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Vertical Distribution of NO_{2} in an Urban Area: Exposure Risk Assessment in Children

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Abstract

The aim of the study is to perform a potential health risk assessment on children in contracting respiratory symptoms due to inhaling traffic-generated nitrogen dioxide (NO₂) in two typical high-rise naturally-ventilated residential building designs (slab and point block) located close to busy major expressways in a tropical climate. A total of six buildings were selected for the study. Ogawa passive samplers (PS-100) were used for NO₂ measurements in each building over a period of 5 weeks during the predominant monsoon seasons. Health risk assessment showed children residing at the mid floors of the buildings had the highest health risk regardless of their age .i.e. infants, children (1 year and under), children (8-10 years)compared to those residents residing at the high and low floors. This was expected since the highest concentration of traffic-generated NO, concentration occurred at the mid floors of the buildings. In a typical floor, children (1 year and under) had the highest followed by children (8-10 years) whilst new born infants had the least potential health risk in contracting respiratory symptoms. The reason might could be new born infants obtain passive immunity from their mothers and in children (1 year and under), the passive immunity fall during this age period as they are developing their very own immunity against respiratory symptoms. Children (8-10 years) had the their potential health risk to respiratory symptoms in between the other two age groups as these children could have developed more immunity against respiratory symptoms compared to the children (1 year and under) but less immunity compared to infants. Based on the mean overall HR values, children living in a slab block has about 1.27 times more risk in contracting a respiratory symptoms due to NO₂ inhalation compared to those living in a point block.

Keywords: Air pollution; Outdoor NO₂; Indoor NO₂; Exposure risk assessment; Slab block; Point block

Introduction

In urban air, NO_2 , a secondary air pollutant, is mostly derived from local vehicular traffic through the oxidation of NO by O_3 in the atmosphere [1-3]. NO_2 is a highly reactive oxidant and corrosive in nature, but it is also a good surrogate indicator of traffic-generated pollutants [4]. NO_2 acts mainly as an irritant affecting the mucosa of the eyes, nose, throat, and respiratory tract. Prolonged exposure to high NO_2 concentration levels may contribute to the development of acute or chronic bronchitis whilst low concentration levels of NO_2 exposure may cause increased bronchial reactivity in some asthmatics, decreased lung function in patients with chronic obstructive pulmonary disease and increased risk of respiratory infections, especially in young children [5,6]. In view of the adverse health effects of NO_2 , the World Health Organization set guideline values for NO_2 (a 1-hour level of 200 $\mu g/m^3$ and an annual average of 40 $\mu g/m^3$) [7].

There is limited study on the potential health risk assessment on children in contracting respiratory symptoms due to inhaling trafficgenerated nitrogen dioxide (NO₂) in high-rise naturally-ventilated residential building located close to busy major expressways in a tropical climate. The US EPA has taken some initiative in developing a total risk integrated methodology [8] which is a set of models for assessing exposure and risk for criteria air pollutants and hazardous air pollutants. Most human exposure assessment models are often based on the outdoor pollutant concentration levels which are used as the input parameter for predicting total human exposure [9]. The U.S. EPA has developed several computer-based exposure models applicable to pollutants which are directly or indirectly linked to mobile sources [10-12]. A comparison of some of the models for human exposure to air pollution is discussed by Duan [13]. Some indirect exposure methods for estimating population exposures to indoor pollutants have been developed [14].

J Civil Environ Eng ISSN: 2165-784X JCEE, an open access journal

Motivation of the study

In Singapore, about 1 out of 5 children are asthmatic and Singapore ranks number one in the Asia Pacific region in terms of the number of asthmatic kids between the ages 13-14 Y [15]. Singapore is a small nation with a hot and humid climate all year round, and has a land mass area of 712.4 km². The island has a current population of 5.18 million and a very high population density of 7126 persons/ km² as at Jun 2011. Singapore is ranked third in the world population density. About 83% of the residents live in high-rise public housing which is naturallyventilated [16]. The land constraints and the very high population density are the main reasons for these buildings to be usually high-rise and in close proximity to each other. The point and slab block designs are typical residential housing designs. The point block is generally 'H' shape on plan which has 4 homes in each horizontal storey with 2 homes facing the expressway while the other two are facing away from the expressway. The slab block is rectangular on plan and normally has 18-20 homes, in each horizontal storey with their living rooms facing the expressway. Since Singapore does not have natural resources, the citizens including children have become a vital asset to the government. Motor vehicle population has inched upwards to 926,000 of which about 62% are due to car ownership [16]. The motor vehicle population continues to grow every year despite congestion pricing measures which could be due to the increasing number of new

