Developing Street-level $PM_{2.5}$ and PM_{10} Land Use Regression Models in High-Density Hong Kong with Urban Morphological Factors

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ABSTRACT. Monitoring street-level particulates is essential to air quality management but challenging in high-density Hong Kong due to limitations in local monitoring network and the complexities of street environment. By employing vehicle-based mobile measurements, Land Use Regression (LUR) models are developed to estimate the spatial variation of $PM_{2.5}$ and PM_{10} in the downtown area of Hong Kong. Sampling runs were conducted along routes measuring a total of 30km during selected measurement period of total 14 days. In total, 321 independent variables were examined to develop LUR models by using stepwise regression with $PM_{2.5}$ and PM_{10} as dependent variables. Approximately, 10% increases in the model adjusted R^2 were achieved by integrating urban/building morphology as independent variables into the LUR models. Resultant LUR models show that the most decisive factors on street-level air quality in Hong Kong are frontal area index, an urban/building morphological parameter, and road network line density and traffic volume, two parameters of road traffic. The adjusted R^2 of the final LUR models of $PM_{2.5}$ and PM_{10} are 0.633 and 0.707 respectively. These results indicate that urban morphology is more decisive to the street-level air quality in high-density cities than other cities. Air pollution hotspots are also identified based on the LUR mapping.

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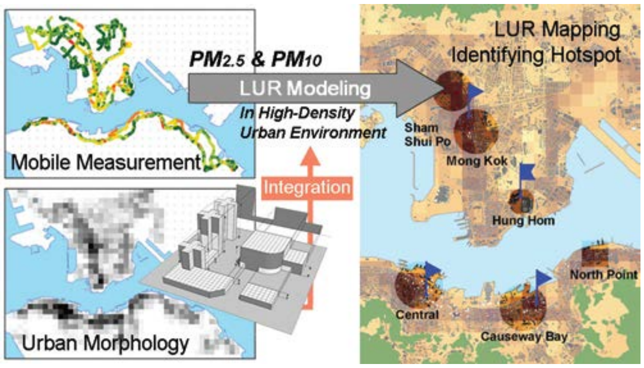

1. INTRODUCTION

Many epidemiological investigations proved that particulate matters (PM) were associated with adverse health outcomes. Particulate air pollution leads to higher health risks of cardiovascular and respiratory diseases [1]. These health impacts and risks are further accentuated in high-density urban environment. In cities with compact urban development, the dispersion of street-level particulates is impeded by their high-density urban morphology because densely-constructed buildings block air ventilation and consequently retard the dispersion [2]. Several retrospective epidemiological studies in Hong Kong showed that health risks (measured as the hospitalization and mortality) connected to cardiovascular and respiratory diseases were significantly associated with both long-term and short-term exposure to $PM_{2.5}$ and PM_{10} [3–8]. Therefore, monitoring street-level air pollution in high-density urban environment is essential to prevent or mitigate the health risks. Several studies have been conducted to observe the temporal and spatial variation of street-level particulate air pollution in Hong Kong by using either historical monitoring data from the existing Air Quality Monitoring Network (AQMN) of Hong Kong Environmental Protection Department (HKEPD) [9,10] or stationary measurements at sampling sites [11–14]. However, the coverage of such monitoring network is very limited. Among the 15 AQMN stations, only three roadside stations monitor street-level air quality within the urban environment (Figure S-4, SI), while the number of roadside sampling locations in other studies are also limited (not more than three in general). The complex urban morphology and compact urban traffic network in Hong Kong make the conditions of air quality vary significantly from site to site. However, the street-level air quality of many high-density sites and those with heavy traffic in downtown Hong Kong is not monitored by AQMN. Thus, quantifying the street-level air pollution and identifying hotspots of human exposure are difficult by using AQMN, because it provides insufficient information about the spatial variation of pollutants.

Land Use Regression (LUR) has become a popular method to explore the spatial variation of outdoor air pollution in environmental studies and to assess the health risks of human exposure to pollutants in epidemiological and public health studies [15] in Europe [16–23] and North America [24–28]. The application of LUR is also increasing in other regions [29–31]. The reason for such extensive applications of LUR models is mainly because it can be used to evaluate human exposure to air pollution in unmonitored areas and to identify urban air pollution hotspots which are vital to epidemiological and environmental studies [32].

The aim of this study is to develop LUR models for a sub-tropical high-density urban environment by focusing on the unique urban scenario of Hong Kong in order to supplement the inadequacy of the local monitoring network and provide a better understanding of the spatial variation of street-level air pollution. The compact high-density urban development of Hong Kong forms much higher buildings and very deep street canyons with intensive traffic and pedestrian activities, which makes it almost impossible to use conventional fixed monitoring locations to represent the conditions of street-level human exposure (Section 1, SI). In this study, under the special circumstance of Hong Kong's street environment, vehicle-based mobile measurements of particulate air pollution are employed as the approach to conduct the sampling of the dataset for LUR development. Mobile measurements are conducted in designated periods and routes in order to minimize the impact of temporal variability and extreme weather conditions on LUR model development. Correlation analysis between outdoor air pollution and building morphology is performed by integrating urban/building morphological parameters into the LUR model. As such, the study results can be not only used for the purpose of air quality management and human exposure evaluation but also directly as a reference in the optimization of urban development strategies and decision-making in urban planning on the basis of air quality considerations.

