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Personal Exposure and Inhaled Dose Estimation of Air Pollutants during Travel between Albany, NY and Boston, MA

Vineet Kumar Pal [1] and Haider A. Khwaja [1,2,*]

[1] Department of Environmental Health Sciences, School of Public Health, University at Albany, Albany, NY 12201, USA; vineetkumar.pal@nyulangone.org
[2] Wadsworth Center, New York State Department of Health, Empire State Plaza, Albany, NY 12201, USA
* Correspondence: hkhwaja@albany.edu

Abstract: Out of eight deaths caused worldwide, one death is caused due to air pollution exposure, making it one of the top global killers. Personal exposure measurement for real-time monitoring has been used for inhaled dose estimation during various modes of workplace commuting. However, dose-exposure studies during long commutes are scarce and more information on inhaled doses is needed. This study focuses on personal exposures to size-fractionated particulate matter (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP) and black carbon (BC) inside a bus traveling more than 270 kms on a highway between Albany, NY and Boston, MA. Measurements were also made indoors, outdoors, and while walking in each city. Mean PM (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP) and mean BC concentrations were calculated to estimate the inhaled exposure dose. The highest average $PM_{2.5}$ and PM_{10} exposures concentrations were 30 ± 12 and 111 ± 193 μg/m^3, respectively, during Boston to Albany. Notably, personal exposure to BC on a bus from Albany to Boston (5483 ± 2099 ng/m^3) was the highest measured during any commute. The average inhaled dose for $PM_{2.5}$ during commutes ranged from 0.018 μg/km to 0.371 μg/km. Exposure concentrations in indoor settings (average $PM_{2.5}$ = 37 ± 55 μg/m^3, PM_{10} = 78 ± 82 μg/m^3, BC = 5695 ± 1774 ng/m^3) were higher than those in outdoor environments. Carpeted flooring, cooking, and vacuuming all tended to increase the indoor particulate level. A high BC concentration (1583 ± 1004 ng/m^3) was measured during walking. Typical concentration profiles in long-haul journeys are presented.

Keywords: air pollution; exposure concentrations; inhaled dose; commuters; black carbon; particulate matter

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1. Introduction

With rapid urbanization and vehicular rise, the elevated levels of pollutant particles in air pose a greater concern for public health than ever before. The particulate matter (PM) from outdoor air pollution has been classified as members of Group 1 carcinogens (agents carcinogenic to humans) by the International Agency for Research on Cancer [1]. Air pollutants have been previously reported to be associated with adverse health conditions, including cardiovascular diseases, diabetes, neurodegenerative disorders, reduced life expectancy, and the development of several types of cancers [2–18].

Personal exposure to particulate matter is a multifactorial phenomenon and requires a complex measurement process that is the focus of much current research in the field of atmospheric pollution and adverse effects to public health. Background air quality measurement is an alternative field study, but scientists have shown that personal exposure assessment methods yield higher correlations to adverse human health outcomes than the direct measurement of background concentrations [19,20]. Hence, personal exposure measurements seem to be a better choice for assessing health adversities owing to air pollutants. Personal monitors have been used to assess the link between public health and air quality [21,22]. These personal monitors not only provide real-time air pollutant

exposure levels in micro- as well as outdoor environments, but also assess various exposure degrees considering the population as a whole [23,24]. Common approaches to personal exposure predictions majorly include time-activity considerations. Here, a personal exposure measurement is calculated by the sum of the product of time spent, corresponding to its pollutant concentration present in each micro-environment.

The exposure to and uptake of pollutants during commuting in transport and indoor micro-environments is clearly one of the key areas through which enhancements in public health could be made using various regulations. PMs are key products of various vehicular exhausts, dust, tree burning, etc., whereas black carbon (BC) is usually released as a result of the incomplete combustion of diesel fuel. The amount of PM entering the lungs is one of the key physiological links for studying air pollutants effects on human health. However, few studies have assessed the exposure to PM during commuting [21,25]; exposure studies on long-haul journeys are scarce [26].

Studies have shown that exposure in terms of inhaled dose varies significantly with the modes of commute due to the interaction of numerous factors such as route topography, urban morphology and meteorology, traffic conditions, pollutant levels, and inhalation rates [27–29]. In an exposure study conducted in Dublin, Ireland, the $PM_{2.5}$ ranged from 104–128 $\mu g/m^3$ during a bus commute [30]. Commuters traveling by bus experienced higher $PM_{2.5}$ exposure than those using other travel modes (car, cyclist, pedestrian), indicating differences in physiological state (breathing rate, frequency), exposure durations, and exposure levels. However, other studies reported that commuting by motor vehicles results in higher exposure to traffic-related air pollution when compared to commuting by cycling or walking [21,31–34]. Studies of pedestrian exposure to pollutants also yielded conflicting results, with some suggesting that individuals walking are less exposed to particles when compared to commuters in a bus or car [35,36], whereas some reported conflicting findings [37–39]. The variation in the findings of these studies on local commuters makes the assessment of commuter exposure and inhaled dose in long-distance routes of particular health interest, particularly as the effects of long-distance commuting have not been studied previously.

Our study focused on exposure during long-distance commutes between two capital cities of the northeastern United States (Albany, NY and Boston, MA), as well as indoors, outdoors, and while walking in each city. The study was designed to fill the existing knowledge lacunae by fulfilling these underlying objectives: (i) to measure the exposure levels to size-fractionated PM (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP) and BC during long-haul commutes between the two cities; (ii) to evaluate pollutant exposure levels during city walking and in outdoor and indoor micro-environments; (iii) to estimate air particulates related to inhaled doses during long-haul commutes; and iv) to explore the influence of potential sources of PM and BC exposure in indoor and outdoor micro-environments. The results of this study clarify the disparities between personal exposures in distinctive micro-environments at diverse locations and allow the evaluation of long-distance commuter dose for further epidemiologic research, assisting policy-makers with a basis for possible exposure reduction.

2. Methodology

2.1. Field Study

Albany and Boston are the capital cities of New York (NY) and Massachusetts (MA) with 1.1 million and 4.9 million inhabitants, respectively. They are growing fast in population, which has led to the growth of vehicular traffic and industrial activities. For measurements, an interstate highway (I-90) was selected. This route is 270 km long between Albany and Boston (Figure 1) and is routinely used by commuters to travel between the two cities.

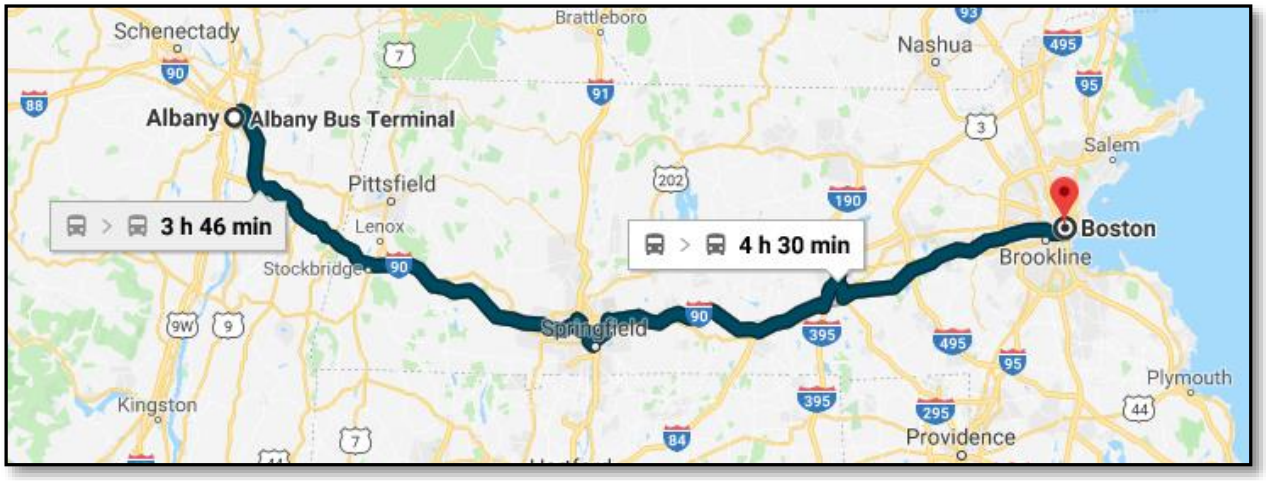


Figure 1. A schematic diagram of the bus route from Albany, NY to Boston, MA. (Source: Google Maps, 2019. Accessed 12 May 2019, Wadsworth Center, Albany, NY 12201-0509).

Private diesel-powered and public buses were used to measure exposure concentrations for long-haul and local (Albany) commutes, respectively. The buses had a capacity of 55 passengers, were naturally ventilated, and had closed windows. The average long-haul bus journey time was about 4 h 30 min, while the journey time of the local buses was about 1 h. In the current study, field sampling was also carried out indoors, outdoors, and while walking in each city. Different activities performed in indoor or outdoor environments were noted in a time-series diary during the day. The indoor sampling sites in Boston and Albany were in urban residential areas near busy roads.

2.2. Sampling and Analysis

The personal exposure sampling was performed using an Aerocet 531S, a real-time PM sampling device in Mass profiler mode that provides a PM mass concentration/m^3 of sampled air for particle size portions of PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP. In addition, the Aerocet 531S measures temperature and relative humidity.

