LINKING INFANT LOCOMOTION DYNAMICS WITH FLOOR DUST RESUSPENSION AND EXPOSURE

by

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To my parents and brother.

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ABSTRACT

Infant exposure to the microbial and allergenic content of indoor floor dust has been shown to play a significant role in both the development of, and protection against, allergies and asthma later in life. Resuspension of floor dust during infant locomotion induces a vertical transport of particles to the breathing zone, leading to inhalation exposure to a concentrated cloud of coarse (> 1μm) and fine (≤ 1μm) particles. Resuspension, and subsequent exposure, during periods of active infant locomotion is likely influenced by gait parameters. This dependence has been little explored to date and may play a significant role in floor dust resuspension and exposure associated with forms of locomotion specific to infants. This study explores associations between infant locomotion dynamics and floor dust resuspension and exposure in the indoor environment. Infant gait parameters for walking and physiological characteristics expected to influence dust resuspension and exposure were identified, including: contact frequency (steps min^{-1}), contact area per step (m^2), locomotion speed (m s^{-1}), breathing zone height (cm), and time-resolved locomotion profiles. Gait parameter datasets for standard gait experiments were collected for infants in three age groups: 12, 15, and 19 months-old (m/o). The gait parameters were integrated with an indoor dust resuspension model through a Monte Carlo framework to predict how age-dependent variations in locomotion affect the resuspension mass emission rate (mg h^{-1}) for five particle size fractions from 0.3 to 10 μm. Eddy diffusivity coefficients (m^2 s^{-1}) were estimated for each age group and used in a particle transport model to determine the vertical particle concentration profile above the floor.

Probability density functions of contact frequency, contact area, locomotion speed, breathing zone height, and size-resolved resuspension mass emission rates were determined for infants in each group. Infant standard gait contact frequencies were generally in the range of 100 to 300 steps min^{-1} and increased with age, with median values of 186 steps min^{-1} for 12 m/o, 207 steps min^{-1} for 15 m/o, and 246.2 steps min^{-1} for 19 m/o infants. Similarly, locomotion speed increased with age, from 67.3 cm s^{-1} at 12 m/o to 118.83 cm s^{-1} at 19 m/o, as did the breathing zone height, which varied between 60 and 85 cm. Resuspension mass emission rates increased with both infant age and particle size. A 19 m/o infant will resuspend comparably more particles from the same indoor settled dust deposit compared to a 15 m/o or 12 m/o infant. Age-dependent variations in the resuspension mass emission rate and eddy diffusivity coefficient drove changes in the vertical

particle concentration profile within the resuspended particle cloud. For all particle size fractions, there is an average of a 6% increase in the resuspended particle concentration at a height of 1 m from the floor for a 19 m/o compared to a 12 m/o infant. Time-resolved locomotion profiles were obtained for infants in natural gait during free play establish the transient nature of walking-induced particle resuspension and associated exposures for infants, with variable periods of active locomotion, no motion, and impulsive falls. This study demonstrates that floor dust resuspension and exposure can be influenced by the nature of infant locomotion patterns, which vary with age and are distinctly different from those for adults.

1. INTRODUCTION

Early life inhalation exposure to the biological and chemical components of indoor settled dust has been shown to contribute to the risk of asthma and allergies later in life [1]. Exposure to floor dust is of importance for infants and young children because they spend a majority of their time indoors and are in close proximity to the floor while crawling, walking, and playing [1]. Floor dust is composed of abiotic particles, bacteria, fungi, pollen, mite and animal allergens, and particle-bound semi-volatile organic compounds, such as phthalates [79], phenols, PFAS and organophosphates [2, 83-88]. Although a number of floor dust components have been shown to increase the risk of developing conditions like asthma, other studies have shown that exposure to microorganisms and allergens in floor dust can improve immunity and lessen sensitivity to allergies [3, 77]. Early life exposure to diverse groups of microorganisms can play a role in improving immunity against asthma [4]. Inhalation through resuspended airborne bioaerosols, hand to mouth contact and dermal exposure are three main potential exposure pathways in infants [23, 78]. Multiple studies in indoor environments like homes and daycare centers have been conducted to link specific floor dust and airborne viral, fungal and bacterial communities and composition to asthma and allergies in children [73-80]. These have shown that seasonal and geographical variations is a factor affecting the abundance and composition in airborne microbes.

To better understand the role of indoor floor dust in affecting infant health, physical processes leading to and affecting inhalation exposure must be studied in detail. This will help provide more accurate estimates of exposure to contaminants. Among the different mechanisms by which infants can be exposed to particles indoors, resuspension of floor dust plays an important role since it can be the most significant source for inhalation exposure to coarse particles [5]. When a person walks on a dust laden floor, they stir-up, or resuspend, settled particles, a fraction of which are transported to the breathing zone due to the buoyant human thermal plume and bulk airflow in an indoor space.

Indoor particle resuspension has been quantified using material balance models in order to predict indoor particle concentrations [6]. Previously, resuspension studies have expressed resuspension in terms of the resuspension emission rate, resuspension rate coefficient, and the resuspension fraction [6]. Most resuspension studies measure particle concentrations at the breathing zone height of a typical adult (1 to 1.5 m) to evaluate inhalation exposure [7]. Resuspended particle concentrations have been shown to be dependent on various parameters, including the surface concentration of particles, flooring type, activity type and intensity, walking style, ventilation configuration, and relative humidity [6].

Light occupant activities such as walking can increase the mass concentration of airborne super micron particles by 100% [71]. Several studies have characterized particle resuspension considering various indoor activities [5, 6, 8] investigated particle resuspension from a floor surface by mimicking walking. Their results revealed that air swirl created by walking has discernable impact on the particle resuspension rate. Salimifard et al. (2017) studied the effect of relative humidity and air swirl velocity variations on resuspension of biological particles from indoor surfaces [8]. Their results showed that resuspension rates of dust mite particles strongly depend on relative humidity, suggesting indoor humidity is important in determining particle resuspension rates. The experiments also found a notable effect of air swirl velocity on the resuspension rates of bacterial spore particles with increases over two orders of magnitude with the presence of a small swirl velocity of 0.3 cm/s near the surface.

Tian et al. (2014) studied the impact of floor type, relative humidity, and surface loading on resuspension [5] and found that the difference in resuspension caused by flooring type is significant for coarse particles (3.0–10 µm) carpets which were associated with 2–4 times higher resuspended concentration in comparison with hard floorings. They also found higher surface dust loading resulted in higher dust emission rates for all experimental conditions and significantly lower resuspension fractions under the 70% RH for hardwood floors among all their particle size ranges, compared to carpets. The study by Khare and Marr (2015) evaluated the vertical gradient in concentrations of resuspended viruses using a turbulence transport model for adults walking [7] and found differences in vertical concentration gradients from the floor level, resulting in implications for different exposure levels in people of varying heights. Researchers in [18], studied resuspension rates from human activity under various environmental conditions of 0.8–10µm particles with resuspension rates ranging from 10^{-5} to 10^{-2} h^{-1}. They found person-to-person variability in walking, which can be attributed to walking pace, walking style, and type of shoe, and that “heavy and fast” walking resuspended more particles than less active walking given the same experimental conditions. Also, similar to [5], the hard floor was found to be associated with the lower particle resuspension rates compared to the other types. The study in [70] estimated source strength for PM10 is 2.4 mg $min^{-1}$for different types of human activities like sitting, low and high intensity walking. Vacuum cleaning was also shown to increase the residence time (>19 days) of the particles in the living room [6, 70].

The nature of airflow around a human body during locomotion can also affect floor dust resuspension. Variations in airflow can be caused by the buoyant thermal plume generated by the human body [13, 14]. The thermal plume and turbulence caused by locomotion can affect the transport of particles to the breathing zone; it is expected that both will be influenced by infant age and locomotion style. Walking induces the production of vortex regions surrounding the body, which can affect particle concentrations in this region [15]. Evaluation of wake formation during locomotion have been done computationally and experimentally [16]. Computational analyses have been performed by modelling moving manikins using computational fluid dynamics (CFD) simulations and estimating particle concentrations around the body [15, 17]. Such studies have identified the dependence of resuspended particle concentrations on locomotion velocity. In Tao et al. (2017) it is shown that for the same manikin, a slower velocity leads to greater breathing zone concentrations of resuspended particles and vice versa. However, it has also been previously shown that higher walking velocities lead to higher resuspension rates [18].

Overall, the intensity and type of locomotion can affect multiple factors that affect resuspension, from differences in foot contact with the floor to the changes in airflow and turbulence in the air around the moving person. The material balance model presented in Tian et al. (2014) singles out two important gait parameters: the foot contact area and the contact frequency (steps per unit time) [5], making the connection explicit between locomotion and resuspension.

To investigate the influence of infant locomotion parameters on particle resuspension, gait parameters for infants must be studied. Infant locomotion parameters have been studied extensively by researchers and psychologists as a means to determine overall infant development and interactions. Infants by averaging between 500 and 1,500 walking steps per hour, may have taken 9,000 walking steps and traveled the length of 29 football fields, by the end of each day [71].

Contact frequency and parameters affecting it has been studied extensively for walking and crawling infants [9-12] and are shown to vary from 200 to 2500 steps h^{-1} for infants from ages 12 to 19 months old. This data, along with infant contact areas, have been previously obtained through pressure sensitive mat experiments [9]. Other infant gait parameters that show correlation to the contact frequency are proportion of time in motion, locomotion speed, and step length [9, 12]. Walking infants are shown to be in motion 33% of the time, whereas crawlers are in motion only 20% of the time, with walkers travelling three times the distance as crawlers [47]. Speed increases with walking experience and with overall infant age [47]. Infant locomotion parameters are shown to vary with age, locomotion experience and type, and external factors like presence of obstacles, toys, or caretakers [9]. Inclusion of detailed infant gait characteristics in a resuspension model can give better estimates of the resuspension emission rate. In order to evaluate infant exposure to resuspended floor dust, breathing zone concentrations during locomotion need to be determined.
Apart from these, other infant characteristics that could potentially play a role are infant head height, head angle, and trunk angle. These parameters, which have been measured previously, together can affect the breathing zone concentration and exposure for a locomoting infant, which additionally now could vary with infant age and development [19- 22].

Not much is known about the resuspended particle concentrations and size distributions of a walking or crawling infant. Being closer to the floor, they are possibly exposed to much higher concentrations. This has been shown in previous studies that have simulated crawling or walking infants or children. All studies have shown a two factor or higher increase in the concentrations at the infant breathing zone height due to the resuspension process during walking or crawling [56-61]. Researchers in [56] also showed that an infant receives much of their respiratory tract deposited dose of particles in their lower airways nearly four times greater respiratory tract deposited dose of resuspended fluorescent bioaerosols compared to an adult.

The objective of this study is to obtain relevant infant locomotion parameters to determine how they influence particle resuspension emission rates and inhalation exposure. Better assessments of locomotion parameters to resuspended floor dust can help shed light on the resulting infant breathing zone concentrations and exposure that are linked to asthma, allergic conditions, and respiratory disorders later in life.

2. RESUSPENSION AND LOCOMOTION PARAMETERS

2.1 Particle Resuspension Parameters

Particle resuspension and subsequent exposure is primarily affected by two sets of dynamics: near-surface dynamics and bulk airflow dynamics. Locomotion affects both dynamics due to the constant contact of the feet (for walking) or both hands and feet (for crawling) with the floor, as well as the turbulent airflow created around the body due to the movement of limbs while walking or crawling. Multiple studies have focused on tracking the migration of carpet dust into the air due to human activity induced resuspension, a large part of this human activity being locomotion. For infants, locomotion can include walking, crawling, movement during playing, and falling.

Indoor dust disturbing activities can increase particle concentrations by several orders of magnitude when compared to background levels [5, 24]. Research in [25] has showed that indoor activities such as walking, vacuum cleaning, and sitting on upholstered furniture cause the resuspension of particles from surfaces. Multiple previous studies have reported various resuspension parameters to quantify resuspension due different types of indoor activity. Most resuspended were coarse particles. Mechanical movements such as walking and vacuum cleaning emit up to 10^8 particles per minute, five orders of magnitude lower than the emission from frying or burning candle/incense [5]. In an indoor environment, resuspension can be the most significant source for inhalation exposure to coarse particles that have higher mass-based concentrations than number-based. Resuspension fractions and resuspension rates are most commonly used terms to quantitatively explain resuspension. Resuspension rate coefficients for one adult walking for the size range PM0.8 – 10 were found to range from 10^{-5} - 10^{-2} h^{-1}. Since stroke frequency and number of people performing the activity are accounted for, resuspension fraction can be easily used for many types of repetitive activity, e.g., walking, dusting, vacuum cleaning [5].

Most resuspension studies have experimental chambers or test rooms that have a fan to ensure that the room air is well-mixed. This well-mixed condition results in near-uniform resuspended particle concentrations throughout the room and negligible vertical concentration gradients. However, many indoor environments, such as homes and childcare centers, have poor ventilation and may not follow this well-mixed assumption.

Previous experiments have been performed to test the effect of switching the ceiling fan on and off on vertical variations in particle concentrations. They found that with the ceiling fan operating, there did not seem to be a difference in resuspended particle size distributions by height [26]. The air motion induced by the fan evenly distributed particles of all diameters vertically in the room. When the ceiling fan was off, a particle concentration difference as a function of height (concentration gradient) and particle diameter existed because a forced vertical air movement was not present. This concentration difference increased as particle diameters became larger because the importance of gravitational settling increased as well as turbulent diffusion.

Our study assumes a non-mixed condition in an attempt to model resuspension in poorly ventilated indoor spaces and hence, focuses on a vertical gradient in concentrations of resuspended particles formed due to the turbulence created by infants while walking. This gradient would result in higher concentrations near the floor, resulting in greater resuspended particle exposures for infants, them being shorter and therefore, closer to the floor than adults.

Many studies have shown that particle detachment and resuspension depend on many factors, including: the airflow velocity, relative humidity, particle diameter, airflow turbulence intensity, substrate acceleration, and electrostatic charge. The turbulence created by a moving body in the air causes an upward vertical motion of the particles entrained into the air [27]. However, for the particles to enter the air, surface and contact forces play a major role.

2.2 Locomotion Parameters

Most infant locomotion studies usually have experiments and observations conducted in a laboratory or homes, depending on the experimental needs. In a laboratory, they are done usually in a large playroom, sometimes filled with toys or obstacles and mostly with the mother or caregiver present.

Depending on the kind of locomotion we want to look at, two types of measures can be taken: standard gait and natural gait measures [9]. Standard gait measures are collected when infants move over a pressure-sensitive mat like GAITRite or Protokinetic Walkway (GAITRite© or ProtoKinetics©) that recorded the timing and placement of steps as the infant is made to walk in a straight-path. Gait measures like contact frequency, locomotion speed, step length, step width, and locomotion distances can be recorded.

In natural gait tasks or sessions, also called free play tasks, infants are not made to walk or crawl and are free to move as they like and are not made to walk only on a pressure sensitive mat. However, a pressure sensitive mat could be present and can still record locomotion data, if the infant happened to move or play over it [35]. There are also multiple cameras that video record each infant's task, which then can be processed and if needed, video coded by multiple scorers using Datavyu [9-12, 35. 44]. Video coding involves coders looking at the processed video of the infant task and scoring the type of activity against time. This results in infant activities assigned to times within the whole task's time period and is very useful in looking at natural infant behavior. Such information is especially useful and is usually reported for free play tasks that closely represents real infant motion.

The biggest difference between standard gait and natural gait measurements is the tendency of walking infants to move in curved paths instead of straight. Another difference is in infant locomotion performance. For standard gait tasks, infants are made to walk in a straight line until they walk from start to finish over the pressure sensitive mat and represents somewhat of a best performance scenario [9]. Infants, especially when learning to walk, can fall or stall multiple times while walking and it would usually not be in a straight path [35]. Therefore, standard gait measures should be taken as best performance scenarios and natural gait measures paint more of a real picture of infant locomotion.