2. MATERIALS AND METHODS

Previous LUR studies typically set up 20-100 fixed sampling locations within the study area [15]. However, compact urban development, crowded space and bustling activities occurred within street canyons in the downtown area of Hong Kong has made it almost impossible to set up sufficient fixed long-term street-level sampling locations without random interference. In this study, the sampling of the concentration of street-level particulate air pollution is conducted in the downtown area of Hong Kong by using mobile measurements which were tested to be feasible and provide valid data for such a purpose [33,34]. LUR models of street-level $PM_{2.5}$ and PM_{10} were then developed.

2.1 THE MOBILE MEASUREMENTS. Mobile measurements have been increasingly used to monitor the air pollution in the last decade [35–43], especially for the development of LUR models [33,34,44–46]. The spatial continuity of mobile measurement makes it possible to detect the spatial variability of air pollutants concentration at a much higher spatial resolution and locate the place where its concentration culminates high level ("air pollution hotspots") that may not be possible to be identified by using a limited number of fixed monitoring locations, especially in cases like Hong Kong (Section 1, SI).

2.1.1 THE MOBILE MEASUREMENT PLATFORM. A Toyota HiAce vehicle with necessary particulate matter monitor and meteorological sensors on board served as the mobile measurement platform that is used to measure the concentration of air particulates and meteorological variables. The concentration levels of $PM_{2.5}$ and PM_{10} (the concentration level of particles <2.5 or 10μm in aerodynamic diameter, $\mu g/m^3$) were continuously measured using the TSI DUSTTRAK™ DRX Aerosol Monitor with a time interval of 1s. The calibration of photometric factor and size fraction of the DUSTTRAK™ monitor is essential to avoid positive bias when monitoring a specific aerosol different from the ISO A1 test dust. The aerosol monitor was calibrated for the specific aerosol of the urban street-level environment in Hong Kong using gravimetric samples from a HKEPD roadside air quality monitoring station (Section 2.1.1, SI). Air temperature (T_a,°C) and relative humidity (RH, $\%$) were measured by the meteorological sensor and used for humidity correction of the measured PM data. Global Positioning System (GPS) loggers were used to record the corresponding geographical location of each measurement data. A video camera was used to record the surrounding situations, providing a reference for any other factors influencing the measurements during data post-processing. The sampling time lag, particle deposition, self-contamination and impact of turbulence caused by the moving vehicle of mobile measurements are minimized by elaborately designing and assembling of the measurement platform (Section 2.1.2, SI).

2.1.2 SAMPLING ROUTE DESIGN AND TIME SELECTION. Spatial distribution of urban land use, population density, traffic networks, building morphology and natural topography were quantitatively analyzed in the geographic information system (GIS) using the urban planning dataset provided by the Hong Kong Planning Department (PlanD). Two sampling routes with a total length of approximately 30km located in the downtown area of Hong Kong (the northern part of Hong Kong Island and Kowloon peninsula respectively, Figure 1) were designated based on the variability of urban morphology, land use and traffic characteristics (Section 2.2, SI) in order to attain a broad coverage of various urban settings (Table S-2, SI). Measuring varying urban settings provides a comprehensive data range and variation for the independent variables dataset (Table 1), because urban morphology, land use and traffic are important independent variables for LUR modeling.

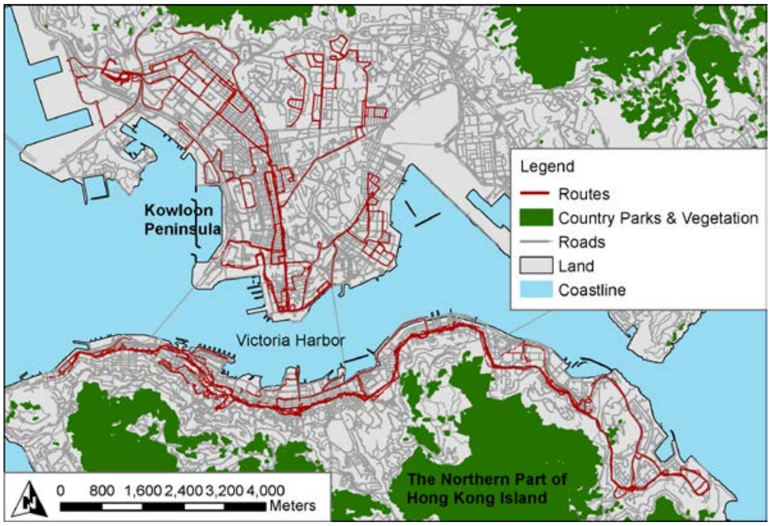

Figure 1. The sampling routes of mobile measurement campaigns (also see Figure S-8, SI).

