

3D built-environment attributes and household road traffic noise exposure in Hong Kong

Mengdi Guo^{1,3}, Jianxiang Huang¹, Michael Yuxuan Ni²

¹ Department of Urban Planning and Design, 8/F Knowles Building, the University of Hong Kong, Pokfulam Road, Hong Kong

² School of Public Health, G/F, Patrick Manson Building (North Wing), 7 Sassoon Road, Pokfulam, Hong Kong

³ Corresponding Author Email: mdguo@hku.hk

Abstract. Road traffic noise is an environmental health hazard in Hong Kong and other high-density cities. The dense built environment modifies noise propagation, reflects, absorbs or diffracts sound depending on building morphology, road configuration, and open space layout, etc. Mitigation of urban traffic noise is of growing concerns to planning and design practitioners. Existing assessment methods are limited in reliably accounting for localized variations in noise exposure associated with a high-density city. The aim of this research is to 1) develop a 3D database of road traffic noise exposure for a large number of households in a high-density city; 2) explore the linkages between built environment attributes and road traffic noise exposure. A 3D built environment database was constructed for Hong Kong using building geometries, topography and urban traffic noise data. Window coordinates for each household were extracted using address and building floor plans. Computer simulation was conducted to determine traffic noise exposure at window locations using CadnaA for a random sample of 8,158 households across the city. Results revealed that 76.3% of the households are exposed to excessive road traffic noise by WHO standards. Household traffic noise exposure are significantly associated with proximity to secondary road, story-level of the flat, and other urban form attributes. The 3D database is of value for public health research in relation to noise and urban noise mitigation measures. The next step is to develop an efficient and reliable simulation tool to support planning and design decisions in traffic noise mitigation.

1. Introduction

Noise is an environmental hazard associated with health issues such as cardiovascular diseases, diabetes, sleep disturbances, etc. [1], [2]. Residents in high-density cities are especially vulnerable to noise due to the agglomeration of noise sources, built-up structures, and urban residents in a limited area. Road traffic is a ubiquitous source of environmental noise that is widely spread across the city. Around one million residents in Hong Kong were subjected to excessive road traffic noise according to the Environmental Protection Department (EPD) [3], [4].

Population noise exposure in urban area was found correlated with a variety of built environment attributes, including yet not limited to traffic conditions, density of buildings and roads, building morphology, material characters, microclimate, provision of open space, etc. [5]–[7]. Wang and Kang found significant impacts of morphological attributes on noise exposure with a study of Greater Manchester and Wuhan [5]. The impact of individual attribute varies in the two cities. For instance, building coverage and road traffic noise exposure are positively correlated in Greater Manchester, yet negatively correlated in Wuhan. A study in Hong Kong found dwelling scale and peripheral street



canyon index were linked to road traffic noise exposure in large street block groups [6]. Ryu et al. found ground space index, floor space index, traffic volume, traffic speed and road coverage significantly correlated with noise exposure of gridded urban area in Cheongju, Korea [7]. The studies of Silva, Oliveira and Silva and Guedes, Bertoli and Zannin stated that environmental noise was associated with construction density, provision of open space, and spatial configuration in Braga, Portugal [8], [9].

In existing studies, understandings of the relationship between population noise exposure and built environment attributes were mixed. Due to data limitation, not many studies have investigated the noise impacts of built environment attributes; even less effort was put into high-density cities. Existing studies either limit in resolution of data provision or representativeness of selected cases, which may lead to the loss of statistical power or misclassification of household or individual noise exposure [5], [6], [9], [10]. In regional scale researches, individual noise exposure is usually calculated using averaged noise levels of the most exposed façade [11], [12]. A less accurate approach is to calculate noise exposure at building level, using noise mapping in combination with interpolation methods [13], [14]. Precise simulation of individual or household noise exposure is usually conducted in neighborhood or smaller scale studies [8], [9]. It can hardly be applied to a large area due to limits in data provision and high assessment cost.

This study aims to advance the spatial resolution of household traffic noise exposure simulation in dense urban area of Hong Kong, in order to enhance the understanding of traffic noise exposure in high-density cities and inform noise mitigation measures in urban planning practices. In detail, we will 1) develop a database of annual averaged road traffic noise exposure of households from public health cohorts in Hong Kong, 2) and evaluate the linkages between built environment attributes and household road traffic noise exposure. This study is supported by a comprehensive built environment database of Hong Kong for precise identification of built environment attributes for each household address. We use the state-of-the-art noise simulation tools to calculate household road traffic noise exposure with high spatial resolution and reliable accuracy. Section two introduces the methods and data used in this study; section three presents result and discussion; the study is concluded in section four.

