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Air quality in an urban public transportation Network: Local-scale determinants

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Abstract

Air quality, in terms of particles and particulate polycyclic aromatic hydrocarbons (PAHp), is measured in urban public transport systems serving a major French conurbation. The systems comprise both conventional and dedicated public transport services (DPTS). The objective of this study is to identify determinants of the air quality inhaled by users. Mobile measurements indicate that the latter is being dictated by transport system-independent (external) and system-dependent (internal) variables or a combination thereof. The external variables consist of outdoor processes that lead to accumulating or discharging ambient particulate pollution. Internal variables, in contrast, encompass the particulate generation inside vehicles and transfer processes specific to the configuration, structure and use of public transport and related facilities. Consequently, air quality in transport services and transit stations is highly variable and quite difficult to explain by means of regional and/or urban background pollutions; it exhibits strong temporal and spatial fluctuations (when measured in seconds or meters), which in some cases are superimposed on durable trend lines (i.e. extending to tens of minutes or kilometers). This array of variables moreover results in a variety of particulate pollution, including: authigenic particles in certain DPTS, coarse particles from transport corridors, and PAHp-loaded fines from road traffic.

Keywords: urban area, dedicated public transport services, particulate pollution, mobile measurements.

1 Introduction

For the past several decades, air quality has been a major public health concern. Poor air quality may be responsible for various pathologies; this is especially true

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in urban areas, where the transportation sector is one of the principal causes of air quality deterioration [1, 2]. Such a statement focuses, in particular, on airborne particulate matter and polycyclic aromatic hydrocarbons (PAH), as well as their respective increased risks of cardiovascular and respiratory diseases and cancer [3, 4].

Airborne particles and PAH levels are two parameters widely considered in the evaluation of urban air quality [5, 6]. Despite significant variations from one site to the next, around 25% of all particulate matter (PM) in the atmosphere is thought to originate from road transport, especially diesel engines (gas oil-fired) [7]. Exhaust PM is initially composed of carbon nuclei (a few nanometers in diameter), capable of adsorbing various organic species (unburned hydrocarbons, oxygen derivatives and PAH). Hence, PAH-laden fine particles are often considered as indicators of high-temperature combustion sources, which are typical of environments affected by road transport emissions. Several PAHs are known for their carcinogenic, mutagenic and teratogenic risks for human beings [8]. Benzo[a]pyren is often used to assign exposure threshold values (e.g. 1 pg/L for particulates with a 50% efficiency cut-off at a 10-μm aerodynamic diameter (PM_{10}), yearly average value [9]). Through collisions, fine exhaust particles agglomerate (i.e. nucleation phenomenon) and can increase in size up to several tens of microns. Exhaust particles in the atmosphere further accumulate with micrometric dust particles, originating in part from local or distant sources (including industries and agriculture) as well as from the wear of urban materials (e.g. re-suspended road particles or the abrasion of metal or concrete surfaces). The accumulation of PM in the atmosphere, even at relatively low concentrations (i.e. 50 ng/L), may result in short-term respiratory effects; over the longer term, ambient particles can lead to mutagenic and carcinogenic risks.

Many initiatives have been taken across several urban areas around the world to promote the modal shift from private automobile to public transit; they are intended to reduce total emissions generated by the transportation sector, i.e. through decreased numbers of vehicles in circulation and less congestion [10 - 12]. In some places, Park and Ride (P+R) facilities have been set up as components of urban sustainability strategies in order to encourage drivers entering the urban area to leave their car at the periphery and more easily manage the use of public transit services into the city center [13]. To achieve maximum benefit, such P+R facilities are often associated with urban mass transit running on dedicated rights-of-way, also called dedicated public transport services (DPTS). Compared to conventional public transit, DPTS offer the advantages of: facilitating vehicle movements in urban traffic, improving service efficiency for the public transport users (PTU) (speed, punctuality), and reducing vehicle fuel consumption through steadier engine operations (i.e. vehicles avoiding congestion, fewer stop-and-start episodes). Furthermore, DPTS can be equipped with lower emission engines (e.g. electric or natural gas-powered), thus reducing the local concentrations of pollutants inherent in diesel or gasoline fuels (especially PM or NOx) [14].