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Received February 11, 2012; Accepted May 28, 2012; Published May 30, 2012

Citation: Cheong KWD, Tham KW, Balasubramanian R, Kalaiarasan M (2012) Vertical Distribution of NO_2 in an Urban Area: Exposure Risk Assessment in Children. J Civil Environ Eng 2:115. doi:10.4172/2165-784X.1000115

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residents. The increasing motor vehicle and resident population have caused concerns on the indoor and outdoor air quality in the urban areas, especially in high-rise residential buildings located near major roads and expressways as on-road motor vehicles are main sources of traffic-generated NO_2 in urban areas. To address the health impact issues among children who are living in naturally-ventilated high-rise residential buildings in contracting respiratory symptoms due to inhalation of traffic-generated NO_2 , a potential health risk assessment study was conducted in the two typical building designs, the slab block (3 buildings) and point block (3 buildings) design using an established health risk model [17]. This paper will form a scientific basis for town planning of new urban developments in terms of mitigating health impacts in a tropical climate.

Sampling strategy

The locations of the measurement sites are shown in Figure 1. Three buildings were located in close proximity to the Central Expressway (CTE). CTE is one of the most highly-utilized expressways which link many residential towns to the Central Business District of Singapore. Two buildings were located along the Ayer Rajah Expressway (AYE). The AYE is located at the southern-western part of Singapore. It enables traffic movement from the city to the residential area along the west, and ends at Tuas checkpoint before going to Malaysia. One of the buildings was located along the Pan Island Expressway (PIE). The PIE is the oldest and longest expressway in Singapore. It extends along the length of the island, connecting Tuas in the west to Singapore Changi Airport in the east. All expressways in Singapore are dual carriageways with each carriageway having 3 lanes [18].

Once the building has been selected, sampling locations in each building were identified for the measurement of NO₂ and environmental parameters such as temperature, relative humidity (RH), wind speed and direction at the different heights of the building. The measurements were made at the windward face of the building. All the buildings selected for the study were naturally-ventilated highrise residential buildings and whose proximity to expressway are less than or equal to 30 meters downstream of the expressway. The ground on which the buildings stood was reasonably flat and almost the same level as the expressways. The predominant winds blew almost perpendicularly towards the building facades where the living rooms were located. As a result, most of the traffic-generated NO₂ was infiltrate into the buildings. All the measurement sites were selected such that the adjacent buildings nearby the site did not interfere with the predominant wind flow direction i.e. these measurements can be considered as being conducted in an open street geometry and streetcanyon effect is negligible. The main obstacles for airflow towards the buildings were the trees and hedges planted along the expressways. In each expressway, the trees were planted in a single row and had drooping branches with dense and complex canopy structures as shown in Figure 2. This type of greenery has become a unique feature in Singapore for naturally-ventilated high-rise residential buildings that are located in close proximity to expressways. The average tree canopy spans up to about 4-5 storey high. Facing the tree canopy is 1 m tall hedges which are about 0.7 m wide.

Instrumentation and measurement

For each building, indoor and outdoor NO₂ exposure levels were made using Ogawa passive samplers (PS-100) at every third floor of the buildings over a period of 5 weeks during the predominant Northeast (December-early March)/Southeast (June-September) monsoon seasons. Households with no/minimal smoking activity were selected for the measurement. Cooking hours per day ranged from 0.5-3hr mostly in the evenings as most of the adults were working during the day and children were at schools. All the measurements were done from the year 2005 to the year 2008. The location of instruments in a typical point and slab block is shown in Figures 3 and 4, respectively. Ogawa PS-100 passive samplers were used to measure indoor and outdoor NO₂ concentration levels of building. Sampling and analysis



Figure 1: Location of Measurement Sites along the Different Expressways.



