcement mechanisms, leading to higher emissions from older, high-mileage motorcycles. This regulatory gap exacerbates air pollution, particularly in enclosed environments such as parking areas, where high traffic density and poor ventilation contribute to pollutant accumulation.

Meteorological factors also play a crucial role in PM dispersion and accumulation. Wind speed significantly affects pollutant dispersal, as evidenced by its negative correlation with PM concentrations. Higher wind speeds ($\beta = -10.463$ for PM0.3) facilitate pollutant dilution, while elevated humidity ($\beta = -0.699$ for PM0.3) is associated with lower PM levels, likely due to particulate deposition, as highlighted by Birim *et al*. (2023). These findings align with global research highlighting the complex interactions between weather conditions and urban air pollution, as noted by Arslan and Toltar (2023). The significant coefficients for PM sizes indicate that increased motorcycle traffic volume leads to higher pollutant levels, with smaller PM sizes being more affected. Furthermore, high PM levels in confined spaces like parking areas pose serious health risks to students, faculty, and staff due to prolonged exposure to air pollutants. This aligns with prior research emphasizing the need for improved ventilation and emission control measures in high-traffic zones, as reported by Borhani *et al*. (2021) and Odunlami *et al*. (2018). Poor ventilation in motorcycle parking lots has been identified as a key factor contributing to localized pollution hotspots, further reinforcing the importance of effective mitigation strategies. The PM concentrations observed in this study exceed WHO air quality guidelines, which set a 15 $\mu g/m^3$ limit for PM2.5 over 24 hours, as reported by Pai *et al*. (2022). Exposure to 10 $\mu g/m^3$ of PM increases the risk of lung cancer by 15% and cardiovascular death by 5%, raising major health concerns for the campus population. Given that measured PM levels surpass these limits, the risk of cardiovascular and respiratory illnesses is higher for employees and students.

To mitigate these risks, targeted policy interventions are essential. Implementing stricter emission regulations, similar to Thailand's Euro 4 standards, can help reduce motorcycle-related pollution. Expanding investment in electric motorcycles and public transit offers cleaner transportation alternatives. Regular emissions testing and vehicle maintenance programs should be enforced to ensure compliance with air quality standards. Additionally, well-ventilated parking areas and improved urban planning can help minimize PM accumulation in confined spaces. These measures are crucial for reducing air pollution and protecting public health.

5. CONCLUSION

This study provides strong empirical evidence of the direct link between motorcycle emissions and air quality degradation in a high-traffic academic setting. The findings highlight the urgent need for specific measures such as tougher pollution restrictions, incentives for electric motorcycles, and better urban traffic management. However, achieving long-term air quality improvements requires multi-sector collaboration among government agencies, research institutions, and environmental organizations to ensure effective and sustainable policy implementation.

Despite its contributions, this study has limitations. Conducting research at a single institution may limit the applicability of findings to other urban areas in Cambodia. Additionally, the single-day measurement period does not account for seasonal variations in air pollution. Future research should extend the study duration to capture seasonal fluctuations in PM concentrations and incorporate multiple monitoring locations for broader data accuracy. Assessing the impact of emission reduction policies through longitudinal studies and tracking PM levels before and after regulatory implementation is essential.

Further research should look into economic incentives for cleaner mobility, such as electric bike subsidies, tax breaks for emission-free vehicles, and improvements in public transportation infrastructure. Expanding air quality monitoring networks beyond ITC to multiple urban areas will provide a comprehensive dataset for policy development. Integrating air pollution data into Cambodia's national environmental monitoring system will enable policymakers to develop science-based regulations to mitigate urban air pollution and protect public health. As motorcycle-dominated cities like Phnom Penh continue to grow, proactive interventions-stricter emission regulations, alternative transportation solutions, and enhanced urban planning-are essential to ensuring a sustainable and healthier future for all.

ACKNOWLEDGEMENTS

The authors would like to thank the Institute of Technology of Cambodia (ITC) management for allowing them to carry out this study on campus. Special thanks go to the faculty members and research assistants who provided invaluable support during data collection and analysis. We also appreciate the participation of students and staff who contributed to the survey on motorcycle usage patterns. Lastly, we thank the contributions of previous researchers, whose work laid the groundwork for this analysis.

REFERENCES

Ministry of Public Works and Transport, "Urban Transport Developments in Cambodia," presented at the ASEAN Regional Transport Conference, Ha Long, Vietnam, Oct. 2023.

Alaran, A. J., O'Sullivan, N., Tatah, L., Sserunjogi, R., & Okello, G. (2024). Air pollution ($PM_{2.5}$) and its meteorology predictors in Kampala and Jinja cities, in Uganda. *Environmental Science: Atmospheres*, *4*(10), 1145–1156.

Alimo, P. K., Lartey-Young, G., Agyeman, S., Akintunde, T. Y., Kyere-Gyeabour, E., Krampah, F., Awomuti, A., Oderinde, O., Agbeja, A. O., & Afolabi, O. G. (2024). Spatial distribution and policy implications of the exhaust emissions of two-stroke motorcycle taxis: A case study of southwestern state in Nigeria. *Journal of the Nigerian Society of Physical Sciences*, 1898–1898.

