Case Report

Estimation of the Inhaled Dose of Airborne Pollutants during Commuting: Case Study and Application for the General Population

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Received: 13 July 2020; Accepted: 18 August 2020; Published: 20 August 2020

Abstract: During rush hours, commuters are exposed to high concentrations and peaks of traffic-related air pollutants. The aims of this study were therefore to extend the inhaled dose estimation outcomes from a previous work investigating the inhaled dose of a typical commuter in the city of Milan, Italy, and to extend these results to a wider population. The estimation of the dose of pollutants inhaled by commuters and deposited within the respiratory tract could be useful to help commuters in choosing the modes of transport with the lowest exposure and to increase their awareness regarding this topic. In addition, these results could provide useful information to policy makers, for the creation/improvement of a mobility that takes these results into account. The principal result outcomes from the first part of the project (case study on a typical commuter in the city of Milan) show that during the winter period, the maximum deposited mass values were estimated in the “Other” environments and in “Underground”. During the summer period, the maximum values were estimated in the “Other” and “Walking (high-traffic conditions)” environments. For both summer and winter, the lowest values were estimated in the “Car” and “Walking (low-traffic conditions)” environments. Regarding the second part of the study (the extension of the results to the general population of commuters in the city of Milan), the main results show that the period of permanence in a given micro-environment (ME) has an important influence on the inhaled dose, as well as the pulmonary ventilation rate. In addition to these results, it is of primary importance to report how the inhaled dose of pollutants can be strongly influenced by the time spent in a particular environment, as well as the subject’s pulmonary ventilation rate and pollutant exposure levels. For these reasons, the evaluation of these parameters (pulmonary ventilation rate and permanence time, in addition to the exposure concentration levels) for estimating the inhaled dose is of particular relevance.

Keywords: pollution; PM; commuting; travel mode; active transportation; micro-environment; risk assessment; pulmonary ventilation rate

1. Introduction

The association between traffic-related air pollution and health is well recognized and reported in the literature, from both epidemiological and toxicological studies [1]: these chemical factors may affect human health, especially in urban areas, representing hotspots of traffic emissions. In particular, exposure to air pollutants in traffic environments has been related to long- and short-term cardiovascular and respiratory effects [2]. During rush hours, commuters are exposed to high concentrations of...
traffic-related air pollutants [3], usually exceeding air quality standards [4]. Moreover, commuting in rush hours may have the potential to disproportionately contribute to daily exposures, despite the time spent in them being reduced on average to 1.5–2 h per day [4–6]. For these reasons, many studies have been conducted in several cities: the results generally show that motorists and public transport commuters are exposed to higher pollutant levels than cyclists and pedestrians [7]. Contrariwise, due to the high pulmonary ventilation rate measured in active commuting, cyclists and pedestrians may inhale a higher dose of pollutants, despite lower exposure [8]. In recent years, it has been suggested that assessing the health impact in transport micro-environments (MEs) by only considering the exposure to environmental pollutant concentrations is not entirely representative of personal exposure: the use of the inhaled pollutant dose may be one of the most interesting parameters to explore to complete the fundamental information brought by exposure assessment.

The aims of this study were therefore to further elaborate, using the multiple-path particle dosimetry model for the estimation of the deposited particulate matter (PM) mass in the different regions of the respiratory tract (i.e., head, tracheobronchial and pulmonary [9]) and extending the results to the general commuter population of Milan, the results obtained in a previous study [10] investigating the exposure to airborne pollutants and the inhaled dose of a typical commuter in the city of Milan, Italy. The objective was to extend the results to a wider population (commuters within the Milan metropolitan area, one of the most polluted across Europe); for this purpose, the exposure levels measured in the breathing zone of a typical commuter were associated with the average residence times spent within the various transit MEs by the evaluated population.

Briefly, the previous study [10], on which this work is based, aimed to evaluate the exposure of commuters to different pollutants (nitrogen dioxide (NO$_2$) and fractionated particulate matter (PM), including ultrafine particles (UFPs)) using miniaturized and portable real-time monitoring instruments in selected MEs. In particular, measurements were performed along a typical commuter route, considering different traffic and non-traffic MEs. Principal results show that higher exposure levels were measured in Underground (for all PM fractions and NO$_2$) and in the Car (UFP), while lower exposure levels were measured in Car (PM and NO$_2$) and in Train (UFP).

The present study was therefore performed to evaluate in greater depth the issue of the pollutants inhaled dose in different MEs, first investigating the deposition of different fractions of PM in the respiratory tract, and then extending the results to the general population of Milan.

2. Materials and Methods

2.1. Study Design and Instrumentation

This study was based on data collected during a monitoring campaign conducted in winter and summer 2019, the methods of which are presented elsewhere [10]. Briefly, to simulate a typical home-to-work (and return) commuter route, a fixed route was defined a priori from a Lombardy provincial city to the Milan city center, the largest city in the region and one of the most populous metropolitan cities in Europe (Figure 1).