Figure 2: Dense Complex Canopy Structure in Front of the Slab Block along the CTE.





was performed according to manufacturer protocols [19]. The passive samplers were exposed in duplicate together with a field blank. Each sampler was transported to and from the site in a sealed plastic bag in an airtight container. The methodology used for traffic and the indoor and outdoor NO₂ measurements has been published elsewhere [20]. NO₂ exposure models were derived using the data from field measurement and the results from these exposure models were fed into the established health risk model as input parameters. For the indoor measurements, the passive samplers were placed in the living rooms about 1.5-1.8 m high [21] from the floor (breathing zone) and at least 1m away from the any wall obstructions. For outdoor measurements, the passive samplers were located at the outdoor balcony and the lift lobby. The upstream background NO₂ levels were also measured using the passive samplers. All the passive samplers were exposed to exposure protection air for 1 week and kept refrigerated after each test. The samplers were sent back to the laboratory for chemical analysis within three days after the samples were collected. Field blanks were collected at the measured locations to determine any potential background contamination during sampling, transport and storage. 24hr temperature and relative humidity data were obtained from both indoors and outdoors using HOBO® Data Loggers placed at the living room, lift lobby areas and outdoor balconies of the selected households. The outdoor wind speed and direction were obtained using Ultrasonic Vaisala Wind Sensors (WS425) at three representative floors (low, mid and high floors) from 1000-2000 hr.

Health risk model

The potential health risk of children in contracting respiratory symptoms due to inhalation of traffic-generated NO₂ was based on the health risk model described by Pandey et al. [17]. The model account for age specific dose rates, age-specific breathing rates, age-specific body weights, diurnal concentration of the pollutant, occupancy factor (percentage of population likely to be in the building at a given interval of time) and the lowest observed adverse effect levels (loael). Loael is defined as the lowest tested dose of a substance that has been reported to cause harmful (adverse) health effects on people or animals. Exposure occurs when a person comes in contact with a pollutant. A person's exposure to a pollutant is defined as the contact of the pollutant at one or more boundaries of the person i.e. mouth or skin at specific concentrations over a period of time. Dose occurs only when the pollutant crosses the physical boundary of a person. The analysis divides the children into three age-specific categories namely, infants, children (1 year and below) and children (8-10 years).

$$Doserate(D) = [BR / BW] \int_{0}^{24} C(t)OF(t) dt$$
(1)

where, D is the age-specific dose rate (μ g kg⁻¹), BR is age-specific breathing rate (L min⁻¹), BW is age-specific body weight (kg), C(t) is diurnal concentration of the pollutant (μ g m⁻³), and OF(*t*) is occupancy factor of zone (percentage of population likely to be in the zone at a given interval of time).

For the estimation of the potential health risks of a child due to









Age Group	Inhalation Volume (m ³ /day)	Body Weight (kg)
Children 8-10 year old	10	30
Children under 1-year old	3.8	10
New born	0.8	3

Source: Cerna et al. [22]

 Table 1: Breathing Rates and Body Weights of Children.

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inhalation of NO_2 , the following expression as shown in Equation (2) was used.

 $Health \ risk \ (HR) = [Doserate / pollu \tan t \ specific \ loael]$ (2)

Information on the inhalation volume and body mass is obtained from Cerna et al. [22] as shown in Table 1. A loael value of 1.5 μ g/kg per day for NO₂ as used by Pandey et al. [17] was adopted for this study. All these information is not available in Singapore. For the NO₂ loael value, it is the dose value at which expiratory flow rate becomes lower than 100%. This value was estimated, based on the dose-response model constructed on the basis of data available in Neuberger et al. [23]. The HR value is dimensionless and is useful for making relative comparisons.

Results and Discussion

Vertical distribution profile of NO₂

The indoor / outdoor (I/O) ratio values of NO₂ concentration in the apartments of all the point and slab blocks turned out to be less than unity, which suggests that the transport of traffic-generated NO₂ was mostly from outdoors to indoors rather than from within internal sources. The major outdoor source was the nearby traffic. For the point block, the I/O ratio of NO₂ concentration ranged from 0.84-0.98 (0.93 \pm 0.04). An I/O ratio close to unity indicates that the outdoor air pollution made a significant contribution to the indoor air quality of the building.

The mean weekly mass concentration at the various floors of a building exceeded the WHO [7] maximum allowable annual mean value of 40 μ g/m³. This is of major concern since the health of residents including that of "sensitive" populations such as asthmatics, children, and the elderly is likely to be adversely affected. The vertical distribution profile of traffic-generated NO₂ of a typical point block has been published elsewhere [20]. The vertical distribution profile of traffic-generated NO₂ of a typical slab block is similar to that of a typical point block. Figures 5 and 6 show the typical vertical distribution profiles

of traffic-generated NO₂ in a point and slab block, respectively. The only difference between the point block and slab block configurations is that at corresponding floors, the NO₂ mass concentration for slab block was much higher than that of point block under similar traffic and meteorological conditions. This difference could be attributed to the slab block configuration which tends to slow down the wind speed thus allowing the accumulation of NO₂ mass concentration in front of the building.