In order to connect infant locomotion parameters to resuspension in this study, we use standard gait recorded parameters for those parameters that are part of the mathematical model of resuspension. This ensures uniformity in the analysis and gives a rough upper threshold in the resuspended particle emissions and concentrations. However, in the last portion of our analysis, we aim to look at case studies of real infants' behavior with respect to locomotion and use video coded data from free play tasks. Such analysis would help us look at the realistic proportion of infant locomotion values.

Standard gait was shown to improve with infant age and locomotion experience, validating this as a factor of infant development [9, 35]. The parameters and their dependence on infant ages helps in categorizing data and shows dependence of resuspension on infant age groups. Locomotion data obtained from NYU's Infant Action Lab is categorized into three age groups: 12, 15, and 19 months old (m/o).

2.3 Connecting Infant Locomotion and Resuspension Parameters

For this study, infant locomotion parameters that affect the resuspension process and factors affecting resuspension were identified. A comprehensive list of parameters and their respective details are presented in Tables 2-1 and 2-2. We can categorize the locomotion parameters as contact parameters that affect surface forces during resuspension and non-contact parameters that affect the airflow dynamics during the resuspension process. This is done to look at how each locomotion parameter can affect specific mechanisms that play a role in particle resuspension. Contact parameters include contact frequency, contact area (infant foot area), rate of fall, contact pressure, and contact impulse and non-contact locomotion parameters include: infant locomotion speed.

These parameters along with their interaction to the floor surface factors like surface type and surface roughness affect surface dynamics in resuspension. Particle resuspension is closely dependent on the shape and size of the particle and the nature of the contact of the particle with the flooring and the flooring type [5]. This is said to be because of the differences in the adhesion force (surface energy) and the nature of the micro and macroscale roughness that are present. There is also the possibility of the presence of a downward electrostatic force that could significantly alter the nature of adhesion and resuspension of particles from flooring. Relative humidity affects the water film on any surface, which consequently affects particle adhesion to the surface and may make particles more difficult to remove [28].

Infant contact locomotion parameters can affect airflow around the foot, turbulence intensities, and vibration forces, all of which affect resuspension. All of these factors would vary with the kind of infant activity like walking, crawling, and falling. The model in [29] studied particle adhesion to the floor, and the airflow generated by the stepping down and up of the foot during the gait cycle. They found floor and particle roughness, foot size, background flow velocity, and human activity velocity to affect the particle resuspension rate in an indoor environment. Earlier efforts hypothesized that during the gait cycle, high speed airflow is generated at the floor level and leads to particle resuspension [30].

Past research on turbulence intensities [27] has shown turbulence in the form of large eddies is common in the indoor environment; for example, walking generates bursts of air beneath the feet which cause highly oscillatory velocities in the region close to the surface [31]. As turbulent eddies carried by the bulk flow dissipate into smaller eddies, the smaller eddies penetrate deep into the boundary layer, transporting the kinetic energy of turbulence to the particles at the surface, giving particles enough energy to detach from the surface [32, 33].

Another factor that has been associated with resuspension is vibration. The infant locomotion parameters contact pressure and contact impulse can affect the surface vibration magnitude. A previous study that looked at resuspension from mattresses, showed vibrations and increased movement caused an increase in resuspension [69]. Here, peak surface vibrations were generally higher than 0.1 g in magnitude. However, previously reported walking-induced peak floor vibrations were much lower, less than 0.1 g, and frequencies of 4 to 20 Hz, [31]. When surface frequencies fall below the natural frequency of particles, i.e., 107 Hz for a 10 μm particle, identified in [34], such low frequencies like those shown by footfalls may not be have explicit effects on resuspension due to footfalls on the floor, but may still be a initiator or driver of particle detachment from the surface. Studies show that low frequency surface vibrations, including those caused by footfalls, had little impact on particle resuspension [8, 31, 34].

A moving body creates turbulence in the surrounding air and results in the formation of a wake which causes the detached particles to move upward [15]. Human activity has a significant influence on indoor airflow patterns by producing distinct wake flow regions and unsteady vortex shedding over the body. When the particles have moved into the wake they gradually propagate to higher regions as the airflow produced by legs and flow upwards into the back [27]. Figure 1 shows a schematic connecting resuspension, an infant walking and airflow resulting in wake and vertical particle transport to the infant BZ.

Table 2-1 connects locomotion and infant physiological characteristics like infant breathing zone height to infant inhalation exposure. Conventionally, the breathing zone is defined as the zone within a 0.3 m radius of a person's nose and mouth, and it has been generally assumed that a contaminant in the breathing zone is homogeneous and its concentration is equivalent to the concentration inhaled by the person [36]. For this analysis, we do not require a 3-dimensional zone, rather a vertical height from the floor that represents the breathing zone height.

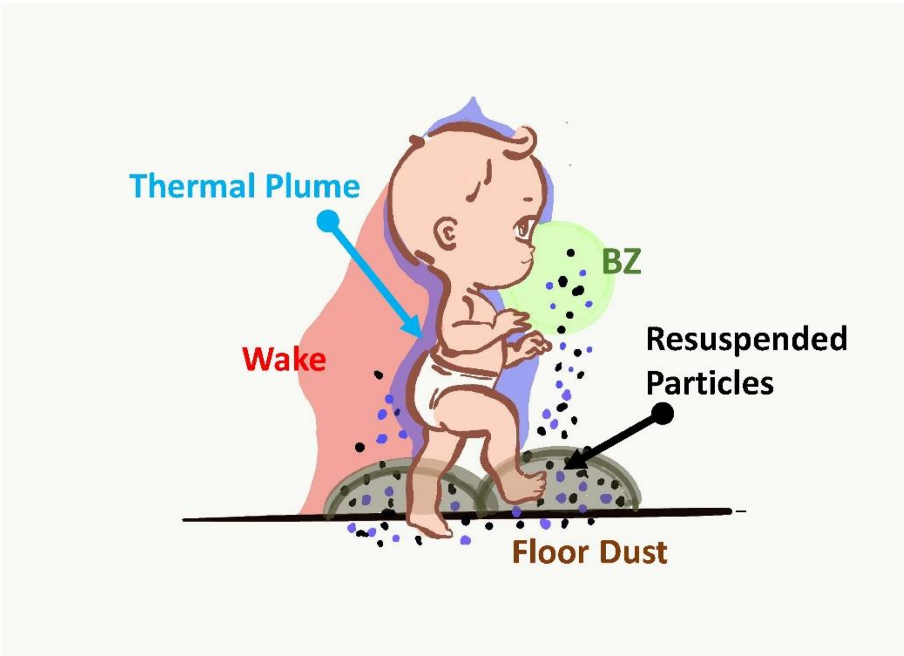


Figure 1. Locomotion, resuspension, and airflow.

Breathing zone height is important for infant exposure to the resuspended particles. Most indoor air resuspension studies use particle monitors roughly at the breathing zone level to estimate emissions [5, 6, 18]. For infants, this parameter depends on infant heights, which in turn depends on infant age groups. During a locomotion period, it is shown that crawling infants, for a majority of time, look to the floor. Infants learning to walk or crawl, in general, have more variations in breathing zone heights due to changing head angles and uncertainty in locomotion as they learn to move [11, 19, 20].

Using infant height and reported infant head circumference values by the CDC, we can estimate this parameter. This study emphasizes the vertical concentration gradient that is established during walking induced resuspension. Consequently, vertical heights closer to the floor have higher concentrations than farther away. Breathing zone heights that are different for adults and infants will, hence, result in higher breathing zone concentrations and exposure in infants.

Table 2-1. Relationships between infant locomotion parameters and floor dust resuspension.

Locomotion Parameters	Units	Description	Measurement Technique(s)	Selected References	Influencing Factors	Reported Values	Implications For Dust Resuspension
1. Contact frequency	[second^{-1}] (or) [minute^{-1}] (or) [hour^{-1}]	Number of contacts of infant limb per unit time.	1. GAITRite 2. Video data coding	Adolph, K. E. (2012), [9] Adolph, K. E. (2008) [65] Adolph, K. E. (1998), [64] Cole, W.G.	1. Locomotion type: *crawling or walking* 2. Age 3. Walking/crawling experience 4. External factors: *diapers; obstacles; presence of toys, caretaker; floor*	Crawlers: Less than 1000 steps per hour Walkers: Less than 3000 steps per hour	Contact frequency (f_s) in resuspension fraction and emission rate
2. Contact area	[meters^2]	Area of contact between infant limb and floor.	GAITRite	Adolph, K. E. (2012), [9]	1. Locomotion type: *crawling or walking* 2. Age 3. Body dimensions and development	Data could be obtained from GAITRite experiments. *(Published data not present)*	Contact area (A_s) in resuspension fraction and emission rate
3. Proportion of time in motion	[percent, %] (or) [fraction]	Time that the infant is engaged in locomotion-driven resuspension of dust.	Video data coding	Adolph, K. E. (2012), [9]	1. Locomotion type: *crawling or walking* 2. Age 3. Walking/crawling experience 4. External factors from ***'contact frequency'***	Crawlers: Less than 25% (or) 0.25 Walkers: Less than 50% (or) 0.5	1. Contact frequency (f_s) in resuspension fraction and emission rate

Table 2-1. continued.

4. Rate of fall	[$hour^{-1}$] (or) [number of falls/hour]	Number of falls per unit time. *Sudden dust resuspension event induced by fall.*	Video data coding	Adolph, K. E. (2012), [9]	1. Locomotion type: *Crawling or walking* 2. Age 3. Walking/crawling experience 4. External factors from ***'Contact frequency'***	<u>Crawlers</u>: Less than 25 falls per hour <u>Walkers</u>: Less than 50 falls per hour	
5. Velocity (or) Locomotion speed (or) Distance travelled per time	[meters/ hour]	Distance per unit time at which the infant is engaged in locomotion-driven resuspension of dust	1. GAITRite 2. Video data coding	Adolph, K. E. (2012), [9]	1. Locomotion type: *crawling or walking* 2. Age 3. Walking/crawling experience 4. External factors from ***'contact frequency'***	<u>Crawlers:</u> Less than 130 m/h <u>Walkers:</u> Less than 350 m/h	2. The total number (or) mass of floor dust that is resuspended (C_j) *(affects resuspension fraction,* $\mathbf{r_{aj}}$*)*
6. Step length	[cm]	Distance between steps during a resuspension event. *Applicable only to infants who can walk.*	GAITRite	Badaly, D. and Adolph, K.E., (2008), [12]	1. Locomotion type: *crawling or walking* 2. Age 3. Walking/crawling experience 4. External factors from ***'contact frequency'***	<u>For 14-month-old infants</u>: Range: 10 to 38 cm	

Table 2-1. continued.

7. Contact pressure	[Pascals, Pa] (or) [percent, %] if data is normalized	Pressure exerted by a step. *Contact of foot/limb with floor – contact force per contact area.*	GAITRite	GAITRite Manual Gaitrite.com	1. Locomotion type: *crawling or walking* 2. Age 3. Walking/crawling experience 4. External factors from ***'contact frequency'***	Data could be obtained from GAITRite experiments. *(Published data not present)*	The total number (or) mass of floor dust that is resuspended (C_j) *(affects resuspension fraction,* $\mathbf{r}_{aj}$*)*
8. Contact impulse	[Newton-second] (or) [Pa•m^{2}s]	Change in momentum of floor surface and floor dust deposit concentration due to contact with floor during locomotion.	GAITRite *Can be obtained from contact pressure, contact area, and contact time from step time.*	N/A	1. Locomotion type: *crawling or walking* 2. Age 3. Body dimensions and development 4. External factors: *Floor type*	Data could be obtained from GAITRite experiments. *(Published data not present)*	

Table 2-2. Relationships between infant parameters and infant inhalation to dust: breathing zone concentration and height.

Locomotion Parameters	Units	Description	Measurement Technique	Selected References	Influencing Factors	Reported Values	Implications for Infant Inhalation Exposure To Resuspended Dust
1. Head height (or) Infant Height	[cm]	Infant (head) height with respect to horizontal floor level.	Motion tracking sensor. *(Head mounted eye tracker)*	Kretch, Franchak, & Adolph, (2014), [19]	1. Locomotion type: *crawling or walking* 2. Age 5. Body dimensions and development	<u>Crawlers</u>: 33.94 cm <u>Walkers</u>: 68.78 cm	
2. Head angle (or) pitch	[degrees]	Infant head inclination with respect to horizontal level. *Crawling infants whose heads are more inclined to the floor could have greater exposure to resuspended particles.*	Head mounted eye tracker.	Franchak, Kretch, Soska, & Adolph, (2011), [20] Kretch, Franchak, & Adolph, (2014), [19]	1. Locomotion type: *crawling or walking* 2. Age 3. Body dimensions and development 4.	<u>Crawlers</u>: -60° to 20° <u>Walkers</u>: -30° to 20°	Infant breathing zone height, which affects exposure as there exists a vertical particle concentration gradient above the floor.
3. Trunk angle	[degrees]	Infant trunk inclination with respect to horizontal level. *Infants could have more exposure than adults due to their greater trunk angles as they bend forward*	Motion tracking sensors.	Yaguramaki, N. and Kimura, T., (2002), [21] Garciaguirre, J.S., Adolph, K.E. and Shrout, P.E., (2007), [22]	1. Locomotion type: *crawling or walking* 2. Age 3. Body dimensions and development 5.	<u>Maximum forward bent (stance)</u>: 98° (+/-) 9.51° <u>Max forward bent (swing)</u>: 96.93° (+/-) 10.55°	

Table 2-2. continued.

4. Velocity (or) Locomotion speed (or) Distance travelled per time	[meters/ hour]	Distance per unit time at which the infant is engaged in locomotion-driven resuspension of dust. *CFD simulation shows slower speeds lead to higher BZ particle concentrations.*	GAITRite Video data coding	Tao, Y., Inthavong, K. and Tu, J. (2016). [17] Goldasteh (2014) [16]	1. Locomotion type: *crawling or walking* 2. Age 3. Walking/crawling experience 5. External factors from ***'contact frequency'***	Crawlers: Less than 130 m/h Walkers: Less than 350 m/h	Particle concentrations (C_j) at infant breathing zone height, which affects exposure.
5. Proportion of time in motion	[percent, %] (or) [fraction]	Time that the infant is engaged in locomotion-driven resuspension of dust. *Longer locomotion period could result in greater BZ concentrations and extended exposure*	Video data coding.	Adolph, K. E. (2012), [9]	1. Locomotion type: *crawling or walking* 2. Age 3. Walking/crawling experience 5. External factors from ***'contact frequency'***	Crawlers: Less than 25% (or) 0.25 Walkers: Less than 50% (or) 0.5	

3. METHODS

3.1 Locomotion Parameters

Infant locomotion parameters, obtained from NYU, Contact Frequency and Contact Area distributions were required to be integrated into our model. We also obtained infant heights (required for Breathing Zone, BZ, heights) and infant locomotion speed as these are parameters useful for future infant resuspension and exposure modelling.

We obtained the large datasets foreach of the four parameters in each infant age group – 12 m/o, 15 m/o and 19 m/o infants as shown below:

Number of datapoints for all infant parameter distributions:

- 12 m/o infants: 131
- 15 m/o infants: 116
- 19 m/o infants: 125

Each sample of each infant age group can be explained by reliable distributions due to the large sample size. (n>100). All locomotion data obtained here are standard gait data, meaning, they were measured using a pressure sensitive carpet on which the infants are made to walk.

We assumed a foot contact area, A_S, of 0.01 m^2, from reported measured values for 2 y/o children in [45] as data is yet to be obtained from NYU. The contact area was obtained using foot dimension values measured using a 3D handheld scanner that scanned the plantar (the area under the foot) surface of the feet for different aged children, making them highly useful for this study. This is the most accurate previously reported values for the foot contact area parameter for this study, especially since the 2 y/o children are very close in age to our study's infant age group.

Contact frequency, f_S, was obtained from measurements at NYU's Infant Action Lab. For each of the three age groups, distributions were fitted using MATLAB's statistical toolbox to obtain a probability distribution curve for each of these age groups resulting in distribution curves for contact frequency for each infant age group.