2. Methods and Data

For participants of public health cohorts in Hong Kong, we identified the geo-coordinates of their household window locations in 3D urban space, calculated the annual averaged road traffic noise exposure for selected households, linked the noise exposure with built environment attributes, and analyzed the relationship between traffic noise exposure and built environment characters.

Data input of this study includes: 1) iB1000 digital topographic map that covers a majority of Hong Kong urban area for the year 2015, obtained from Lands Department [15], 2) household addresses of FAMILY Cohort [16] and Birth Cohort [17] participants, 3) flat-unit information fetched from CentaData [18], 4) built environment information obtained from OpenStreetMap, an open map data platform [19], 5) territory-wide traffic noise database of road network in Hong Kong for the year 2015, calculated with road traffic database of Hong Kong [20], average traffic speed obtained from Google Map, and topography data [15], using the CRTN algorithm [21] as endorsed by the Hong Kong Environmental Protection Department (EPD) [22], and 6) data obtained from other open data platform such as Google and Housing Authority. The cleaning, analyses and linkages of the above databases were executed in the ArcGIS 10.4, using programming languages Python 2.7 and R 3.3.1. The spatial reference was “Hong Kong 1980 Grid System” [23].

2.1. Identifying major window locations of households in 3D urban space

A semi-manual method is used to identify 3D geo-coordinates of the centre point of the living or bed room window for apartments of FAMILY Cohort and Birth Cohort participants. A sum of 8,158 window coordinates was identified from the household addresses of both cohorts: 6,358 from FAMILY Cohort and 1,800 from Birth Cohort.

Firstly, address data of the cohort participants was paired with flat-unit and floor plan information and cleaned in the meanwhile. Flat-unit information of households living in private housing estates was automatically fetched from CentaData (Centadata Company Limited, no date). Most flat-unit information of public housing estates was obtained by field study, except for the few with available data in open data platform. A pilot field visit to 48 buildings of 6 public housing estates in Shek Kip Mei, Hong Kong was conducted in Jan 2017 (Figure 1 left & middle), in order to obtain flat-unit information. Field investigation of a large number of public housing estates were carried out in early June of 2017. The pairing process added flat-unit attributes such as floor plan, apartment information, etc. to the address database and excluded the samples without valid flat-unit information.

Next, 3D coordinates were added to the address database using floor plan and flat-unit information obtained in the pairing process. A floor plan was matched with the building outline in ArcGIS space (Figure 1 right); the window location was pinpointed on the building outline, at the middle of the largest window of living or bed room; X-Y coordinates of the point was then calculated in ArcGIS space. Height attribute (Z coordinate) of each window point was calculated using the base and roof level of the building, total storeys of the building and the actual storey of household.

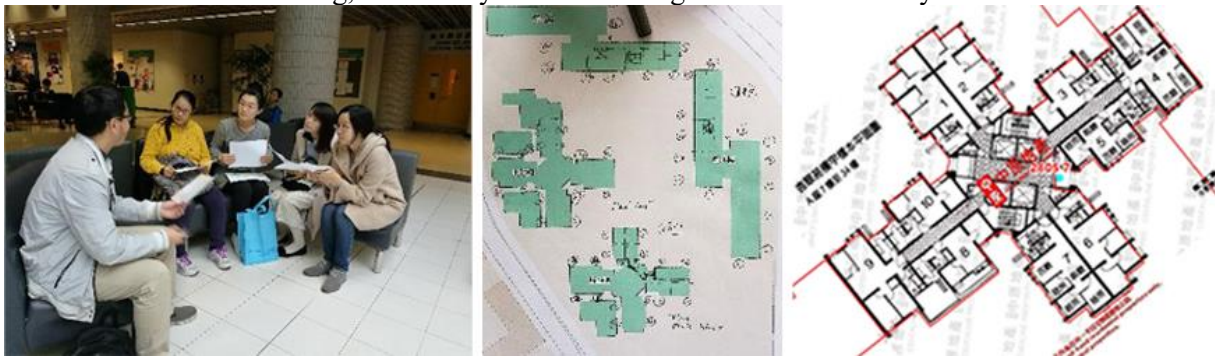


Figure 1. left, briefing of pilot field visit to public housing estates in Shek Kip Mei in January 2017; middle, flat unit information obtained in the visit; right, match floorplan with building outlines in GIS database and pinpoint window location in ArcGIS platform.