Health risk assessment study

Exposure model: The NO₂ exposure models for NO₂ mass concentration developed for a typical a 22-storey point block and a 16-storey slab block is shown in Equations (1)-(2) based on the observational data collected over different measurement periods. Find Graph version 2.01 was used for the regression analysis. It was found that the Gaussian plus a line model function was the best function to fit the measured daily mean vertical distribution profile of NO₂ ($r^2 = 0.91$ -0.94; p < 0.04) for the point and slab blocks. For the mean estimated dose rate and the dimensionless health risk values, conventionally employed somatic and respiration parameters for the various age groups were used as shown in Table 1.

For the 22-storey building, the generalized exposure model is shown in Equation (1):

Weekly mean indoor NO₂ concentration
=
$$55.074 + 12.212e^{-0.5 \left[\frac{H-22.274}{14.456}\right]_2} - 0.071H$$

(µg/m³) (r² = 0.94) (1)

For the 16-storey building, the generalized exposure model is shown in Equation (2):

Eleer	Dose Rate(µg kg ⁻¹)			HR(dimensionless)			
FIOOI	New born	Children (1 yr and under)	Children (8-10 yr)	New born	Children (1 yr and under)	Children (8-10 yr)	
22	8.32 ± 1.30	11.86 ± 1.08	10.40 ± 1.05	0.79 ± 0.06	1.13 ± 0.07	0.99 ± 0.02	
21	8.41 ± 0.98	11.98 ± 1.23	10.52 ± 1.27	0.80 ± 0.05	1.14 ± 0.05	1.00 ± 0.06	
20	8.53 ± 1.16	12.15 ± 1.36	10.66 ± 1.42	0.81 ± 0.03	1.16 ± 0.03	1.01 ± 0.07	
19	8.68 ± 0.75	12.35 ± 1.01	10.83 ± 1.13	0.83 ± 0.01	1.18 ± 0.08	1.03 ± 0.05	
18	8.83 ± 1.04	12.58 ± 2.02	11.04 ± 1.16	0.84 ± 0.06	1.20 ± 0.05	1.05 ± 0.07	
17	9.02 ± 1.31	12.86 ± 1.79	11.28 ± 0.73	0.86 ± 0.09	1.22 ± 0.06	1.07 ± 0.04	
16	9.23 ± 1.70	13.16 ± 0.96	11.54 ± 0.84	0.88 ± 0.03	1.25 ± 0.09	1.10 ± 0.05	
15	9.46 ± 1.08	13.48 ± 1.45	11.82 ± 0.89	0.90 ± 0.06	1.28 ± 0.07	1.13 ± 0.08	
14	9.69 ± 0.99	13.81 ± 2.22	12.11 ± 1.45	0.92 ± 0.03	1.31 ± 0.04	1.15 ± 0.02	
13	9.92 ± 1.98	14.14 ± 2.35	12.40 ± 1.96	0.94 ± 0.02	1.35 ± 0.03	1.18 ± 0.06	
12	10.13 ± 2.15	14.43 ± 1.92	12.66 ± 0.91	0.96 ± 0.07	1.37 ± 0.09	1.21 ± 0.04	
11	10.3 ± 1.88	14.68 ± 1.73	12.88 ± 1.14	0.98±0.08	1.40 ± 0.04	1.22 ± 0.03	
10	10.43 ± 1.27	14.86 ± 2.02	13.04 ± 1.49	0.99 ± 0.05	1.42 ± 0.07	1.24 ± 0.05	
9	10.50 ± 2.01	14.97 ± 1.18	13.12 ± 1.24	1.00 ± 0.09	1.43 ± 0.03	1.25 ± 0.01	
8	10.52 ± 1.67	14.99 ± 1.64	13.14 ± 1.03	0.97 ± 0.04	1.43 ± 0.05	1.25 ± 0.04	
7	10.48 ± 0.75	14.93 ± 1.08	13.10 ± 0.68	0.94 ± 0.03	1.39 ± 0.07	1.20 ± 0.06	
6	10.3 9± 1.39	14.80 ± 1.15	12.98 ± 0.59	0.92 ± 0.06	1.36 ± 0.06	1.15 ± 0.03	
5	10.25 ± 1.44	14.61 ± 2.38	12.81 ± 1.17	0.91 ± 0.05	1.33 ± 0.04	1.12 ± 0.02	
4	10.09 ± 1.91	14.39 ± 1.67	12.62 ± 1.39	0.89 ± 0.08	1.29 ± 0.06	1.09 ± 0.04	
3	9.92 ± 0.96	14.13 ± 1.35	12.40 ± 0.83	0.87 ± 0.05	1.25 ± 0.04	1.08 ± 0.05	
2	9.74 ± 0.78	13.89 ± 2.06	12.18 ± 0.74	0.86 ± 0.02	1.24 ± 0.03	1.07 ± 0.06	
1	9.58 ± 1.20	13.65 ± 1.51	11.98 ± 1.07	0.85 ± 0.09	1.22 ± 0.02	1.04 ± 0.05	