3.2 Resuspension Fractions

For the modelling, we needed a useful measure of resuspension parameter from literature to obtain the source term or the emission rate term. Resuspension fraction values for the corresponding size ranges reported in [5] was used for the carpet type 'HD'. This was chosen since it closely mimics the locomotion induced resuspension process due to a human walking that we are attempting to model in our study. The methods in [5] use adult locomotion parameters like a fixed contact area and contact frequency in their material balance model to determine emission rate terms, however without accounting for the range of adult locomotion parameters. Since we use a probabilistic model, we can incorporate infant locomotion parameters to determine emission rate terms.

The study in [5] reported resuspension fraction values, for five particle size fractions: [0.4 - 0.5μm], [0.5 - 1 μm], [1 - 3μm], [3 - 5μm], [5 - 10μm]. From this data, we fit probability distributions (approximated to be normal distributions) over the range of each of the five resuspension fractions to obtain a distribution curve for resuspension fractions in these five particle size ranges.

It should be recognized that using such existing resuspension parameters, even with similarities in the resuspension process, can have uncertainties. These can be due to differences in measurement techniques. Since this study focused on adult locomotion, all concentration measurements to obtain resuspension fractions were made at approximate adult breathing zone height. Our study looks at infant locomotion and resuspension fractions would be inevitably dissimilar. However, since a consistent test mechanism and the dimensionless resuspension fractions were used instead of human participants, these helps eliminate the impact of varied walking style, improving experimental reproducibility, thus making it useful here.

Determining the Source Term

The source term, $S(z)$, is the link between resuspension and infant locomotion. For this study, the source term is given by the expression:

$$S_j = r_{aj} L_j A_S f_S \quad (1)$$

where,

r_{aj} is the resuspension fraction,

L_j is the floor dust loading, assumed to be the same as reported in [5]

A_S is the foot contact area,

f_S is the contact frequency in number of steps per time.

These parameters, their definitions and data sources are shown in Table 3-1. Change in floor surface loading with respect to time is small and hence, is taken to be a constant. The source term in Eqn (1) is an integration of both locomotion and resuspension processes, the primary objective of this work. Such an explicit connection has not known to be mathematically made in any previous work. Our overall modelling considerations are:

- Assume carpet type HD from study from the study Tian, Yilin, et al., 2014.
- Continuous walking happens for 90 seconds until steady state.
- All locomotion parameters used are standard gait data.
- No ventilation or mixing in the chamber.

Locomotion parameters for each infant age groups are best explained by distributions, shown in previous infant locomotion research and the resulting statistical measures denoting those distributions, instead of a single value, shown from previous infant studies. To integrate a group of values for each locomotion and resuspension parameters in order to obtain our output, i.e., the Source term using Eqn (1), we need probabilistic modelling. Here, we use Monte Carlo simulations to best achieve this.

Monte Carlo methods captures variations in parameters by using randomness which results in a distribution of possible outcomes, here, the Source term, S_j. In general, the first step is to explain each parameter using a probability distribution (by fitting a large dataset) and obtain a random value for that parameter. Next, using these random values as inputs, the output is computed using Eqn (1), and this process is done multiple times in order to get a range of outputs that denotes our possible set of outcomes. This range of outputs also follows a distribution, albeit different from the two inputs, since it is a random combination of input distributions.

Monte Carlo simulation was performed to integrate known distributions to obtain the source term distributions for an infant walking and also in our study, required for the transport model. Here, contact frequency and resuspension fractions are distributions and contact area are assumed to be a constant, but will be a distribution once we obtain enough data.

This was performed for each size fraction and age group and giving rise to 15 distributions of the source term. Since infant locomotion that depends on infant age cannot be sufficiently justified by a single value for a locomotion parameter, it is imperative to look at the corresponding range of Source terms obtained as Monte Carlo analysis output for an understanding of the variations and wide ranges presumably present in emissions due to resuspension by infant locomotion.

A schematic of the overall methods and modelling procedure is shown in Figure 2.

Table 3-1 Locomotion and resuspension parameters – descriptions and data source.

Resuspension Parameters	**Description, [units]**	**Definition**	**Data source**
r_{aj}	Resuspension fraction, [-]	Size resolved fraction of particles resuspended per unit foot contact area per unit time	Tian, Yilin, et al., 2014
f_S	Contact frequency, [h^{-1}]	Number of steps per unit time	NYU data
A_S	Contact area, [m^2]	Area of foot contact	NYU data
L_j	Floor surface loading, [mass m^{-2}]	Size resolved mass of particles per unit floor area	Tian, Yilin, et al., 2014
S_j	Resuspension emission rate, [mass h^{-1}]	Mass of particles emitted by resuspension per unit time	Not used in model
j	Particle size range, [um]	Particle size fraction or range	Found from modelling

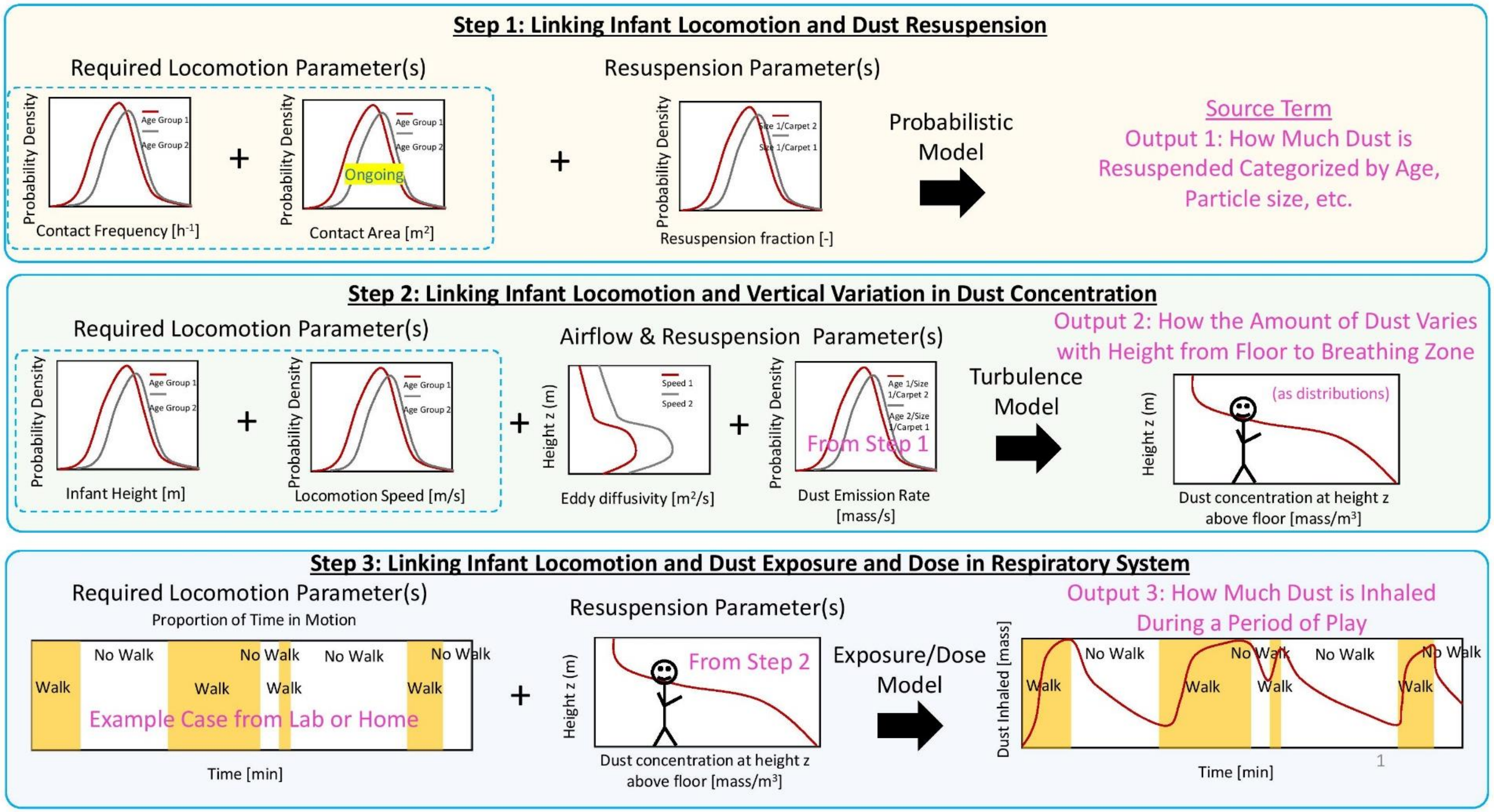


Figure 2. Methods overview.

3.3 Particle Transport Model

To relate infant locomotion parameters to particle resuspension and to emphasize the differences in exposure between infants and adults due to their heights, our methods for the particle transport model was based on modeling in [7, 37]. For incompressible fluid flows, the airborne particle concentration, *C*, in the vertical must satisfy the continuity equation using the Eulerian approach as shown below:

$$\frac{dC}{dt} + \frac{d}{dz}(w - v_s)C = D\frac{d^2C}{dz^2} + R(C) + S(z) \quad (2)$$

where w is the vertical advective velocity, D is the diffusion coefficient, $R(C)$ is the rate of particle generation by chemical reaction, $S(z)$ is the source term and v_s is the deposition velocity.

$$v_s = \frac{(\rho_p - \rho_f)gd^2}{18\mu} C_C \quad (3)$$

where ρ_p and ρ_f are densities of particle and air respectively, d is particle diameter, μ is air viscosity and C_C is the Cunningham slip correction factor.

The particle velocity is assumed to be the same as that of air from the drift-flux model (Chen et al., 2006). Here, R(C) and the diffusion term $D\frac{\partial^2 C}{\partial z^2}$ are ignored as there is no chemical reaction in this scenario and turbulent dispersion is much stronger than Brownian diffusion. The vertical velocity and particle concentration can be decomposed into their mean, $\overline{w}$ and $\bar{C}$, and fluctuating components, w′ and C′, respectively as shown:

$$\frac{dC}{dt} + \frac{d}{dz}(\overline{w} + w' - v_s)(\bar{C} + C') = S(z) \quad (4)$$

The closure problem generated by the time averaged term, $\overline{w'C'}$, can be overcome by using K-theory:

$$\overline{w'C'} = -k\frac{dC}{dz} \quad (5)$$

Where, k is the eddy diffusion coefficient. The final equation now becomes:

$$\frac{dC}{dt} = k\frac{d^2C}{dz^2} + \frac{dk}{dz}\frac{dC}{dz} - v_s\frac{dC}{dz} + S(z) \quad (6)$$

Using the equation for eddy diffusion coefficient, *k*:

$$k = |w'|L_l \quad (7)$$

where σ_w is the absolute value of fluctuating component of vertical air velocity and L_l is the mixing length. The time period for the locomotion was taken to be 90 seconds of turbulence and the arm movement to be primarily responsible for turbulent mixing, the mixing length was taken to be the height from the ground until the end of the infant arm.

3.3.1 Eddy Diffusion Coefficients: Extrapolation

For infants, we used extrapolated or scaled the eddy diffusion coefficient, k, profile with vertical height, z, of an adult walking using results in [7] since we were not able to make vertical velocity measurements and use Eqn (7)., for this. This comes very close to explaining the eddy diffusivity profile. Such profiles have a characteristic curve with k values peaking around the height of the mixing length (here, the end of the swing arm while walking) and reduces until individual's head above which turbulence dies out [7,43]. Such extrapolation methods have also been previously done to determine vertical variations of eddy diffusivity in previous studies in [7] and atmospheric turbulence studies [46].

Eddy diffusion coefficient for locomotion is assumed to be mainly dependent on:

1. Height of moving body, heights of infants or adults (affecting mixing length, Eqn (7))
2. Locomotion speed (affecting vertical air velocity)
3. Type of turbulence (e.g., walking, crawling etc.)

As the eddy diffusion coefficient depends on vertical height, each infant age group's median height was chosen to be a parameter affecting the characteristic eddy diffusion curve.

Using curves from the literature, the eddy diffusion coefficient profiles for each of the three age groups of infants were found after being scaled based on the ratio of adult to infant height. The maximum eddy diffusivity value of the characteristic curve, (say k1), along with its corresponding vertical location, (say h1), follow the ratio of heights of the two individuals (here, adult and infant), shown by the simple Eqn 8.

$$\frac{k1(known)}{k2(unknown)} = \frac{h1(known)}{h2(unknown)} = \frac{Adult\ height}{Infant\ median\ height} \tag{8}$$

Then, using the obtained maximum k values along with the corresponding vertical height, we use trial and error to curve fit a suitable cubic polynomial characteristic for each median infant height and hence, infant age group. This was done for the three infant age groups as they differ in median heights, resulting in vertical eddy diffusivity profiles for each age group of infants. The resulting equations obtained are:

The equations for each age group are shown in 9(a) to 9(f):

For a 12-month-old- infant,

$$For\ z < 1m,\ \ k = 0.2101z^3 - 0.4951z^2 + 0.3018z + 0.02054 \tag{9a}$$

$$For\ z > 1m,\ \ k = \frac{2.35 - z}{176.42} \tag{9b}$$

For a 15-month-old infant,

$$For\ z < 1m,\ \ k = 0.1891z^3 - 0.4459z^2 + 0.2653z + 0.0149 \tag{9c}$$

$$For\ z > 1m,\ \ k = \frac{2.35 - z}{93.29} \tag{9d}$$

For a 19-month-old infant,

$$For\ z < 1m,\ \ k = 0.2101z^3 - 0.4951z^2 + 0.2948z + 0.0165 \tag{9e}$$

$$For\ z > 1m,\ \ k = \frac{2.35 - z}{84} \tag{9f}$$

Eddy diffusion coefficient being also dependent on vertical velocities, we hypothesize, would also be affected by locomotion speed. For the purpose of this study, we have not included this in our modelling since further experiments would be best to verify the kind of dependence. Previous studies have shown faster movement causes higher air velocities that would potentially affect vertical air velocities [8, 15, 17]. An accurate dependence has never been established mathematically; however, such dependence would help in theoretically determining the eddy diffusion coefficient gradient profiles.

3.4 Solving the Transport Model

To discretize the transport equation, Eqn (6), a second order, Point Jacobi scheme was used and solved in MATLAB. The vertical space was divided into 22 nodes, space step of 0.11 m for a total height of 2.35 m (space step, Δz), same as assumed in [7], and a time step of 9×10^{-4} s (time step, Δt) was used for a total time of 90 s, shown in Figure 3. This space and time step were chosen to be small enough so that the numerical methods used, could converge and result in a low residual value at each vertical node. The total height worked well with this choice to give us accurate results. It is important to note that both space and time steps depend on the choice of total height and total time of the simulation.

For the core of the space, a central differencing scheme was used since both boundary conditions cannot be determined without ceiling and floor node results. At the floor and the ceiling nodes, a one-sided forward and backward differencing scheme was used since there is a fixed initial and boundary condition at both these nodes. The source term applies only to the first node (i=1) at the ground. This represents the foot contact and the resulting resuspended particles onto the air zone and acts as a bridge between the contact-locomotion-resuspension process and the vertical transport process of the resulting resuspended particles in the air. The numerical method discretized equations are shown in supplementary Eqns (S1), (S2) and (S3) in the Appendix.

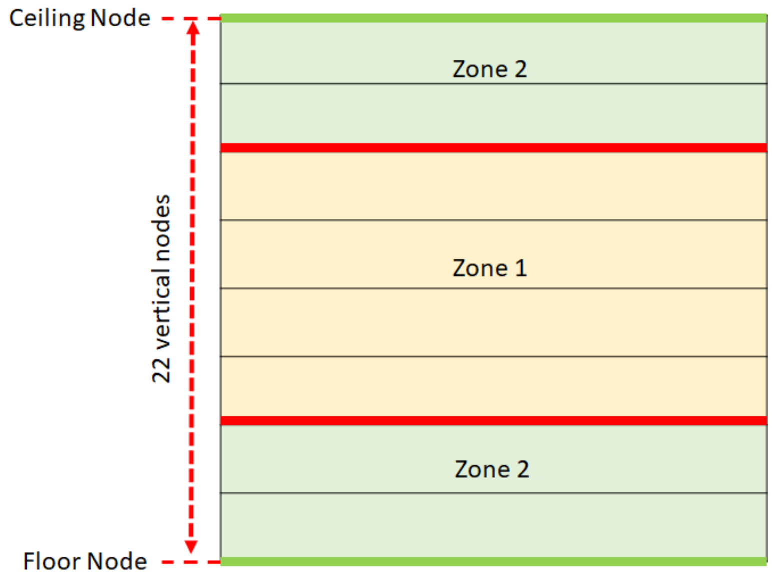


Figure 3. Discretization of the particle transport model.