The relationship between air quality inside and outside of vehicles can vary depending on various parameters [15, 16]. More specifically, the objective of this research is to identify clear determinants for air quality in urban public transport systems. To achieve this goal, mobile measurements have been recorded inside public transport vehicles (PTV), at different station stops and in the surrounding air. The aim of this campaign is to investigate the greatest possible range of causes of quality variation in the air being inhaled by PTU over the various phases of their trip. Air quality will be assessed herein through its particulate content and particle-associated PAH (PAHp). Measurements are conducted in a given urban background subjected to typical urban pollution sources, including road traffic [17].

Having adopted a transport policy intended to favor the shift towards public transport, in addition to P+R facilities, the City of Nantes (western France: 47°12'17" N, 1°32'46" W) features a wide array of DPTS. This situation provides additional opportunities to assess both the in-vehicle and immediate outdoor air quality inhaled by DPTS users. A secondary objective therefore is to determine any possible significant differences in air quality among the various DPTS categories.

The methodology and materials used to examine pollutant concentrations in the air, along with the study site characteristics and organization of the measurement campaign will be presented first. Then, results will be given and discussed for the various urban areas located within the perimeter of this study area. These results will provide input for interpreting the air quality signals recorded at (as well as in the vicinity of) each DPTS line's stations and PTV. Correlations will subsequently be sought between outdoor particulate pollution levels and the air quality at stations and in PTV. This step will be performed for different particle categories with respect to: transport line configuration, transport typology, the local urban context, and road traffic density.

2 Materials and methods

2.1 Study site characteristics

This study focuses on an urban renewal zone within central Nantes, located between two arms of the Loire River (namely Ile-de-Nantes). This island extends 4.9 km from east to west and 1 km in width at its maximum. This area constitutes a major corridor between the city center and southern sectors of the Nantes conurbation (approx. 600,000 population). At its central part, the island is crossed by a tramway (hereafter denoted TW) line. Also, a bus (RBW) line runs through the eastern part of the island. More recently (in 2013), a "chronobus" (PBW) line was introduced on the island from west to east cutting perpendicularly the tramway and bus lines, ultimately reaching the Nantes railway station. The TW and both kinds of rapid transit buses (BRT) offer PTU a high level of service. The RBW, like the tramway, benefits from a reserved section of the street, inaccessible to other vehicles, along with a priority assignment at intersections. The PBW benefits from a dedicated lane in the street, as delineated by ground markings, yet in some areas it runs through mixed traffic segments; PBW vehicles are also assigned priority at intersections. Both the RBW and PBW systems are powered by natural gas (NG), while the tramway is electric-powered. To allow for a comparison with conventional public transport, an ordinary bus line (OB, consisting of NG-powered vehicles) has been considered in greater detail in this study; this line was chosen for its location along the possible route of a DPTS project.

The study area encompasses all three types of DPTS + OB line configurations within a single urban expanse of 3.4 km^2. The proximity of transport modes helps maintain meteorological conditions and road traffic volumes relatively homogeneous over the course of each campaign. As such, more reliable comparisons can be drawn between DPTS categories than would be the case from distinct sites [18, 19]. Moreover, this choice highlights the contrasts due to different urbanization strategies at the district scale.

2.2 Data collection periods and protocol

This study was carried out by means of 4 measurement campaigns, lasting 4-5 hours each, on the 5th and 13th of June 2014 and on the 10th and 11th of July 2014. The measurements were all conducted during the morning in order to remain within a single time slot, which moreover corresponds to the gradual daily increase in traffic. Weather conditions were cloudy or overcast. The air temperature was 15°-21°C. A light wind was mainly blowing northeasterly or southeasterly, though it once veered southwesterly.

The chosen investigation method adopted the perspective of a PTU by surveying the study site's various public transport lines using a portable data acquisition device. The protocol was based on measurements inside in-use vehicles and at a number of station stops (1 to 11): 4, 5 and 4 stations for PBW, RBW and TW, respectively. The numbering of stations follows the data collection order (see Table 1). An extra station (no. 0) serves as a terminal site for measurements conducted in OB vehicles (i.e. an 11-0 segment). Two stations offer interconnections between DPTS lines, namely Station 2 (PBW/TW) and Station 3 (PBW/RBW). In order to compare and interpret results on the monitored public transport lines, air quality measurements were also carried out on some pedestrian trips, i.e. Segments 4-5, 8-9 and 0-1. On the same days, three additional areas, located in the center of Nantes (namely Sites S_A, S_B and S_C), were monitored to supplement the existing dataset with respect to the influence of urban environment and traffic conditions on ambient pollution levels.