Arslan, H., & Toltar, A. (2023). The influence of meteorological parameters on PM2.5 and PM10 values in Ümraniye and Silivri districts of İstanbul. *Environmental Research and Technology*, *6*(4), 288–301.

Beddows, D. C. S., & Harrison, R. M. (2021). PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles. *Atmospheric Environment*, *244*, 117886.

Birim, N. G., Turhan, C., Atalay, A. S., & Gokcen Akkurt, G. (2023). The Influence of Meteorological Parameters on PM10: A Statistical Analysis of an Urban and Rural Environment in Izmir/Türkiye. *Atmosphere*, *14*(3), 421.

Borhani, F., Shafiepour Motlagh, M., Stohl, A., Rashidi, Y., & Ehsani, A. H. (2021). Changes in short-lived climate pollutants during the COVID-19 pandemic in Tehran, Iran. *Environmental Monitoring and Assessment*, *193*(6), 331.

Chang, P.-K., Griffith, S., Chuang, H.-C., Chuang, K. J., Wang, Y.-H., Chang, K.-E., & Hsiao, T.-C. (2021). Particulate Matter in a Motorcycle-Dominated Urban Area: Source Apportionment and Cancer Risk of Lung Deposited Surface Area (LDSA) Concentrations. *Journal of Hazardous Materials*, *427*, 128188.

Chatzidiakou, L., Krause, A., Popoola, O. A. M., Di Antonio, A., Kellaway, M., Han, Y., Squires, F. A., Wang, T., Zhang, H., Wang, Q., Fan, Y., Chen, S., Hu, M., Quint, J. K., Barratt, B., Kelly, F. J., Zhu, T., & Jones, R. L. (2019). Characterising low-cost sensors in highly portable platforms to quantify personal exposure in diverse environments. *Atmospheric Measurement Techniques*, *12*(8), 4643–4657.

Dimitrov, R. D., Wrobel, R., & Krasteva, M. T. (2020). Environmental Performance of Motorcycle Gasoline Engines. *2020 7th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE)*, 1–4.

Guerra, E. (2019). Electric vehicles, air pollution, and the motorcycle city: A stated preference survey of consumers' willingness to adopt electric motorcycles in Solo, Indonesia. *Transportation Research Part D: Transport and Environment*, *68*, 52–64.

Hassani, A., & Hosseini, V. (2016). An assessment of gasoline motorcycle emissions performance and understanding their contribution to Tehran air pollution. *Transportation Research Part D: Transport and Environment*, *47*, 1–12.

Hernández-Gordillo, A., Ruiz-Correa, S., Robledo-Valero, V., Hernández-Rosales, C., & Arriaga, S. (2021). Recent advancements in low-cost portable sensors for urban and indoor air quality monitoring. *Air Quality, Atmosphere & Health*, *14*(12), 1931–1951.

Istiana, T., Kurniawan, B., Soekirno, S., Nahas, A., Wihono, A., Nuryanto, D. E., Adi, S. P., & Hakim, M. L. (2023). Causality Analysis of Air Quality and Meteorological Parameters for PM2.5 Characteristics Determination: Evidence from Jakarta. *Aerosol and Air Quality Research*, *23*(9), 230014.

Kim Oanh, N. T., Thuy Phuong, M. T., & Permadi, D. A. (2012). Analysis of motorcycle fleet in Hanoi for estimation of air pollution emission and climate mitigation co-benefit of technology implementation. *Atmospheric Environment*, *59*, 438–448.

Kirešová, S., & Guzan, M. (2022). Determining the Correlation between Particulate Matter PM10 and Meteorological Factors. *Eng*, *3*(3), 343–363.

Lewchalermvongs, C., Lewchalermvongs, P., Chuesuphan, C., Weeranukunjit, C., Boonkangwan, C., Chaikittiporn, M., Srikirinth, P., & Glinpatgij, T. (2024). A game-theoretic approach for route planning on traveling by public transportation in the PM2.5 pollution: A case study in Bangkok. *Transportation Research Interdisciplinary Perspectives*, *27*, 101185.

Liang, C. (2019). *Air pollution by motorcycles in big cities: The case of Bangkok* [Master of Arts, Chulalongkorn University].

Lin, Y.-C., Chou, F.-C., Li, Y.-C., Jhang, S.-R., & Shangdiar, S. (2019). Effect of air pollutants and toxic emissions from various mileage of motorcycles and aerosol related carcinogenicity and mutagenicity assessment. *Journal of Hazardous Materials*, *365*, 771–777.

Mahalana, A., Yang, L., Dallmann, T., Lestari, P., Maulana, K., & Kusuma, N. (2022). *Measurement of real-world motor vehicle emissions in Jakarta*.

Mahesh, S., Ramadurai, G., & Shiva Nagendra, S. M. (2019). Real-world emissions of gaseous pollutants from motorcycles on Indian urban arterials. *Transportation Research Part D: Transport and Environment*, *76*, 72–84.

Marquet, O., & Miralles-Guasch, C. (2016). City of Motorcycles. On how objective and subjective factors are behind the rise of two-wheeled mobility in Barcelona. *Transport Policy*, *52*, 37–45.