The temporal resolution for Aerocet 531S was 1 min and the flow operation was at 2.83 L min^{-1}. The instrument can store up to 6000 sample records for three months. Aerocet 531 records were retrieved utilizing Comet Deploy v2.0.4 software by Met One Instruments into MS Excel files. Both instruments (Aerocet 531 and MicroAeth AE51) have been used to determine PM mass and BC concentrations during commuting and in indoor and outdoor micro-environments [36,40–42]. The calibration of the Aerocet 531 and MicroAeth AE51 was performed by the manufacturer.

Before starting the measurements, instruments were manually zeroed. Both monitors were positioned inside a backpack with inlets that were externally connected to the strap. The researcher took a window seat, and the instruments were placed on the researcher's lap with the inlets located at a breathing zone. The locations were tracked utilizing a GPS device (Garmin GPSMAP 78SC).

2.3. Datasets

The seven campaigns (Table 1) in this study were selected according to the sampling convenience; they include: (1) bus trip from Albany to Boston (Figure 1); (2) walk in Boston (Figure 2); (3) bus trip from Boston to Albany; (4) bus trip from Albany to Boston; (5) indoor micro-environment in Boston; and (6) and (7) representing 24 h personal exposure in Albany on different days of the week.

Table 1. Description of the sampling campaigns.

Campaign	Description (Route)	Date (Day/Month/Year)	Time (h:min)	Tot. Time (min)	Length (km)
1	Bus commute from Albany to Boston	7 February 2019	20:48–23:24	156	270
2	Walk in Boston	8 February 2019	16:51–18:25	94	5
3	Bus commute from Boston to Albany	10 February 2019	13:50–18:16	266	270
4	Bus commute from Albany to Boston	15 February 2019	16:15–20:14	239	270
5	Indoors, Boston	16 February 2019	11:25–21:19	594	3
6	Full day personal exposure-1, Albany	6 March 2019–7 March 2019	17:53–15:09	1276	10
7	Full day personal exposure-2, Albany	11 March 2019–12 March 2019	14:45–15:35	1490	8

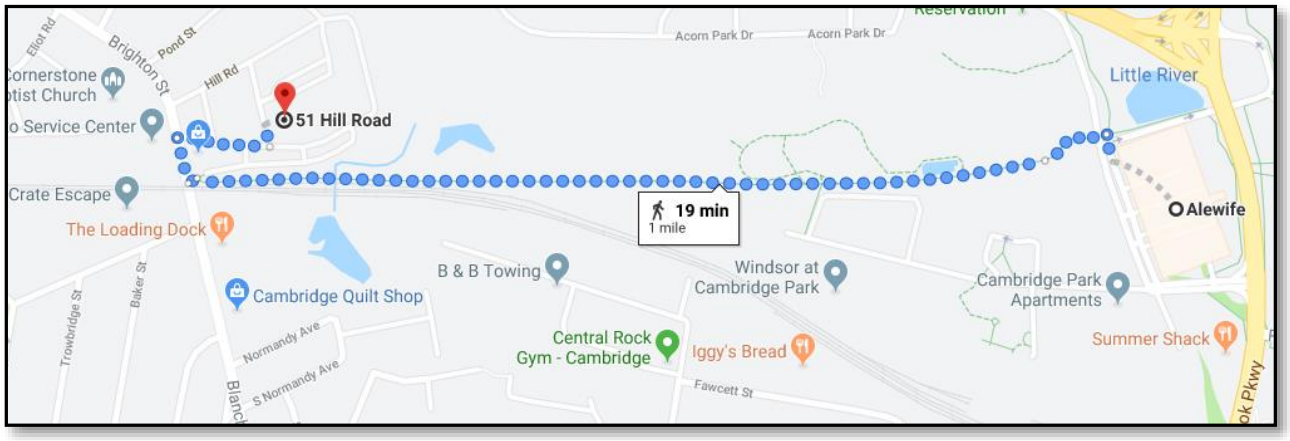


Figure 2. A scehematic diagram of the evening walk route in Boston, Massachussetts. (Source: Google Maps, 2019. Accessed 12 May 2019, Wadsworth Center, Albany, NY 12201-0509).

3. Results and Discussion

3.1. Exposure Concentrations during Long-Haul Journeys

Table 2 summarizes the statistical results of PM (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP) and BC levels during various sampling campaigns. Personal exposure concentrations of size-segregated PM and BC at 1-min resolution were monitored in the bus (Campaigns 1, 3, and 4, Table 1) during the four and a half-hour journey between Albany and Boston (Figure 1). The in-bus pollutant concentrations varied significantly from trip to trip. The highest PM_{10}, $PM_{2.5}$ and PM_1 exposure concentrations were recorded for passengers traveling between Boston and Albany (Campaign 3) followed by Campaigns 4 and 1 (Table 2). Similar patterns were found in the results of PM_4, PM_7, and TSP. The ranges of PM_{10}, $PM_{2.5}$, and PM_1 exposure concentrations were 2.2–1492 $\mu g/m^3$, 1.1–146 $\mu g/m^3$, and 0.2–20 $\mu g/m^3$, respectively. BC, produced by incomplete combustion, is a significant constituent of traffic-associated air pollutants linked with health problems, including cardiopulmonary diseases, cancer, and even birth defects. The highest concentration levels of BC (mean = 5483 $\pm$ 2099 ng/m^3) occurred during the Albany to Boston commute (Campaign 4). Mean PM_{10}, $PM_{2.5}$, PM_1, and BC concentrations during the weekend (Campaign 3) were found to be higher than during the weekday (Campaign 1), mainly due to higher levels of long-haul commuting on Sundays and Fridays.

Table 2. Summary statistics (mean ± SD and range) of exposure concentrations of PM (μg/m^3) and BC (ng/m^3).

Campaign	PM_1	$PM_{2.5}$	PM_4	PM_7	PM_{10}	TSP	BC
1	0.80 ± 0.19 (0.4–1.3)	2.2 ± 0.5 (1.0–3.6)	2.8 ± 0.6 (1.2–5.4)	3.1 ± 1.0 (1.2–13)	3.5 ± 1.8 (1.6–22)	7.0 ± 12 (2.0–137)	474 ± 250 (56–837)
2	1.6 ± 1.9 (0.3–7.8)	15 ± 21 (1.1–69)	25 ± 34 (2.4–115)	28 ± 36 (2.9–122)	30 ± 37 (3.3–125)	37 ± 43 (3.8–140)	1583 ± 1004 (16–3705)
3	2.5 ± 3.3 (0.2–20)	16 ± 26 (1.1–146)	46 ± 79 (1.1–465)	85 ± 144 (1.5–998)	111 ± 193 (2.2–1492)	149 ± 258 (3.8–2220)	959 ± 411 (20–1625)
4	10 ± 2.4 (2.9–16)	30 ± 12 (7.4–64)	37 ± 13 (9–73)	43 ± 15 (11–97)	47 ± 17 (13–112)	57 ± 21 (13–112)	5843 ± 2099 (1038–8791)
5	15 ± 29 (1.2–203)	37 ± 55 (2.5–485)	50 ± 65 (3.1–560)	55 ± 72 (3.7–631)	60 ± 76 (4.1–689)	78 ± 82 (5.5–774)	5965 ± 1774 (2239–8571)
6	2.2 ± 2.3 (0.7–11.4)	10 ± 19 (2.3–107)	20 ± 43 (2.9–317)	28 ± 65 (3.2–568)	32 ± 78 (3.2–732)	38 ± 93 (3.2–907)	1593 ± 2064 (7.0–10408)
7	0.65 ± 0.75 (0.1–13)	2.3 ± 2.7 (0.4–54)	5.5 ± 21 (0.9–789)	16 ± 218 (0.9–8329)	27 ± 434 (0.9–16591)	54 ± 452 (0.9–16789)	179 ± 266 (2.0–2025)

The temporal variability of PM_{10}, $PM_{2.5}$, PM_1, and BC exposure concentrations for long-haul commutes is shown in Table 2. Relatively sharp peaks of PM_{10}, $PM_{2.5}$, and PM_1 were observed near cities, especially at Worcester, MA; Springfield, MA; and Rensselaer, NY (Figure 3), depicting proximity to high rush-hour city traffic volume and its emission sources, which produce PM from the vehicular exhaust and resuspended road dust. The traffic during the commute was variable, which explains sudden spikes and valleys in Figure 3a–c. The bus was almost at full passenger capacity, with inconsistent sampling paradigms (passenger use of restroom, instability in sampling procedures, stopping of bus at non-assigned stops or emergency stops due to road construction) during the commute. The researcher tried maintaining the same sampling conditions as much as was feasible during the whole sampling process during the bus commute. The instantaneous PM_{10}, $PM_{2.5}$, and PM_1 peaks near cities with a concurrent increase in BC concentrations indicated increased traffic density. All the contributions to BC levels were mainly from the diesel exhaust. At Rensselaer, NY, PM_{10}, $PM_{2.5}$, PM_1, and BC peak concentrations were over 1492 μg/m^3 146 μg/m^3, 20 μg/m^3, and 1600 ng/m^3, respectively. On the other hand, forest reserves (Beebe Hill State Forest, NY) exhibited low PM_{10}, $PM_{2.5}$, PM_1, and BC exposure concentrations. This is attributed to the fact that open space and forests facilitate the increased dispersion of pollutants as compared to the near-city environments.

