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Roadside Vehicle Particulate Vertical Dispersion Model for Friction Course Materials: A Case of Hong Kong

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ABSTRACT

Background and Objective: The rapid urban development has caused various pollution in Hong Kong. However, the current measures adopted are aimed at controlling the surface level emission, while the vertical dispersion of pollutants is less investigated. This research project aims to identify the vertical dispersion patterns of particulate matter and noise emitted from road traffic and their decay rates with increasing vertical distance from the source and examine the possible correlation between traffic noise frequency levels and vehicle-emitted particulate. **Materials and Methods:** Three sets of equipment have been installed at three different heights on building facades perpendicular to the road surface, facing traffic to monitor PM concentrations (PM_1, $PM_{2.5}$, $PM_{4.25}$ and PM_{10}), noise frequencies and other environmental data namely temperature, relative humidity and wind speed. **Results:** The study anticipates uncovering a positive relationship between vehicular particulate matter emissions and traffic-related noise on lower floors, specifically at an 800 Hz noise frequency. Analysis of the three-dimensional plots indicates that pollutant concentrations are highest at lower levels. Notably, PM_1, $PM_{2.5}$ and $PM_{4.25}$ demonstrate relatively high R-squared values (PM_1 = 0.674, $PM_{2.5}$ = 0.649 and $PM_{4.25}$ = 0.538), indicating a satisfactory fit of these models to the data. **Conclusion:** By highlighting the often-overlooked vertical transmission of particulate matter and noise from vehicles, this research contributes to a deeper understanding of air and noise pollution levels in high-rise urban environments. These insights hold the potential to inform future urban planning initiatives aimed at enhancing public health outcomes.

KEYWORDS

Vertical dispersion, particulate matters (PM), urban planning, air pollution, noise pollution, pollutant dispersion

INTRODUCTION

Air pollution is one of the critical health risks and contributes to noncommunicable diseases[1] and excessive noise can lead to hypertension, sleep disturbances and other health impacts[2], both pollutants have raised global concerns. The government of the Hong Kong Special Administrative Region has expressed concern about air pollution and noise pollution in Hong Kong. Hong Kong is made up of islands and a peninsula,

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spanning 1000 km^2 and home to over 7.5 million people[3]. Prolonged and transient exposure to air pollution can result in various health conditions like cardiovascular mortality and pulmonary insufficiency[4]. To mitigate the consequences of air and noise pollution, the Environmental Protection Department of Hong Kong SAR Government has implemented control measures.

For example, in 2021, the Hong Kong government announced that furl-propelled private cars will no longer be permitted to be registered in Hong Kong by the year 2035[5]. Additionally, the Hong Kong government has enacted the Motor Vehicle Idling (Fixed Penalty) Ordinance (Cap.611) to regulate air pollution levels induced by vehicle emissions. This ordinance regulates the duration of engine idleness for moving vehicles and reduces air pollutant emissions from idling engines. The government also supports the adoption of new energy vehicles, such as electric vehicles, through the provision of first registration tax (FRT) concessions[6]. This incentivizes vehicle owners to switch to fuel-efficient and ecologically sustainable automobiles. Additionally, the government has been consistently adopting the use of low-noise materials to resurface roads[7] to mitigate the impact of noise pollution on residents.

However, the implemented control measures primarily focus on pollutant emissions at ground level, overlooking the vertical flow of emitted pollutants and Hong Kong's unique topography, which consists mostly of tall buildings with mixed land uses[8]. Collecting and analyzing pollutant data only horizontally is therefore insufficient. There is also a lack of recognition regarding the vertical dispersion patterns of traffic-emitted pollutants and noise. Therefore, one of the objectives of this study is to address this research gap by developing a vertical dispersion model. A previous study by Chan and Kwok[8] investigated the vertical dispersion of suspended particulate matter in Hong Kong. Data was collected from four sites: Two street canyons and two open streets. Sampling was done at various height levels from buildings, excluding rooftops due to equipment constraints. The study observed an exponential decline in urban PM concentrations with height, but the rate of decrease differed for different classes of suspended particulates. Additionally, the vertical concentration gradient of particulate matter varied between street canyons and open streets due to various factors influencing mixing and dispersion.