Munir, M. M., Adrian, M., Saputra, C., & Lestari, P. (2022). Utilizing Low-cost Mobile

Monitoring to Estimate the PM2.5 Inhaled Dose in Urban Environment. *Aerosol and Air Quality Research*, *22*(6), 220079.

Odunlami, O. A., Elehinafe, F. B., Oladimeji, T. E., Fajobi, M. A., Okedere, O. B., & Fakinle, B. S. (2018a). Implications of Lack of Maintenance of motorcycles on Ambient Air Quality. *IOP Conference Series: Materials Science and Engineering*, *413*, 012055.

Odunlami, O. A., Elehinafe, F. B., Oladimeji, T. E., Fajobi, M. A., Okedere, O. B., & Fakinle, B. S. (2018b). Implications of Lack of Maintenance of motorcycles on Ambient Air Quality. *IOP Conference Series: Materials Science and Engineering*, *413*, 012055.

Pai, S. J., Carter, T. S., Heald, C. L., & Kroll, J. H. (2022). Updated World Health Organization Air Quality Guidelines Highlight the Importance of Non-anthropogenic $PM_{2.5}$. *Environmental Science & Technology Letters*, *9*(6), 501–506.

Paidi, V., Håkansson, J., Fleyeh, H., & Nyberg, R. G. (2022). CO2 Emissions Induced by Vehicles Cruising for Empty Parking Spaces in an Open Parking Lot. *Sustainability*, *14*(7), 3742.

Paraschiv, S., & Paraschiv, L. S. (2019). Effects of wind speed, relative humidity, temperature and air pressure on PM10 concentration for an urban background area. *IOP Conference Series: Materials Science and Engineering*, *595*(1), 012059.

Rahmadani, A. A., Syaifudin, Y. W., Setiawan, B., Panduman, Y. Y. F., & Funabiki, N. (2024). Enhancing Campus Environment: Real-Time Air Quality Monitoring Through IoT and Web Technologies. *Journal of Sensor and Actuator Networks*, *14*(1), 2.

Roșca, E., Ruscă, F., Dinu, O., Burciu, Ștefan, Oprea, C., Ilie, A., & Coman, C. (2023). A Moderation effect of atmospheric conditions on PM2.5 traffic related concentration. *Romanian Journal of Transport Infrastructure*, *12*(1), 1–17.

Sokharavuth, P., Thiv, S., Nara, C., Him, C., Sokyimeng, S., Henze, D. K., Holmes, R., Kuylenstierna, J. C. I., Malley, C. S., Michalopoulou, E., & Slater, J. (2023). Air pollution mitigation assessment to inform Cambodia's first clean air plan. *Environmental Research*, *220*, 115230.

Talla, A., Ngohe-Ekam, P. S., & Nkeumaleu, A. T. (2018). Evaluation of the Impact of Motorcycles in Urban Transport on Air Pollution: A Case of Douala City in Cameroon. *Journal of Scientific Research and Reports*, *20*(1), 1–11.

Thangavel, P., Park, D., & Lee, Y.-C. (2022). Recent Insights into Particulate Matter (PM2.5)-Mediated Toxicity in Humans: An Overview. *International Journal of Environmental Research and Public Health*, *19*(12), Article 12.

Ting, Y.-C., Chang, P.-K., Hung, P.-C., Chou, C., Chi, K., & Hsiao, T.-C. (2023). Characterizing emission factors and oxidative potential of motorcycle emissions in a real-world tunnel environment. *Environmental Research*, 116601.

Tsai, J.-H., Huang, P.-H., & Chiang, H.-L. (2017). Air pollutants and toxic emissions of various mileage motorcycles for ECE driving cycles. *Atmospheric Environment*, *153*, 126–134.

Wang, P., Zhang, R., Sun, S., Gao, M., Zheng, B., Zhang, D., Zhang, Y., Carmichael, G. R., & Zhang, H. (2023). Aggravated air pollution and health burden due to traffic congestion in urban China. *Atmospheric Chemistry and Physics*, *23*(5), 2983–2996.

Wang, Y., Wang, H., Zhang, B., Liu, P., Wang, X., Si, S., Xue, L., Zhang, Q., & Wang, Q. (2024). High-resolution mapping of on-road vehicle emissions with real-time traffic datasets based on big data. *EGUsphere*, 1–26.

Wigan, M. (2002). Motorcycles as a Full Mode of Transportation. *Transportation Research Record: Journal of the Transportation Research Board*, *1818*(1), 39–46.

Woo, S.-H., Jang, H., Lee, S.-B., & Lee, S. (2022). Comparison of total PM emissions emitted from electric and internal combustion engine vehicles: An experimental analysis. *Science of The Total Environment*, *842*, 156961.

Zhang, Z., Man, H., Zhao, J., Huang, W., Huang, C., Jing, S., Luo, Z., Zhao, X., Chen, D., He, K., & Liu, H. (2024). VOC and IVOC emission features and inventory of motorcycles in China. *Journal of Hazardous Materials*, *469*, 133928.