4. RESULTS AND DISCUSSION

All data used was standard gait data where the child is made to walk on a gait carpet and parameters are recorded using the gait mat or video recording. This usually gives a standard for the best performance metric for these locomotion variables and also ensures uniformity in the analysis.

4.1 Locomotion Parameters

Table 4-1 shows all the statistical parameters for the infant locomotion parameters considered for our analysis.

Table 4-1 Locomotion parameter distribution statistics.

Walking Experience, [months]				
Infant Age group	Median	Range	Mean	Standard Deviation
12 m/o	1.41	(0.1 – 5.5)	1.47	1.01
15 m/o	2.55	(0.2 – 5.5)	2.65	1.34
19 m/o	6.11	(1.9 – 9.5)	6.12	1.71
Locomotion Speed, [cm s^{-1}]				
Infant Age group	Median	Range	Mean	Standard Deviation
12 m/o	67.33	(6.0 – 134.0)	71.49	25.06
15 m/o	89.41	(39.4 – 155.1)	87.16	22.51
19 m/o	118.81	(30.0 – 220.7)	117.77	37.53
Contact Frequency, f_S, [steps s^{-1}]				
Infant Age group	Median	Range	Mean	Standard Deviation
12 m/o	3.11	(1.7 – 4.7)	3.17	0.58
15 m/o	3.46	(2.2 – 5.7)	3.51	0.61
19 m/o	4.10	(2.4 – 5.3)	4.04	0.61
Breathing Zone (BZ) height, [cm]				
Infant Age group	Median	Range	Mean	Standard Deviation
12 m/o	68.30	(61.8 – 75.2)	68.78	2.73
15 m/o	71.41	(63.8 – 77.9)	70.88	2.71
19 m/o	74.87	(68.5 – 83.1)	74.66	2.96

4.1.1 Walking Experience

Figure 4. shows distributions of walking experience in months. Locomotion experience is determined from parental reports based on the first day that infants traveled 10 feet across a room without stopping [9]. We see an increase in the median values from Table 4-1 and Figure 4., with 19 m/o infants having the highest median at 6.11 months of walking. We also see an increase in the mean, as well as, a general increase in the range of walking experience values from 12 to 19 months old, 19 m/o infants having walked for much longer times since the onset of walking. The walking experiences of 12 m/o and 15 m/o show a significant overlap in the range of values, unlike the 19 m/o infant's walking experience range. This overlap has been observed previously in 12 m/o and 14 m/o infants reported in [9].

Infant locomotion experience or walking experience, in this case, has shown to be correlated to other locomotion parameters and infant age (or infant test age). Such a correlation establishes the dependence and importance of having certain months of walking to be able to walk well, meaning, walking with higher velocities, step length and lower step widths. This can be seen from previous studies in 19 m/o infants [9]. This is also shown in studies for infant ages between 12 to 19 months old, similar to our infant age groups, that show an extremely high correlation (r=0.86) between walking experience and infant test age. Walking experience has also shown to be significantly correlated ($r > 0.65$) with measures of functional infant locomotion skill such as walking speed, proportion of time in motion, contact frequency and step length [9].

4.1.2 Contact Frequency

In their gait mat studies, NYU' lab recorded Contact frequency, f_S, as Cadence in the units of steps per second. Figure 5., shows contact frequency distributions for each of the three infant age groups. Table 4-1 shows the median values to increase from 1.41 to 6.11 steps s^{-1}, along with an overall higher average contact frequency in 19-month-olds than in 12-month-old infants. We also see an increase in ranges of contact frequency values, with up to 5.3 steps s^{-1} shown in 19 m/o infants.

This trend with infant age is attributed to the high correlation between infant age, walking experience and contact frequency, reported in previous studies [9]. These parameters can successfully explain the differences in contact frequency distribution for different age groups in Figure 5.

Contact frequency, unlike other gait parameters, has been measured in various units of steps per time. Making a comparison of our data to previous studies is not straightforward. However, a good approximation for comparison purposes can be made by looking at previously reported proportion of time in motion data. Studies have shown that infants in the age group of 12 to 19 months old, similar to our study, walk for 33% of the time on average, for test observation periods of 15 to 60 minutes long [47].

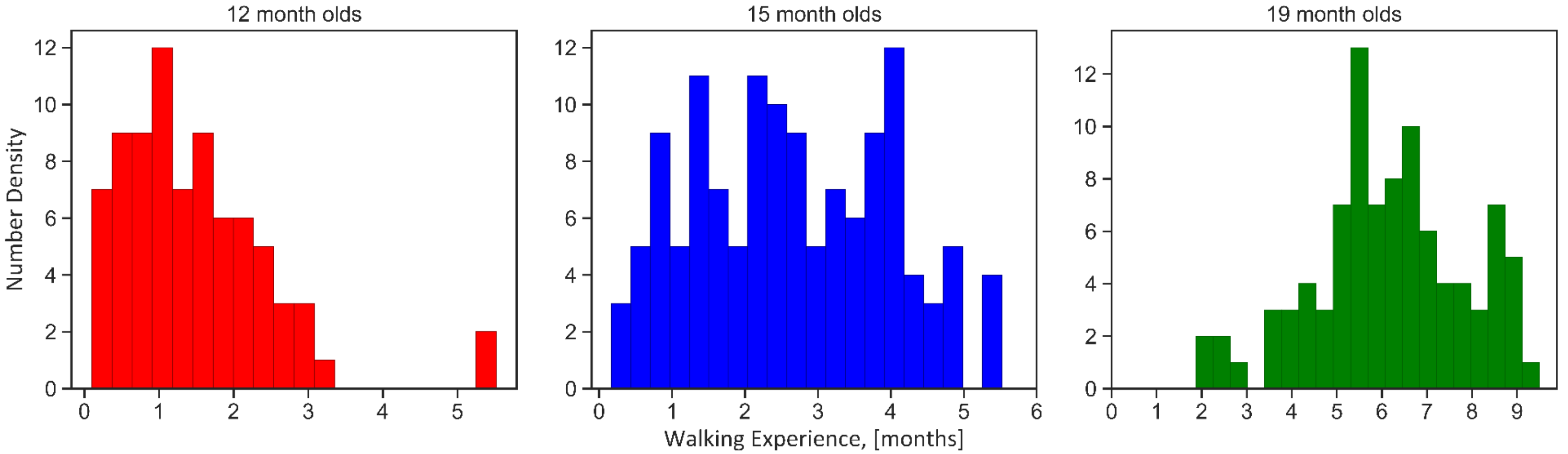


Figure 4. Walking experience distributions in infants of ages 12 months, 15 months, and 19 months old.

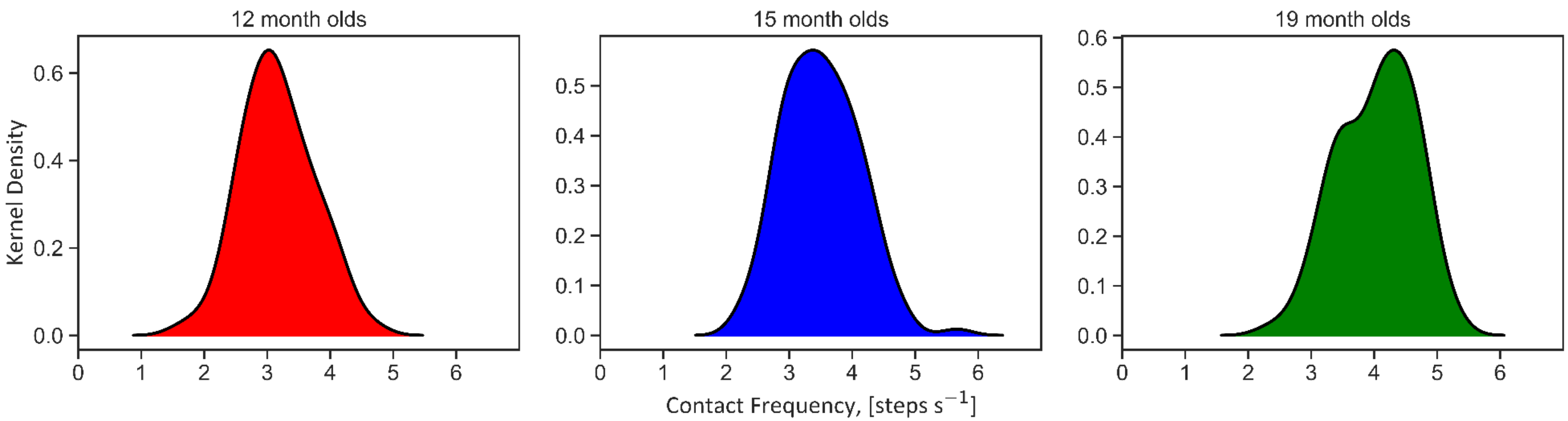


Figure 5. Contact frequency distributions in infants of ages 12 months, 15 months, and 19 months old.

Assuming the infant walks for a period of 15 minutes in length for 33% of the time, contact frequencies from our data, will have median contact frequencies of 923.7 steps h^{-1} for 12 m/o, 1027.6 steps h^{-1} for 15 m/o, and 1217.7 steps h^{-1} for 19 m/o infants. These values can now be compared with previous locomotion studies. Contact frequencies in the range of 200 to ~ 2500 steps h^{-1} are shown for infants of ages 13 to 19 months old [48]. Novice walkers are also shown to take more steps (mean = 1456 steps h^{-1}) than experienced crawlers (mean = 636 steps h^{-1}) [47]. For 12 m/o infants, studies have shown contact frequencies up to ~ 2500 steps h^{-1} and 15-month-old infants have shown a range of 100 to 7000 steps h^{-1} during free play [35].

Attempting to compare our data to values in literature, using the values adjusted with 33% of motion time in walking infants, we see our values do fall within the ranges of data from these previous studies. Most previous studies agree on steps h^{-1} as a uniform measurement; however, we also see high variations in the observation time periods in different studies. Each locomotion period for infants of these ages are in orders of minutes or seconds and a direct conversion from the unit of steps s^{-1} to steps h^{-1}, for comparison purposes, can overestimate or underestimate the actual infant locomotion skill. For example, a previous study reported that a 14 m/o infant is shown to have an average of 190 steps min^{-1} in a laboratory setting [49]. Using our average values for a 15 m/o infant for comparison, we see that directly converting the values of 3.51 steps s^{-1} to the time scale of min^{-1}, we get 210.6 steps min^{-1}, which is in agreement. Here, using the adjustment with proportion of time in motion (33%), done previously for the hour timescale, will give us an estimate that does not agree with the reported value.

In multiple previous studies aimed at measuring Cadence in adults, average values close to 71 steps min^{-1} for men and 69 steps min^{-1} for women was reported during a continuous period walking [50]. These values are lower than infant contact frequencies, especially since adults would have to take lesser steps to move the same distance due to greater speeds.

4.1.3 Locomotion Speed

Figure 6. shows the distributions of infant locomotion speed in cm s^{-1}
The median values increase from 67.3 cm s^{-1} to 118.81 cm s^{-1} from 12 m/o to 19 m/o infants. From Table 4-1, we also see the mean values showing a similar increase with infant age. The range of

values also show a steady increase with age, with 19 m/o infants moving with a maximum speed of 220.7 cm s^{-1}. Therefore, this data shows older infants generally move faster than younger ones.

Previous studies have shown speed to have a strong dependence on walking experience. The longer the infant has walked, the better, more efficiently and faster it can walk. This has been shown in a previous study [12], that showed high correlation ($r(161) = 0.51$) between walking experience and speed. Since, a higher infant age almost always guarantees more time that the infant has walked, this dependence of locomotion speed can be extended to infant age. Such a trend is in agreement with our data, showing older, more experienced infants being able to move faster. For infant walking observations, infant speeds are shown to vary across walk sequences [51].

An important gait parameter that factors into walking speeds is the step length. New walkers show a step length of ~ 25 cm and more experienced walkers like 14 m/o infants can take steps of up to 37.3 cm long. This has been shown by previous correlations in [12], where walking experience correlated highly ($r(161) = 0.58$) with step length.

We tried to compare walking speeds across the range of infants that fell within our infant age groups. New walkers, typically ~ 12 m/o in age, showed speeds of up to 80 cm s^{-1} [12]. Previously, locomotion speeds for 14 m/o walking infants were measured in [12] and were found to range from 22 to 133.5 cm s^{-1} with an average speed of 79.81 cm s^{-1}. Over the range of infant age group similar to our study, from 12 to 19 m/o infants, we see that speeds from 20 cm s^{-1} to over 200 cm s^{-1} can be shown [51]. This agrees very well with our range of values as well as averages.

4.1.4 Breathing Zone Height

NYU's data had infant height data and we used them to obtain breathing zone heights. Breathing zones (defined previously in methods) here were obtained by using reported CDC's statistical data on infant head circumferences using Eqn 10, shown here.

$$Breathing\ Zone\ Height = Infant\ Height - \left[\frac{1}{2\pi}\ Infant\ Head\ Circumference\right] \qquad (10)$$

This provides a good estimate of the Breathing Zone Height in the vertical plane which is useful for infant resuspension and exposure studies.

From the distribution curves of infant Breathing Zone (BZ) heights in Figure 7 and Table 4-1, we see the median infant BZ heights show an increase from 68.3 cm to 74.87 cm in from 12 m/o to 19 m/o infants. The average BZ heights show the same trend, along with ranges where a 19 m/o infant can have a maximum BZ height of 83.1 cm. Since older infants have a higher height, their BZ heights would also be higher than younger infants. BZ heights, hence, follow the same trend as infant height variations and values.

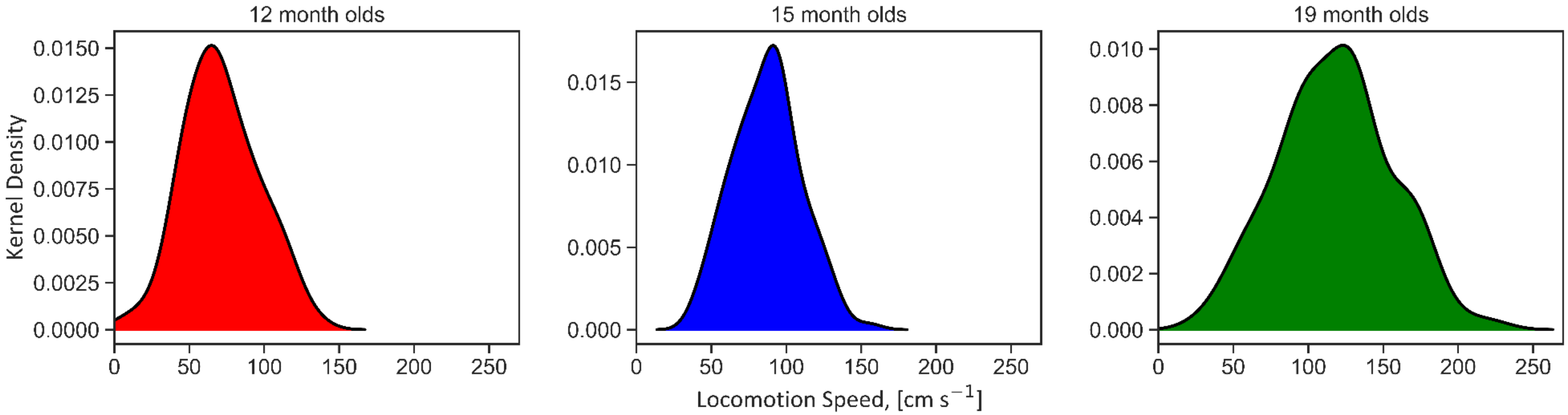


Figure 6. Locomotion speed distributions in infants of ages 12 months, 15 months, and 19 months old.