Meteorological data from Hong Kong Observatory (HKO) and air quality monitoring data from HKEPD of the five consecutive years before mobile measurements were reviewed to select optimal measurement periods. This is to avoid the regional-dominant influence of the long-distance transportation of air pollution from the Pearl River Delta (PRD) region of Mainland China especially during the winter time [47] because the regional-dominant air pollution mode affects Hong Kong only one-third of time in the year [48]. As a result, mobile measurements were mainly conducted during summer months (from May to September) because air quality is dominated by local emission sources during summer time [11,12]. Similar selection of measurement season has been used to avoid season-specific influence in previous LUR study [34]. It allows the development of LUR models to understand the relationship between local urban development and air quality without regional influence. The meteorological conditions, such as rainfall and strong wind, which restrain the concentration level and weaken the spatial variability of particulate air pollution were also avoided [9]. The daily time period with relatively stationary background concentration (between 2:00 pm and 10:00 pm during which the hour-to-hour changing gradient is smaller than other hours) was selected based on the diurnal pattern of street-level air pollution in Hong Kong. In total,14 times of mobile measurements were conducted during the summer months of 2014 and 2015. Each measurement was conducted during a two-hour period between 2:00 pm to 10:00 pm. (All details in Section 2.3, SI).

2.1.3 QUALITY CONTROL AND POST-PROCESSING OF MEASURED DATA. We strictly followed our measurement time selection and avoided any dramatic changes on background weather and PM concentration. Driving manners were carefully controlled during all mobile measurements to diminish data noise caused by random impact factors (e.g. controlling the driving speed to be relatively stationary). Finally, 14 times of mobile measurements were successfully conducted during the summer months of 2014 and 2015 (Table S-3, SI). High humidity leads to water condensation and results in a higher reading when using light-scattering laser photometer based aerosol monitors. The following humidity correction for the TSI DUSTTRAK™ equipment in previous studies [49,50] was used to correct the measured data and eliminate the influence of high humidity in this study.

$$Correction\ Factor = 1 + 0.25\frac{RH^2}{(1-RH)} \tag{1}$$

Videos recorded during mobile measurements provide information about surrounding environment and are used for the removal of affected data. For example, data measured under the situation where the mobile measurement vehicle was behind or very close to another heavy-duty diesel vehicles were removed because they were likely to be significantly affected by the heat and polluting exhaust. Different from fixed sampling locations, mobile measurements enhance the spatial coverage but also introduce the limitation that the sampling time is very short at each location. A common driving speed of 30km/h involves only less than a minute of monitoring at a specific urban lot in the downtown area of Hong Kong for each sampling day. Therefore, measuring behind a high-emitting vehicle possibly affects all data on that day for the specific urban lot. Data measured at any locations close to construction sites were also deleted (Section 2.4.1, SI). After identifying and deleting those highly contaminated data, the noise of measured data caused by other random factors were eliminated by using the Savitzky–Golay (S-G) filter (Section 2.4.2, SI).

After finishing a mobile measurement on a specific route, weather and air quality data at all the monitoring stations along the specific mobile measurement route in the same period were obtained from HKO and HKEPD official records as the background reference. According to these background reference data, temporal adjustments were conducted for each mobile measurement dataset to eliminate the impact of the temporal difference (Method of temporal adjustment used in this study is given in the Section 2.4.3, SI).

2.2 DEPENDENT VARIABLES OF THE LUR MODEL. Mobile measurement data of the concentration of $PM_{2.5}$ and PM_{10} are used to develop the dependent variables of the LUR models. Identifying the optimal spatial scale is critical when analyzing the geographically distributed data collected from mobile measurements. Following the method of a previous mobile measurement air pollution spatial modeling study [51], we employed the semivariogram modeling to test the optimal spatial resolution for the data aggregation (Section 3.1, SI). A grid aligned with the local geo-dataset grid system was generated using the optimal spatial resolution of 300m. It was used for the spatial aggregation to produce the dependent variables of $PM_{2.5}$ and PM_{10}. There are finally 222 spatially aggregated concentration estimates that were used as the dependent variable for the LUR modeling. The data variability of these $PM_{2.5}$ and PM_{10} concentration values is shown in Figure 3.

2.3 INDEPENDENT VARIABLES OF THE LUR MODEL. Based on previous LUR studies [15], four categories of potential independent variables were identified to profile the spatial distribution of the emission intensity: (1) traffic and transport, (2) local energy supply, (3) land use, and (4) population. The dynamic potential of pollution dispersion was analyzed by using two categories of potential independent variables: (1) physical geography and (2) urban/building morphology. We analyzed 24 parameters using 13 different buffer sizes (14 buffer sizes for sky view factor) and 8 parameters using nearest distance analysis for each aggregated data point to check all potential independent variables for the LUR models for $PM_{2.5}$ and PM_{10} (Table 1).

Table 1. Summary of independent variables at different buffers included in the LUR model development. A total of 321 candidate independent variables were checked for LUR development.