With the intent to analyze (i) the exposure concentration and the (ii) dose of selected pollutants inhaled by the subjects (and to estimate the dose inhaled by the general population) in different transit MEs typically frequented by commuters, the environments were divided as follows: Walking (in low-traffic (LT) and high-traffic (HT) conditions), Bike, Car, Underground, Train, Indoor (office), and Other MEs (defined as the transition period (2 min) while moving from one environment to another). Car ventilation (e.g., ventilation intensity, windows closed) was maintained in constant conditions during all journeys [11]. The residence times (min) and the route length (km) of the different MEs are reported in Table 1.
The continuous determination of size-fractionated PM (PM$_{1}$, PM$_{2.5}$, PM$_{4}$, and PM$_{10}$) concentrations was performed using a portable direct-reading monitor (Aerocet 831-Met One Instrument Inc., Grant Pass, Oregon, USA), worn by one of the authors (G.F.) using a backpack. PM$_{2.5}$ samples were also collected using a GK2.05 sampler (BGI Inc., Waltham, MA, USA), operated with a sampling pump with a flow rate equal to 4 L/min; particles were collected using polytetrafluoroethylene filters. The mass concentration was determined by gravimetric analysis following a standard reference method [12,13] and previous studies [14–16]. Gravimetric data were used to correct the PM data acquired via the direct-reading instrument by calculating a daily correction factor applied a posteriori to the whole PM dataset [17].

2.2. Estimation of the Inhaled Dose

In this study, the estimation of the inhaled doses of different PM fractions for (i) a selected subject and for (ii) the general commuter population in the city of Milan was performed. The dose estimation for the selected subject (in good physical condition and aged 30 years) study was carried out...
using the MPPD V.3.04 (multiple-path particle dosimetry) [18] model, using the Yeh–Shum symmetric model for humans. The default physiological parameters (breathing frequency: 12 breaths/min; tidal volume: 625 mL; inspiration fraction: 0.5; pause fraction: 0) were entered for the model computation. The deposition fraction in the respiratory tract (reported for the pulmonary, tracheobronchial, and upper airways, as well as the total) was used to estimate the PM mass (µg) inhaled by the subject, following Equation (1):

$$\text{Deposited mass: } DF \times C \times t \times V \quad (1)$$

Equation (1). Estimation of the inhaled dose (µg). DF: deposition fraction (estimated via MPPD V.3.04 model); C: exposure concentration (µg/m³) (measured during the monitoring campaign); t: time spent in a particular ME (h) (registered using a time activity diary); V: subject minute ventilation (m³/h) (measured during the monitoring campaign).

Equation (2) was used to estimate the dose inhaled by the general commuter population [19]:

$$\text{Inhaled Dose: } C \times t \times VE \quad (2)$$

Equation (2). Inhaled dose estimation (µg). C: exposure concentration (µg/m³); t: time spent in a particular ME (min); VE: pulmonary ventilation rate (m³/min).

In this study, Equation (2) was used to estimate the dose inhaled by the general population (according to gender, time spent in a particular ME, ME, moment of the day and season) while commuting in different transit MEs. In particular, the exposure concentration data refer to those acquired in the case study [10], the values of residence times (15, 30, 30 and 90 min), as well as the MEs visited by the subject and the gender, were acquired from the most recent Italian census (ISTAT—Istituto Nazionale di Statistica (2011), available at [20]), while the pulmonary ventilation rates, selected for women and men, refer to values reported in the literature [21]. In particular, “light activity levels” were selected for passive commuting (38.2 ± 2.4 L/min and 31.0 ± 4.1 L/min for men and women, respectively) and “moderate activity levels” for active commuting, such as cycling and walking (73.5 ± 4.8 L/min and 63.7 ± 7.7 L/min for men and women, respectively). The inhalation dose data were also processed according to the period of the day (morning: to work/evening: homeward) and to the season (summer/winter), starting from the exposure data obtained from the monitoring campaign.

For the calculations, the commuting period results from the ISTAT database were selected by considering the most similar commuting period (8:15–9:15 a.m.) to the study design, applied also for the evening return to home and for both the summer and winter periods (even if the commuting patterns could change over seasons).

Data were analyzed using the Statistical Package for the Social Sciences Statistic version 20.0 (IBM, Armonk, NY, USA), and a significance level of 0.05 was used in all statistical tests.

3. Results and Discussions

3.1. Case Study

Table 2 reports the mass (µg) of size-fractionated PM deposited in different sections of the respiratory tract, as a function of the season.

Figure 2 shows the PM mass (µg) deposited in the respiratory tract, estimated for the summer and winter periods. As reported in the figure, the PM deposited mass was higher during the winter period for all PM fractions, even if the differences between the estimates for summer and winter were minimal (<1 µg for PM₁, PM₂.₅, and PM₄; >2 µg for PM₁₀). Moreover, the mass deposited in the upper airways (H) contributed significantly to the mass deposited in the whole airways (total) for both summer and winter (47% for PM₁, 62% for PM₂.₅, 74% for PM₄, and 96% for PM₁₀, on average).