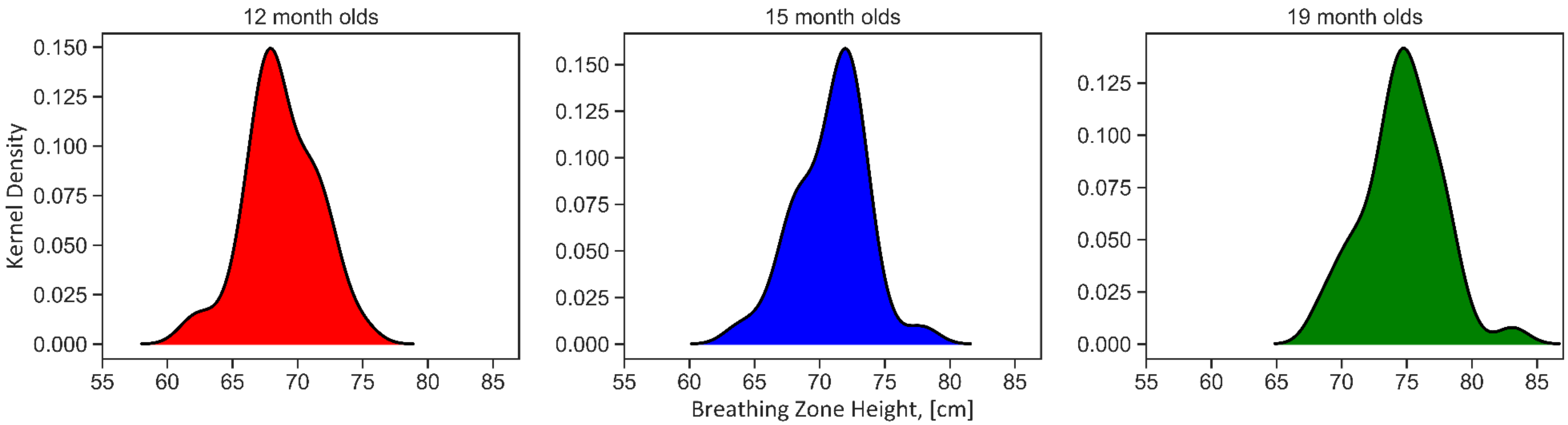


Figure 7. Breathing zone height distributions in infants of ages 12 months, 15 months, and 19 months old.

As infants get older, they grow taller and this has important effects in infant locomotion skill. Body dimensions and growth play an important role the ability to move. Better posture maintenance leads an infant to transition from crawling to walking [49]. An increase in infant height for a walking infant is especially beneficial. Apart from better posture control due to upper body strength and growth, development of muscle and an increase in leg length can result in longer steps and smaller step widths. This results in higher locomotion speeds and better and more efficient overall locomotion skill. An increase in height with therefore, signifies better locomotion and can be seen from our data, where older, taller infants can walk faster, longer distances and with more steps per unit time. Essentially, better walking can be shown with higher previous walking experience and the increase in height can aid in this process. Breathing zones can also vary during a walk or crawl sequence for an infant depending on the head angle or tilt. This is shown in previous studies [19, 20] where crawlers look more towards the floor than walkers who look ahead.

4.2 Source Term Distributions

Figure 8. shows the normalized Source term, $\frac{S_j}{L_j}$, or resuspension emission rate distributions for all the infant age groups and size fractions, generated by Monte Carlo analysis. We obtain normalized source terms to remove the dependence of the floor dust loading L_j on the emission rates. Since, dust loading values are dependent on resuspension fractions and hence, on the resuspension emission rates, normalizing can give us useful numbers that are applicable to a wide variety of dust loadings, given the surface type is similar. Figure 9 shows the Source terms or resuspension emission rate distributions using the dust loading values in [5]. From our analysis, there is an increase in median normalized Source term values with increase in infant age for a given particle size range. For the size fraction (5 – 10μm), the values increase from 1.554 x 10^{-5} mg s^{-1}/ mg m^{-2} to 2 x 10^{-5} mg s^{-1}/ mg m^{-2}. This slight increase and without a change in the order of magnitude, is shown in all particle size ranges.

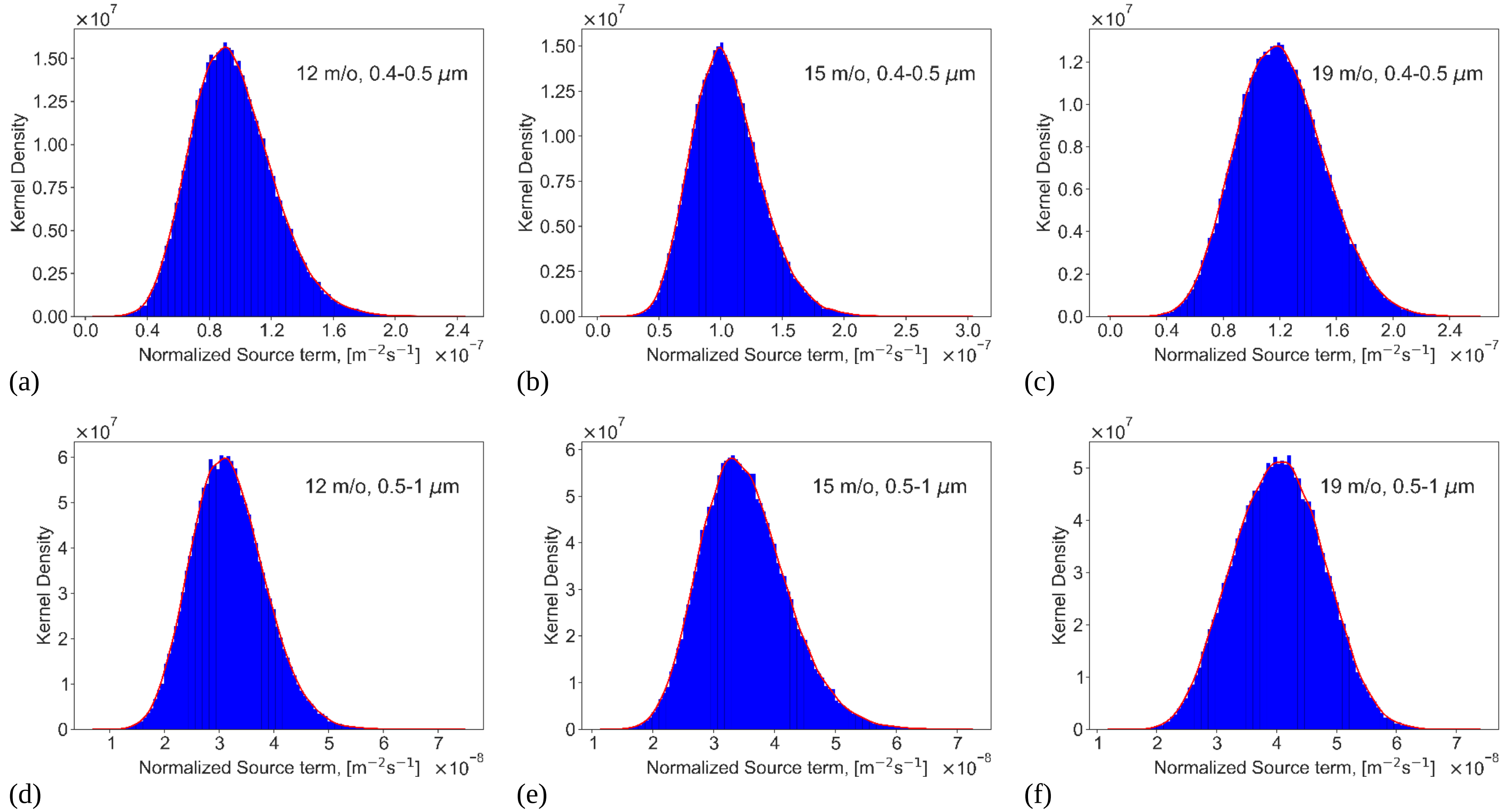


Figure 8. Normalized source term distributions for 12 m/o, 15 m/o and 19 m/o infants for all particles size fractions.

Figure 8. continued.

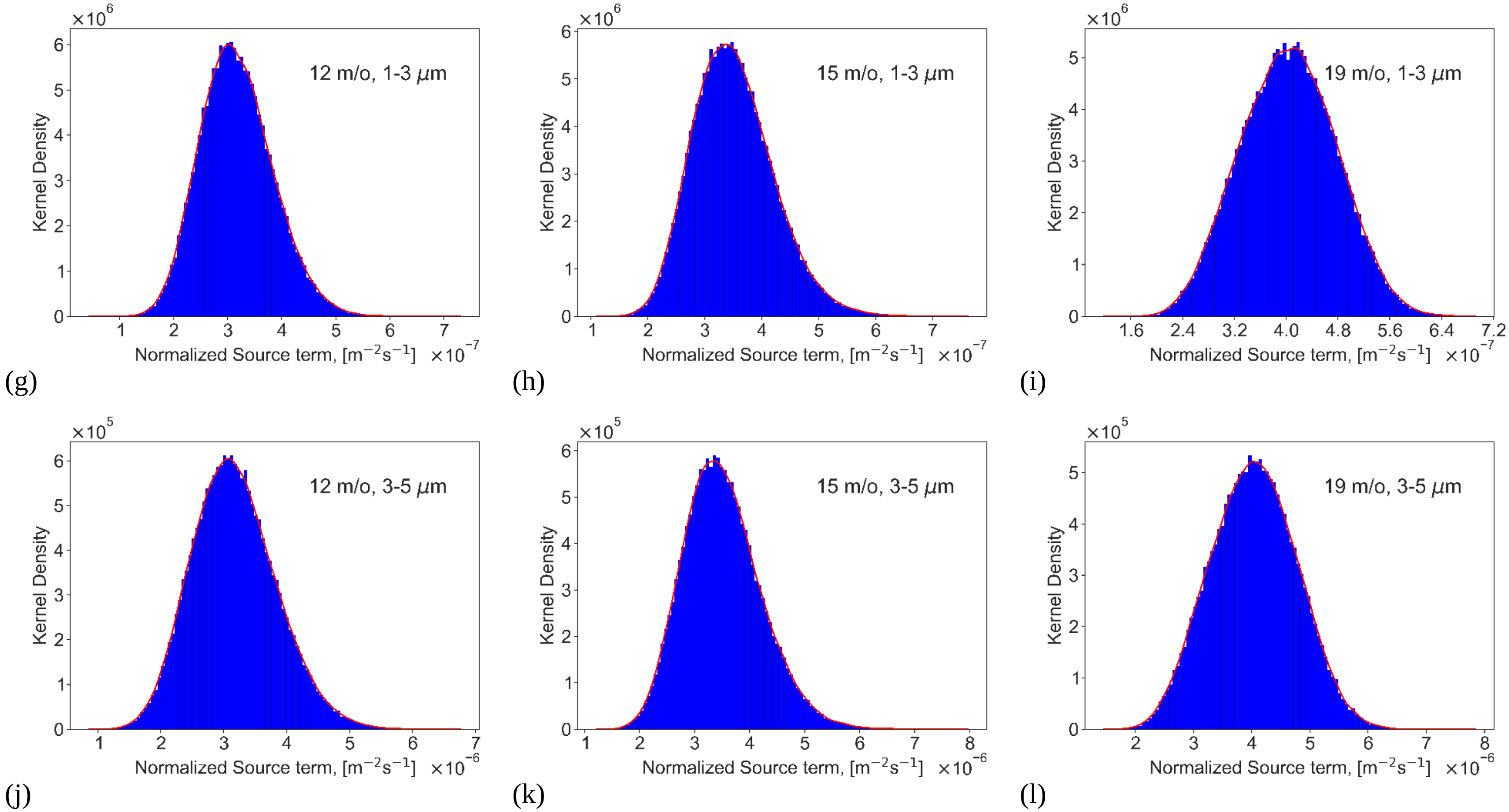
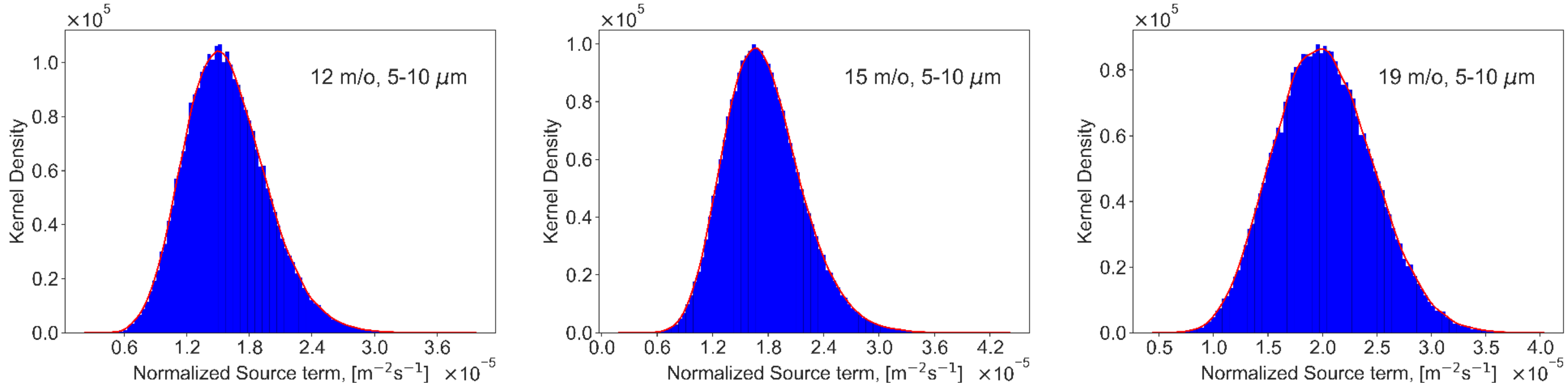


Figure 8. continued.



(m) (n) (o)

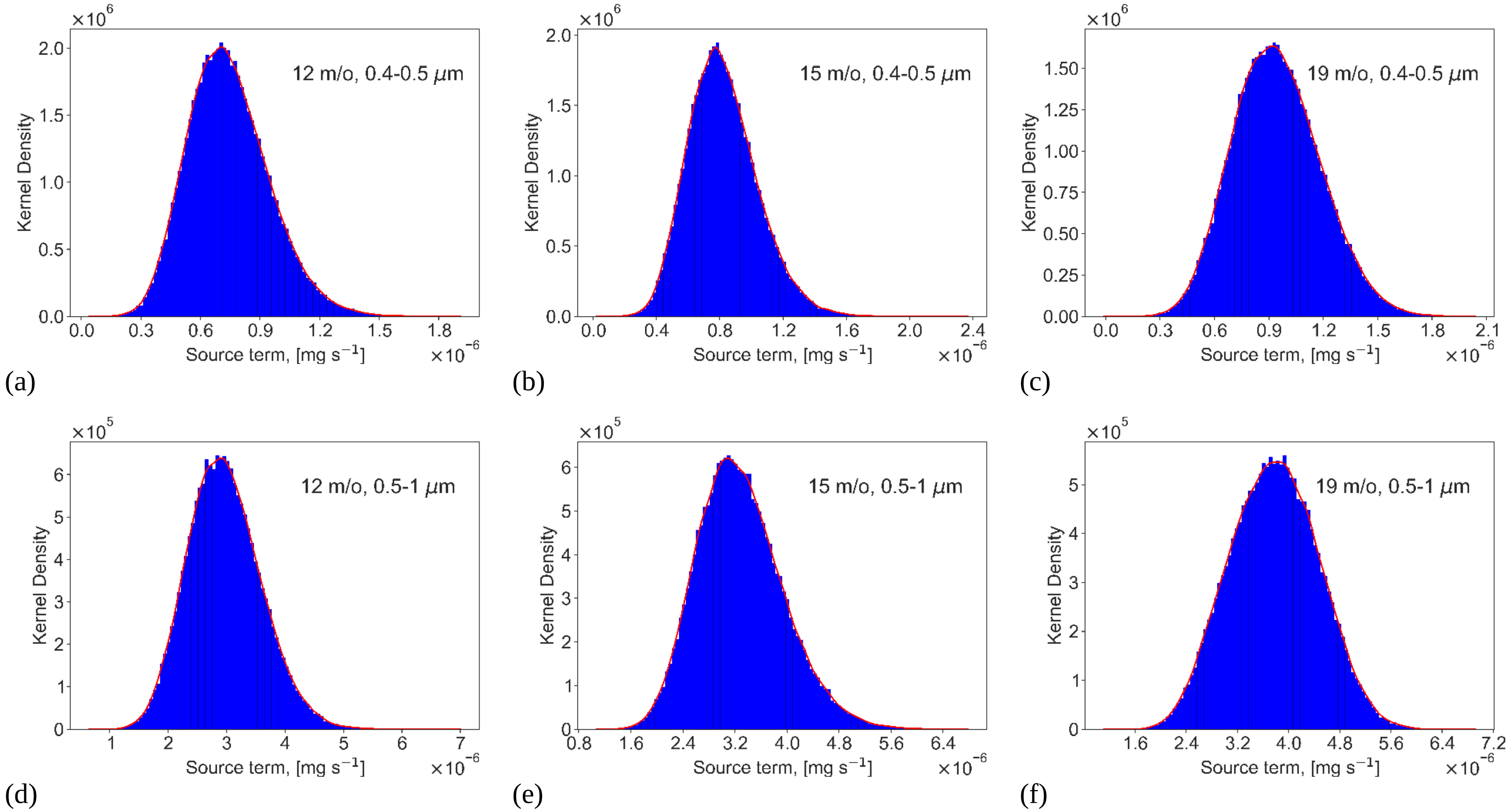


Figure 9. Source term distributions for 12 m/o, 15 m/o and 19 m/o infants for all particles size fractions.