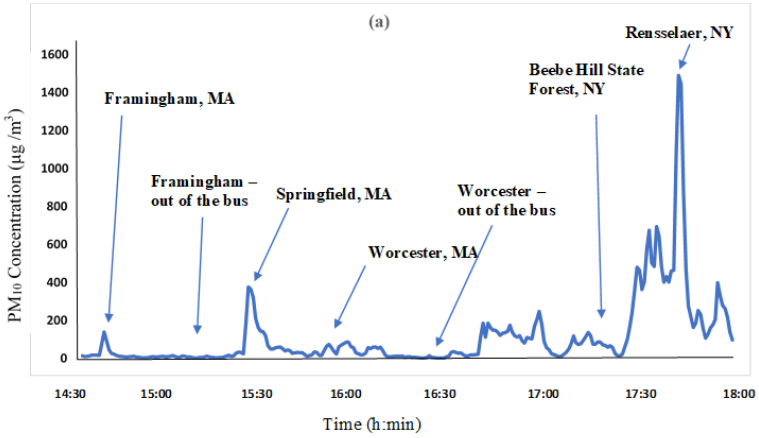


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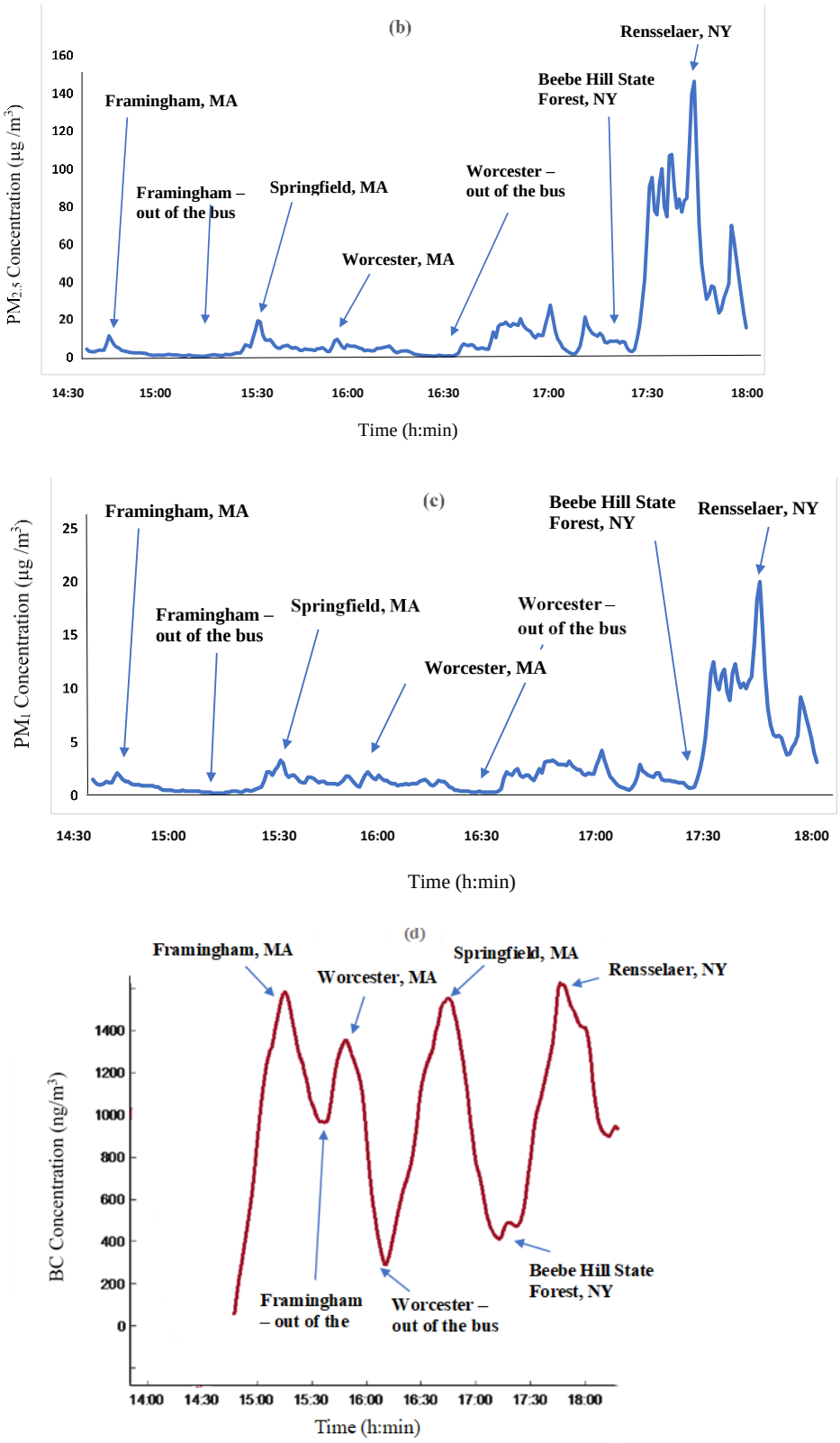


Figure 3. Exposure concentration for a typical bus journey from Boston to Albany during the Campaign: 3 (**a**) PM_{10}, (**b**) $PM_{2.5}$, (**c**) PM_1, and (**d**) BC.

The studies showing poor air quality for bus commuters are scarce. Previously, in Hong Kong [28] and Lisbon [34], exposure levels for PM_{10} and $PM_{2.5}$ buses which were air-conditioned were found to be 74 µg/m^3 and 51 µg/m^3 and 70 ± 82 µg/m^3 and

56 ± 55 μg/m^3, respectively. Praml and Schierl (2000) measured higher PM_{10} concentrations (110–165 μg/m^3) in Munich [27]. The mean $PM_{2.5}$ exposure level in our study (Table 2) was close to that in Sydney (30 μg/m^3; [43]) and London (35 μg/m^3; [44]), though lower compared to the results in Florence (56 μg/m^3; [25]), Mexico City (78 μg/m^3; [45]), and India (77 μg/m^3; [46]), and higher than that detected in Barcelona (25 μg/m^3; [36]). The PM_1 exposure levels in the present work were lower than those obtained in Taipei (31 μg/m^3; [47]) and Shanghai (155 μg/m^3; [48]).

3.2. Concentration Profile during Walk

Figure 4 depicts the evening walk route in Boston, MA. PM and BC exposure concentrations varied significantly along the route. Mean $PM_{2.5}$, PM_{10}, and BC levels were 15 ± 21 μg/m^3, 30 ± 37 μg/m^3, and 1583 ± 1004 ng/m^3, respectively. Higher short-term peaks occurred while walking, as the result of the emissions from neighboring vehicles as well as the re-suspension of the road dust. In our study, the $PM_{2.5}$ and PM_{10} personal-exposure levels of pedestrians were lower than those obtained in London ($PM_{2.5}$ = 27.7–37.7 μg/m^3) [44], Taiwan ($PM_{2.5}$ = 214 μg/m^3) [31], and Guangzhou, China (PM_{10} = 55–78 μg/m^3) [49]. Our BC exposure concentration was lower than the data obtained in Barcelona (5.7 μg/m^3) [36].

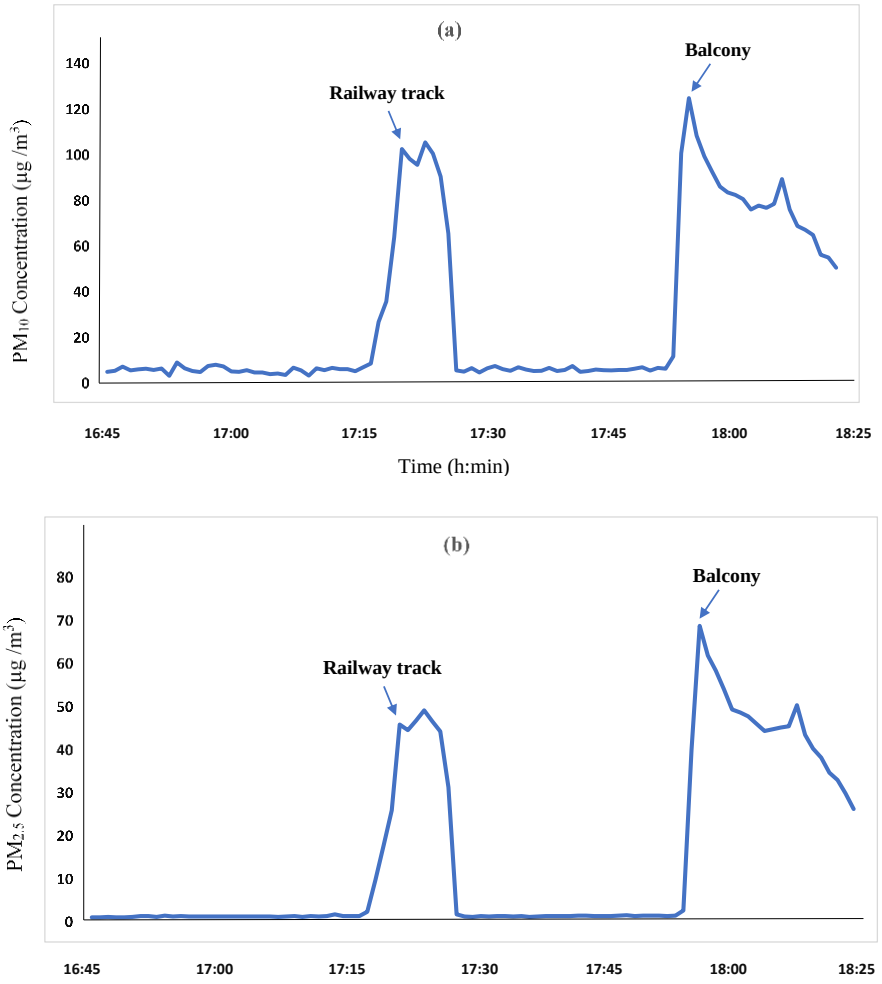


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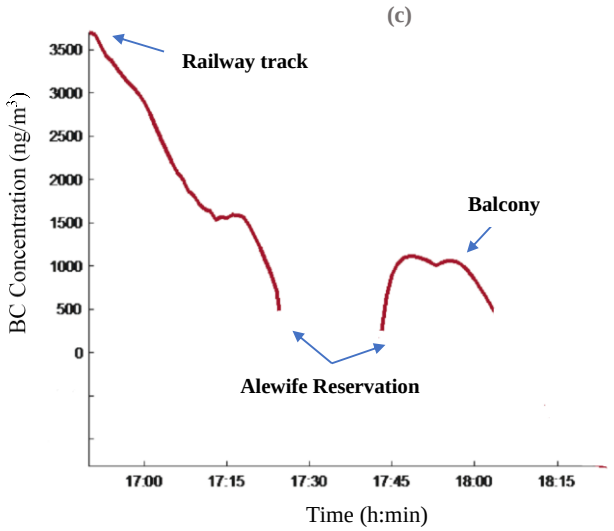


Figure 4. (**a**) PM_{10}, (**b**) $PM_{2.5}$, and (**c**) BC exposure concentrations for a walk in Boston (Campaign 2). Note: MicroAeth AE51 background noise (or negative values) were excluded from BC exposure analysis.