Table 1: Indices, land use, urban setting and local road traffic for the monitored stations and segments: trips are indexed from top to bottom; daily mean road traffic values are taken from 2012 [20].

Type of transport	Index	Land use typology	Urban setting	Road traffic (in veh./day)
PBW	Station 1	Recreational	Spaced	11,900
PBW	Segment 1-2	Recreational/Residential	Spaced	6,200-13,100
PBW/TW	Station 2	Residential	Spaced	16,400
PBW	Segment 2-3	Residential	Mixed	10,200
PBW	Station 3	Residential	Confined	23,100
PBW	Segment 3-4	Residential	Mixed	6,900-20,600
PBW	Station 4	Industrial (transport sector)	Spaced	10,800
On foot	Segment 4-5	Residential/Industrial	Spaced	11,700
RBW	Station 5	Residential/Recreational	Spaced	21,100
RBW	Segment 5-6	Residential	Confined	20,400
RBW	Station 6	Residential	Confined	19,700
RBW	Segment 6-3	Residential	Confined	21,400
RBW/PBW	Station 3	Residential	Confined	23,100
RBW	Segment 3-7	Residential	Confined	23,400
RBW	Station 7	Residential	Confined	23,700
RBW	Segment 7-8	Residential	Mixed	25,100
RBW	Station 8	Residential	Spaced	22,400
On foot	Segment 8-9	Residential	Spaced	18,600
TW	Station 9	Residential	Spaced	21,600
TW	Segment 9-10	Residential	Spaced	34,600
TW	Station 10	Residential	Mixed	14,600
TW	Segment 10-2	Residential	Mixed	14,300
TW/PBW	Station 2	Residential	Spaced	16,400
TW	Segment 2-11	Residential	Mixed	16,700
On foot	S_A	Residential	Confined	5,600-28,900
On foot	S_B	Residential	Spaced	4,000-15,000
On foot	S_C	Recreational	Spaced	6,400
TW/OB	Station 11	Residential	Confined	23,300
OB	Segment 11-0	Residential	Spaced	12,800-21,500
OB	Station 0	Industrial (food sector)	Spaced	21,300
On foot	Segment 0-1	Recreational	Spaced	10,800-20,500

All station stops were equipped with shelters for waiting PTU. When the shelter configuration permitted, air quality was measured not only on the front side of the shelter (where PTU typically wait for PTV) but also behind the shelter glass, in the aim of evaluating any pollution screen effect from traffic or the surroundings. Table 1 shows all of this study's measurement segments and stations.

2.3 Air quality measurements

Air quality measurements were conducted in real time by using an autonomous particle counter (Grimm EDM 1.108) connected in series to a particle-bound PAH (denoted PAHp) detector (Grimm 130). Data were stored on-site on a mobile computer. Particle concentrations were optically measured every 6 seconds by 780 nm-wavelength light scattering by individual dust particles at a right angle to the light source. PAHp measurements were recorded every minute (by means of photo-ionization of aromatic cycles exposed to a KrCl 222 nm excimer lamp). This protocol did not differentiate among PAH congeners.

A particle counter is able to measure particulate number concentrations (PN) from 1 particle/L to $2{\cdot}10^6$ particles/L. In this case, a liter (L) is used instead of a cubic meter (m^3) in order to maintain consistency with the lung volumes and capacities of PTU. Following the gravimetric measurement of internal filters (GF/F grade glass microfiber and/or PTFE disks), the accessible mass concentrations amount to: from 0.1 ng/L to 100 μg/L. The size of detected particles ranges from 0.35 μm to 23 μm. After appropriate calibration by measuring (through GC/MS analysis) PAH in the filter sample extracts, the PAHp detector was able to measure between 0.001 ng and 5 ng of PAHp per liter. Measurement accuracy exceeded 85%, for a variability below 5% regarding the particle counter and below 10% regarding the PAH detector.