2.2. Simulation of household road traffic noise exposure

We use annual-averaged road traffic noise exposure (L_{den}), a metric recommended by WHO and mandated by European Noise Directive [24], [25] for health studies, to evaluate long-term noise exposure for the 8,158 households identified in 2.1. We use CadnaA, an extensively validated software that has been widely applied to simulate noise exposure in high-density cities, such as Wuhan, Tianjin, and Singapore, to simulate the traffic noise exposure at the identified household window locations [5], [26], [27]. The input data consists of a territory-wide database of buildings, topography, road centrelines with annual averaged road traffic noise levels ($L_{A_{den}}$), and 3D coordinates of receiver points located one metre away from the identified window location in perpendicular direction to the building façade [28]. Urban area of Hong Kong was divided into 237 sub-areas (blue frames in **Figure 2** left), in order to fit in the calculation capacity of CadnaA. The 8,158 identified household addresses were located in 211 sub-areas. For each sub-area, built environment and traffic data for simulation was assembled within a 300-metre outer buffer (red frames in **Figure 2** left) [22].

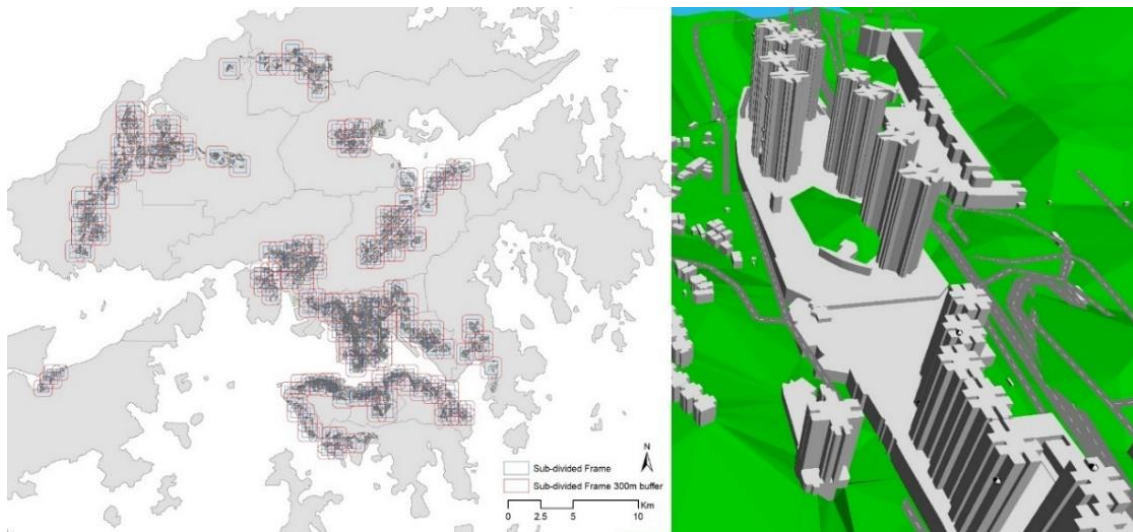


Figure 2. left, Hong Kong urban area was divided into 237 sub-areas (blue frames) in ArcGIS platform for acoustic simulation in CadnaA space, the built environment and traffic data for calculation was collected within a 300-metre outer buffer (red frames) of the sub-area; right, 3D view of noise simulation in CadnaA.

2.3. Statistical analysis

We examined the linkages between household road traffic noise exposure and built environment attributes using multi-variant regression analysis. Variables of household road traffic noise exposure, flat-unit information and built environment attributes were assembled in previous sections and linked with cohort address data. A total of 6,363 households were selected with variables summarized in **Table 1**.

Table 1. Summary of household road traffic noise exposure, flat-unit information, and built environment attributes linked with 6,363 households in the FAMILY Cohort and the Birth Cohort.

<i>Variables</i>	<i>Unit</i>	<i>Mean</i>	<i>Std. Dev.</i>	<i>Min</i>	<i>Max</i>
<i>Household exposure to road traffic noise</i>	dB(A)	61.18	9.57	27.3	86
<i>Household proximity to the nearest highway or major road</i>	100 Metre	1.80	1.60	0.06	11.39
<i>Household proximity to the nearest secondary road</i>	100 Metre	0.32	0.23	0	2.00
<i>Traffic noise level of the nearest road</i>	dB(A)	68.1	6.16	0	84.68
<i>Density of all roads in a 500m buffer</i>	1/km	3.96	6.47	0	31.06
<i>Building coverage in a 500m buffer</i>	%	28.85	12.3	3.23	94.49
<i>Average building height in a 500m buffer</i>	Metre	28.86	12.33	6.59	73.83
<i>Number of flat units per floor of the building</i>	count	9.62	5.25	1	60
<i>Actual storey of the flat</i>	count	16.2	10.54	1	58
<i>Total storeys of the building</i>	count	31.82	9.64	1	65