Figure 9. continued.

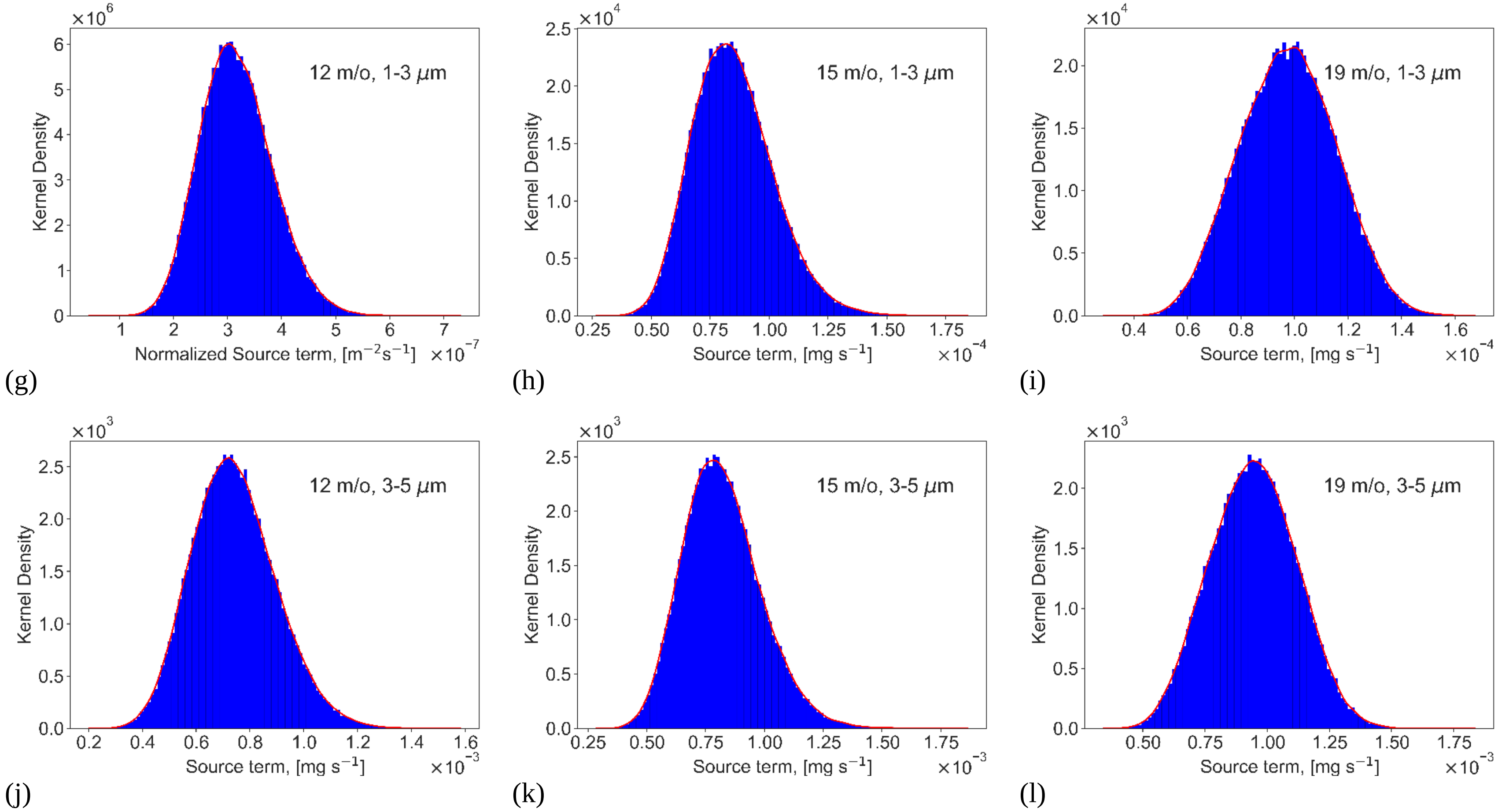
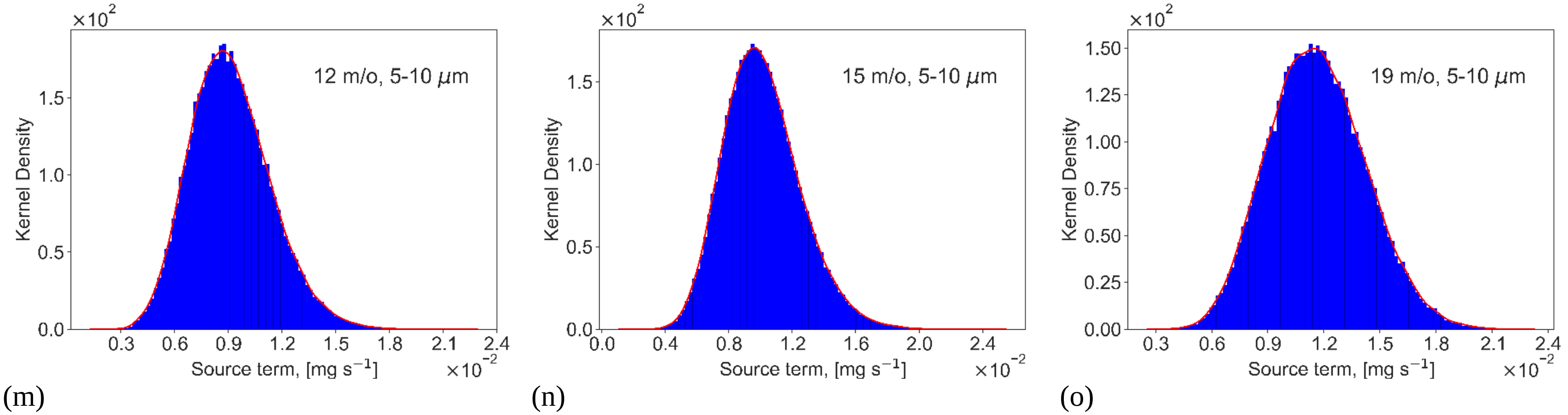


Figure 9. continued.



There is an increase in median normalized Source term values with increase in particle size for a given infant age. For 15 m/o infants, the values increase from 1.03 x 10^{-7} mg s^{-1}/ mg m^{-2} to 1.72 x 10^{-5} mg s^{-1}/ mg m^{-2}. There is significant increase, with particles in the lowest size range (5 – 10µm) having two orders of magnitude larger values than those in the largest size range (0.4 - 0.5µm). Such a trend is shown for all infant ages. Our results also show that median normalized Source terms follow the same variation with size as in [5] since Source terms depend on resuspension fractions.

There is a difference in the variation of the normalized Source term values with infant age compared to its variation with particle size. This can be explained by looking at the variations in locomotion parameters with infant age and resuspension fractions with particle size, since both locomotion parameters (here, contact frequency) and resuspension fraction values are varying inputs in the Monte Carlo Analysis to determine the Source term.

From our previous results, we see an increase with contact frequency with infant age, this increase stays within the same order of magnitude. Resuspension fraction values, on the other hand, increase drastically with particle size, with higher orders of magnitudes for larger particle sizes. This helps explain the variations shown in the median Source terms with particle size and infant age. We also see narrower distributions in a given size fraction (here, 0.5 - 1µm) for 12 m/o infants with a smaller range of 9.04 x 10^{-9} mg s^{-1}/ mg m^{-2} to 7.27 x 10^{-8} mg s^{-1}/ mg m^{-2}, and smaller inter-quartile range of 8.96 x 10^{-9} compared to a 19 m/o infant with a range of 1.422 x 10^{-8} mg s^{-1}/ mg m^{-2} to 7.163 x 10^{-8} mg s^{-1}/ mg m^{-2} and a larger inter-quartile range of 1.039 x 10^{-8}. This can be attributed to the differences in the contact frequency distributions between 12 m/o infants and 19 m/o infants.

We report all our normalized source term values in the units of mg s^{-1}/ mg m^{-2}, where our emission rate timescale is in the order of seconds. Such a unit is not too useful for comparison with other locomotion studies, however, is accurately used for our study. Most infant locomotion studies have continuous movement periods in the order of seconds and the data obtained from NYU for our study also reported contact frequency in terms of steps s^{-1}.In order to get absolute resuspension emission rate values, we use floor dust loading values from [5], same study having the resuspension fractions. Also, we convert our emission rate units to mg h^{-1}, the values obtained are shown in Table 4-2.

Table 4-2 Source terms in mg h^{-1}.

Source term Range, [mg h^{-1}]					
Infant Age group	(0.4 – 0.5µm)	(0.5 – 1µm)	(1 – 3µm)	(3 – 5µm)	(5 – 10µm)
12 m/o	3.70e-04 – 0.0068	3.05e-04 – 0.0245	0.056 – 0.062	0.903 – 5.52	7.19 – 80
15 m/o	3.17e-04 – 0.0082	0.0045 – 0.0236	0.115 – 0.645	1.21 – 6.53	6.57 – 89
19 m/o	2.38e-04 – 0.0073	0.0046 – 0.0241	0.123 – 0.583	1.43 – 6.41	12.1 – 80.9
Source term Median, [mg h^{-1}]					
Infant Age group	(0.4 – 0.5µm)	(0.5 – 1µm)	(1 – 3µm)	(3 – 5µm)	(5 – 10µm)
12 m/o	2.61e-03	1.05e-02	2.72e-01	2.64	32.3
15 m/o	2.89e-03	1.18e-02	3.01e-01	2.91	35.8
19 m/o	3.36e-03	1.36e-02	3.51e-01	3.40	41.6

In comparing emission rates from other studies that used an idealized fixed activity scenario as an emission source, we see that our values are in agreement with previous studies. In [5], we can obtain source terms for an adult walking continuously with contact frequency 1980 steps h^{-1} and contact area of 0.021 m^2, giving us an average emission rate value of 12 mg h^{-1} for 5 - 10µm particles. When comparing our values, all infant ages and size fractions, including the median values which are in the range of 32.3 to 41.6 mg h^{-1} for a 12 m/o to 19 m/o infant, infants show larger range of values in comparison that is attributed to higher infant contact frequencies.

In [18], from reported resuspension rates and using similar floor dust loading, we see emission rates of close to 10 mg h^{-1} for 5 - 10µm particles for a single adult walking at a contact frequency of 114 steps/min in an old carpet. In such comparisons, flooring type and dust loading values pose uncertainties in differences in resuspension emission rates. Also, such emission rates specific to infant walking with accurate locomotion parameters included, has never been reported previously to our knowledge. Such comparisons also help show differences between adult and infant resuspension due to walking.

Previous studies on indoor emission sources [67] such found higher emission rates for cooking for PM2.5 particles, close to 3 mg min^{-1}, and lower than 1 mg min^{-1} for activities such as microwaving or dusting. Each type activity results of emission of particles in a specific size range, resulting in differences in mass and number concentrations. For example, this study found that frying can have three times the number of PM2.5 particles than sweeping the floor, indicating smaller particles are dominant in indoor processes such as cooking [68]. Sweeping or dusting, where resuspension is the emission source, would result in lower PM2.5 concentrations as research has shown coarser particles resuspend more.

An important factor to note is that these are prescribed activities, i.e., the people in the study are made to perform them in a certain way for a fixed period of time. In reality, the times of these activities may not reflect real indoor activity patterns and periods. However, since our values also reflect resuspension emissions from an infant walking for a continuous period of time (ideal), this comparison is valid.

In order to make comparisons of emission rates for realistic indoor activities and hence, realistic infant locomotion, we use adjusted values. When moving to a larger unit of time, conversions without the right adjustments to the periods of locomotion for that timescale would be inaccurate. Previously for contact frequency, we used proportion of time in motion for such an adjustment. We also explained why the variation in units of contact frequency measurements is not straightforward for comparisons. This can be applied here by assuming a time period in between 15 to 60 minutes that the infant activity was observed and the 33% as the proportion of walking period. By using this, we attempt to get realistic infant resuspension emission rates. Assuming the total period to be 40 minutes, our values can be adjusted for the hour timescale and is a good estimation that includes the range of real infant locomotion.

In doing these, we get the values shown in Table 4-3. This is now appropriate to compare other studies with emission rates with actual indoor activity patterns, instead of prescribed simulated activity.

Table 4-3 Adjusted source terms in mg h^{-1}.

Adjusted Source term Range, [mg h^{-1}]					
Infant Age group	(0.4 – 0.5µm)	(0.5 – 1µm)	(1 – 3µm)	(3 – 5µm)	(5 – 10µm)
12 m/o	8.13e-05 – 0.0015	6.7e-05 – 0.0054	0.0125 – 0.1359	0.1987 – 1.2148	1.5822 – 17.6064
15 m/o	6.97e-05 – 0.0018	0.001 – 0.0052	0.0253 – 0.1418	0.2666 – 1.4365	1.4454 – 19.5869
19 m/o	5.24e-05 – 0.0016	0.001 – 0.0053	0.0271 – 0.1282	0.3136 – 1.4110	2.6687 – 17.7905
Adjusted Source term Median, [mg h^{-1}]					
Infant Age group	(0.4 – 0.5µm)	(0.5 – 1µm)	(1 – 3µm)	(3 – 5µm)	(5 – 10µm)
12 m/o	5.75e-04	0.0023	0.0599	0.5806	7.11
15 m/o	6.355e-04	0.0026	0.0662	0.6398	7.88
19 m/o	7.389e-04	0.0030	0.0773	0.7476	9.1444

[52] shows an emission rate of 31 mg h^{-1} for fungal and bacterial aerosols in an occupied classroom per occupant. Our study, focusing only on resuspended dust, has shown up to 18 mg h^{-1} of coarse mode particle emission rates adjusted for realistic infant locomotion patterns. Since indoor sources could stem from resuspension, occupant associated microbe emissions, outdoor sources [73] and depends on the indoor conditions, occupant based total emissions being higher is expected. Total particulate matter emissions in a school [53] has shown an average of 21 to 472 mg h^{-1} at different locations.

The emission rate reported in the literature is a bulk term which is specific to the type of activity but subject to variations in activity intensity and frequency, flooring material, particle surface loading, etc. [6]. However, such comparisons are able shed light on the differences in simulated and realistic emission monitoring experiments and, also in specific factors like differences in emissions from different sources with respect to particle sizes and magnitude of emission rates

4.3 Eddy Diffusion Coefficients

Figure 10. shows Eddy Diffusion coefficients, *k*, at varying heights resulting from different age group of infants. These curves are fitted using Eqns (9a – 9f), shown previously using cubic polynomial curve fitting. It is conjectured that the values of eddy diffusion coefficients vary with infant height since turbulence profiles over the head of the walking adults in [7, 43] with peak values at the end of the moving limb, here, the beginning of the moving leg.