In another study conducted by Jung *et al.*[9] in New York City, indoor and outdoor traffic-related airborne pollutants were measured between October, 2005 and July, 2010. The researchers categorized residential block heights into three groups: 0-2nd, 3rd-5th and 6th-32nd floor. The highest median concentration of contaminants was observed outdoors in the 3rd-5th floor group, but the statistical significance was poor. High-rise buildings, defined as structures with more than six stories, had lower concentrations compared to low-rise buildings, likely because they were situated away from commercial buildings and roadways, with open green spaces acting as a buffer. The maximum concentration of pollution on the 3rd-5th floors was likely due to the upward mixing of pollutants from ground-level traffic and the downward mixing of hydrocarbons and black carbons produced from rooftop boiler chimneys during winter months, resulted in poor statistical significance in the study. Wu *et al.*[10] conducted a study in the Chinatown region of Boston, USA, focusing on the vertical distribution of particulate matter in a 35 m-tall building with 11 floors. They collected 23 sample profiles and found a noticeable 50% decrease in pollution levels at a height of 35 m above ground level. Particle number concentration ("PNC") was well mixed at heights below 20 m, which was the predominant height of buildings in the area[11].

Over the past decade, research has focused on the vertical dispersion patterns of pollutants in top-tiered cities in China, including Hangzhou[12], Guangzhou[13] and Shanghai[14-16], as well as in Hong Kong[17]. While it's commendable that researchers have explored pollutant impacts using innovative methods like Unmanned Aerial Vehicles (UAVs), the use of UAVs for scientific data collection in Hong Kong is still in the preliminary stage and subject to control by the Civil Aviation Department. This makes using UAVs for scientific data collection in Hong Kong unfeasible due to policy regulations and issues with the reliability of data. On the other hand, several studies have attempted to explore the vertical correlation between pollutants by installing instruments either on a landmark building[13] or in close proximity to an express highway[16]. These studies collected necessary data at a fixed location over a certain period of time. However, the generalizability of data obtained from a single location across different time periods remains unclear. Moreover, there has been limited investigation into the relationship between pollutant emissions and noise frequencies from road vehicles. To address these gaps, this study takes an innovative approach by examining the potential correlations between noise frequencies and pollutant emissions at various locations in Hong Kong with friction course pavements. This study aims to measure traffic characteristics, wind, particulate matters (PM_1, $PM_{2.5}$ and PM_{10}) and noise within open streets at different heights and identify the vertical distribution and dispersion patterns of particulate matter and noise emitted from road traffic and their decay rates with increasing vertical distance from the source; and examine the correlation between traffic noise frequency levels and vehicle-emitted particulate matters and validate their predictability on UFP concentration. The data and insights gained from this study could provide a better understanding of pollutant and noise emissions in different environments, benefiting governmental air quality and traffic management control in urban planning and enhancing the quality of life for Hong Kong residents.

MATERIALS AND METHODS

Study area: Hong Kong (22°15 N and 114°10 E) is located on the southeast coast of mainland China, facing South China Sea.[5]. It is widely recognized as one of the most densely populated cities globally, with a total population of over 7.5 million people residing in 24% of total land area[15]. The city's mountainous terrain has necessitated meticulous planning and thoughtful urban development. Due to the limited availability of land, a mixed land-use strategy characterized by high-rise and densely packed structures has been predominantly employed in the development of most districts in Hong Kong.

The road networks in Hong Kong have experienced significant congestion since the 1970s[18]. The Environmental Protection Department is responsible for monitoring air quality and operates 18 fixed monitoring stations that adhere to the highest international standards for air quality evaluation. These stations collect data to inform the public about the current state of air quality, provide forecasts regarding future air quality and aid in assessing public exposure to air pollution[19].

Concurrently, the Highways Department has collaborated with The Hong Kong Polytechnic University (PolyU) to develop and implement an innovative road surfacing material specifically designed for local roads in Hong Kong, as the concrete-paved road surfaces might easily deteriorated with consistently heavy traffic day by day. The jointly developed material consists of finely graded bitumen. The smooth and polished surface texture of the road pavement minimizes road noise and enhances passenger comfort. Considering is the factor of having a variety of road pavement materials concurrently being used, Hong Kong can be considered an ideal location for establishing a model that explores the vertical relationship between air quality and noise emissions from road traffic. Other cities can subsequently adopt this modeling approach as a benchmark for decision-making regarding road resurfacing.