VARIABLES USED AS INDEPENDENT VARIABLES	UNITS	ANALYSIS METHODS	BASIC DATA SOURCE
Emission Intensity of Pollution Sources			
Traffic & Transport			
Expressways and trunk road line density	km/km^2	buffer	Hong Kong Transport Department (TD)
Primary road line density	km/km^2	buffer	TD
Secondary road line density	km/km^2	buffer	TD
Tertiary road line density	km/km^2	buffer	TD
Ordinary road line density	km/km^2	buffer	TD
Road area ratio (%)	%*	buffer	TD
Traffic volume of public transport vehicles	Passenger Car Unit (PCUs)	buffer	TD
Traffic volume of private and government vehicles	PCUs	buffer	TD
Count of bus stops	number	buffer	Openstreetmap.org
Distance to marines ports & routes	km	distance	Openstreetmap.org
Local Energy Supply			
Distance to local power stations	km	distance	PlanD
Land Use			
Residential land use area (RES)	m^2	buffer	PlanD
Commercial land use area (COM)	m^2	buffer	PlanD
Industrial land use area (IND)	m^2	buffer	PlanD
Government land use area (GOV)	m^2	buffer	PlanD
Open space land use area (OPN)	m^2	buffer	PlanD

Population			
Population density	person//km^2	buffer	Hong Kong Census and Statistics Department (C&SD) and PlanD
Dynamic Potential of Pollution Dispersion			
Physical Geography			
Longitude (Δx to the coordinate origin of HK1980 Gird)	m	distance	GPS data of the data point
Latitude (Δy to the coordinate origin of HK1980 Gird)	m	distance	GPS data of the data point
Elevation above the Hong Kong Principal Datum ("mPD")	m	distance	Hong Kong Lands Department (LandsD)
Distance to waterfront	km	distance	PlanD
Distance to city parks	km	distance	PlanD
Distance to country parks	km	distance	PlanD
Greening coverage ratio	%	buffer	PlanD
Urban/Building Morphology			
Mean of building height	m	buffer	PlanD
Std of building height	m	buffer	PlanD
Mean of building ground coverage ratio	%	buffer	PlanD
Std of building ground coverage ratio	%	buffer	PlanD
Mean of building volume density	%	buffer	PlanD
Std of building volume density	%	buffer	PlanD
Sky view factor (SVF)	[0-1]	buffer	PlanD
Frontal area index (FAI)	Dimensionless quantity	buffer	PlanD

Size of buffers used to develop LUR models (m): 50,100,200,300,400,500,750,1000,1500,2000,3000,4000,5000

SVF is a point based value. Therefore, except all buffer analysis, the original point SVF is also included as an independent variable and represented as 0 m buffer.

*All data of percentage (%) are standardized to [0-1] during LUR model development.

2.4 PARAMETERIZING URBAN/BUILDING MORPHOLOGY. One of the most important advantages of this study is to comprehensively integrate urban/building morphological factors into LUR models as the independent variables. The integration has been only adopted in a limited amount of previous studies [52,53], but in fact, very essential to high-density urban scenario. Moreover, compared with those previous LUR studies, the variations in urban development in Hong Kong cannot be fully represented by only using common street configurations due to the high variability and complexity of the building morphology. In Hong Kong's unique urban environment, it is common that two building forms have the same plot ratio or height but largely different permeability of air ventilation and solar radiation [54]. More complicated surface properties are necessary to depict the spatial distribution of urban morphology in Hong Kong. Therefore, 8 urban/building morphological parameters at 13 different buffers (14 for sky view factors, as shown in Table 1) are selected as the potential independent variables for the LUR model development and calculated in GIS based on the urban planning datasets (Figure 2 and Table 2). Fontal area index (FAI) is a wind-direction-dependent measure of the conditions of air ventilation in urban areas and is widely used to evaluate the horizontal permeability of the wind from a specific direction of an urban lot [55,56]. In this study, the weighted average of FAI was calculated for each lot by using 16 wind directions and corresponding frequency recorded by the nearest HKO meteorological station.