Regarding the estimation of the PM deposited mass as a function of the ME visited by the commuter, as reported in Table 3, and considering the total mass deposited in the entire respiratory tract, for the winter period the maximum values were estimated in the “Other” environments and in “Underground”,
for all the PM fractions considered, followed by the “Indoor” and the “Walking (LT)” environments. The lowest values were estimated in the “Car” and “Walking (LT)” environments. For the summer period, the maximum values were estimated in the “Other” and “Walking (HT)” environments. As during the winter, the lowest values were found in the “Car” and “Walking (LT)” environments. For the summer period, the maximum values were estimated in the “Other” environments and in the “Walking (HT)” environments. The lowest values were estimated in the “Car” and “Walking (LT)” environments. The lowest values were estimated in the “Car” and “Walking (LT)” environments. The lowest values were estimated in the “Car” and “Walking (LT)” environments. The lowest values were estimated in the “Car” and “Walking (LT)” environments. The lowest values were estimated in the “Car” and “Walking (LT)” environments. The lowest values were estimated in the “Car” and “Walking (LT)” environments.

**Table 2.** Particulate matter (PM) mass values (µg) deposited in the respiratory tract during the monitoring period (8:00 a.m. to 3:00 p.m.) (sections: H: head; TB: tracheobronchial; P: pulmonary; total: H + TB + P).

| Season  | Pollutant | H    | TB   | P    | Total |
|---------|-----------|------|------|------|-------|
| **Summer** | PM₁      | 0.76 | 0.29 | 0.57 | 1.62  |
|         | PM₂₅     | 3.17 | 0.56 | 1.35 | 5.07  |
|         | PM₄       | 5.60 | 0.74 | 1.26 | 7.60  |
|         | PM₁₀      | 11.24| 0.41 | 0.08 | 11.73 |
| **Winter** | PM₁      | 0.87 | 0.33 | 0.66 | 1.87  |
|          | PM₂₅     | 3.94 | 0.69 | 1.68 | 6.31  |
|          | PM₄       | 7.29 | 0.96 | 1.64 | 9.89  |
|          | PM₁₀      | 15.80| 0.58 | 0.12 | 16.50 |

**Figure 2.** PM deposited mass (µg) in the respiratory tract (H: head; TB: tracheobronchial; P: pulmonary; total: H + TB + P). Black: PM₁; Blue: PM₂₅; Green: PM₄; Yellow: PM₁₀.

**Table 3.** PM deposited mass (µg) in the respiratory tract (H: head; TB: tracheobronchial; P: pulmonary; total: H + TB + P) estimated across the micro-environments (MEs) visited by the commuter.

| ME       | Winter          | Summer         |
|----------|-----------------|----------------|
|          | Head | TB  | P    | Total | Head | TB  | P    | Total |
| PM₁      |      |     |      |       |      |     |      |       |
| Walking (LT) | 1.233 | 0.217 | 0.524 | 1.975 | 1.400 | 0.246 | 0.595 | 2.241 |
| Walking (HT) | 6.039 | 1.061 | 2.568 | 9.668 | 6.256 | 1.099 | 2.660 | 10.016 |
| Bike     | 2.961 | 0.520 | 1.259 | 4.741 | 1.929 | 1.393 | 0.882 | 3.104 |
| Car      | 0.923 | 0.162 | 0.393 | 1.478 | 0.553 | 0.097 | 0.235 | 0.885 |
| Underground | 10.966 | 1.927 | 4.662 | 17.555 | 3.207 | 0.563 | 1.363 | 5.134 |
| Train    | 2.496 | 0.439 | 1.061 | 3.995 | 2.021 | 0.355 | 0.859 | 3.236 |
| Indoor   | 4.048 | 0.711 | 1.721 | 6.480 | 3.427 | 0.602 | 1.457 | 5.486 |
| Other    | 11.023 | 1.937 | 4.687 | 17.647 | 8.702 | 1.529 | 3.700 | 13.930 |
A problem stated by the scientific literature regards the lack of data to provide a systematic basis for comparing the exposure concentrations in different transportation modes, due to different sources of variability (i.e., period of the day, season, and location) [22]. As stated by the authors, indeed, transportation mode exposure concentrations can vary in accordance with these environmental factors (i.e., season and time of day), which are related to atmospheric stability and pollutant dispersion. Moreover, exposure concentration levels in different transportation modes may be affected by the traffic flow, by proximity to emissions hotspots, and by emissions from other vehicles [11,23]. For example, Frey and collaborators, in their recent paper, reported how PM$_{2.5}$ exposure concentration levels are sensitive firstly to the mode of transport, followed by the time of the day and by the monitoring season [22].