Study design: The study was carried out from May, 2023 until November, 2023. The collection of accurate and representative data is crucial for understanding the dispersion patterns of particulate matter and noise, as well as assessing the potential impact of noise and particulate matter on the surrounding environment. To achieve this, an integrated approach employed involving the use of a set of machines listed in Table 1 for collecting data and the consolidation of data.

Anemometers, Trolex AIR-XD dust monitors, B&K 2245 sound level meters and electronic devices will be used on-site to measure the required data simultaneously at three levels of locations perpendicular to the target road surface.

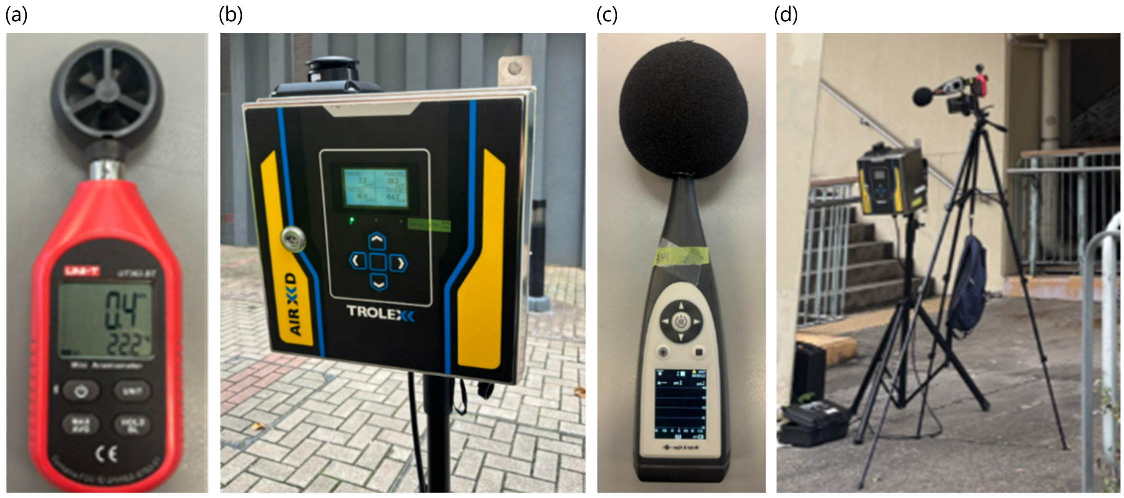

Fig. 1(a-d): Equipment image and its setup, (a) UT363BT anemometer, (b) Trolex AIR-XD dust monitor, (c) B&K 2245 sound level meter and (d) Overall setup

Table 1: List of equipment employed and its main functions

Name of equipment	Function
UT363BT anemometer	Measure wind speed
Trolex AIR-XD dust monitor with portable battery pack	Screening particulate with different size
B&K 2245 sound level meter with noise partner app	Noise level measurement
Computer	Extract the data recorded from dust monitor and sound level meter
Mobile phones	Used to record the real-time situation of the target road surface

Sampling setup and data collection process: To ensure comprehensive data collection, the instruments were strategically positioned at three different heights perpendicular to the target road surface. The heights chosen depended on the total height of the selected architecture. The rationale behind this setup is as follows:

The first level where the machines were set up would be the ground level. This height represents the immediate vicinity of the road surface, where the highest volume of noise and concentration of particulate matter is expected to be recorded by the machines as it is closest to the point where direct emissions from vehicles are released. Placing an instrument at this height allows the team to capture the primary emission sources and investigate the initial dispersion patterns by comparing them with data from other levels.

The second level where the instruments were set up would be one level above the ground surface. This intermediate height provides insights into the vertical dispersion of particulate matter from the road surface. By placing an instrument at this level, researchers could observe and examine the behavior of particles as they ascend from the immediate vicinity of the road, potentially influenced by wind patterns and turbulence.

The highest level where the team places instruments for data collection would be two levels or more above the ground surface. This height records data from a higher point from the ground and on the extent of vertical dispersion and the potential for particles to disperse further into the surrounding environment.