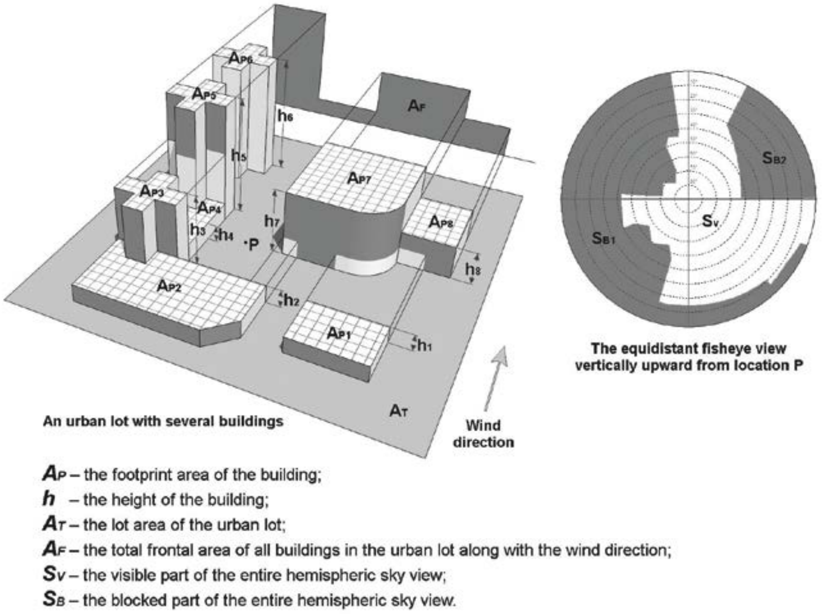

Figure 2. Inputs for the calculation of all urban/building morphological parameters used in this study.

Table 2. Calculation equations of 8 building morphological parameters included in the LUR model development. Information of approximately 50,000 buildings was processed in GIS to analyze the urban/building morphology of Hong Kong.

Urban Morphological Parameters	Unit	Calculation Method		Theoretical Meaning
Mean of building height	m	$\bar{h} = \frac{1}{n}\sum_{i=1}^{n} h_i$	(2)	Vertical building development intensity.
Std of building height	m	$SD_h = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (h_i - \bar{h})^2}$	(3)	Diversity of building height within a specific area.
Building coverage ratio of each urban lot	%[a]	$\lambda_P = (\sum_{i=1}^{n} A_{Pi})/A_T$	(4)	Building ground coverage intensity.
Std of building coverage ratio of all lots within each buffer area	%	$SD_{\lambda_P} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (\lambda_{Pi} - \overline{\lambda_P})^2}$	(5)	Diversity of building coverage within a specific area.
Building volume density of each urban lot	%	Total building volume of each lot is: $V = \sum_{i=1}^{n} A_{Pi} h_i$ $\boldsymbol{V_{max}}$ is the highest $\boldsymbol{V}$ among all $\boldsymbol{n}$ lots whole city. The building volume density of lot $\boldsymbol{j}$ is: $BVD_j = V_j/V_{max}$	(6) (7)	A measure of building volume within per unit area.
Std of building volume density of all lots within each buffer area	%	$SD_{BVD} = \sqrt{\frac{1}{n}\sum_{j=1}^{n} (BVD_j - \overline{BVD})^2}$	(8)	Diversity of building development intensity.
Sky view factor (SVF)	[0-1]	$\Psi_{sky} = S_V/(S_V + \sum_{i=1}^{n} S_{Bi})$	(9)	A measure of the openness to the sky of a given location in a lot [57].
Frontal area index (FAI, weighted average are calculated using 16 wind directions)	C[b]	$\lambda_F = A_F/A_T$	(10)	A wind direction – dependent measure of the urban ventilation condition of a lot [56].

a: All data of percentage (%) are standardized to [0-1] during LUR model development.
b: Calculated FAI is a dimensionless quantity.

2.5 LUR MODELING AND CROSS VALIDATION. First, A Distance-Decay REgression Selection Strategy (ADDRESS) [58] was adopted to select around 30 candidate independent variables (one or two critical buffers were identified for each variable) as the input of further stepwise regression modeling among all 321 potential independent variables (Section 3.2.1, SI). Then, stepwise multiple linear regression was conducted to establish LUR regression models of

$PM_{2.5}$ and PM_{10} as determined by minimum Akaike information criterion (AIC) [59,60]. The significance level (prob > |t|) and variance inflation factor (VIF) of each independent variables were checked to confirm the variables significance level and ensure that there is no collinearity issues in resultant regression models (Section 3.2.3, SI). The adjusted R^2 values of each model were examined to evaluate the model performance. Both the root-mean-square error (RMSE) from leave-one-out cross validation (LOOCV) and the adjusted R^2 of 10-fold cross validation were used to validate the LUR models (shown in Table 3, details in Section 3.2.4, SI). The final models also show reasonably good performance (0.582 and 0.611 for $PM_{2.5}$ and PM_{10} respectively) in an external validation using a separately sampled mobile measurement dataset (Section 3.2.5, SI).