3.3. Differences in Exposure during Different Activities

Taking into consideration the temporal variation, mass concentrations of PM and BC were constantly measured for 2 consecutive 24 h-days in Albany, NY (Campaign 6 and 7; Table 2), covering cooking, vacuuming, commuting, and other activities. The 24 h averaged concentrations of PM_{10}, $PM_{2.5}$, PM_1 and BC during Campaign 7 were 27 ± 434 μg/m^3, 2.3 ± 2.7 μg/m^3, 0.65 ± 0.75 μg/m^3, and 179 ± 266 ng/m^3, respectively (Table 2). There was a significant variation in size-fractionated PM and BC concentrations, which are principally caused by the indoor events (e.g., cooking and cleaning). As seen in Figures 5 and 6, while levels of PM_{10}, $PM_{2.5}$, PM_1, and BC rose sharply during cooking, they fell sharply once it halted. It should be pointed out that the kitchen was ventilated by an exhaust fan during cooking. Concentrations of PM_{10}, $PM_{2.5}$, PM_1, and BC reached as high as 54.2 μg/m^3, 10.4 μg/m^3, 2.7 μg/m^3, and 4222 ng/m^3, respectively, with background values of 20.9 μg/m^3, 1.3, 0.5 μg/m^3 and 235 ng/m^3 for PM_{10}, $PM_{2.5}$, PM_1, and BC (Figures 5 and 6), which was averaged from midnight to 07:30 AM while no activities occurred in the room. Increased episodic exposure due to high levels of PM and BC is to be expected for inhabitants who spend longer time in the kitchen, as cooking can generate airborne PM and BC. Studies have shown that the airborne PM levels are dependent on kitchen type, fuel use, and style of cooking [50–52]. In the current study, another sharp peak associated with increased levels of PM_{10}, $PM_{2.5}$, PM_1, and BC was found due to cleaning. The peak concentrations were 75.4 μg/m^3, 13.3 μg/m^3, 2.4 μg/m^3, and 1766 ng/m^3, respectively. A major source of exposure associated with cleaning is the re-suspension of particulate matter. A carpeted floor increases particle trapping, thereby augmenting the overall PM within a home. Although cooking contributes additional fine fractions, an increase in the coarse fraction was observed during cleaning events. In addition to cooking and cleaning, elevated PM_{10} (173.6μg/m^3), $PM_{2.5}$ (57.9 μg/m^3), PM_1 (8.6 μg/m^3), and BC (2639 and 2278 ng/m^3) concentrations were measured during local bus commutes during the 24 h measurement period (Figures 5 and 6), which can be mainly attributed to the influence of neighboring vehicular emissions and re-suspension of dust generated by roads. The results of our study ($PM_{2.5}$ = 57.9 μg/m^3) indicate that Albany's in-city $PM_{2.5}$ exposure concentrations were found to be lower than those in India (77 μg/m^3) [46] and Mexico (78 μg/m^3) [45].

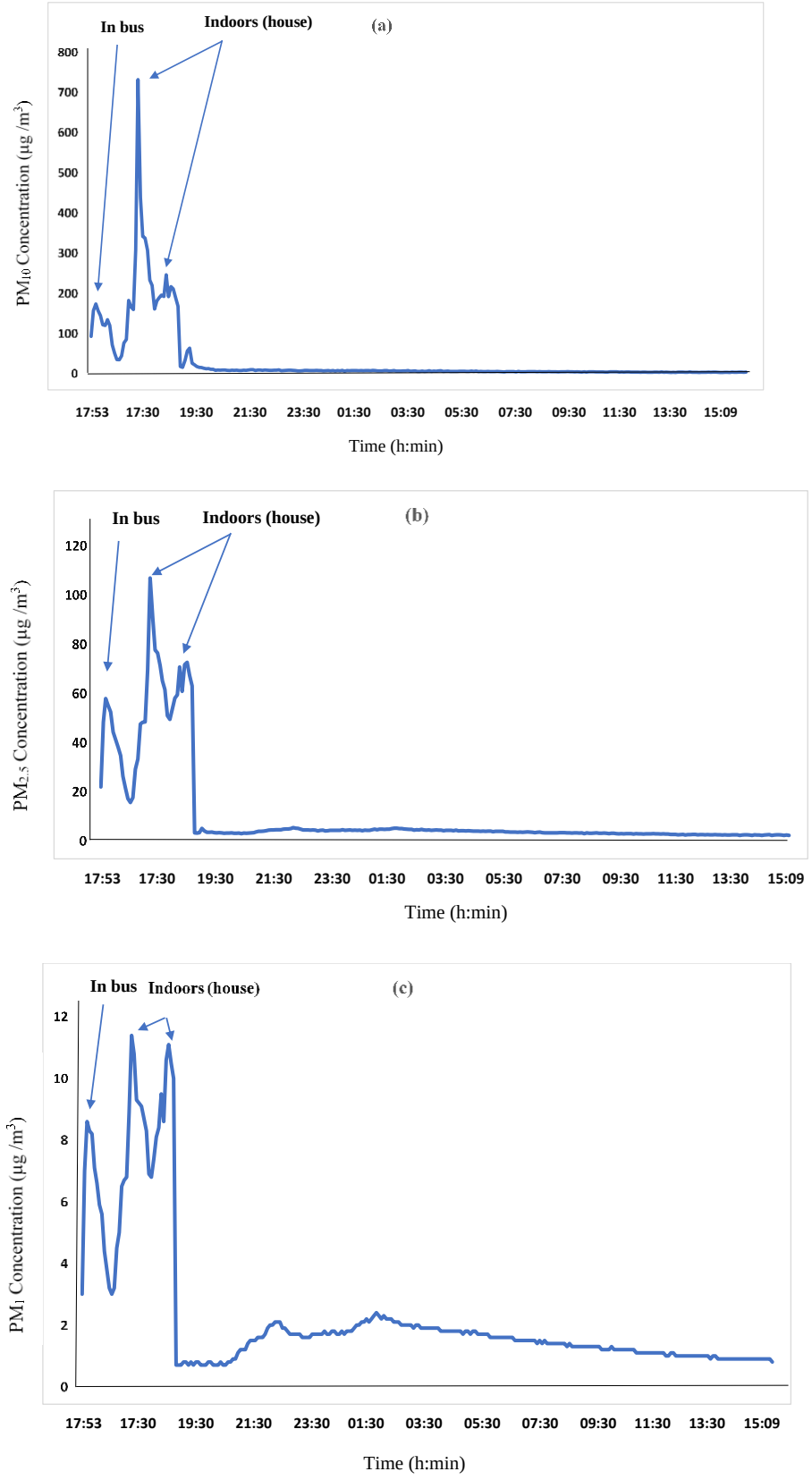


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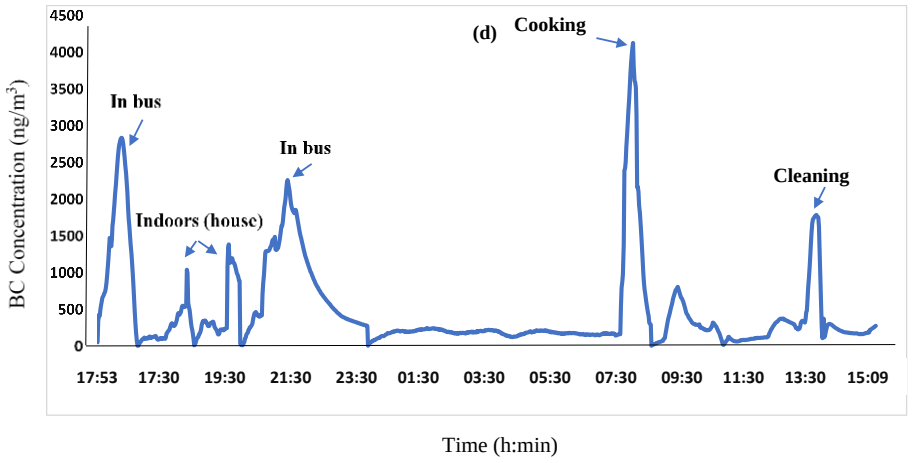


Figure 5. Exposure concentration variations for 24 h in Albany, NY (Campaign 6): (**a**) PM_{10}, (**b**) $PM_{2.5}$, (**c**) PM_1, and (**d**) BC.