Not considering the “Other” environment (as it is difficult to characterize, since it includes all the periods of transition while moving from one ME to another), for the winter period the highest values of PM deposited mass were estimated in the “Underground”, “Indoor”, and “Walking (HT)” environments. Although the time spent in the “Underground” environment was small (0.4 h) and the estimated subject ventilation rate was moderate (0.66 m$^3$/h), this environment was characterized by the highest PM exposure concentrations [10], probably due to the presence of indoor PM sources (e.g., abrasion of rails, wheels, and brakes and resuspension of particles) [4]. Conversely, the time spent in the “Indoor” environment, due to the study design, was the highest among the investigated environments (>1.5 h). Finally, in the “Walking (HT)” environment, we measured the highest pulmonary ventilation rate values (1.30 m$^3$/h); this could justify the high inhaled dose of pollutants in this environment. During the summer, the “Walking (HT)” environment was the environment characterized by the highest PM deposited mass values, due to the combination of a high subject pulmonary ventilation rate (1.30 m$^3$/h) and high exposure concentration levels. During both winter and summer, the mass deposited values were lower in the “Car” and “Walking (LT)” environments; this can be justified by the reduced permanence time in these environments (<20 min for the “Walking (LT)” environment and <1 h for the “Car” environment).

These results show how the different factors taken into account for the calculation of the inhaled dose (i.e., exposure concentration, time spent in a particular environment, and lung ventilation rate) can contribute significantly to the PM deposited mass. Even if not specifically performed in this study, a sensitivity analysis was carried out by the authors in a similar study conducted in the city of Milan; the principal results show how the parameters having a major impact on the inhaled dose are the time spent in a ME and personal exposure levels. In this case, VE seems to have a low impact on the inhaled dose, both for MEs and kinds of pollutants [24].

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### Table 3. Cont.

| ME                  | Winter | Summer |
|---------------------|--------|--------|
|                     | Head   | TB     | P      | Total  | Head   | TB     | P      | Total  |
| PM$_4$              |        |        |        |        |        |        |        |        |
| Walking (LT)        | 2.189  | 0.287  | 0.494  | 2.971  | 2.454  | 0.322  | 0.554  | 3.329  |
| Walking (HT)        | 11.457 | 1.504  | 2.585  | 15.546 | 11.028 | 1.448  | 2.489  | 14.964 |
| Bike                | 5.814  | 0.763  | 1.312  | 7.889  | 3.509  | 0.461  | 0.792  | 4.761  |
| Car                 | 1.510  | 0.198  | 0.341  | 2.049  | 0.930  | 0.122  | 0.210  | 1.261  |
| Underground         | 21.110 | 2.771  | 4.764  | 28.644 | 6.103  | 0.801  | 1.377  | 8.281  |
| Train               | 4.311  | 0.566  | 0.973  | 5.850  | 3.337  | 0.438  | 0.753  | 4.528  |
| Indoor              | 7.425  | 0.975  | 1.676  | 10.076 | 5.968  | 0.783  | 1.347  | 8.099  |
| Other               | 20.145 | 2.644  | 4.546  | 27.335 | 3.549  | 1.377  | 8.281  | 21.342 |
| PM$_{10}$           |        |        |        |        |        |        |        |        |
| Walking (LT)        | 5.857  | 0.214  | 0.043  | 6.114  | 5.355  | 0.196  | 0.039  | 5.590  |
| Walking (HT)        | 26.306 | 0.963  | 0.193  | 27.462 | 22.228 | 0.814  | 0.163  | 23.204 |
| Bike                | 13.825 | 0.506  | 0.101  | 14.432 | 7.196  | 0.263  | 0.053  | 7.513  |
| Car                 | 2.524  | 0.092  | 0.018  | 2.635  | 1.609  | 0.059  | 0.012  | 1.679  |
| Underground         | 44.346 | 1.624  | 0.325  | 46.295 | 12.666 | 0.464  | 0.093  | 13.223 |
| Train               | 8.973  | 0.329  | 0.066  | 9.367  | 6.418  | 0.235  | 0.047  | 6.700  |
| Indoor              | 16.018 | 0.586  | 0.117  | 16.722 | 11.533 | 0.422  | 0.084  | 12.039 |
| Other               | 42.550 | 1.558  | 0.312  | 44.420 | 31.820 | 1.165  | 0.233  | 33.218 |
In general, a previous study [7] suggests how the inhaled dose of pollutants is higher during active commuting compared to motorized trips: this can be explained by the subjects’ increased minute ventilation. Another study [25] indicates that, although exposure levels are low during walking trips, pulmonary ventilation rates are generally higher if compared to other MEs; for this reason, it is particularly important to consider both variables for the estimation of the inhaled dose (e.g., exposure concentrations and ventilation rate). It should be noted that the scientific literature also reports that the residence time is an important factor to consider in the inhaled dose estimation, as well as the pulmonary ventilation rate. In fact, active transport (walking and cycling) is characterized by higher exposure levels and inhaled doses of PM$_{2.5}$ than other transport modes on a comparable trip [3,19].