By employing this three-height vertical setup, the study aims to capture a comprehensive picture of the dispersion patterns of particulate matter and its potential relationship with noise on friction course materials in the context of Hong Kong. The appearance and overall setup of the equipment on site is shown in Fig. 1a-d.

Each data collection process was conducted for several hours to obtain a sufficient volume of data, accounting for diurnal variations and potential traffic fluctuations. Data from the anemometer, dust monitor and sound level meter were simultaneously recorded at regular intervals, ensuring synchronization and coherence among the collected datasets. It aims to build the statistical model in exploring the vertical distribution and dispersion patterns of particulate matter and noise emitted from road traffic, which will be illustrated in the findings section with more explanation.

Data analysis: After collecting the data, it was organized by type of data (noise, PM, temperature, relative humidity and wind speed), processed and analyzed using various methods, such as time series, diurnal and statistical methods, to construct the particulate matter emission model. The MATLAB has also been used to analyze PM concentration level, noise level and height measurements and create an independent model. The dataset consists of 16,782 valid measurements from seven different sampling locations, including data on PM pollutant levels and noise frequencies. Each measurement session involved precise recordings of noise levels and PM pollutant levels at one-second intervals, allowing for the capture of temporal fluctuations and trends.

To ensure accurate data collection, a flat and straight road segment surfaced with friction course material was selected as the research site. While the correlation between pollutant levels and vehicle speed has been extensively studied and well-documented, the relationship between pollutants and noise levels has received less attention. This research gap can be attributed to the complex and non-linear nature of the pollutant-noise relationship.

To address this research gap, a novel approach was implemented, which involved creating a pollutant-noise emission matrix. This matrix was designed to capture the intricate interactions between pollutants and noise under varying conditions. The methodology used cluster analysis on particulate matter (PM) pollutant levels, considering a predetermined range of noise levels that encompassed different spectra and measurement heights.

Through this approach, the emission matrix provides a comprehensive understanding of how pollutants are associated with noise levels in different environmental settings. By examining the data across different parameters, such as noise spectra and measurement heights, the matrix offers detailed insights into the complex dynamics of pollutant emissions and their impact on noise levels.

This expanded explanation emphasizes the significance of the study and the methodological approach used to construct the pollutant-noise emission matrix, highlighting its potential to enhance our understanding of pollutant-noise relationships in various contexts.

RESULTS

Identification of suitable sites and road pavements: Significant effort was required to source applicable locations for data collection as Hong Kong. To reduce the disturbance of the general public, instead of inviting households to participate in the study for more generalizable findings[17], the team has sourced seven publicly-used locations like pedestrian footbridges facing highways with friction course pavements. The list of locations and their details is listed in Table 2.

Data availability: An extensive campaign was conducted to monitor air quality and environmental noise at seven locations. The primary objective was to assess the levels of air pollutants, namely PM_1, $PM_{2.5}$, $PM_{4.25}$ and PM_{10}, which were regularly sampled and analyzed. Measurements were taken at three specific elevation levels to capture potential variations in pollutant concentrations within each location.

Table 2: Summary of road pavement data used in this study

Data collection date	Road name	District	Road type
23-25 May, 2023	North Lantau Highway (Section 1)	Islands	Friction course with 30 mm thickness
28-30 May, 2023	North Lantau Highway (Section 2)	Islands	and 10 mm aggregate size (FC 10/30)28-
30 May, 2023	North Lantau Highway (Section 3)	Islands	
5-7 June, 2023	Fanling Highway (Section 1)	Northern	
8 July, 2023	Fanling Highway (Section 2)	Northern	
9 June, 2023	Fanling Highway (Section 3)	Northern	
4-7 November, 2023	Castle Peak Road	Tuen Mum	

Table 3: Coefficients and R-squared values of PM concentration against Noise Frequencies

Model	R-square
PM_1 = 1.454-0.903 Height+0.52$LZeq_{(800)}$	0.674
$PM_{2.5}$ = 5.153-1.420 Height+0.640$LZeq_{(800)}$	0.649
$PM_{4.25}$ = 8.298-1.928 Height+0.732$LZeq_{(800)}$	0.538
PM_{10} = 8.792-3.538 Height+0.807$LZeq_{(800)}$	0.127

The comprehensive environmental monitoring also included the collection of noise measurements across multiple frequency bands. Noise levels were assessed using the LZeq metric at specific frequencies: 630, 800, 1000, 1250 and 1600 Hz. This approach provided insights into ambient noise levels and their potential impacts on the surrounding areas.