3. RESULTS

3.1 THE FINAL LUR MODELS OF $PM_{2.5}$ AND PM_{10}. Using spatially aggregated $PM_{2.5}$ and PM_{10} as the dependent variables, final LUR models were established. The adjusted R^2 values of final LUR models for the 300m-spatially aggregated concentration of both $PM_{2.5}$ and PM_{10} are 0.633 and 0.707 respectively (300m-aggregated dependent variables provide the best model performance, which is consistent with the semivariogram modeling results in Section 2.2. Other models using different dependent variables aggregation resolution are shown in Table S-12, SI for comparison). As indicated by the final models of $PM_{2.5}$ and PM_{10} (Table 3 and Figure S-20, SI), the most essential determinants of the concentration of street-level particulate air pollution in the downtown area of Hong Kong are building morphology and urban road traffic. These results indicate that, beside the commonly applied LUR independent variables such as land use and traffic, building morphology is also one of the determinants of the street-level particulate air pollution concentration in the Hong Kong’s high-density urban environment. To quantify the model performance improvement introduced by adding urban morphology as independent variables, models completely excluding urban morphology were also established for comparison, which showed an adjusted R^2 increase of 0.111 and 0.150 on the model performance of $PM_{2.5}$ and PM_{10} respectively when building morphological variables were used in modeling (Section 3.3, SI). The concentration of street-level air pollutants is largely determined by both emission and dispersion of pollutants. Road traffic measured as the road line density and traffic volume represents the distribution of pollution sources and emission intensity. Building morphology quantified by FAI directly affects air ventilation in urban areas and the dispersion capacity of air pollution, especially in extremely compact urban environment. It should be noted that, as a measure of evaluating urban air ventilation, FAI represents the horizontal permeability of an urban area to prevailing wind. It implies that enhancing urban ventilation by optimizing the building morphology is more important to high-density cities like Hong Kong than other low-density or mid-density cities when dealing with street-level air pollution.

Table 3. Summary of the final resultant LUR regression models of $PM_{2.5}$ and PM_{10}.

SUMMARY OF FIT OF $PM_{2.5}$ LUR MODEL	
Dependent Variable	Spatially averaged $PM_{2.5}$ data using spatial resolution of 300m
R^2	0.646
Adjusted R^2	0.633
RMSE	6.516
Mean of Response	51.759
P-value	<.0001*
10-fold Cross Validation R^2	0.613

PARAMETER ESTIMATES					
Independent Variable	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**	**VIF**
Intercept	27.363	2.458	11.13	<.0001*	n/a
Primary road line density (300m)	1.092	0.252	4.33	<.0001*	1.434
Ordinary road line density (400m)	0.555	0.269	2.06	0.0416*	1.765
Traffic volume of public	5.016e-4	2.277e-4	2.20	0.0298*	1.492

transport vehicles (500m)					
Frontal area index (400m)	15.191	2.750	5.52	<.0001*	1.593

SUMMARY OF FIT OF PM_{10} LUR MODEL					
Dependent Variable	Spatially averaged PM_{10} data using spatial resolution of 300m				
R^2	0.718				
Adjusted R^2	0.707				
RMSE	6.948				
Mean of Response	59.085				
P-value	<.0001*				
10-fold Cross Validation R^2	0.692				
PARAMETER ESTIMATES					
Independent Variable	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**	**VIF**
Intercept	43.523	2.896	15.03	<.0001*	n/a
Primary road line density (300m)	0.816	0.268	3.05	0.0029*	1.421
Traffic volume of private and government vehicles (200m)	2.366e-5	8.051e-6	2.94	0.0040*	1.115
Government land use area (1000m)	-1.760e-5	4.525e-6	-3.89	0.0002*	1.170
Frontal area index (400m)	26.104	2.692	9.70	<.0001*	1.343

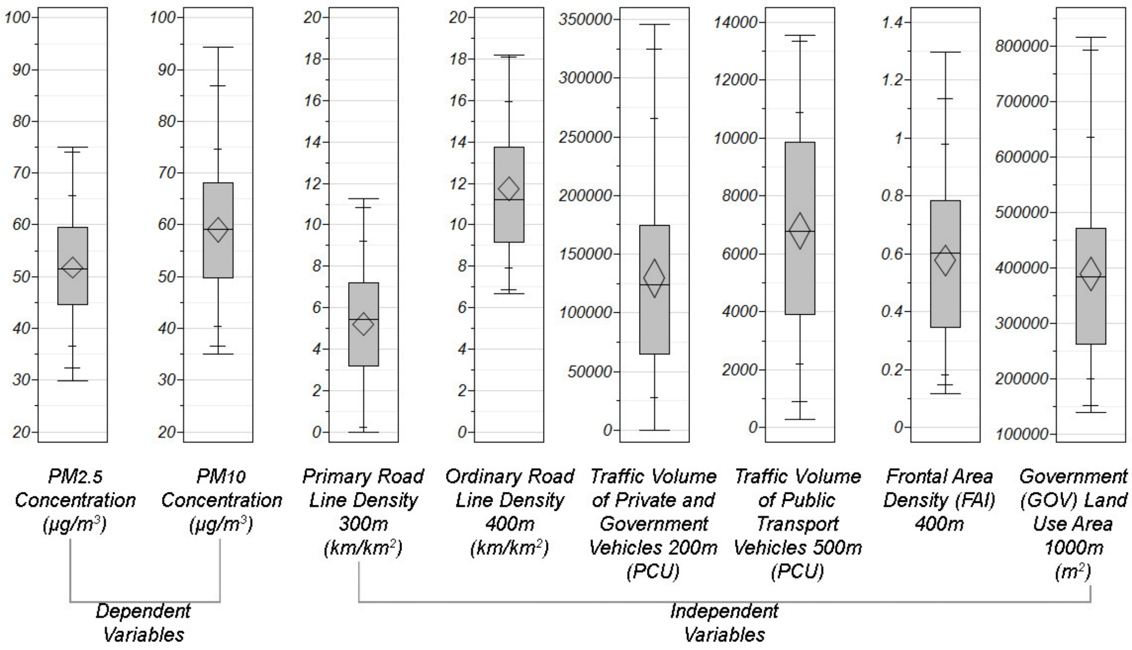

Figure 3. Boxplots of dependent variables and independent variables.