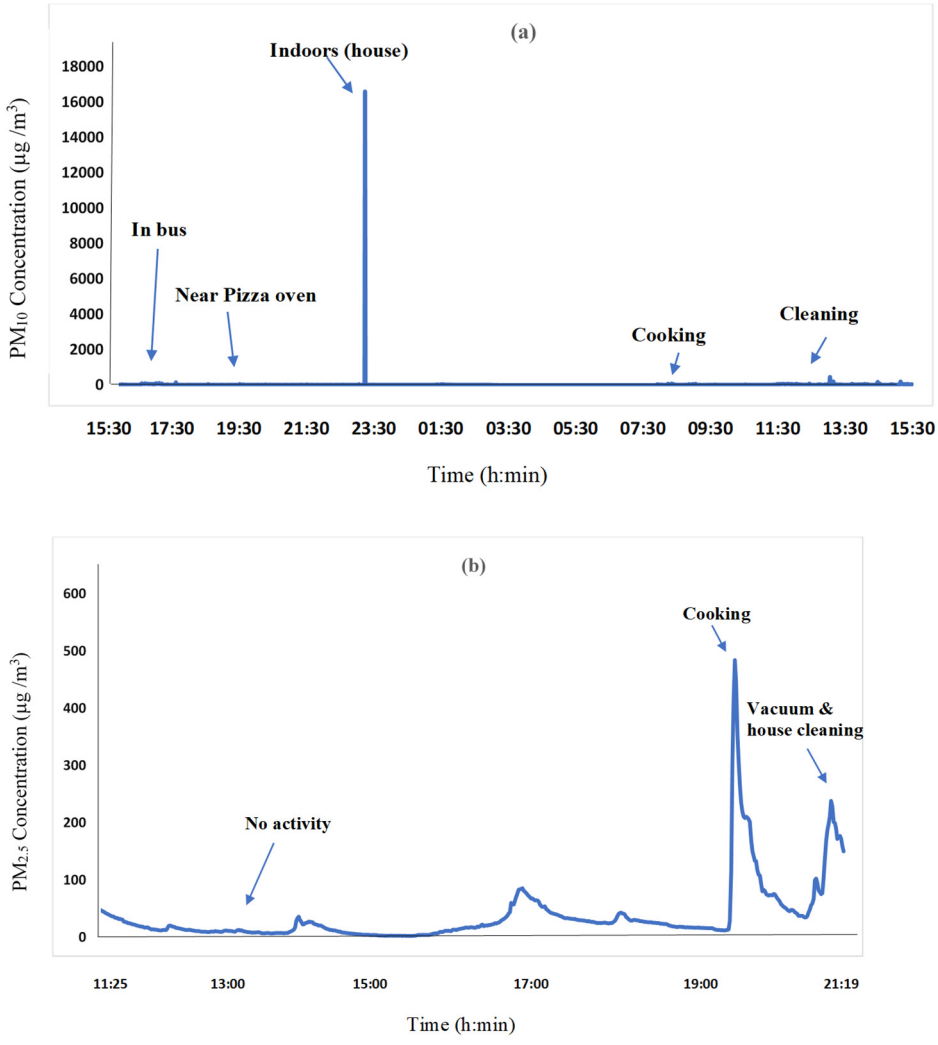


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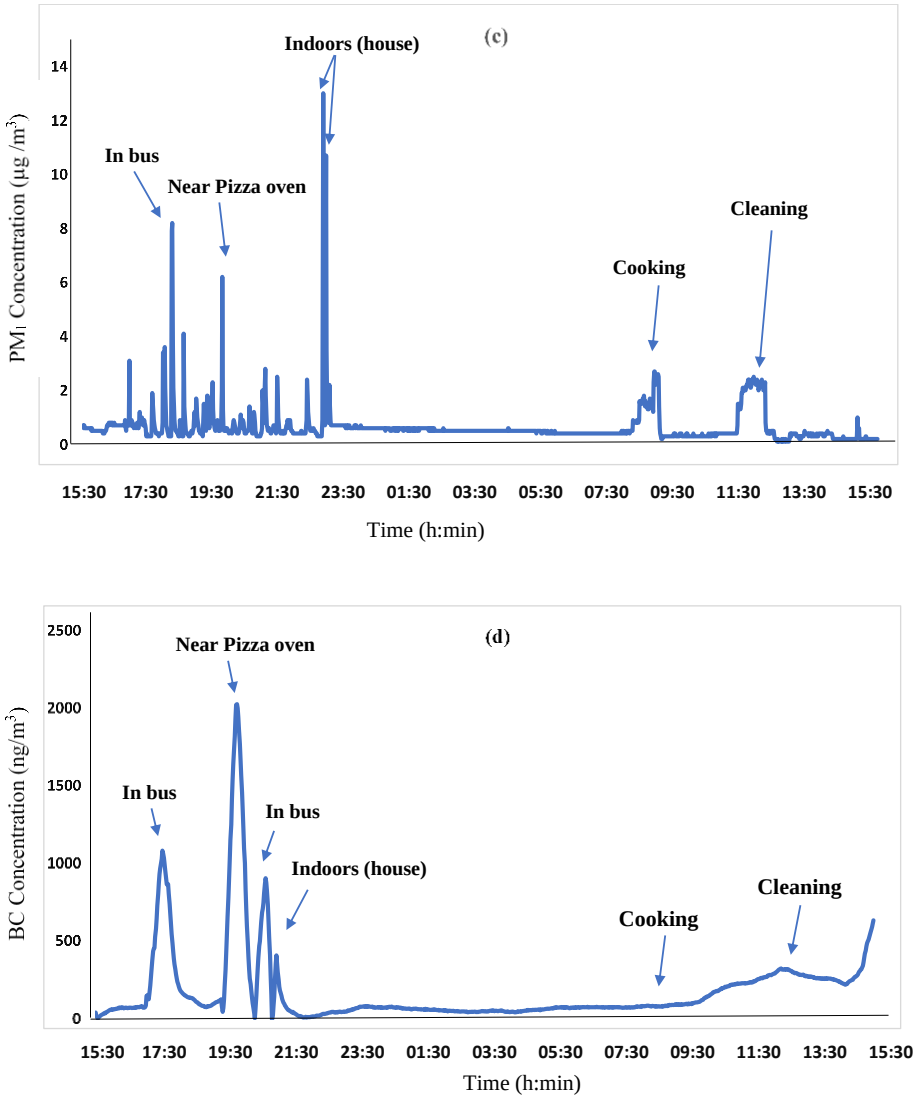


Figure 6. Exposure concentrations variations for 24 h in Albany (Campaign 7): (**a**) PM_{10}, (**b**) $PM_{2.5}$, (**c**) PM_1, and (**d**) BC.

Temporal exposure variations of PM_{10}, $PM_{2.5}$, and PM_1 for in-house in Boston (Campaign 5) are shown in Table 2. The indoor PM_{10}, $PM_{2.5}$, and PM_1 concentrations ranges were 4.1–689 µg/m^3, 2.5–485 µg/m^3, and 1.2–203 µg/m^3, respectively. BC concentration ranged from 2239 to 8571 ng/m^3 with a mean of 5965 ± 1774 ng/m^3 (Table 2). The $PM_{2.5}$ levels in our study were similar to those obtained in-house in the vicinity of city traffic sources elsewhere, e.g., Baltimore, MD (6.7 µg/m^3; [53]), Cincinnati, OH (10.4–30.8 µg/m^3; [54]), Huddersfield, UK (18.9 µg/m^3; [55]), and Amsterdam, Netherlands (25.0 µg/m^3; [56]). Figure 7 illustrates the indoor level of BC (Campaign 5). The BC exposure concentrations in the present study (5965 ± 1774 ng/m^3) were in agreement with other studies involving BC measurements in roadside houses and schools such as Cincinnati, OH (< 1.0 µg/m^3; [54]), Berlin, Germany (2.0 µg/m^3; [57]), and Libby, USA (2.7 µg/m^3; [58]). As expected, PM_{10}, $PM_{2.5}$, PM_1, and BC concentrations spiked during discrete indoor activities (cooking and household cleaning). Cooking was done mainly during the evening (~19:30), and the distinctive levels varied depending on the length of cooking, type of ventilation, and cooking settings in the kitchen. The cooking mainly included dry or fried cooking with moderate use of spices and salt. The inhabitants had the highest $PM_{2.5}$, PM_1 and BC exposures of 485 µg/m^3, 203 µg/m^3, 8571 ng/m^3, respectively, during cooking episodes. The concentration of $PM_{2.5}$ during cooking (485 µg/m^3) was nearly 19 times higher than that during the

non-cooking hours (~25 μg/m^3). Sharp increases in $PM_{2.5}$, PM_1 and BC concentrations of 221, >100, and >8000 ng/m^3, respectively, were recorded during the vacuuming and use of limonene-containing soap for cleaning. An essential plan could be to spread awareness among the general population towards having adequate ventilation, especially during cooking, in order to moderate the exposure to atmospheric pollutants. We would like to caution our readers that factors such as ventilation rates, flooring, opening and closing of windows and doors, and spatial characteristics of indoor micro-environments can affect the sampling process. However, we did not account for these factors as they were beyond the scope of this study.