3. Results and Discussion

Territory-wide distribution of road traffic noise exposure ($L_{A_{den}}$) at window location of the 8,158 households was shown in **Figure 3**, where each column represented one household. Traffic noise level of road centre lines was presented in coloured lines. Average household road traffic noise exposure was 62.91 dB(A) in Hong Kong Island, 63.87 dB(A) in Kowloon, and 59.77 dB(A) in New Territories. A high variation in traffic noise exposure was observed between households living close by. Around 76.3% of the studied households have a road traffic noise exposure higher than 55 dB(A), the WHO

day time noise standard [29]; while around 36.7% exceeded the Hong Kong's local standard [30]. The database improves the spatial resolution of household road traffic noise exposure and is of value to advance researches on health impacts of road traffic noise in high-density cities like Hong Kong.

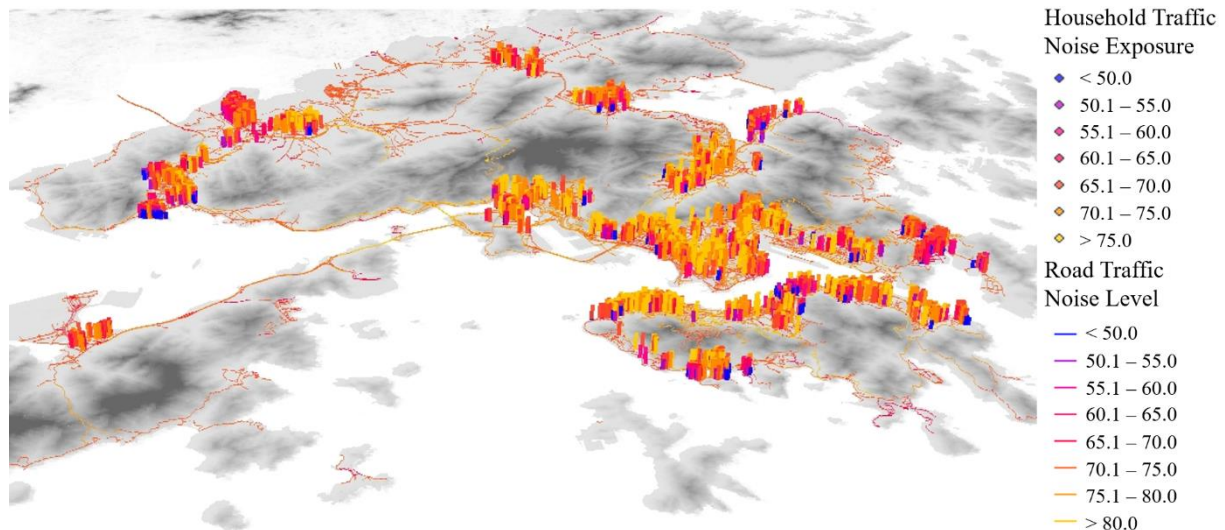


Figure 3. Territory-wide distribution of road traffic noise exposure simulated at the window locations of the 8,158 households selected from the FAMILY Cohort and the Birth Cohort, and traffic noise levels of road centrelines.

The result of regressing household road traffic noise exposure on built environment attributes was presented in Table 2, where the dependent variable was household road traffic noise exposure; independent variables were flat-unit and built-environment attributes stated in Table 1. Results showed correlations between household road traffic noise exposure and road traffic attributes, built environment density, and flat locations in 3D urban space.

- Road-traffic variables, such as proximity of highways or secondary roads, were associated with household road traffic noise exposure ($p < 0.001$). Noise impacts of secondary roads on households are higher than those of the highways or major roads: regression results showed that being 100m closer to the nearest highway or major road was linked with an increase of 1.55 dB in household road traffic noise exposure; the increment was 7.78 dB for a nearest secondary road, although major roads have higher traffic noise levels. A possible reason is that households in Hong Kong are most likely to live close to a secondary road in a dense neighborhood; while a highway, although generating higher levels of traffic noise in itself, is often located further away and equipped with sound barriers.
- Correlations were found between household traffic noise exposure and urban form. Household noise exposure increases 0.1dB if the building coverage increases one percent; it decreases 0.17dB if average building height of the area increases one meter (both $p < 0.001$). Peak traffic noise exposure appears at the height of 20 stories (**Figure 4**): for households below 20 story, living one story higher is linked to higher road traffic noise exposure ($p < 0.001$). A higher residential building is negatively associated with household noise exposure ($p < 0.01$).
- Results suggest a need for 3D noise simulation at household level, since household noise exposure depend significantly on the orientation of the apartment, location of windows, presence of nearby buildings, and proximity of road traffic, etc. Much of the variability will be lost if a 2D simulation is used as it is currently employed by the Hong Kong EPD [3].