Specialized machines were employed for these measurements. The Trolex AIR-XD dust monitor accurately measured and quantified air pollutant concentrations, offering insights into particulate matter levels at each location and height. Simultaneously, the B&K 2245 Sound Level Meter captured and analyzed noise levels, contributing to the understanding of the acoustic environment across the monitoring sites.

In addition to air quality and noise data, other environmental parameters such as wind speed, temperature and humidity were recorded by the UT363BT Anemometer. This comprehensive dataset enabled a detailed assessment of environmental conditions and their spatial variations over the monitoring period, providing valuable information for understanding local air quality and noise dynamics. This study specifically focuses on heavy-duty vehicles weighing 5.5 tons or more, with the aim of exploring the characteristics, performance and operational aspects of these substantial vehicles within this weight range.

Regression analysis for the sampling result: Initially, a regression analysis was carried out to create a mathematical model that establishes the association between noise levels at various frequencies, corresponding PM measured values and measurement point heights. The major goal of this regression model was to study the effect of elevation of the measurement location on noise levels across several frequency bands and the correlation between noise levels and the corresponding PM measured values.

Following the regression analysis, the resulting models were assessed using their coefficients and R-squared values to validate their authenticity and goodness of fit. The coefficients provide useful information about the size and direction of the relationship between frequency-specific noise levels and the height of the measurement site. The R-squared value, also known as the coefficient of determination, is a statistical metric used in regression models to evaluate how much of the variance in the dependent variable can be explained by the independent variable. It represents the model's ability to predict responses to observable data. The R-squared value normally ranges between 0 and 1. A score around 1 suggests a high level of model fit, whereas a value near -1 indicates a poor fit.

The specific coefficients and R-squared values derived from these regression models are presented in Table 3, which provides a comprehensive summary of the model's performance as well as insights into the relationship between noise levels and measurement point height across different frequency ranges.

Regression model: The regression model is listed in Table 3.