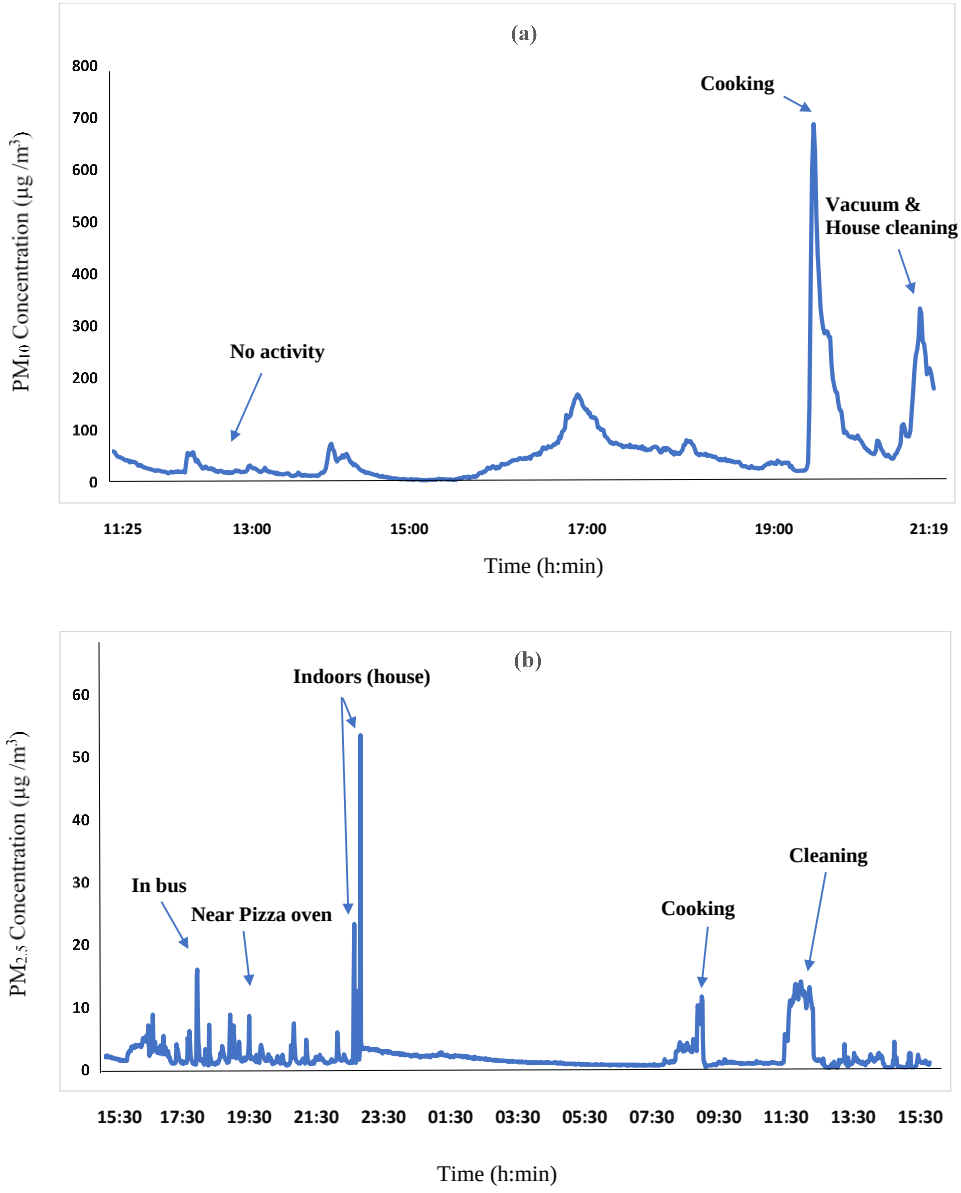


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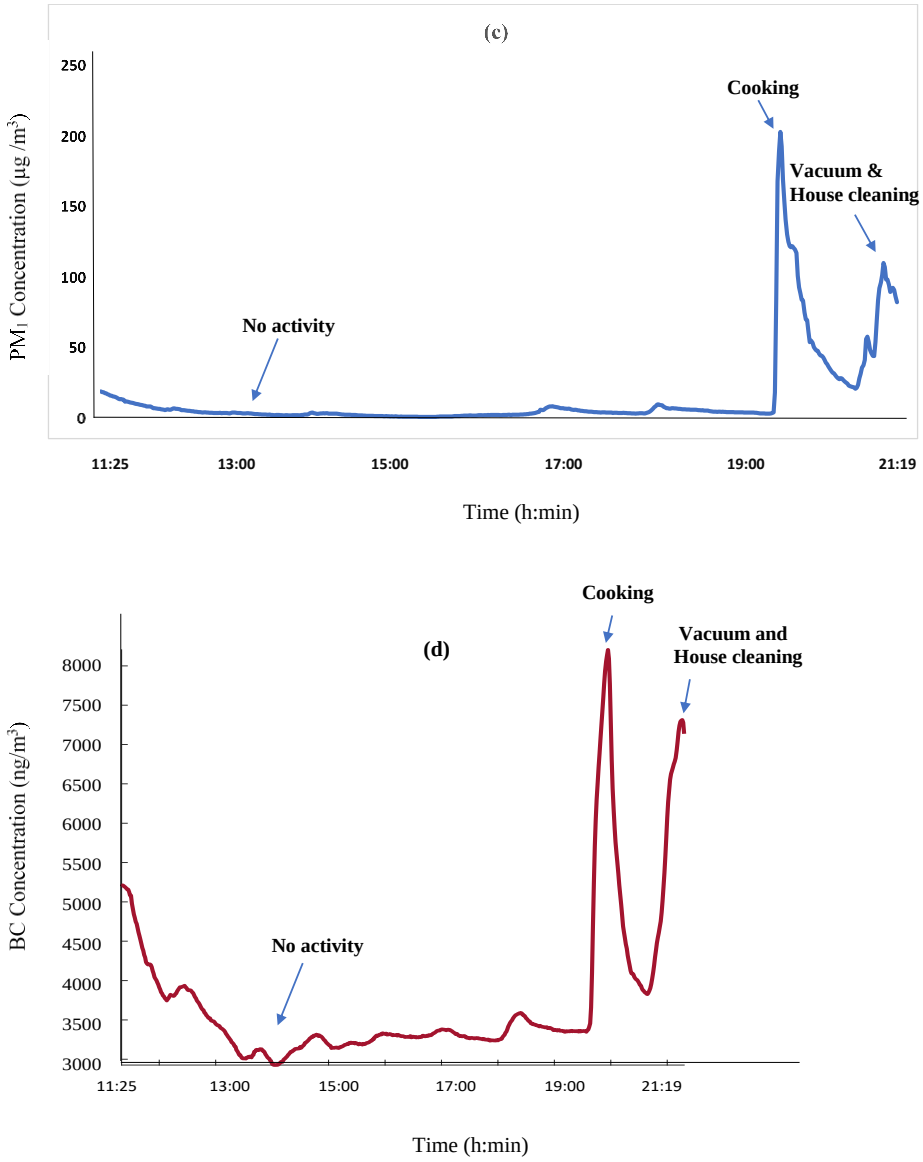


Figure 7. Mass concentration of (**a**) PM_{10}, (**b**) $PM_{2.5}$, (**c**) PM_1, and (**d**) BC inside house in Boston (Campaign 5).

3.4. Inhaled Dose

The average inhaled dose during commutes was estimated using the following equation [59]:

$$\text{Dose } (\mu g/km) = C_i \times V_E \times t/km \quad (1)$$

where, C_i = average concentration of pollutants measured during a trip; V_E = minute ventilation per minute; t = time spent in a trip in minutes; and km = distance of the route in kms. Other pathways of intake were not evaluated. The estimated values for V_E for light-intensity activities (e.g., driving, seated or while standing) and for activities which require high intensity (e.g., cycling) are 13.9 L/min and 55.9 L/min. Since all the activities performed during the study were light-intensity activities, a V_E of 13.96 L/min was used for dose calculation purposes. The dose calculations help to understand the quantity of contaminants that can actually reach the person's body, making them more suitable for understanding the risk associated with consuming contaminated air.

Table 3 presents the estimated inhaled doses for PM segregated by size (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10} and TSP) and BC for the different campaigns. Mean inhalation doses exhibited considerable variances across campaigns (Table 3). Indoor resulted in the highest

inhalation doses of PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP, and BC with mean values of 40.3, 102, 136, 152, 164, 216, and 16.4 μg/km, respectively. The indoor inhalation is higher as the distance travelled is much less compared to other campaigns. Additionally, indoor environments are much more closed micro-environments with less indoor-to-outdoor ventilation, hence, the particulate matter concentrations indoor tend to be elevated compared with outdoor micro-environments. An individual (including both adults and children) spends nearly 90% of their time indoors, in a closed environment, raising a concern for strict measures to monitor and regulate indoor air quality [60]. Compared to commute by bus, pedestrians inhaled higher doses while walking, which was mainly due to four-fold higher ventilation rates, although both the exposure concentrations and travel time while walking were much lower than those for the bus trips. The mean ratio of walking/bus commute inhaled $PM_{2.5}$ and BC doses in our study was higher than those obtained in Barcelona ($PM_{2.5}$ = 1.95, BC = 2.02; [36]) and Ireland ($PM_{2.5}$ = 4.2; [61]). Results of the present work for pedestrian/bus ratio for PM_{10} and PM_1 were in agreement with other personal exposure studies [48,61]. The results suggest that inhaled dose can be strongly influenced by the time spent and distance commuted by an individual in a specific micro-environment. Additionally, internal dose estimation provides vital information about the quantity of contaminants that can actually reach a person's body as compared to measuring contaminant concentration in the air alone. This makes internal dose estimation (with evaluating parameters such as time spent and distance commuted in a specific micro-environment) more suitable for understanding personal exposure associated with consuming polluted air. Hence, exposure and uptake of pollutants is undoubtedly a crucial part through which enhancements in public health could be attained using regulated steps in upcoming years.