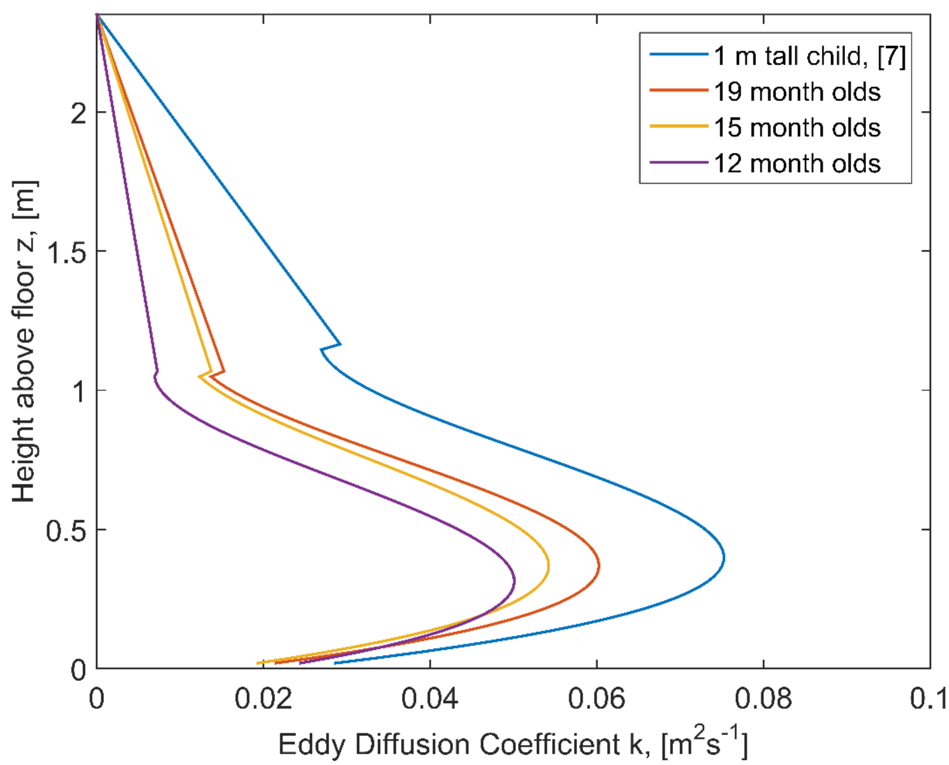


Figure 10. Eddy diffusion coefficient variations with vertical height for 1 m tall child [7], 12 m/o infant, 15 m/o infant and 19 m/o infant.

Form NYU's data on infant heights, we found that the median height of 12-month-old infants was less than 15-month-olds which in turn was lower than 19-month-olds and, the 1 m tall child reported in [7] (Median heights for 12 m/o, 15 m/o, 19 m/o infants: 75.7 cm < 78.9 cm < 82.5 cm). The peak values represent maximum turbulence occurring at a point of maximum mixing. During locomotion, the arm and leg movements are responsible for the mixing resulting in turbulence during locomotion. This also explains the decay in turbulence over the heads of the walking infant.

The eddy diffusion coefficients increased with the age group of walking infants in the room. The maximum diffusivities across the vertical span were 0.05 $m^2 s^{-1}$ for 12-month-old infants, 0.054 $m^2 s^{-1}$ for 15-month-old infants, and 0.06 $m^2 s^{-1}$ for 19-month-old infants.

The results for one person walking in [7] indicated that body movement affected air in a region nearly bounded by the human height and turbulence dampened out rapidly above the human head, and only traces of turbulence were recorded 40 cm above the head. Eddy diffusion curves were used in a unique way in resuspension due to human walking indoors in [7] to determine vertical particle transport. Prior to the study in [7], we have not seen *k* values reported in literature as a result of human movement or even other indoor activities.

Moreover, such a profile for eddy diffusion coefficients *k* with respect to vertical heights has never been obtained for infants. This is especially important since infant height is an important factor signifying development and locomotion skill in infants. Eddy diffusivities, in general however, are an important parameter in atmospheric dispersion and heat transfer which have been reported in previous studies. [54] looked at eddy diffusivity variations with vertical height at different distances from the turbulence source, derived theoretically. The curve profile of *k* vs *z* follows similarly as our study and in [7], however the dependence of *k* on vertical height is different. Since [7] used an empirical cubic polynomial curve to best fit measured values, such a difference is expected. Overall, resuls in [54] shows an increase in k to a maximum value close at the source height and a subsequent decrease with vertical height, a trend that is in agreement our eddy profiles and [7].

Atmospheric boundary layer characterizations have previously used vertical variation of k based on many theoretical and empirical models [46, 55]. Among the various ways to explain the *k* vs *z* curve, researchers have previously used a similar scaling/ extrapolation procedure with a cubic polynomial fit [46] as in our study. All of these studies have also reported the height of the turbulent boundary layer (for the atmosphere) and wind velocities to be important factors to determine the region of maximum eddy diffusion value and the position, which support the assumptions made during our extrapolations to determine infant *k* vs *z* profiles. Also, the profiles themselves follow similar curves as these previous studies and [7], making our values a good estimate for infants walking and making these eddy diffusivity profiles a unique contribution to literature for infant movement. This can aid further studies in infant turbulence around a moving infant and particle transport studies.

4.4 Vertical Concentration Gradient Profiles

The transport model in this study that integrated locomotion parameters was able to determine vertical concentration gradients of resuspended particles due to an infant walking in an indoor environment. Figure 11 shows the normalized vertical concentrations variations with vertical height, for a total height of 1 m, of resuspended particles at steady state, normalized with respect to concentration at the zone closest to floor, that are resuspended by 12 m/o, 15 m/o and 19 m/o infants walking, for different particle sizes.

The vertical concentration gradient curves are plotted until a total height of 1 m since we are only looking at infants (less than 1 m tall) and turbulence above the head is negligible [7]. The transport model has three important factors affecting its output vertical concentration values with height –

a) Infant locomotion parameters dependent on infant age (here, contact frequency) in the Source term,

b) Resuspension fractions dependent on size in the Source term,

c) Particle settling velocity dependent on particle size and,

c) Infant heights dependent on infant age in the eddy diffusivity curves.

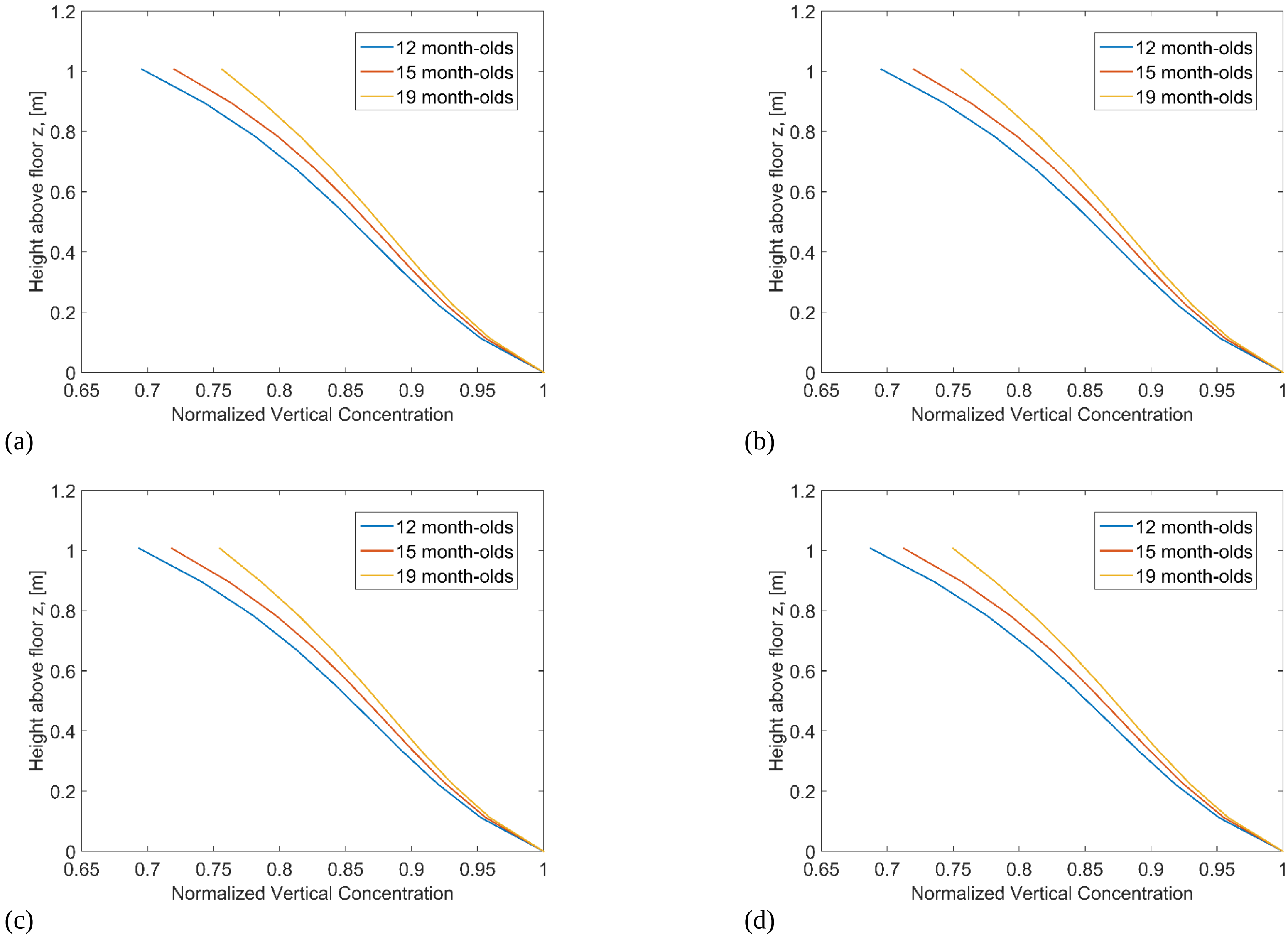
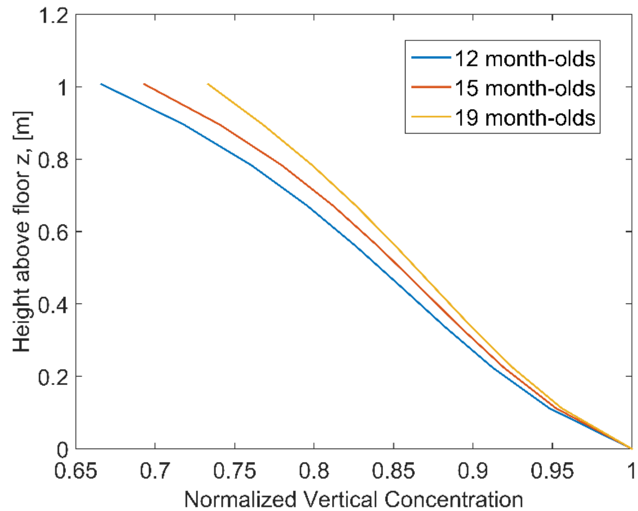


Figure 11. Vertical concentration gradient profiles for the particle size fractions for (a) 0.4-0.5 µm, (b) 0.5-1 µm, (c) 1-3 µm, (d) 3-5 µm, and (e) 5-10 µm for all infant age groups.

Figure 11. continued.



(e)

It is important to note however, that all the above-mentioned factors affect the absolute vertical concentration values and not the normalized concentrations. The normalized values would only be affected by eddy diffusivity values and particle settling since normalization effectively removes dependence on the near floor concentration magnitudes and hence, the source terms.

Figure 11. shows normalized vertical concentrations varying with vertical height for each infant age group and particle size. For a given size fraction, we see that the concentration curve for the 19 m/o infant has a higher slope than the 12 m/o infant, resulting in higher normalized vertical concentrations resuspended at a given height for a 19 m/o compared to a 12 m/o infant. This means older infants can resuspend more particles to greater heights than younger infants at a given height for a particle size fraction. This trend between infant age groups is shown in all the curves for all particle size fractions. For the particle size fraction 0.4 - 0.5μm, a 19 m/o can resuspend close to 75% of near floor particles at 1 m height, whereas a 12 m/o can only resuspend close to 70% of near floor particles at the same height. Across, all size fractions, a 19 m/o infant has an average normalized vertical concentration of 6% higher than a 12 m/o infant.

This variation among infant ages can be attributed to greater k values with respect to vertical height, z, for 19 m/o infants compared to 12 m/o and 15 m/o infants. Higher k magnitudes, as seen in older infants and taller people from [7], causes greater vertical transport to take place, thus resulting in higher percent of particles travelling to more heights.

For a given infant age group, we see that the concentration curve for the higher particle sizes show lower normalized vertical concentrations at a given height compared to higher size fractions. This means larger particles are resuspended to lower heights than smaller ones. At a given height, there is a greater normalized concentration value for smaller particle sizes than larger ones. This trend is true for all infant age groups. Between the particle size ranges of (0.5 - 1 μm) and (5 - 10μm), for a 19 m/o infant, we see, the higher size fraction has close to 70% of near floor particles resuspended, whereas, (5 - 10μm) particles contains close to 67% of near floor particles resuspended at 1 m height.

Larger particles have shown to have greater resuspension and emission rates[6], however, once resuspended, it is easier for smaller (having lower settling velocity) particles to be transported to greater heights compared to larger (having lower settling velocity) particles. Therefore, such variation is shown in vertical concentration gradient profiles with height and agrees with previous studies [7]. Results in [7] also emphasized this effect where the particle distribution followed a hyperbolic shape that was more extreme for particles larger than 20-µm because of their larger settling velocities and those below 10-µm followed a linear curve.

Looking at absolute concentration values is crucial for a comprehensive comparison which will integrate all contributing factors for vertical resuspended particle concentrations. This would now depend on all the factors previously mentioned, including resuspension source strength or the emission rate, which in turn depend on infant locomotion and size dependent resuspension fractions. From our analysis, between particles in (0.5 - 1 µm) and (5 - 10µm) size ranges, we found near floor concentrations using Source term estimates in Table 4-2 for a 19 m/o infant. This was 0.002 mg m^{-3} and 5.67 mg m^{-3}. Since absolute particle concentrations depend on source strengths, we see more than three magnitudes higher near floor concentrations for the larger size range. Using this, we can now determine absolute vertical concentrations for the size ranges at a particular height using the normalized gradient values. Larger size fractions have lower normalized concentrations with 67% of the near floor concentrations and 70% of near floor concentrations for 5 - 10µm particles at 1 m height. The lower normalized fraction of near floor concentrations is not able to overcome the much higher order of magnitude of absolute near floor concentrations for larger sizes. This gives us higher absolute concentrations at a height of 1 m for larger particles than smaller, even though the gradient values show otherwise.

This exercise was done to emphasize the importance of looking at absolute values when comparing different source strengths by using this gradient as a reference. As an extension, one would need to only know either source strengths or near floor concentrations and use these concentration gradient profiles to determine absolute concentrations at different heights.

To effectively compare breathing zone concentrations between an infant and an adult, this study's infant vertical concentration gradient profiles along with those in [7] for an adult can be used. This must be used along with source term dependent near floor absolute concentration values for both cases, keeping floor dust loading same in both cases. For the adult, at the largest particle size fraction, using the contact frequency and area in [5], we obtain the source term of 12 mg h^{-1} and a near floor concentration of 1.38 mg m^{-3}. Using the gradients, and comparing between a 19 m/o infant and an adult, we obtain a vertical concentration of 4.3 mg m^{-3} at the median infant BZ (~75 cm) and 1.2 mg m^{-3} at the adult BZ (~150 cm, adult height = 180 cm). This shows us that the infant mainly due to its larger source strength and even with smaller vertical transport due to lower k values can face more than thrice the concentration in its BZ compared to an adult, at their BZ, for coarse particles. This has very important applications in exposure assessments and such analysis can help predict breathing zone concentrations for different infants or adults, given a Source term estimate. Such a difference may not be as much for much smaller particles.

Previous studies have aimed to look at the potentially higher concentrations at the BZ that an infant or child could be exposed to. Studies have conducted measurements at the breathing zones of crawling or walking infants and children, using personal sampling, as well as robots mimicking the resuspension process at the infant breathing zone [56-61].