The analytical system (particle counter + PAHp detector + computer) was installed in a 2-wheel shopping cart, for ease of movement into a PTV and along the streets (total weight: less than 15 kg). The (antistatic) air intake pipe outlet was set roughly 1 m above ground, i.e. at an intermediary height between airborne particles from the regional / urban background and particles from immediate sources (exhausts, dust (re)suspension, wheel and asphalt abrasion, etc.). One meter also corresponds to the mean height of children and individuals seated at stations as well as in PTV.

3 Results and discussion

3.1 Air quality in various urban areas

Air quality inside the PTV partly depends on the ambient pollution levels. On-foot measurements show that some industrial areas (like Station 4, i.e. Nantes' central railway station; see below) and zones displaying dense road traffic (i.e. over 20,000 veh./day like Station 11 and S_A) reveal elevated PN concentrations (Figure 1). These latter zones concentrate both individual vehicles and PTV, which could locally account for increased PAHp concentrations (up to 83±3 pg/L at specific spots). Since 94%±2% of PN consist of particles < 1 μm in diameter, it is likely that the measured PAHp-laden particles originate from vehicular exhausts, wear of asphalt and/or a (re)suspension of fines from road surfaces. The predominance of < 1 μm particles may further contribute to keeping the alveolar mass concentration (PM_{Alv}) low, i.e. similar to that found in recreational areas. Hence, in densely trafficked zones, the degree of particulate pollution may not be accurately captured by relying exclusively on mass concentrations. This shortcoming is apparent when considering the absence of significant differences in PM_{Alv} concentrations between industrial / heavily-trafficked zones and green / recreational areas.

The industrial activity in Nantes City principally comprises light and intermediate industries involved in producing consumer-business-oriented goods or services. Such activities often take place in small or medium-sized facilities, e.g. commercial complexes or warehouses. Measurements indicate that distinct industrial activities account for different types of pollution. More specifically, an industrial area close to Nantes' central train station shows increased PN and PM_{Alv} concentrations yet low PAHp levels. Comparatively speaking, the zone of heavy truck traffic around Station 0, which corresponds to an area dedicated to the food industry, exhibits low PN and PM concentrations yet high PAHp levels (Figure 1). In the following, PM shall denote PM_{Alv}, PM_{Tho} and PM_{Inh} grouped together. Put otherwise, the PAHp content of dust nearly doubles. This assessment accompanies a step-up in the contribution of coarser particles (i.e. > 1 µm in aerodynamic diameter): from 6%±2% to 11%±1% of PN. Possible reasons might include the (re)suspension of polluted dust and/or soil particles, tire wear and/or the tearing of asphalt fragments by passing trucks.