Table 3. Estimated inhaled doses for sampling campaigns (μg/km).

Campaign	PM_1	$PM_{2.5}$	PM_4	PM_7	PM_{10}	TSP	BC
1	0.01	0.02	0.02	0.03	0.03	0.06	0.004
2	0.43	3.86	6.5	7.32	7.90	9.67	0.41
3	0.04	0.22	0.63	1.16	1.53	2.05	0.01
4	0.13	0.37	0.46	0.53	0.57	0.70	0.07
5	40.3	102	136	152	164	216	16.4
6	3.95	18.1	35.5	48.8	56.4	68.2	2.83
7	1.69	5.87	14.3	40.7	69.7	139	0.46

4. Conclusions

This study examined the personal exposure to size-fractionated PM and BC during long-haul journeys as well as indoor and outdoor environments. We measured PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP and BC inside buses on a 270 km-long highway segment between two capital cities (Albany, NY and Boston, MA) and evaluated the inhalation doses. Substantial in-bus pollutant level differences were found from trip to trip. Results showed that commuters were exposed to high pollutant levels near cities. The mean ratio of $PM_{2.5}$ to PM_{10} during bus commutes ranged from 62% to 65%. These higher ratios indicate that the ambient air and the air quality in buses is greatly affected by vehicular combustion. A large contrast in mass concentrations of PM and BC was observed between in-bus and walking modes. The inhalation doses from walking were much higher than the doses during bus trips. The mass concentrations of PM_{10}, $PM_{2.5}$, PM_1, and BC fluctuated due to specific indoor activities (cooking and household cleaning) of the inhabitants and peaked at 689 $\mu g/m^3$, 485 $\mu g/m^3$, 203 $\mu g/m^3$, and 4222 ng/m^3, respectively. The strengths of the current study include comparisons of PM and BC for multiple campaigns, ranging from bus commute, walk, and indoor environment. This study is the first of its kind to compare personal exposure between two capital cities, Albany and Boston. However, the study has a few limitations: first, the study is based on convenience personal exposure for a single individual with a single sampling event for each campaign. The results may not be indicative of the exposure on a group level or if the sampling is conducted multiple times

for the same campaign. Secondly, additional factors such as temperature, humidity, indoor factors (ventilation rate and spatial and temporal characteristics), geographic location, and seasons can affect the sampling process on a given day; however, we did not account for these factors as they were beyond the scope of the current study. Thirdly, day and time at which the sampling was performed varies for each campaign. The pollutant concentration may change according to the specific day and time of commute. Therefore, caution should be exercised in generalizing our findings. Nonetheless, the study provides personal exposure concentrations and dose assessment for various modes of commute in Albany and Boston.

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References

1. Loomis, D.; Grosse, Y.; Lauby-Secretan, B.; El Ghissassi, F.; Bouvard, V.; Benbrahim-Tallaa, L.; Guha, N.; Baan, R.; Mattock, H.; Straif, K. The carcinogenicity of outdoor air pollution. *Lancet Oncol.* **2013**, *14*, 1262–1263. [CrossRef]
2. Seaton, A.; MacNee, W.; Donaldson, K.; Godden, D. PM air pollution and acute health effects. *Lancet* **1995**, *345*, 176–178. [CrossRef]
3. Gauderman, W.J.; Gilliland, G.F.; Vora, H.; Avol, E.; Stram, D.; McConnell, R.; Thomas, D.; Lurmann, F.; Margolis, H.G.; Rappaport, E.B.; et al. Association between air pollution and lung function growth in southern California children. *Am. J. Respir. Crit. Care Med.* **2002**, *166*, 76–84. [CrossRef]
4. Li, N.; Xia, T.; Nel, A.E. The role of oxidative stress in ambient PM-induced lung diseases and its implications in the toxicity of engineered nanoparticles. *Free Radic. Biol Med.* **2008**, *44*, 1689–1699. [CrossRef]
5. Kampa, M.; Castanas, E. Human health effects of air pollution. *Environ. Pollut.* **2008**, *151*, 362–367. [CrossRef]
6. Arbex, M.A.; Santos, U.d.P.; Martins, L.C.; Saldiva, P.H.N.; Pereira, L.A.A.; Braga, A.L.F. Air pollution and respiratory system. *J. Bras. Pneumol.* **2012**, *38*, 643–655. [CrossRef]
7. Khwaja, H.A.; Fatmi, A.; Malashock, D.; Aminov, Z.; Siddique, A.; Carpenter, D.O. Effect of air pollution on daily morbidity in Karachi. *J. Local Glob. Health Sci.* **2012**, *3*, 1–13. [CrossRef]
8. Chen, H.; Burnett, R.T.; Kwong, J.C.; Villeneuve, P.J.; Goldberg, M.S.; Brook, R.D.; van Donkelaar, A.; Jerrett, M.; Martin, R.V.; Brook, J.R.; et al. Risk of incident diabetes in relation to long-term exposure to fine PM in Ontario, Canada. *Environ. Health Perspect.* **2013**, *121*, 804–810. [CrossRef]
9. Janssen, N.A.H.; Fondelli, P.; Marra, M.; Ameling, C.; Cassee, F.R. Short-term effects of PM2.5, PM10, and PM2.5–10 on daily mortality in The Netherlands. *Sci. Total Environ.* **2013**, *463*, 20–26. [CrossRef]
10. Jung, C.R.; Lin, Y.T.; Hwang, B.F. Air pollution and newly diagnostic autism spectrum disorders: A population-based cohort study in Taiwan. *PLoS ONE* **2013**, *8*, e75510. [CrossRef]
11. Kloog, I.; Ridgway, B.; Koutrakis, P.; Coull, B.A.; Schwartz, J.D. Long- and short-term exposure to PM2.5 and mortality: Using novel exposure models. *Epidemiology* **2013**, *24*, 555–561. [CrossRef] [PubMed]
12. Tsai, S.S.; Chang, C.C.; Yang, C.Y. Fine PM air pollution and hospital admissions for chronic obstructive pulmonary disease: A case-crossover study in Taipei. *Int. J. Environ. Res. Public Health* **2013**, *10*, 6015–6026. [CrossRef] [PubMed]
13. López-Villarrubia, E.; Iñiguez, C.; Costa, O.; Ballester, F. Acute effects of urban air pollution on respiratory emergency hospital admissions in Canary Islands. *Air Qual. Atmos. Health* **2016**, *9*, 713–722. [CrossRef]
14. Kim, K.H.; Kabir, E.; Kabir, S. A review on the human health impact of airborne PM. *Environ. Int.* **2015**, *74*, 136–143. [CrossRef]
15. Kioumourtzoglou, M.A.; Schwartz, J.D.; Weisskopf, M.G.; Melly, S.J.; Wang, Y.; Dominici, F.; Zanobetti, A. Long-term PM2.5 exposure and neurological hospital admissions in the northeastern US. *Environ. Health Perspect.* **2016**, *124*, 23–29. [CrossRef]