3.2. General Population

Estimation of the pollutant inhaled dose was carried out on a commuter population that usually travels in the city of Milan using the methodology described in paragraph 2.2. The estimated values of the inhaled dose of size-fractionated PM segregated by ME, time spent commuting, and gender are reported in Table 4. These data were further subdivided according to the season (summer/winter) and the commuting period of the day (morning/afternoon). As expected, Table 4 shows how the period of permanence in each ME impacts on the inhaled dose. Furthermore, as previously discussed, higher values of inhaled doses of PM were estimated during active commuting (“Cycling” and “Walking”), due to the increased pulmonary ventilation rate. In addition, due to the lower pulmonary ventilation rate in women, it seems that women inhale a lower dose of pollutants, although there is no statistically significant difference between the inhaled doses of pollutants between women and men ($p > 0.05$ for all PM fractions; Mann–Whitney $U$ test, performed after checking the normality—resulting neither normally nor log-normally distributed—of the data distribution via Kolmogorov–Smirnov test).

Statistically significant differences ($p < 0.05$) were not found by comparing the two monitoring periods (morning/afternoon) but as expected, occurred as a function of the considered ME.

Following the literature [11], the non-parametric Kruskal–Wallis test was used to assess the differences (in terms of inhaled dose) among the MEs groups. Furthermore, pairwise post hoc Mann–Whitney tests were used to further investigate the data when the Kruskal–Wallis test results were found to be significant [26]. This test allowed the statistically significant differences to be identified within the data. However, in order to limit the Type I error rate, a Bonferroni correction was applied for each post hoc Mann–Whitney test. As such, the statistically significant value of 0.05 was divided by the number of the possible comparisons among the groups ($N = 10$). The resulting value was the critical value ($p$) considered in the post hoc Mann–Whitney test [26].

In detail, as reported in Table 5, statistically significant differences were found between the “Walking” environment and the other MEs. Moreover, there were no statistically significant differences between the two active transport methods (“Cycling” and “Walking”).

Further differences in the inhaled doses estimated across different MEs can also occur according to the season. In fact, during winter the differences between MEs corresponded with those of the entire study period (i.e., statistically significant differences were found between active and passive commuting); in summer, however, the only statistically significant differences were found for the ME “Walking” versus the MEs “Train” and “Car” (Table S1).
### Table 4. Estimated values of the inhaled dose (µg) for the different fractions of PM, divided by the ME considered, time spent commuting, gender, and monitoring period. The colors qualitatively indicate the increase in the doses of inhaled pollutants (from green—lower inhaled doses, to red—higher inhaled doses).

| ME | Time (min) | Gender | Summer | Winter | Male | Female |
|----|------------|--------|--------|--------|------|--------|
| 15 | Female     | 2847   | 5320   | 3782   | 9292 |        |
| 30 | Female     | 5685   | 10,660 | 7564   | 14,758 |        |
| 60 | Female     | 11,370 | 21,320 | 15,129 | 29,515 |        |
| 90 | Female     | 17,055 | 31,980 | 22,603 | 44,273 |        |
| 15 | Male       | 3503   | 6568   | 4661   | 9093  |        |
| 30 | Male       | 7005   | 13,136 | 9321   | 18,185 |        |
| 60 | Male       | 14,011 | 26,272 | 18,643 | 36,371 |        |
| 90 | Male       | 21,016 | 39,408 | 27,964 | 54,556 |        |
| 15 | Female     | 5126   | 5830   | 4162   | 2832  |        |
| 30 | Female     | 10,251 | 11,660 | 8323   | 5663  |        |
| 60 | Female     | 20,503 | 23,320 | 16,646 | 31,327 |        |
| 90 | Female     | 30,754 | 34,979 | 24,969 | 51,990 |        |
| 15 | Male       | 6316   | 7184   | 5128   | 3489  |        |
| 30 | Male       | 12,632 | 14,368 | 10,256 | 6979  |        |
| 60 | Male       | 25,265 | 28,736 | 20,513 | 13,957 |        |
| 90 | Male       | 37,897 | 43,104 | 30,769 | 50,936 |        |
| 15 | Female     | 5607   | 3244   | 4446   | 3331  |        |
| 30 | Female     | 11,015 | 6489   | 8892   | 6662  |        |
| 60 | Female     | 22,030 | 12,977 | 17,988 | 13,324 |        |
| 90 | Female     | 33,044 | 19,466 | 26,677 | 19,986 |        |
| 15 | Male       | 6750   | 3998   | 8829   | 6701  |        |
| 30 | Male       | 13,573 | 7996   | 10,957 | 8209  |        |
| 60 | Male       | 27,146 | 15,991 | 21,915 | 16,419 |        |
| 90 | Male       | 40,719 | 23,987 | 32,872 | 24,628 |        |
| 15 | Female     | 9062   | 3920   | 10,387 | 5714  |        |
| 30 | Female     | 19,924 | 7839   | 20,774 | 13,428 |        |
| 60 | Female     | 39,848 | 15,678 | 45,188 | 22,856 |        |
| 90 | Female     | 59,772 | 23,518 | 62,323 | 34,283 |        |
| 15 | Male       | 11,495 | 4523   | 11,985 | 6593  |        |
| 30 | Male       | 22,989 | 9045   | 23,970 | 13,186 |        |
| 60 | Male       | 45,978 | 16,990 | 47,941 | 26,372 |        |
| 90 | Male       | 68,967 | 27,136 | 71,911 | 39,558 |        |