Table 2: Predicted Dose Rates and HR Values Due to NO, Inhalation at the Various Floors of a Typical 22-Storey Point Block.

Citation: Cheong KWD, Tham KW, Balasubramanian R, Kalaiarasan M (2012) Vertical Distribution of NO₂ in an Urban Area: Exposure Risk Assessment in Children. J Civil Environ Eng 2:115. doi:10.4172/2165-784X.1000115

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Floor		Dose Rate(µg kg⁻¹)			HR(dimensionless)			
	New born	Children (1 yr and under)	Children (8-10 yr)	New born	Children (1 yr and under)	Children (8-10 yr)		
16	10.61 ± 1.13	15.13 ± 1.55	13.27 ± 1.24	1.01 ± 0.04	1.44 ± 0.03	1.26 ± 0.05		
15	10.74 ± 1.28	15.30 ± 1.36	13.42 ± 1.48	1.02 ± 0.02	1.46 ± 0.01	1.28 ± 0.02		
14	10.90 ± 0.96	15.53 ± 1.19	13.62 ± 1.36	1.04 ± 0.06	1.48 ± 0.04	1.30 ± 0.04		
13	11.12 ± 1.35	15.84 ± 1.28	13.90 ± 1.55	1.06 ± 0.05	1.51 ± 0.08	1.32 ± 0.03		
12	11.43 ± 1.49	16.27 ± 2.62	14.27 ± 0.76	1.09 ± 0.04	1.54 ± 0.04	1.36 ± 0.03		
11	11.80 ± 1.16	16.82 ± 1.71	14.75 ± 1.86	1.12 ± 0.03	1.60 ± 0.06	1.41 ± 0.06		
10	12.25 ± 1.81	17.45 ± 2.55	15.31 ± 1.69	1.17 ± 0.05	1.66 ± 0.05	1.46 ± 0.02		
9	12.71 ± 1.12	18.11 ± 1.94	15.88 ± 1.51	1.21 ± 0.02	1.72 ± 0.08	1.51 ± 0.03		
8	13.10 ± 1.61	18.67 ± 2.33	16.37 ± 1.90	1.25 ± 0.07	1.78 ± 0.09	1.56 ± 0.07		
7	13.35 ± 0.98	19.03 ± 1.88	16.69 ± 1.05	1.27 ± 0.04	1.81 ± 0.05	1.59 ± 0.04		
6	13.42 ± 1.81	19.13 ± 2.01	16.78 ± 1.30	1.28 ± 0.06	1.82 ± 0.06	1.53 ± 0.07		
5	13.31 ± 1.86	18.97 ± 1.95	16.64 ± 1.64	1.22 ± 0.02	1.75 ± 0.02	1.49 ± 0.03		
4	13.07 ± 1.37	18.63 ± 1.44	16.34 ± 1.77	1.18 ± 0.03	1.65 ± 0.05	1.56±0.02		
3	12.77 ± 1.52	18.20 ± 2.27	15.96 ± 1.81	1.16 ± 0.04	1.62 ± 0.05	1.46 ± 0.04		
2	12.48 ± 1.65	17.79 ± 1.96	15.60 ± 1.47	1.13 ± 0.02	1.59 ± 0.08	1.43 ± 0.05		
1	12.26 ± 1.70	17.47 ± 1.42	15.32 ± 1.63	1.11 ± 0.05	1.53 ± 0.06	1.41 ± 0.06		

Table 3: Predicted Dose Rates and HR Values Due to NO, Inhalation at the Various Floors in a Typical 16-Storey Slab Block.