16. Shi, L.; Wu, X.; Yazdi, M.D.; Braun, D.; Awad, Y.A.; Wei, Y.; Liu, P.; Di, Q.; Wang, Y.; Schwartz, J.; et al. Long-term effects of PM2.5 on neurological disorders in the American Medicare population. *Lancet* **2020**, *4*, e557–e565. [CrossRef]
17. Li, A.J.; Pal, V.K.; Kannan, K. A review of environmental occurrence, toxicity, biotransformation and biomonitoring of volatile organic compounds. *Environ. Chem. Ecotoxicol.* **2021**, *3*, 91–116. [CrossRef]
18. Pal, V.K.; Li, A.J.; Zhu, H.; Kannan, K. Diurnal variability in urinary volatile organic compound metabolites and its association with oxidative stress biomarkers. *Sci. Total Environ.* **2021**, *818*, 151704. [CrossRef]
19. Schwartz, J.; Dockery, D.W.; Neas, M.L. Is daily mortality associated specifically with fine particles? *J. Air Waste Manag. Assoc.* **1996**, *46*, 927–939. [CrossRef]
20. Dockery, D.W. Epidemiologic evidence of cardiovascular effects of PM air pollution. Environ. *Health Perspect.* **2001**, *109*, 483–486.
21. Gulliver, J.; Briggs, D.J. Personal exposure to particulate air pollution in transport microenvironments. *Atmos. Environ.* **2004**, *38*, 1–8. [CrossRef]
22. Spinazzé, A.; Cattaneo, A.; Scocca, D.R.; Bonzini, M.; Cavallo, D.M. Multi-metric measurement of personal exposure to ultrafine particles in selected urban microenvironments. *Atmos. Environ.* **2015**, *110*, 8–17. [CrossRef]
23. Schiavon, M.; Rada, E.C.; Ragazzi, M.; Antognoni, S.; Zanoni, S. Domestic activities and PM generation: A contribution to the understanding of indoor sources of air pollution. *Int. J. Sustain. Dev. Plan.* **2015**, *10*, 347–360. [CrossRef]
24. Hou, L.; Barupal, J.; Zhang, W.; Zheng, Y.; Liu, L.; Zhang, X.; Dou, C.; McCracken, J.P.; Díaz, A.; Motta, V.; et al. Particulate Air Pollution Exposure and Expression of Viral and Human MicroRNAs in Blood: The Beijing Truck Driver Air Pollution Study. Environ. *Health Perspect.* **2016**, *124*, 344–350. [CrossRef]
25. Fondelli, M.C.; Chellini, E.; Yli-Tuomi, T.; Cenni, I.; Gasparrini, A.; Nava, S.; Garcia-Orellana, I.; Lupi, A.; Grechi, D.; Mallone, S.; et al. Fine PM concentrations in buses and taxis in Florence, Italy. *Atmos. Environ.* **2008**, *42*, 8185–8193. [CrossRef]
26. Huang, H.; Hsu, D. Exposure levels of PM in long-distance buses in Taiwan. *Indoor Air* **2009**, *19*, 234–242. [CrossRef]
27. Praml, G.; Schierl, R. Dust exposure in Munich public transportation: A comprehensive 4-year survey in buses and trams. *Int. Arch. Occup. Environ. Health* **2000**, *73*, 209–214. [CrossRef]
28. Chan, L.Y.; Lau, W.L.; Lee, S.C.; Chan, C.Y. Commuter exposure to PM in public transportation modes in Hong Kong. *Atmos. Environ.* **2002**, *36*, 3363–3373. [CrossRef]
29. Suárez, L.; Mesías, S.; Iglesias, V.; Silva, C.; Cáceres, D.D.; Rudolph, P.R. Personal exposure to PM in commuters using different transport modes (bus, bicycle, car and subway) in an assigned route in downtown Santiago, Chile. *Environ. Sci. Process Impacts* **2014**, *16*, 1309–1317. [CrossRef]
30. McNabola, A.; Broderick, B.; Gill, L.W. Relative exposure to fine PM and VOCs between transport microenvironments in Dublin: Personal exposure and uptake. *Atmos. Environ.* **2008**, *42*, 6496–6512. [CrossRef]
31. Kaur, S.; Nieuwenhuijsen, M.J.; Colvile, R.N. Fine PM and CO exposure concentrations in urban street transport microenvironments. *Atmos. Environ.* **2007**, *41*, 4781–4810. [CrossRef]
32. Dons, E.; Int Panis, L.; Poppel, M.V.; Theunis, J.; Wets, G. Personal exposure to BC in transport microenvironments. *Atmos. Environ.* **2012**, *55*, 392–398. [CrossRef]
33. Karanasiou, A.; Viana, M.; Querol, X.; Moreno, T.; de Leeuw, F. Assessment of personal exposure to particulate air pollution during commuting in European cities. *Sci. Total Environ.* **2014**, *490*, 785–797. [CrossRef] [PubMed]
34. Ramos, C.A.; Wolterbeek, H.T.; Almeida, S.M. Air pollutant exposure and inhaled dose during urban commuting: A comparison between cycling and motorized modes. *Air Qual. Atmos. Health* **2016**, *9*, 867–879. [CrossRef]
35. Kaur, S.; Nieuwenhuijsen, M.J.; Colvile, R.N. Pedestrian exposure to air pollution along a major road in Central London, UK. *Atmos. Environ.* **2005**, *39*, 7307–7320. [CrossRef]
36. De Nazelle, A.; Fruin, S.; Westerdahl, D.; Martinez, D.; Ripoll, A.; Kubesch, N.; Nieuwenhuijsen, M. Travel mode comparison of commuter's exposures to air pollutants in Barcelona. *Atmos. Environ.* **2012**, *59*, 151–159. [CrossRef]
37. Briggs, D.J.; de Hoogh, K.; Morris, C.; Gulliver, J. Effects of travel mode on exposures to particulate air pollution. *Environ. Int.* **2008**, *34*, 2–22. [CrossRef]
38. Quiros, D.C.; Lee, E.; Wang, R.; Zhu, Y. Ultrafine particle exposures while walking, cycling, and driving along an urban residential roadway. *Atmos. Environ.* **2013**, *73*, 185–194. [CrossRef]
39. Tan, S.H.; Roth, M.; Velasco, E. PM exposure and inhaled dose during commuting in Singapore. *Atmos. Environ.* **2017**, *170*, 245–258. [CrossRef]
40. Kumar, N.; Chu, A.; Foster, A. An empirical relationship between PM2.5 and aerosol optical depth in Delhi Metropolitan. *Atmos. Environ.* **2007**, *41*, 4492–4503. [CrossRef]
41. Yang, F.; Kaul, D.; Wong, K.C.; Westerdahl, D.; Sun, L.; Ho, K.F.; Tian, L.; Brimblecombe, P.; Ning, Z. Heterogeneity of passenger exposure to air pollutants in public transport microenvironments. *Atmos. Environ.* **2015**, *109*, 42–51. [CrossRef]
42. Oladapo, M.; Akinfolarin, O.M.; Boisa, N.; Obunwo, C. Assessment of PM-based Air Quality Index in Port Harcourt, Nigeria. *J. Environ. Anal. Chem.* **2017**, *4*, 2380–2391.
43. Knibbs, L.D.; de Dear, R.J. Exposure to ultrafine and PM2.5 in four Sydney transport modes. *Atmos. Environ.* **2010**, *44*, 3224–3227. [CrossRef]
44. Kaur, S.; Nieuwenhuijse, M.J.; Colvile, R.N. Personal exposure of street canyon intersection users to PM2.5, ultrafine particle counts and CO in Central London, UK. *Atmos. Environ.* **2005**, *39*, 3629–3641. [CrossRef]

45. Gomez-Perales, J.; Colvile, R.N.; Nieuwenhuijsen, M. Commuter's exposure to PM2.5, CO, and benzene in public transport in the metropolitan area of Mexico City. *Atmos. Environ.* **2004**, *38*, 1219–1229. [CrossRef]
46. Kolluru, S.S.R.; Patra, A.K.; Kumar, P. Determinants of commuter exposure to PM2.5 and CO during long-haul journeys on national highways in India. *Atmos. Pollut. Res.* **2019**, *10*, 1031–1041. [CrossRef]
47. Tsai, D.H.; Wu, Y.H.; Chan, C.C. Comparison of commuter's exposure to PM while using different transportation modes. *Sci. Total Environ.* **2008**, *405*, 71–77. [CrossRef]
48. Yu, Q.; Lu, Y.; Xiao, S.; Shen, J.; Li, X.; Ma, W.; Chen, L. Commuter's exposure to PM1 by common travel modes in Shanghai. *Atmos. Environ.* **2012**, *59*, 39–46. [CrossRef]
49. Zhao, L.; Wang, X.; He, Q.; Wang, H.; Sheng, G.; Chan, L.; Fu, J.; Blake, D.R. Exposure to hazardous VOCs, PM10, and CO while walking along streets in urban Guangzhou. *Atmos. Environ.* **2004**, *38*, 6177–6184. [CrossRef]
50. Chao, Y.H.; Tung, C.W.; Burnett, J. Influence of different indoor activities on the indoor PM levels in residential buildings. *Indoor Built Environ.* **1998**, *7*, 110–121. [CrossRef]
51. Parikh, J.; Balakrishnan, K.; Laxmi, V.; Biswas, H. Exposure from cooking with biofuels: Pollution monitoring and analysis for rural Tamil Nadu. *Energy* **2001**, *26*, 949–962. [CrossRef]
52. Lee, S.C.; Li, W.M.; Ao, C.H. Investigation of indoor air quality at residential homes in Hong Kong—Case study. *Atmos. Environ.* **2002**, *36*, 225–237. [CrossRef]
53. Landis, M.S.; Norris, G.A.; Williams, R.W.; Weinstein, J.P. Personal exposures to PM2.5 mass and trace elements in Baltimore, MD, USA. *Atmos. Environ.* **2001**, *35*, 6511–6524. [CrossRef]
54. Martuzevicius, D.; Grinshpun, S.A.; Lee, T.; Hu, S.; Biswas, P.; Reponen, T.; LeMasters, G. Traffic-related PM2.5 aerosol in residential houses located near major highways. *Atmos. Environ.* **2008**, *42*, 6575–6585. [CrossRef]
55. Kingham, S.; Briggs, D.; Elliott, P.; Fischer, P.; Lebret, E. Spatial variations in the concentrations of traffic-related pollutants in indoor and outdoor air in Huddersfield. *Atmos. Environ.* **2000**, *34*, 905–916. [CrossRef]
56. Fischer, P.; Hoek, G.; Van Reeuwijk, H.; Briggs, D.; Lebret, E.; Van Wijnen, J.; Kingham, S.; Elliott, P. Traffic-related differences in outdoor and indoor concentrations of particles and VOCs in Amsterdam. *Atmos. Environ.* **2000**, *34*, 3713–3722. [CrossRef]
57. Fromme, H.; Lahrz, T.; Hainsch, A.; Oddoy, A.; Piloty, M.; Ruden, H. Elemental carbon and respirable PM in the indoor air of apartments and nursery schools and outdoor air in Berlin (Germany). *Indoor Air.* **2005**, *15*, 335–341. [CrossRef]
58. Ward, T.J.; Noonan, C.W.; Hooper, K. Results of an indoor size fractionated PM school sampling program in Libby. *Environ. Monit. Assess.* **2007**, *130*, 163–171. [CrossRef]
59. U.S. EPA—Environmental Protection Agency. *Exposure Factors Handbook 1*; Office of Research and Development: Washington, DC, USA, 1997; p. 95.
60. Dunton, G.F.; Do, B.; Wang, S.D. Early effects of the COVID-19 pandemic on physical activity and sedentary behavior in children living in the U.S. *BMC Public Health* **2020**, *20*, 1351. [CrossRef]
61. Nyhan, M.; McNabola, A.; Misstear, B. Comparison of PM dose and acute heart rate variability response in cyclists, pedestrians, bus and train passengers. *Sci. Total Environ.* **2014**, *468*, 821–831. [CrossRef]