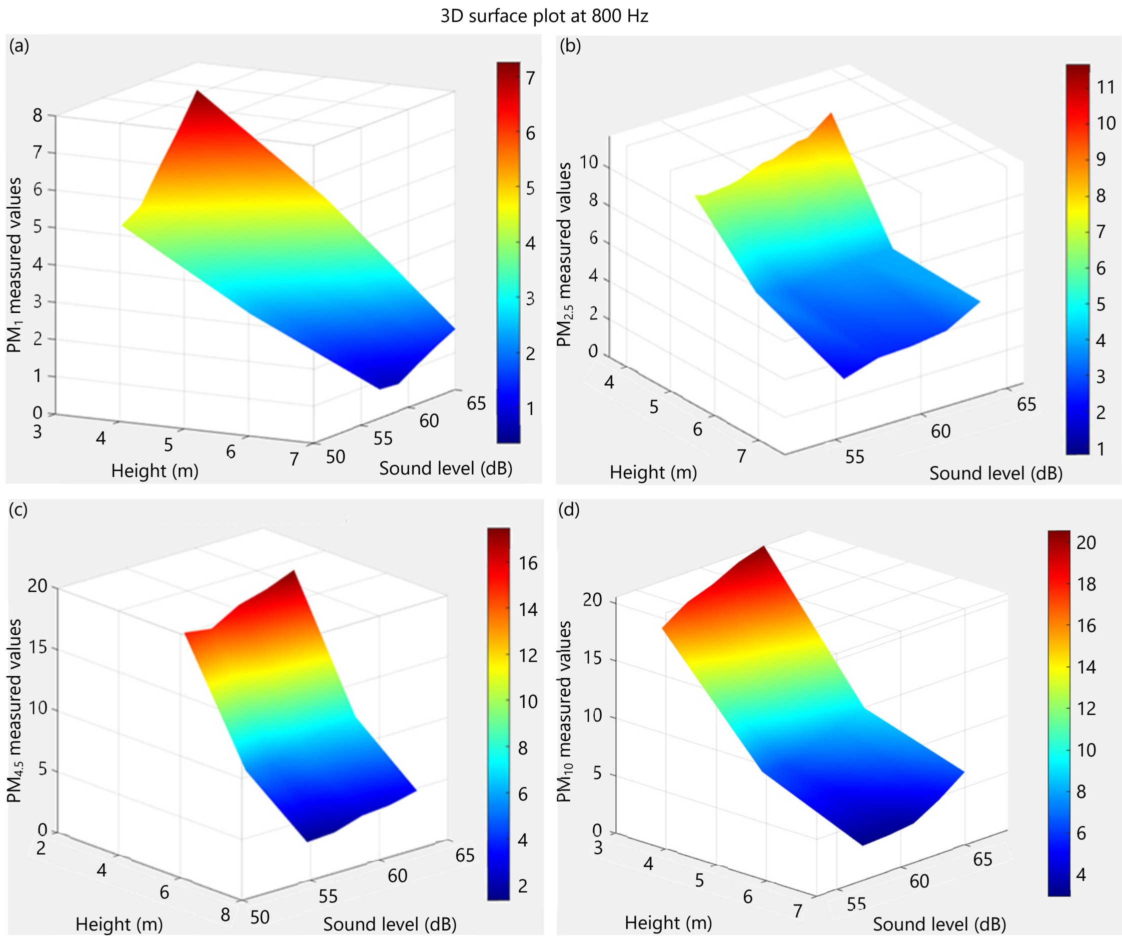

Fig. 2(a-d): Height-noise pollutant matrix

The outcomes derived from the regression model are notably impressive. Both models exhibit a consistent trend, characterized by a negative coefficient associated with the "measuring height" factor. This confirms that as the measurement height increases, the corresponding PM pollutant values decrease. Additionally, within both models, only the frequencies of 800 Hz are found to be statistically significant. This suggests that lower noise frequencies have a more pronounced impact on the model outcomes.

These findings aligned with the specific focus of current study on heavy-duty vehicles, where lower-frequency noise tends to be more prevalent. The observed results are in direct accordance with the research objectives. Among the four models examined, PM_1, $PM_{2.5}$ and $PM_{4.25}$ exhibit relatively high R-squared values (above 0.5), indicating a satisfactory fit of these models to the data.

However, it is crucial to acknowledge that relying solely on noise frequency to represent PM pollutants may not be advisable given the relatively low R-squared values obtained. This implies that noise frequency alone does not account for a substantial portion of the variation in PM pollutant levels. Therefore, caution should be exercised when interpreting noise frequency as the sole predictor of PM pollution based on these regression findings.

Height-noise pollutant matrix: Based on the findings from the previous regression analysis, it was determined that the frequencies of 800 Hz hold statistically significant importance. Therefore, a dedicated height-nose pollutant matrix has been developed specifically tailored to this frequency. This matrix aims to capture and analyze the relationship between height, nasal conditions and pollutant levels at 800 Hz level. The 3-D surface plot between PM measured values, height and sound level has been plotted and displayed in Fig. 2a-d.

The three-dimensional plots offer important insights into pollutant behavior, revealing that pollutant concentrations reach their peak at lower levels. This observation is highly logical and aligns well with the results obtained from linear regression analysis.

Delving deeper into the analysis of the three-dimensional graphs, it becomes evident that all four pollutants exhibit a significant and abrupt decrease specifically at the 6 m height mark. This intriguing phenomenon is likely linked to the weight and characteristics of particulate matter (PM) pollutants, which contribute to this sharp decline in concentration at that particular altitude.

DISCUSSION

This study initially classified the noise and pollutant data collected from May to November, 2023 on 7 sets of road pavement surfaced by friction course materials using cluster analysis. A regression model was then compiled, followed by a height-noise pollutant matrix to analyze the relationship between height, noise frequencies and pollutant levels.