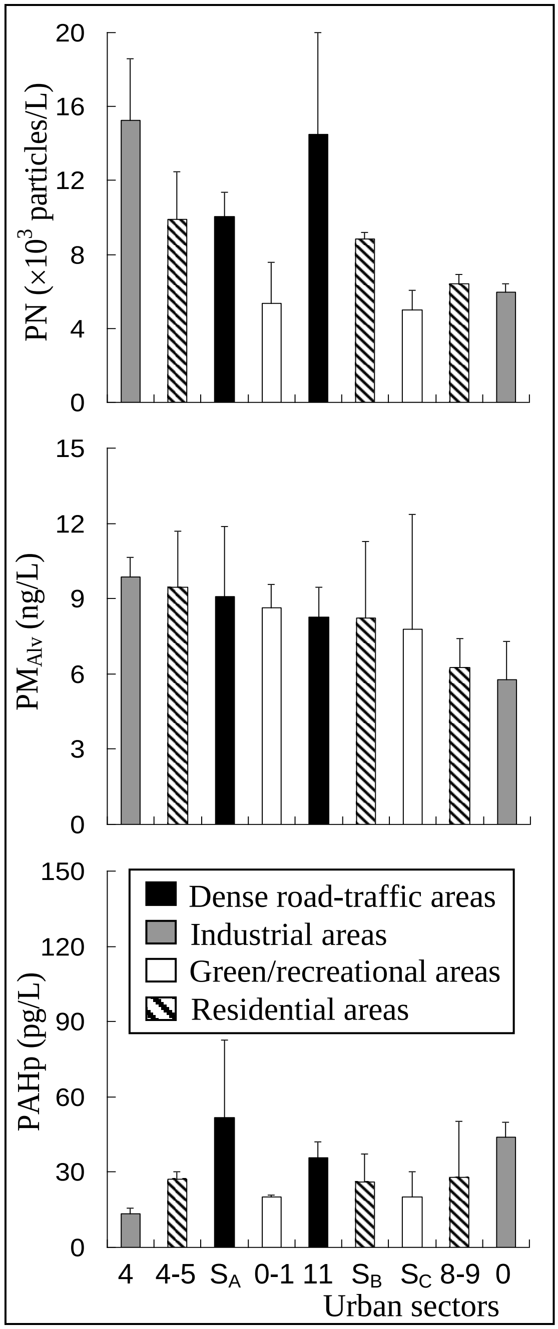

Figure 1: Air quality by urban sector. Areas S_A, S_B and S_C are for additional metering carried out on the same date in central Nantes.

The texture (i.e. the arrangement, dimensions and shapes of buildings) of urban areas and the local road traffic density partially account for immediate air quality, which in turn may influence pollution levels in PTV. For instance, open urban areas, i.e. as depicted by lower-density environments (Area S_B) surrounded by low-rise buildings, and areas that adjoin large bodies of water (Segment 8-9 or 0-1) display moderate PM and/or PAHp levels in spite of the significant road traffic. Conversely, confined urban environments result in degraded air quality via the local accumulation of industrial, residential and road traffic emissions. Such is the case for Area S_A and, to a lesser extent, Station 11 and Segment 4-5, which partially absorbs particulate emissions from the nearby industrial area surrounding Station 4.

3.2 Air quality in vehicles and at stations

The mean PN and PM concentrations at PBW stations (this section of the paper will focus on the front side of shelters, where PTU typically wait for PTV) rapidly increase between Stations 1 and 2 and then stabilize at intermediate levels: (9.3±0.4) 10^3 particles/L and 10.6±0.8 (PM_{Alv}), 23.9±0.8 (thoracic, PM_{Tho}) and 32±1 (inhalable, PM_{Inh}) ng/L, respectively (Figure 2). Furthermore, Stations 2 and 3 show more pronounced PAHp concentrations (50±20 and 47±2 pg/L, respectively). As could be expected, and unlike Station 1 (associated with a recreational area) or 4 (associated with an industrial area), these two stations are located in more heavily-trafficked zones (Table 1), which confirms the previous results on the pivotal role of road traffic on outdoor pollution levels and, presumably, on air quality at stations. The in-vehicle PN and PM concentrations however exceed by a factor of 2.8 to 3.4 the in-station readings. This finding demonstrates a sever downturn in in-vehicle air quality that is not commensurate with outdoor pollution levels. The highest degradation was measured over Segment 1-2, where the mean PM_{Alv}, PM_{Tho} and PM_{Inh} concentrations reach 35±10, 90±10 and 120±20 ng/L, respectively. Since the PBW vehicles run towards Station 4, PM levels tend to gradually decrease, whereas PN exhibits a clear maximum at Station 3. On the one hand, this pattern suggests the existence of in-vehicle sources of coarse particles, which amount to 15%-20% of PN and are being emitted before PBW vehicles leave the terminal stations. On the other hand, this pattern indicates a localized (i.e. near Station 3) extra contamination of the in-vehicle air by outdoor PAHp-laden fines. It is actually possible for the nominal size of PAHp-laden fines, which is not accessible with our measurement system, to rapidly increase by coming into contact with coarse particles previously generated in PBW vehicles.