3.2 LUR GEO-MAPPING AND MODEL VALIDATION. The geo-mapping of the spatial distribution of $PM_{2.5}$ and PM_{10} was developed based on the resultant LUR models, using a spatial resolution of 300m (Figure 4, Figure S-21 and Figure S-22, SI). It was further validated using the results of mobile measurements obtained from Tuen Mun area where medium-density, occasionally high-rise, residential development dominates. Although the area used for validation has a slightly lower building density compared with the main study area, the LUR models performed reasonably well for the concentration of both $PM_{2.5}$ and PM_{10} with adjusted R^2-values of 0.582 and 0.611 respectively (Section 3.2.5, SI). It indicates that the resultant LUR models provide an accurate estimation of the spatial variation of air particulates under different urban settings in Hong Kong.

In Hong Kong, there are three commonly recognized hotspots of street-level air pollution, including Mong Kok, Central and Causeway Bay where the three roadside monitoring stations of AQMN operated by HKEPD are located. The concentrations of $PM_{2.5}$ and PM_{10} at these three stations are over 55 $\mu g/m^3$ and 70 $\mu g/m^3$ respectively. Three other hotspots of air pollution, Sham Shui Po, Hung Hom and Kwun Tong, were also clearly identified in the LUR map, which is consistent with the site selection of two previous local air pollution studies [61,62]. These hotspots are generally characterized by the densely-built building clusters and they are important nodes of local transportation network. The consistency of the LUR mapping with AQMN and previous studies proves that it is reliable as a tool to examine the spatial variation of air particulates and assess human exposure at finer spatial scales in epidemiological studies. Besides all known sites, the LUR models developed in the present study also identified a newly-found air pollution hotspot (North Point in Hong Kong Island) which previously did not draw much attention and was not monitored by HKEPD.