		HR for NO ₂ (Dimensionless)					
Point Block			Slab Block				
Floor	New born	Children (1 yr and under)	Children (8-10 yr)	New born	Children (1 yr and under)	Children (8-10 yr)	
Low floor	0.90 ± 0.02	1.29 ± 0.04	1.10 ± 0.01	1.14 ± 0.04	1.62 ± 0.03	1.44 ± 0.05	
Mid floor	0.98 ± 0.02	1.37 ± 0.03	1.20 ± 0.02	1.21 ± 0.04	1.73 ± 0.02	1.52± 0.04	
High floor	0.83 ± 0.03	1.18 ± 0.02	1.04 ± 0.03	1.04 ± 0.03	1.49 ± 0.04	1.30 ± 0.03	
HR _{mid floor} /HR _{high floor}	1.16	1.15	1.24	1.15	1.16	1.17	
HR _{low floor} /HR _{high floor}	1.09	1.06	1.13	1.10	1.08	1.11	

Table 4: Predicted HR Values at the Different Floors of the 22-Storey Point Block and 16-Storey Slab Block.

Weekly mean indoor NO₂ concentration =

$$74.057 + 13.042e^{-0.5 \left[\frac{H-16.836}{8.207}\right]^2} - 0.195H$$

(µg/m³) (r² = 0.91) (2)

Where H represents the storey in meters as measured from ground floor.

Comparison of predicted health risk (hr) results in buildings: The predicted potential health risk (HR) values of children living in a typical 22-storey point block and a 16-storey slab block are shown in Table 2-4. For both the blocks, the health risk analysis indicated that children living at the mid floors of the buildings had the highest health risk in contracting respiratory symptoms for all age categories: infants, children (1 year and below) and children (8-10 years) compared to the high (lowest) and low floors (second highest) due to NO, inhalation. This was expected since the highest concentration of to NO, concentration occurred at the mid floors of the buildings. In a floor, new born infants had the least potential health risk to respiratory symptoms which could be due the passive immunity obtained from their mothers whilst children (1 year and under) had the highest potential health risk to respiratory symptoms. The reason might be these children's passive immunity fall during this age period and are developing their very own immunity against respiratory symptoms. Children (8-10 years) had the their potential health risk to respiratory symptoms in between the other two age groups as these children could have developed more immunity against respiratory symptoms compared to the children (1 year and under) but less immunity compared to infants. For the point block, the mean overall mean HR value for NO₂ is 1.06 ± 0.18 whereas for the slab block, the meal overall HR value for NO₂ is 1.35 ± 0.21 . Based on the mean overall HR values, children living in a slab block has about 1.27 times more risk in contracting a respiratory symptom due to NO, inhalation compared to those living in a point block.

Conclusion

The study shows children residing at the mid floors of the buildings had the highest health risk regardless of their age. In a typical floor, new born infants had the least potential health risk to respiratory symptoms which could be due the passive immunity obtained from their mothers whilst children (1 year and under) had the highest potential health risk to respiratory symptoms. The reason might be these children's passive immunity fall during this age period and are developing their very own immunity against respiratory symptoms. Children (8-10 years) had the their potential health risk to respiratory symptoms in between the other two age groups as these children could have developed more immunity against respiratory symptoms compared to the children (1 year and under) but less immunity compared to infants. Based on the mean overall HR values, children living in a slab block has about 1.27 times more risk in contracting a respiratory symptoms due to NO, inhalation compared to those living in a point block. Hence in terms of health concern, the point block is of a better design compared to the slab block. It is recommended the point block design is adopted for future housing projects located very close to major roads or expressways since the point block design pose lesser potential health risk in terms of contracting respiratory symptoms compared to the slab block design. To house more residents, taller point block designs could be considered. Other measures to mitigate NO, exposure to children is to introduce more free air passages like intermediate roof garden close to the mid and lower floors so as to suppress any NO₂ peaks at the mid floors.

Acknowledgement

I wish to express my deepest gratitude and acknowledgement to World Future

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Foundation (WFF) especially to Dr Feng Lun and the dedicated staff whose kind and generous support has made this paper possible. WFF is the first philanthropic foundation in Singapore funded by entrepreneurs from mainland China, and is professionally managed by an international team. WFF is dedicated to promote research on environmental protection and sustainability, especially focusing on the development models of future cities.

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