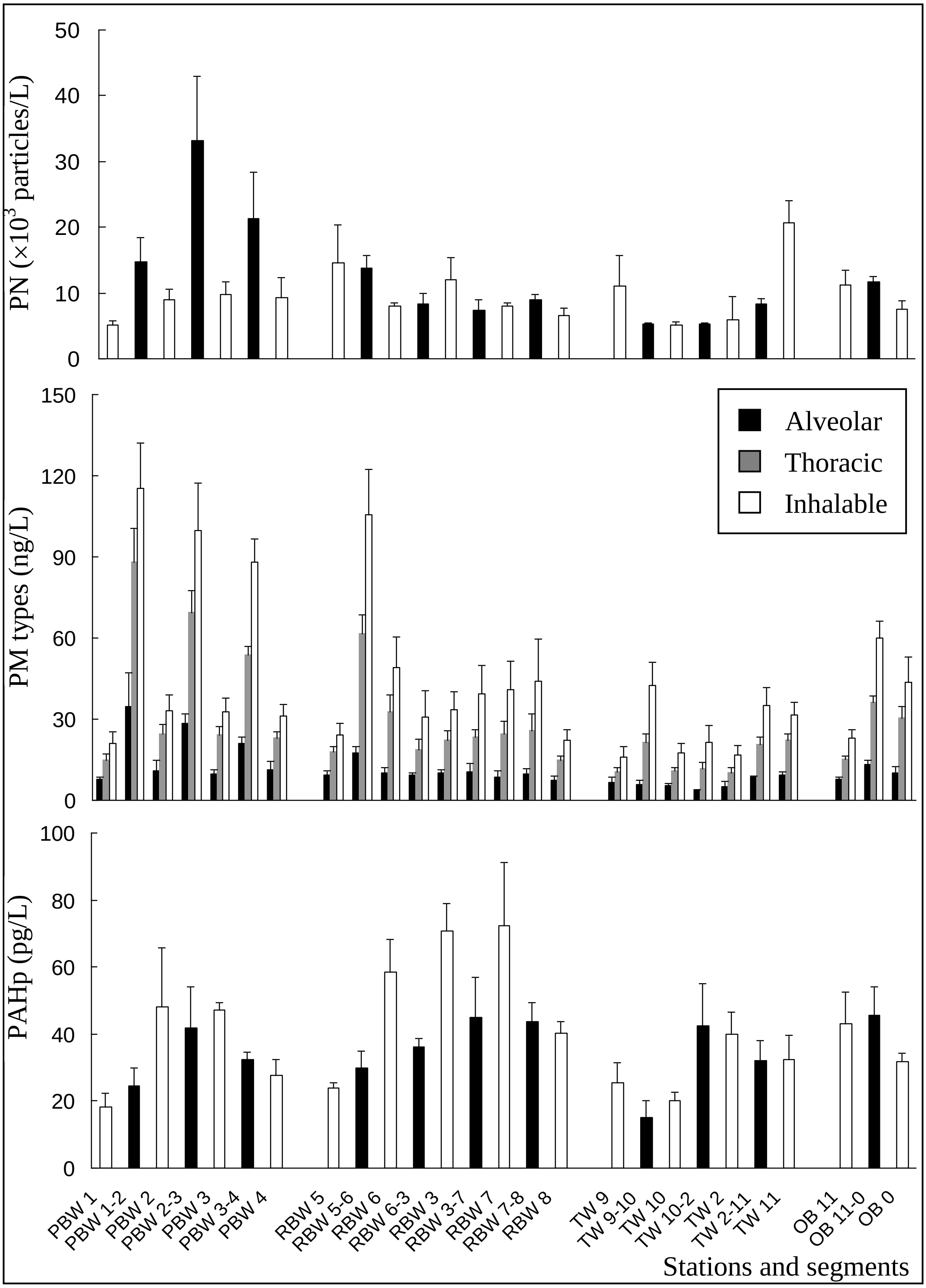

Figure 2: Mean (± standard error) particulate and PAHp concentrations at stations (front side of the shelter) and in PTV. The distinction is drawn in the middle panel between alveolar, thoracic and inhalable particulate matter.

The mean PN and PM concentrations at RBW stations are comparable to those at PBW stations: the mean differences ranges from 3% to 19%. The highest PN concentrations stem from Stations 5 and 3. The latter also displays the highest PM levels (Figure 2). As previously evoked, Station 5 partially absorbs PN emissions from the nearby industrial area around Station 4. Station 3 accounts for the central part of a confined urban environment (a transportation corridor surrounded by medium-sized and tall (> 10-storey) buildings extending from Station 6 to Station 7). Furthermore, this corridor concentrates road traffic (from 19,700 to 25,100 veh./day). This urban context likely contributes to the pronounced PAHp levels at stations as well as in PTV running through the area (Figure 2). As a matter of fact, between Stations 5 and 7, PAHp concentrations increase by a factor of 3 and by +50% at stations and in RBW vehicles, respectively. The strong PM concentration in RBW vehicles (especially coarse PM fractions) at Segment 5-6 is also worth noting. The latter segment immediately follows a terminal/departure station. The larger coarse particle contributions (10%-15% of PN) and significant decreases in in-vehicle pollution levels as RBW vehicles stop at Station 6 indicate an initial contamination of in-vehicle air, a finding that is consistent with measurements conducted in PBW vehicles. Alternatively, the results obtained suggest that certain RBW users and drivers would be exposed, at the very least, to the internally generated coarse particles and the PAHp-laden fines from immediate outdoor pollution.