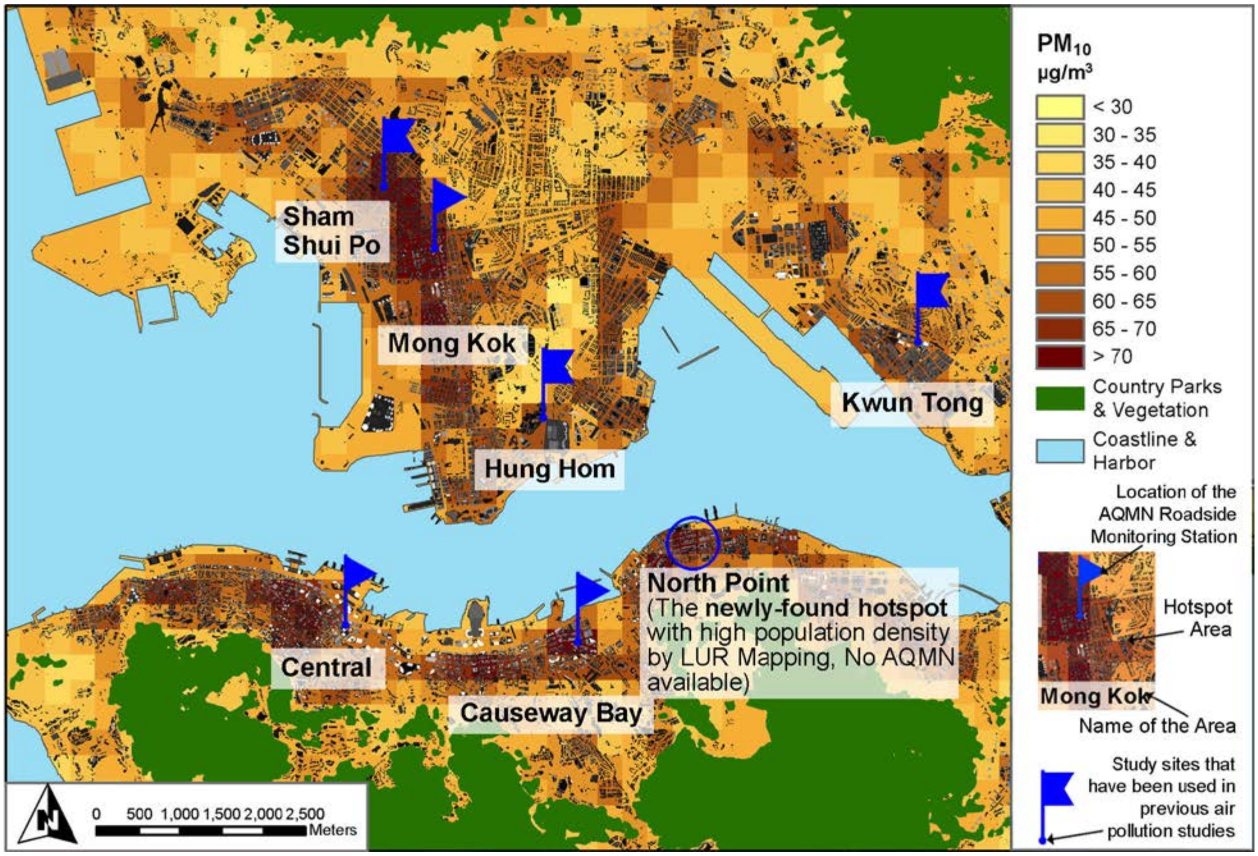

Figure 4. The spatial variation mapping of the concentration level of PM_{10} based on the LUR models developed in this study. Locations of all known and newly-found air pollution hotspots are marked on this map.

4. DISCUSSION

4.1 LUR APPLICATION IN A SUB-TROPICAL HIGH DENSITY CITY. The present study is the first attempt to develop LUR models in a sub-tropical city with extremely compact urban environment. A couple of studies have been conducted to map the spatial variation of $PM_{2.5}$ and PM_{10} in Hong Kong using remote sensing techniques [63,64]. However, the spatial resolution of those studies is limited by satellite images. This study provides a higher-resolution mapping of spatial variability of air pollutants based on LUR models. It can also be used as a reference for future studies on local health impact. [16]. Identifying newly-found street-level air pollution hotspots by LUR mapping is essential for the improvement of Hong Kong's air quality monitoring network, especially in the selection of roadside monitoring locations.

4.2 USING MOBILE MEASUREMENTS TO DEVELOP LUR MODELS - PROS AND CONS.

Mobile measurements have been gaining popularity in air pollution research [35,40,42,43]. There is also great potential in the studies of developing LUR models and mapping the air pollution spatial variation in urban area [33,34]. This study shows that measured data from properly designed mobile measurements are competent at providing data for LUR model development which is a more cost-effective way to cover larger study areas. By monitoring the spatial variability of air pollution using a moving platform, this study shows the feasibility of conducting LUR studies by taking advantage of the well-developed public transport network of Hong Kong. However, the downside is that much more work on the air pollution sampling has to be done and data aggregation has to be carefully handled to reduce uncertainty introduced by temporal variation, short-term events and other impact factors during mobile measurement, as the measurement time is very short at each location. The variations of background concentration and weather condition should be carefully addressed as well. All of the above concerns mean that qualified local meteorological and air quality monitoring networks with real-time data are prerequisites of conducting mobile-measurement-based LUR study. During measurement campaigns, air pollutants are sampled by a moving vehicle. The measurements are therefore representative of air pollution concentrations on the road. It has been emphasized that (Section 1, SI) mobile measurement data can be used to represent outdoor human air pollution exposure in this study because of the unique urban context of Hong Kong. The context indeed has to be well deliberated before extensively applying the mobile measurement method in other cities and regions. Both the experimental design of the mobile measurement and data processing method may need to be adjusted according to specific contexts and scenarios of different study areas.

4.3 DEVELOPING LUR MODELS WITH URBAN/BUILDING MORPHOLOGY. Compared to previous LUR models, the correlation analysis between air pollution and urban/building morphology was improved by parameterizing the urban planning dataset. Mapping air pollution in urban areas is an important part of urban planning and policy decision-making, especially for densely built environment because buildings can significantly change the prevailing climatic conditions in urban areas by disturbing the airflows passing through urban fragments and modifying the radiation balance in urban areas. As a consequence, it alters the dispersion of air pollutants within street canyons [65,66]. Similar to previous LUR models of other cities [17], urban traffic is one of the most decisive factors of air pollutants concentration in Hong Kong. On top of that, this study also finds the street-level concentration of $PM_{2.5}$ and PM_{10} was also significantly determined by urban/building morphology in a high-density built environment due to the poorer air ventilation [67,68].

4.4 LUR AIR POLLUTION MODELING FOR BETTER URBAN PLANNING. Urban air quality and urban planning are closely connected [69,70]. From the view of urban planning, compact urban morphology is more financially viable because it maximizes the use of land resources, reduces transportation cost and allows more efficient use of public facilities [71]. However, compact urban development without proper guidance and management leads to environmental issues and health risks associated with poor air quality. LUR models developed in this study indicate that the air quality in high-density urban development of Hong Kong is able to be improved as long as its urban planning follows the scientific rules to keep urban areas permeable to air ventilation by controlling building geometry and also to prevent intensive vehicular emission hotspot by refining road network planning and traffic controlling.

ASSOCIATED CONTENT

Supporting Information. Supporting information (SI) contains further methodological and technical details about the mobile measurement campaign, data post-processing/analysis and the model developing procedure as noted in the main text. The supporting information also contains all alternative LUR models using different spatial aggregation resolutions. The Supporting Information is available free of charge on the ACS Publications website via the Internet at http://pubs.acs.org.

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. The authors declare no competing financial interest.

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