## PM<sub>1</sub>

| Time (min) | Gender | Summer | Winter |
|------------|--------|--------|--------|
| 15         | Female | 7655   | 9264   |
| 30         | Female | 15,310 | 18,529 |
| 60         | Female | 30,619 | 37,058 |
| 90         | Female | 45,929 | 55,587 |
| 15         | Male   | 8832   | 10,690 |
| 30         | Male   | 17,665 | 21,379 |
| 60         | Male   | 35,330 | 42,759 |
| 90         | Male   | 52,994 | 64,138 |

## PM<sub>2.5</sub>

| Time (min) | Gender | Summer | Winter |
|------------|--------|--------|--------|
| 15         | Female | 3549   | 6841   |
| 30         | Female | 7098   | 12,681 |
| 60         | Female | 14,197 | 25,362 |
| 90         | Female | 21,295 | 38,044 |

## Car

| Time (min) | Gender | Summer | Winter |
|------------|--------|--------|--------|
| 15         | Female | 4374   | 7813   |
| 30         | Female | 8747   | 15,626 |
| 60         | Female | 17,494 | 31,253 |
| 90         | Female | 26,241 | 46,879 |

## Bicycle

| Time (min) | Gender | Summer | Winter |
|------------|--------|--------|--------|
| 15         | Female | 6224   | 7136   |
| 30         | Female | 12,447 | 14,273 |
| 60         | Female | 24,895 | 28,546 |
| 90         | Female | 37,342 | 42,819 |

## Walking

| Time (min) | Gender | Summer | Winter |
|------------|--------|--------|--------|
| 15         | Female | 7669   | 8794   |
| 30         | Female | 15,338 | 17,588 |
| 60         | Female | 30,677 | 35,176 |
| 90         | Female | 46,015 | 52,764 |

## Train

| Time (min) | Gender | Summer | Winter |
|------------|--------|--------|--------|
| 15         | Male   | 6766   | 8794   |
| 30         | Male   | 15,338 | 17,588 |
| 60         | Male   | 30,677 | 35,176 |
| 90         | Male   | 46,015 | 52,764 |

## Underground

| Time (min) | Gender | Summer | Winter |
|------------|--------|--------|--------|
| 15         | Female | 14,343 | 37,475 |
| 30         | Female | 26,867 | 15,351 |
| 60         | Female | 43,030 | 23,026 |

## End of Table 4.
### Table 4. Cont.

| ME | Time (min) | Gender | Morning | Afternoon | Morning | Afternoon |
|----|------------|--------|---------|-----------|---------|-----------|
|    | 15         | Female | 4351    | 7601      | 6368    | 11,393    |
|    | 30         | Female | 8701    | 15,201    | 12,737  | 22,387    |
|    | 60         | Female | 17,403  | 30,403    | 25,474  | 44,774    |
|    | 90         | Female | 26,104  | 45,604    | 36,211  | 67,161    |
|    | 15         | Male   | 5061    | 9386      | 7848    | 13,793    |
|    | 30         | Male   | 10,722  | 18,722    | 15,605  | 27,507    |
|    | 60         | Male   | 21,445  | 37,464    | 31,390  | 55,173    |
|    | 90         | Male   | 32,167  | 56,196    | 47,085  | 82,760    |

### Underground Walking

| ME | Time (min) | Gender | Morning | Afternoon | Morning | Afternoon |
|----|------------|--------|---------|-----------|---------|-----------|
|    | 15         | Female | 7390    | 8727      | 6633    | 4788      |
|    | 30         | Female | 14,780  | 17,474    | 13,265  | 9976      |
|    | 60         | Female | 29,561  | 34,909    | 26,531  | 21,630    |
|    | 90         | Female | 44,341  | 52,363    | 39,796  | 28,727    |
|    | 15         | Male   | 9107    | 10,754    | 8173    | 9000      |
|    | 30         | Male   | 18,213  | 21,508    | 16,346  | 11,800    |
|    | 60         | Male   | 36,426  | 43,017    | 32,663  | 21,630    |
|    | 90         | Male   | 54,640  | 64,525    | 49,039  | 35,399    |