Compared to PBW and RBW, TW measurements indicate an overall improved air quality: mean PN, PM and PAHp concentrations at TW stations and in transport vehicles amount to 0.4-0.9 and 0.2-0.9 of those for PBW or RBW lines, respectively. This outcome likely stems from the apparent absence of major particulate sources around the TW line. The heavily-trafficked Segment 9-10 (Table 1) encompasses a bridge crossing the Loire River, which as previously mentioned may act as an immediate sink for vehicular emissions of fines and corresponding PAHp. Elsewhere, the surrounding urban texture is typically characterized by single-family homes and medium-sized buildings, which also tends to limit particulate accumulation in the immediate atmosphere. Moreover, since TW vehicles are electric-powered, their direct emissions of combustion-type particles are practically zero. In-vehicle particulate generation processes however cannot be fully refuted (see below). It is worth noting that at Station 2 and in TW vehicles running through Segment 10-2, higher PAHp concentrations (close to 40 pg/L, see Figure 2) are observed. Since the associated PN and PM levels are low, it is possible that PAHp-laden (up to 4±1 ng/g) (ultra)fines, which unlike PAHp cannot not be detected using our analytical system, accumulate locally. TW Station 2 is approx. 50 m from PBW Station 2: both stations are therefore located in a relatively heavily-trafficked zone. The distance between TW and PBW stations, in addition to the time difference between measurements (about 3 h), may be responsible for the discrepancy in PM concentrations. The previous data for TW line air quality do not take into account the high concentrations measured at Station 11, where PN and PM concentrations exceed those in the other TW stations by a factor of 1.9 to 2.8. It was previously mentioned that Station 11 is characterized by dense road traffic (including individual vehicles and PTV) within a confined urban environment. Since this station is located in Nantes' central square and due to the small/medium size of buildings, the confinement is less marked than for other heavily-trafficked zones. Mean PAHp levels are thus comparable to those observed at Station 2 (32±7 vs. 40±7 pg/L) while remaining significantly (50%-60%) less than those observed at RBW stations. The resulting values must nevertheless be compared to the local road traffic, i.e. estimated at 23,300 veh./day.

On the one hand, OB stations display PN and PM concentrations similar to, or less than, RBW stations (by a factor of 0.6 to 1.2) (Figure 2), while on the other hand, except for Segment 5-6 data (which account for in-vehicle generated PM), PN and PM concentrations in the OB vehicle are significantly higher than those in RBW vehicles (factor ranging from 1.4 to 1.6). This means that in the absence of in-vehicle particulate generation and despite increased outdoor/at-station pollution levels, DPTS vehicles may offer enhanced air quality with respect to the PN and PM of ordinary buses. Such is not true however for: all DPTS categories, whole daytime period and the types of pollutants in areas traversed. As an example, the PAHp concentration in a particular PTV is partially influenced by PAHp levels at the stations serviced or the segments crossed (see above). Provided that accumulation (resp. removal) dynamics in the DPTS (resp. OB) vehicles are fast enough, PAHp concentrations in DPTS vehicles would ultimately exceed those in OB vehicles. Such is the case for RBW vehicles running in Segments 3-7 and 7-8, with mean concentrations of 43-45 pg/L (vs. 43 pg/L in OB vehicles). In addition, the DPTS vehicles exposed to in-vehicle particulate generation processes exhibit, at least temporarily, higher PM and PN concentrations than those in OB. These results underscore the importance of equilibrium between in-vehicle particulate build-up and removal along the transit lines.