Table 2. Regressing household road traffic noise exposure on flat-unit and built environment attributes with a subset of 6,363 households living in private housing estates.

Dependent Variable: Household Road Traffic Noise Exposure (dB(A))		
Number of obs.	6,363	
F (9, 6353)	254.66	
Prob > F	0	
R-squared	0.2651	
Adjusted R-squared	0.2641	
Root MSE	8.2011	
Household exposure to road traffic noise (dB(A))	β (95% CI)	p-value
Independent Variables: Road-Traffic Variables		
Household proximity to nearest highway or major road (100m)	-1.547 (-1.678, -1.416)	(0.000***)
Household proximity to the nearest secondary road (100m)	-7.779 (-8.697, -6.861)	(0.000***)
Traffic noise level of the nearest road (dB(A))	0.282 (0.249, 0.316)	(0.000***)
Road density within 500m radius (1/km)	0.055 (0.023, 0.086)	(0.001***)
Control Variables		
Building coverage within 500m radius (%)	0.103 (0.085, 0.122)	(0.000***)
Average building height within 500m radius(m)	-0.167 (-0.186, -0.147)	(0.000***)
Number of flat units per floor of the building (count)	-0.084 (-0.124, -0.043)	(0.000***)
Actual storey of the flat (count)	0.116 (0.095, 0.137)	(0.000***)
Total storeys of the building (count)	-0.037 (-0.064, -0.009)	(0.01**)
Intercept	48.894 (46.304, 51.484)	(0.000***)

* 90% significance level, ** 95% significance level, *** 99% significance level

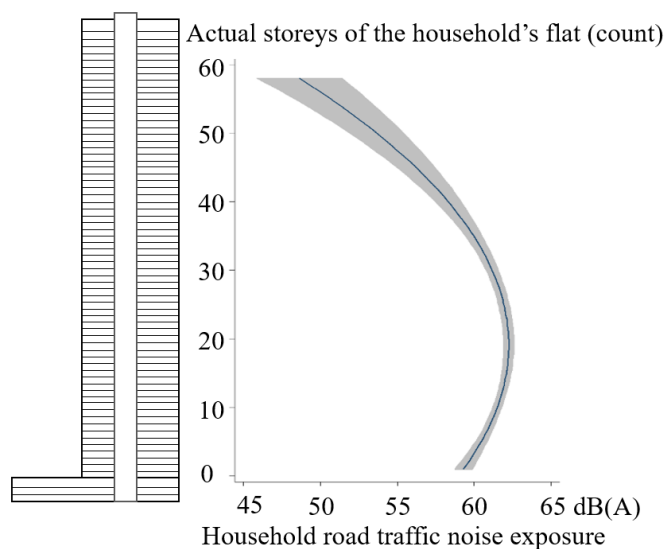


Figure 4. The vertical dimension of household road traffic noise exposure, n = 6,363. Average peak noise exposure appears at the height of 20 storey.

Results have practical implications for urban planning and design practices. Prevailing mitigation measures either work on road network or building design. Road network measures such as low noise road surfaces (LNRS) is mainly applied to major roads and highway. Yet findings of this study suggest that more attention shall be paid to the mitigation of traffic noise on secondary roads. The

mitigation effect of building scale measures, including fins, acoustic balcony & window, building setback, etc., may not work as expected considering the highly complex noise propagation in high-density built environment.

The study is delimited by road traffic noise, while other noise sources are not included such as construction, domestic activities, or aviation. The next step is to evaluate simulation data with those obtained from field measurement and to study the health impact of road traffic noise exposure. A long-term goal is to develop a convenient and reliable software tool for planning and design practitioners. Such tool can provide timely and reliable feedback to decision makers in order to improve urban acoustic environment. Designers shall be able to optimize building forms and layouts, organize floor plans, design façades, etc. based on the noise exposure of buildings in 3D space.

4. Conclusion

A 3D database consisted of household road traffic noise exposure and built environment attributes is developed for a large number of households in Hong Kong; 8,158 households are linked to two public health cohorts (6,358 households from the FAMILY Cohort and 1,800 households from the Birth Cohort) with comprehensive health records. Significant correlations are found between household road traffic noise exposure and urban attributes, i.e. proximity to highways, secondary roads, and floor level of apartments, etc. Results also suggest the necessity to have a 3D noise simulation tool in order to support assessing acoustic impacts of urban planning and design projects.

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