### Car

| ME | Time (min) | Gender | Time (min) | Gender | PM$_1$ | Time (min) | Gender | PM$_{2.5}$ | Time (min) | Gender | Bicycle |
|----|------------|--------|------------|--------|--------|------------|--------|------------|------------|--------|---------|
|    | 15         | Female | 10,294     | 5622    | 2185   | 7317       |        |            |            |        |         |
|    | 30         | Female | 21,588     | 11,243  | 14,389 | 15,034     |        |            |            |        |         |
|    | 60         | Female | 43,176     | 22,486  | 28,779 | 30,069     |        |            |            |        |         |
|    | 90         | Female | 62,674     | 33,729  | 43,168 | 45,103     |        |            |            |        |         |
|    | 15         | Male   | 14,062     | 7996    | 17,024 | 10,279     |        |            |            |        |         |
|    | 30         | Male   | 28,123     | 15,992  | 34,048 | 20,558     |        |            |            |        |         |
|    | 60         | Male   | 56,247     | 31,983  | 68,096 | 41,116     |        |            |            |        |         |
|    | 90         | Male   | 84,370     | 47,975  | 102,145| 61,674     |        |            |            |        |         |

### Walking

| ME | Time (min) | Gender | Morning | Afternoon | Morning | Afternoon |
|----|------------|--------|---------|-----------|---------|-----------|
|    | 15         | Female | 11,171  | 13,077    | 14,773  | 22,466    |
|    | 30         | Female | 22,341  | 26,155    | 29,545  | 44,933    |
|    | 60         | Female | 44,682  | 52,310    | 58,991  | 89,866    |
|    | 90         | Female | 67,023  | 78,465    | 88,636  | 134,799   |
|    | 15         | Male   | 12,889  | 15,089    | 17,045  | 25,923    |
|    | 30         | Male   | 25,778  | 30,179    | 34,091  | 51,846    |
|    | 60         | Male   | 51,556  | 60,357    | 68,181  | 103,691   |
|    | 90         | Male   | 77,335  | 90,536    | 102,272| 155,537   |
Table 5. Mann–Whitney U test significance values. *p* values of <0.005 are highlighted in red.

| Comparison between MEs | Train | Underground | Car | Cycling | Walking |
|------------------------|-------|-------------|-----|---------|---------|
| PM₁                    | Train | 0.747       | 0.555 | 0.058  | 0.001   |
|                        | Underground | 0.658       | 0.043  | <0.001 | <0.001  |
|                        | Car    |             | 0.018  |         | 0.136   |
|                        | Cycling|             |        |         |         |
|                        | Walking|             |        |         |         |
| PM₂₅                   | Train | 0.573       | 1.000  | 0.008  | 0.001   |
|                        | Underground | 0.582       | 0.023  | 0.003  |         |
|                        | Car    |             | 0.006  |         | 0.001   |
|                        | Cycling|             |        |         | 0.444   |
|                        | Walking|             |        |         |         |
| PM₄                    | Train | 0.872       | 0.502  | 0.014  | 0.001   |
|                        | Underground | 0.658       | 0.009  | <0.001 | <0.001  |
|                        | Car    |             | 0.003  |         |         |
|                        | Cycling|             |        |         | 0.271   |
|                        | Walking|             |        |         |         |
| PM₁₀                   | Train | 0.936       | 0.809  | 0.011  | 0.001   |
|                        | Underground | 0.799       | 0.007  | <0.001 | <0.001  |
|                        | Car    |             | 0.003  |         |         |
|                        | Cycling|             |        |         | 0.340   |
|                        | Walking|             |        |         |         |

To provide a broader perspective to the study, the information obtained from the case study and from the general population analysis was associated with the average commuting periods of the general population commuting in the city of Milan. A summary of these data (ISTAT 2011) was shown in Figure 3. Although the permanence time (reported by the Italian census (ISTAT 2011 and used in this part of the study)) in a particular ME (15, 30, 60, 90 min) is different according to the gender, it is possible to notice how the preferred type of commuting is walking (52% and 48%, respectively, for women and men) for short trips (15 min—Figure 3a), followed by commuting by car (24% and 25%, respectively, for women and men) and cycling (8% for both genders). Public transport is not generally chosen for short trips (<15 min). Compared to the 15 min periods, the number of subjects who choose to travel by bike for 30 min (Figure 3b) is reduced to 6% for both women and men. On the contrary, the number of commuters walking for a period of >15 min decreases (9% and 8% for periods of 30 min (Figure 3b) for women and men, respectively, 2% for periods of 60 min (Figure 3c), and 5% for periods of 90 min (Figure 3d), for both genders) while, as expected, the use of public transport (metro and buses) increases with increasing commuting times (Figure 3c,d).