These have found much higher PM and fluorescent bioaerosol concentrations, especially for coarser particles larger than 3µm in the breathing of a crawling infant robot compared to a walking adult, certain carpet types showing more than a two fold increase in BZ concentrations [56-61]. This was attributed to the differences in the BZs of the infant and the adult and the type of locomotion causing difference in particle transport, for a given surface. This is similar to the modeling results of our study.

Constant resuspension for long periods may cause the dust loading from carpets become depleted, which would reduce the source strength and promote better mixing between vertical layers [62]. Even though our study assumes a time independent source strength, the importance of the source or emission rate term in the vertical particle concentrations is emphasized in our study. However, larger particles do settle much faster and are shown to constantly settle and re-entrain into the air depending on the activity [56].

Finally, from the results of our study and previous studies, it is the combination of three main factors that affect BZ concentrations – the height of the BZ, the strength of turbulence (causing particles to transport vertically) and the source strength or resuspension emission rates. Adults have larger turbulence strengths causing more transport and higher gradients of vertical concentrations compared to infants.

However, this increased vertical transport does not result in greater BZ concentrations in adults since they are shown to have lower source terms (affected by locomotion) compared to infants from our study. This along with much lower BZ heights for infants than adults, result in much higher particle concentrations in the infant BZ compared to an adult. Infants may be slightly less efficient at transporting particles vertically (shown from our gradient profiles and in [7]) but their much higher source strengths and lower BZ height cause them to have higher BZ particle concentrations affecting their exposure.

4.5 Infant Locomotion Time Series

Infants for a free play experiment are video recorded and scored for the type of activity or locomotion along with time for a specific total observation time period. We chose the data (coded on Datavyu [44] from [35] that had mostly 15-month-old walking infants and a few 13 and 19-month-old infants. From the video coded data, a time series of different locomotion periods and stationary periods plotted for nine 15-month-old infants and one 13-month-old infant for the 20-minute total observation period. This time series visualization along with the legend for different periods is shown in Figure 12.

Each of these locomotion periods can be attributed to different periods of resuspension and exposure. Walking and crawling periods denote active resuspension periods, where there is constant floor dust resuspension taking place. This period will likely show an increased particle concentration, especially at the infant BZ.

Periods of rest that follow a period of locomotion signify decay periods, that can be characterized by an absence of resuspension due to no locomotion and a reduction in particle concentrations at

the infant BZ. Such reductions would be primarily due to an increased effect of particle settling and a decreased effect of vertical particle transport that is caused by locomotion due to a breakdown of the vertical concentration gradient and an absence of emission rate or source term.
The plots also show periods of fall that will likely signify a period of instantaneous resuspension, characterized by a sudden increase in BZ particle concentrations. Periods of locomotion and fall would be characterized by the presence of vertical concentration gradients and infant locomotion emission rate terms.

Since this is data from a free play experiment [35], such locomotion periods and patterns show realistic activity patterns in infants in such age groups. From Figure 12., it is evident that most infants, both crawl and walk. This has shown be typical for infant in this age group.
We also see the infant walks or crawls for a lot of the observed time, without being asked to. This has shown to be natural for infants as they learn to walk and better their walking skill to interact with their surroundings.

Once infants gain control over the upright posture and stand, they soon figure out walking as a mode of transport that helps them get to a place faster, over crawling [49]. They also learn to interact with objects around them and surroundings in a much more effective way [35]. This helps them explore the world around them from a newer, better perspective and walking enables this process, making these interactions easier and better, playing an important role in overall development.

We see all infants from Figure 12., showing at least one period of fall, also something seen commonly in infants of such ages, still learning to walk. Such falling, however, does not discourage infants from walking further as shown in Figure 12., and also in previous infant locomotion research and acts more like a way for the infant to gauge its own walking skill that the infant is constantly trying to improve with practice [49].

We were able to extract some relevant locomotion parameters from this data such as proportion of time walking, crawling and rest periods. We found on an average that the infant walks for 57% of time, crawls for 2% and 33.7% of the time where the infant is stationary. These are in agreement with previous proportion of time in motion values for infants in similar ages [9].

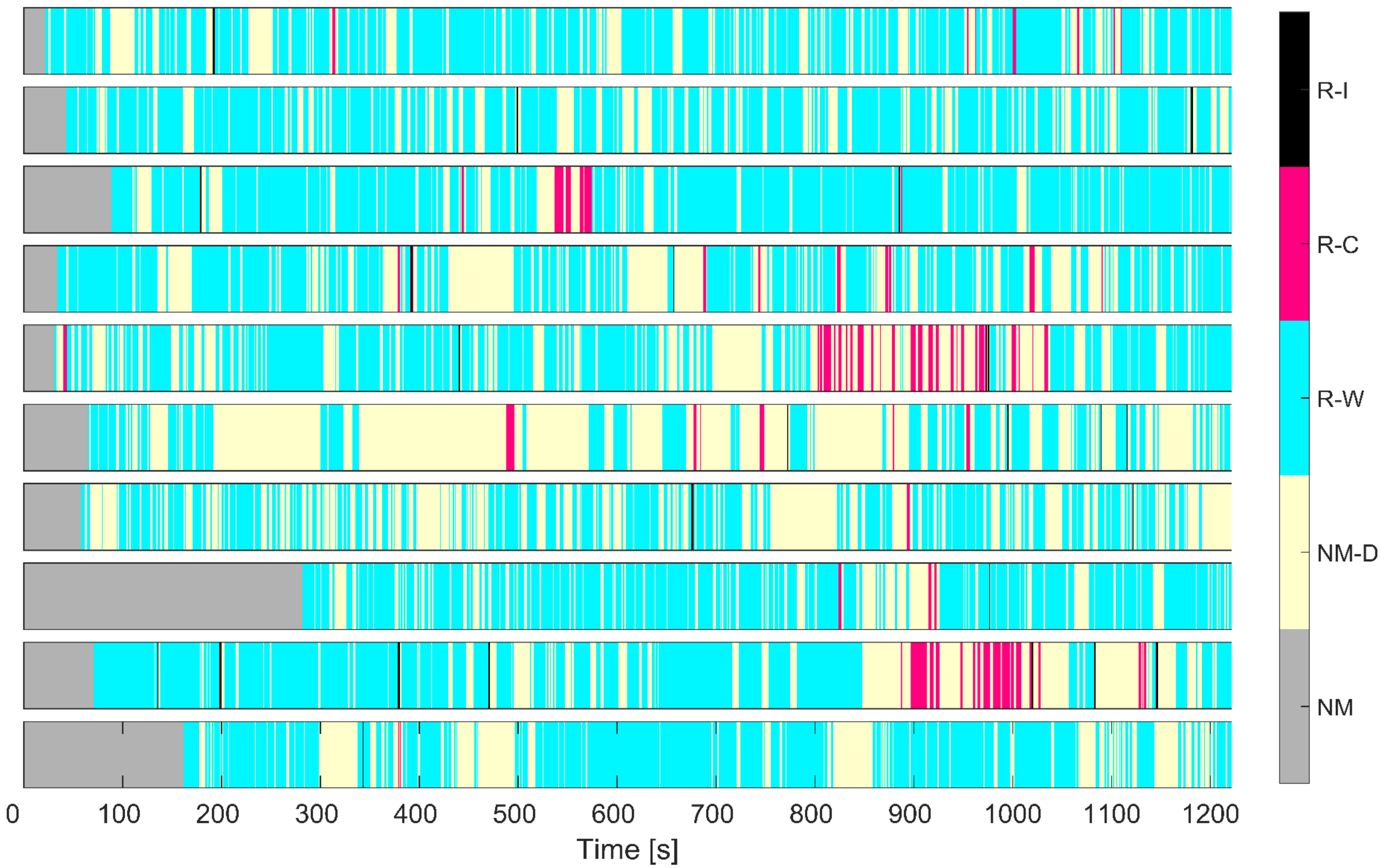


Figure 12. Infant locomotion profiles for 10 infants during a free play task showing periods of motion and rest.

R-W: Active resuspension periods for walking, RC: Active resuspension periods for crawling, NM-D: No motion following a resuspension period, with particle decay, R-I: Impulsive resuspension event (fall), NM: No motion without any preceding motion.

From the active resuspension periods (walking and crawling periods), it would be helpful to look at differences in the resuspension and exposure processes. Walking and crawling signify two very different kinds of resuspension, characterized by a difference in source strengths as well as vertical gradient profiles or vertical particle transport, due to differences in turbulence. They also have different breathing zone heights, crawling infants being much closer to the floor than walking infants. Infant crawling has almost constant contact with the floor, instead of an on/off contact like walking. This constant contact would affect the emission rates of resuspended particles, affecting also the kind of near floor air velocities and damping forces [7, 8, 63], that are shown to affect resuspension. It could be, however, expected that a crawling infant could face higher resuspended concentrations just due to their proximity to the floor, even with the difference in the source term, as it also does not take large turbulent disturbances to effectively transport particles to such a short vertical height. Since larger particles have higher resuspension emission rates but can be transported to less vertical heights shown from our study and [7, 56-61], differences in vertical heights would result in very different size distribution of BZ particle concentrations between a crawling infant, a walking infant and a walking adult.

Figure 12., also shows most infants having multiple, very small periods of rest, i.e., making the locomotion profile extremely discontinuous. Extremely short rest periods need to be inspected in detail to investigate if they result in a visible particle decay and BZ concentration decrease. However, keeping in mind coarse mode particles that are resuspended the most also settle faster, these rest periods may still result in lower BZ concentrations.

Fall periods, along with being associated with a sudden spike in BZ concentrations could be attributed to an increased emission rate due to more vigorous and sudden movement close to the floor, but importantly, also a decrease in BZ height. Researchers in [40] have shown instantaneous turbulent bursts, cause instantaneous lift forces enough to detach a colloidal particle. This period, we hypothesize, could result in much higher particle exposures for a walking infant.

Interestingly, the profile shows fall periods are also almost always followed by locomotion periods, such locomotion that follow a fall, could be characterized by a high initial BZ concentration for that locomotion period and may lead to higher exposure. This is also true for a rest period that follows a fall where the concentration decrease may not be as pronounced due to the high starting concentrations from the previous fall.

Characterizing such infant activity profiles and specific periods (or set of periods) can provide important insights to future exposure studies, in terms of relating activity pattern to exposure periods, but also throwing light on the time varying nature of infant activity profiles.

Previous studies have focused on infant and children BZ concentrations with the use of simulated crawling or walking robots or personal samplers on real children. Such studies have reported and emphasized on the highly transient and fluctuating profiles of infant BZ concentrations. Researchers in [56] reported this kind of fluctuating BZ concentrations with time, even within a continuous period of crawling by a robot. Researchers in [57-61] also reported such fluctuations in BZ concentration for children as well as a robot on wheels (to simulate walking), but importantly, also integrated the constantly varying BZ heights for infants during different activities, estimated using previously observed activity profiles for infants and children.

A constantly varying activity type with time, shown in Figure 12., along with a time varying BZ height depending on the constantly changing activity, would strongly affect BZ concentrations for infants and cause them to be highly transient and fluctuating with time, expected to be much more than what has been reported in these previous studies. Looking at such infant locomotion profiles would be the first step to investigate a more accurate time varying infant BZ concentration and the resulting exposure. Such locomotion profiles along with further studies on variation of BZ heights with activity and time, would help better explain such transience in exposure to resuspended particles in infants. Focusing on periods of interest like walking, crawling or groups of periods like (fall + walk/crawl) or (fall + rest) will help explain many such fluctuations in BZ concentrations. This would also help shed light on comparisons between infant and adult exposure while also aiding in more comprehensive models that can help predict BZ concentration variation and exposure to resuspended particles due to infant locomotion.

5. CONCLUSION

The present study investigated the role of infant locomotion in floor dust resuspension and exposure using a combined statistical-transport model, focusing specifically on infant locomotion dust emission rates and variation of resuspended particle concentrations with vertical height. This study identified infant parameters relevant for resuspension and exposure and was able to effectively integrate real infant contact frequency, contact area and infant heights and BZ heights into various parts of our modelling and analysis. This resulted in a link between infant age and development – older infants were taller, moved faster and had higher contact frequencies, to infant locomotion induced floor dust resuspension and exposure.

Normalized infant age categorized normalized size dependent resuspension emission rates or source terms were found for infant in age groups of 12 to 19 months old. Variations were found in the ranges, distributions, and medians between the three infant ages, with 19 m/o infant having overall highest source term values.

Using scaled eddy diffusivities for different infant ages, based on infant heights, the atmospheric transport equation and emission rates, we were able to provide important insights into the differences in vertical particle concentrations, especially at the infant BZ. We found that vertical gradients for older infants and smaller particles being steeper due to their larger eddy diffusivity values and lower settling rates, respectively.

The study showed the usefulness of these gradients on absolute determining vertical particle concentration and BZ concentrations. A comparison between adults and infants show that infants due to their shorter BZ heights, presumably higher resuspension source strengths due to locomotion differences shows that infants can have much higher BZ concentrations than adults. A 19 m/o infant will have an average normalized vertical concentration of 6% higher than a 12 m/o infant at a given height due to its larger eddy profile.

Our study was also able to extract real infant locomotion time series profiles that can shed light on future exposure studies in infant locomotion. Such locomotion profiles show the high variance in the type of locomotion or activity every infant within a period of locomotion. Since infants can walk, crawl and fall in the same locomotion sequence, characterizing exposure and BZ concentrations need to be more comprehensive. Each locomotion type, along with the corresponding time period would result in differences in active resuspension periods. As shown by our study, this is due to the differences in turbulence as well as BZ heights for each locomotion type. Since the type of infant activity was shown to be highly transient with time, future studies that focus on change in BZ heights with locomotion type and time would help better characterize infant exposure due to resuspension and help understand the high transience in BZ concentrations and the resulting exposure that is present during a period of infant locomotion on a dust laden floor. Overall, this study helped characterize the differences and variations in infant exposure due to the transience of infant behavior. This was done by elucidating variations in locomotion dependent resuspension emission rates, height dependent turbulence strengths through eddy diffusivities and, vertical gradient profiles between infant groups and calling for the need to further investigate infant activity profiles as an important contributor to infant BZ exposure patterns.

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APPENDIX

NUMERICAL METHODS

Discretized form of Eqn (6), solved using numerical methods iteratively using MATLAB until solution converged for the floor, ceiling and zone 1, shown in Figure 3.

Floor Node: i = 1 (Forward difference method)

$$\mathrm{C}_1^{n+1} = \mathrm{C}_1^{n} + \frac{\Delta t}{\Delta z^2}\left[\frac{v_s.\Delta z}{2}\ (4C_2^n - 3C_1^n - C_3^n) + k_1(2C_1^n - 5C_2^n + 4C_3^n - C_4^n) + \frac{1}{4}\ (4k_2 - 3k_1 - k_3)(4C_2^n - 3C_1^n - C_3^n) + S(z)(\Delta z)^2\right] \quad \text{(S1)}$$

Zone 1: i=2 to i_{max-1} (Central difference method)

$$\mathrm{C}_i^{n+1} = \mathrm{C}_i^{n} + \frac{\Delta t}{\Delta z^2}\left[v_s \Delta z\ (C_i^n - C_{i-1}^n) + k_i(C_{i+1}^n - 2C_i^n + C_{i-1}^n) + (k_{i+1} - k_i)(C_{i+1}^n - C_i^n) + \mathrm{S(z)}\ \Delta z^2\right] \quad \text{(S2)}$$

Ceiling Node: i=i_{max} (Backward difference method)

$$\mathrm{C}_{imax}^{n+1} = \mathrm{C}_{imax}^{n} + \frac{\Delta t}{\Delta z^2}\left[\frac{v_s.\Delta z}{2}\ (3C_{imax}^n - 4C_{imax-1}^n + C_{imax-2}^n) + k_{imax}(2C_{imax}^n - 5C_{imax-1}^n + 4C_{imax-2}^n - C_{imax-3}^n) + \frac{1}{4}\ (3k_{imax} - 4k_{imax-1} + k_{imax-2})(3C_{imax}^n - 4C_{imax-1}^n + C_{imax-2}^n) + S(z)(\Delta z)^2\right] \quad \text{(S3)}$$