Both the regression model and the height-noise pollutant matrix have provided insights into the relationship between height, noise levels and particulate matter (PM) concentrations in this study. The regression analysis revealed a negative coefficient for the 'measuring height' factor, indicating that as height increases, PM pollutant values generally decrease for PM_1, $PM_{2.5}$ and $PM_{4.25}$. However, the regression model's R-squared value suggested a less significant association between PM_{10} levels and noise frequency at 800 Hz. While one possible explanation for this difference could be the variation in particle size, with PM_{10} consisting of larger particles that are more susceptible to gravity, as illustrated by Chan and Kwok[8], the limitation of cluster analysis in data cleaning may also have influenced the lower statistical significance of the PM_{10} model. The actual reason for the issues with PM_{10} significance in this study remains debatable.

On the other hand, the height-noise pollutant matrix, represented by the 3-D Surface Plot at 800 Hz, demonstrated a negative correlation between elevation and sound intensity concerning PM readings. This implies that as height increases, pollutant levels decrease. Additionally, there was a positive correlation between sound levels and PM concentrations, indicating that higher sound levels are associated with increased PM concentrations. However, even though a significant linear relationship between variables was found between PM concentrations and noise frequencies from the regression model, the correlation does not imply cause-and-effect[16-19].

Overall speaking, one major limitation of this study is the sample size. Data was collected from 7 sites, resulting in a total of 16,782 valid measurements after cluster analysis. While a large amount of data would help reduce the likelihood of errors in the cluster analysis, future research should consider incorporating a larger sample size to reduce the possibility of missing data or outliers in the data set, leading to a more reliable result. Additionally, while there have been attempts to use UAVs for gathering vertical atmospheric observations with improved flexibility and measurability, it is not recommended to utilize UAVs in Hong Kong due to their densely populated nature and strict regulations imposed by the relevant authorities.

Considering these findings, it can be concluded that there is no linear relationship between PM_{10} levels, height and noise levels on friction course road pavement samples, as indicated by the regression model. However, the height-noise pollutant matrix suggests a possible association between height and pollutant levels, with higher positions relating to lower pollutant levels, while higher sound levels are linked to increased PM concentrations.

Hong Kong, a rapidly developing metropolis, experiences a high volume of vehicles on its extensive road network daily. Road pavement resurfacing is regularly conducted to ensure road safety. Currently, additional pavement materials such as polymer-modified stone mastic asphalt (PMSMA) and polymer-modified friction course (PMFC) have been introduced in road resurfacing works in Hong Kong. Future research could investigate other major pavement materials used in the city to validate the obtained results. Despite its limitations, this study serves as a foundation for future investigations into air and noise pollution in urban environments.

CONCLUSION

This study examines the correlation between traffic noise frequencies and particulate matter emitted by vehicles on friction course road pavements. It also aims to determine the vertical distribution and dispersion patterns of particulate matter and noise from road traffic, as well as how they change with increasing altitudes from the source. The findings suggest that particulate concentration decreases as height increases, while PM concentration increases with higher noise levels.

The research conclusions are expected to enhance understanding of pollutant emissions and their impact on human health. This understanding will aid in examining how different types of airborne pollutants, particularly particulate matter and their correlation with noise affect individuals at varying elevations. These preliminary findings can be used to improve future noise reduction regulations related to construction work and foster better urban planning. However, it is important to note that correlation does not imply causation. While an increase in PM concentrations could relate to higher sound levels or lower measurement points in height, other environmental factors like wind directions and relative humidity can also influence PM concentration readings. Overall, the data and analysis provided by this study will be valuable for enhancing knowledge of the vertical dispersion model of particulate matter in Hong Kong on friction course pavements. Ultimately, this research aims to address various issues and pave the way for future investigations on pollution at a larger scale.

SIGNIFICANCE STATEMENT

This research focuses on the vertical dispersion of particulate matter emissions and traffic noise on friction course pavements in densely populated Hong Kong. The study used linear regression and other statistical modeling to understand the behaviors of pollutants, particularly those originating from roadside vehicles. The findings reveal a significant correlation between traffic-generated $PM_{1/2.5/4.25}$ emissions and traffic noise, especially on the lower floors of buildings, at an 800 Hz noise frequency. These results enhance our understanding of the correlation between air and noise pollution in urban areas. Both results provide valuable insights for future planning and development projects aimed at improving community wellbeing and public health.

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