The analysis of this kind of information is important to consider, especially regarding the estimation of the inhaled dose in active commuting patterns (walking and cycling), as these are preferred to passive commuting for short trips. As reported before, the inhaled dose can be strongly influenced by the time spent in a particular ME and by the subject’s pulmonary ventilation rate. In fact, active transport is thus characterized by a higher inhaled dose of pollutant, if compared with the typical passive means of transport, due to (i) the higher pulmonary ventilation rate of the subjects and to (ii) the longer period of time spent in these kinds of environments. As said, although these aspects have now been consolidated, it is still difficult to define a trend in the study of the commuters’ inhaled dose of pollutants applicable to different urban contexts, since, in addition to environmental (i.e., concentrations of pollutants), micro-environmental, and personal (i.e., physiological parameters) variability, it is necessary to consider population mobility patterns (in turn influenced by different aspects, such as the urban layout). All these aspects can therefore contribute in defining the inhaled dose of airborne pollutants and should be considered for the personal and community choice of the best solution for urban commuting, in terms of the potential impact on health. For example, in the specific case of the city of Milan (information about mobility in the city of Milan is available in a recent study [27]), it is possible to note that active
commuting is typically chosen for the quickest routes (15 min of travel). Therefore, direct comparisons with other studies are not possible; furthermore, this suggests that each specific case should be assessed.

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Figure 3. Proportions of subjects who move through different transport MEs within the city of Milan. In the figure, the data are divided by gender (female or male) and by permanence periods ((a): 15 min, (b): 30 min, (c): 60 min, (d): 90 min).

3.3. Limits of the Study and Future Developments

This study has several limitations: (i) the inhaled doses of pollutants were estimated along a route established a priori, which although was intended to best simulate the path of an average commuter, might not be fully representative of the entire population. Moreover, these results cannot be extended to other urban areas: in fact, the concentrations of pollutants measured in different MEs and the estimation of the inhaled dose are intrinsically characterized by a high variability, especially in urban areas. Geostatistical analyses for the description of the selected route (i.e., the analysis of the population density, land use, etc.) were not conducted. In addition, (ii) the study was carried out considering a single subject, estimating the personal pulmonary ventilation rate, certainly not representative of the entire population. Moreover, (iii) due to the study design, the evening trip (return to home) did not coincide with the evening rush times, as was done for morning commuting. Finally, it is necessary to recognize that different assumptions were used to obtain data regarding the ventilation rate and the estimated inhaled dose via the MPPD model: in this way, considering the use of different levels of approximation, it is necessary to consider the presence of an intrinsic error associated with these estimates. Moreover, the worst case (in terms of deposited mass) was considered in this study, as the clearance was not evaluated or taken into account.
For these reasons, future developments could include measures also during the evening rush hours and conducted along other routes, with the aim of improving the representativeness of this study. In addition, it would be useful to evaluate the influence of micro-environmental conditions (e.g., congested conditions) on the measurement of pollutant exposure concentrations at first and, therefore, on the estimate of the pollutant inhaled dose. Finally, the commuters’ daily exposure assessments and the contextual use of biological measurements should be considered in future studies.

4. Conclusions

This study was divided into two sections: (i) a case study conducted on a commuter who spends different periods of time on different means of transport and (ii) an extension of the results derived from the case study to a larger population (commuters who move within the city of Milan). The principal result outcomes from the case study show that the PM deposited mass was higher during the winter period, for all PM fractions, even if the differences between the estimates for summer and winter were minimal, and that the mass deposited in the upper airways (H) contributed significantly to the mass deposited in the whole airways (total) for all PM fractions considered, followed by the “Indoor” and “Walking (LT)” environments. During the summer period, the maximum values were estimated in the “Other” and “Walking (HT)” environments. For both summer and winter, the lowest values were estimated in the “Car” and “Walking (LT)” environments. Generally, the high deposited mass values during active commuting were justified by the literature since in these environments (for example, “Walking” and “Cycling”), the pulmonary ventilation rates were high if compared to those measured during passive commuting, as is the time spent in MEs. For these reasons, the evaluation of these parameters (pulmonary ventilation rate and permanence time, in addition to the exposure concentration levels) for estimating the inhaled dose is of particular relevance. Regarding the second part of the study, or, rather, the extension of the results to the general population of commuters in the city of Milan, the main results show that the period of permanence in a given ME has an important influence on the inhaled dose, as well as the pulmonary ventilation rate (Table 4). Moreover, during the winter period, statistically significant differences (p < 0.005) occur between the “Walking” ME and passive means of transport (i.e., “Car” and “Underground”), while for the summer period, no statistically significant differences were found between the MEs considered.

Supplementary Materials: The following are available online at http://www.mdpi.com/1660-4601/17/17/6066/s1, Materials and Methods—integration to the text; Table S1: Mann–Whitney U test significance values for the comparison between different micro-environments during summer and during winter. p values of <0.005 are highlighted in red.

Author Contributions: Conceptualization, F.B., G.F. and A.S.; methodology, F.B.; software, G.F.; formal analysis, F.B., G.F. and A.S.; investigation, G.F.; data curation, F.B. and A.S.; writing—original draft preparation, F.B., G.F. and A.S.; writing—review and editing, A.C., D.C., S.R. and M.K.; supervision, A.C., A.S., D.M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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