3.3 Particulate pollution levels around stations

Significant changes in air quality are observed around stations for all but the public transit lines (Table 2). In most cases, the highest mass concentration values are measured at the front side of stations (where PTU typically wait for PTV). The contrast between the front side and the rear of stations is especially pronounced for coarser particles (including PM_{Tho} and PM_{Inh}), whereas lower or insignificant spatial variations are observed for finer (PN or PM_{Alv}) fractions. Furthermore, as the d/D ratio values indicate, the contribution of coarse particles is also greater at the front side of stations, which suggests that the recorded spatial variability in mass concentrations around stations not only originates from the proximity of PTV exhaust emissions but also from induced (re)suspension of coarse particles and their subsequent dynamics of dispersal or deposition. All these observations substantiate the fact that both the BRT and, to a greater degree, the OB accentuate particulate pollution with coarse particles in the vicinity of public transit corridors. This is less so for TW line. Despite a slight trend favoring higher concentrations at the front side of stations, no significant (at a 95% level) values could be observed. Besides, as previously discussed, the TW line offers its PTU an overall improved air quality with respect to bus-type lines, which presumably signifies that from the standpoint of individuals waiting at the station, the monitored TW vehicles are not perceived as an immediate major source of particulate pollution.

Table 2: Ratios of mean particulate concentrations at stations (at the front side of shelters to concentrations measured behind the shelter). n is the total number of data monitoring series. The values in parentheses pertain to the confined and heavily-trafficked RBW Segment 3-7. The values in italics differ significantly ($p < 0.05$) from the unit values. d/D is the ratio of (PN) fraction with a diameter below 1 μm to that with a diameter above 1 μm.

Front/Rear concentration ratio	n	PN	PM_{Alv}	PM_{Tho}	PM_{Inh}	PAHp	d/D
PBW	12	1.4±0.2	1.3±0.2	*1.6±0.3*	1.5±0.5	0.7±0.2	*0.89±0.05*
RBW	15	1.0±0.1	1.3±0.1	1.4±0.3	*1.9±0.5*	1.1±0.2	0.7±0.2
		(0.8±0.1)	(1.2±0.2)	(1.3±0.3)	(*1.9±0.5*)	(*0.4±0.2*)	(*0.72±0.05*)
TW	8	1.1±0.4	1.1±0.1	1.1±0.3	1.3±0.3	1.0±0.1	1.1±0.1
OB	8	*1.7±0.4*	*1.8±0.3*	*2.7±0.5*	*3.1±0.8*	1.1±0.3	*0.83±0.06*

A more detailed observation of the data allows discriminating between various urban situations. As regards the RBW line, when considering the values for Stations 3 and 7 together (both located in the central part of a confined and heavily-trafficked zone, Table 1), PAHp concentrations behind the shelter are more than twice those measured at the front side of stations (i.e. next to RBW corridor) (Table 2). This occurs despite a relatively high local mean PAHp concentration, i.e. 45±11 pg/L. As previously indicated, a heavily-trafficked road runs just 2-3 m behind these stations. When positioned behind the station shelters and provided several cars are idling at a nearby traffic light, the smell of exhaust gases is perceptible. When these cars start and/or traffic intensifies, the mean PAHp concentrations exceed 150 pg/L (up to 180 pg/L), whereas the mean PN and d/D values rise by 65%-80% and 25%-50%, respectively. This finding highlights the local occurrence of episodes of atmospheric loading with PAH-laden fines, yet under the same conditions, parameters remain relatively steady on the front side of stations: 15%-25%, 2%-9% and 3%-11% of relative variation, respectively, which either supports the role of barrier played by the shelter or the rapid agglomeration-deposition and/or volatilization of PAH-laden fines. Overall, the contamination with coarse particles from bus corridors and the accumulation of PAHp-laden fines from the adjacent road make particulate matter levels around RBW stations highly variable. Along with the area's confinement and additional contributions from surrounding urban materials, this contamination momentarily, yet repeatedly, leads to degrading the quality of air being exposed to individuals waiting at stations.

3.4 Particulate transfers between vehicles and the atmosphere

Figure 3 reveals a wide panel of distributions for particulate concentrations and d/D values. When plotted versus the values at surrounding stations, in-vehicle PAHp concentrations and d/D values exhibit nearly linear relationships on the whole. Yet, PM_{Inh}, PM_{Tho} and, to a lesser degree, PM_{Alv} and PN concentrations demonstrate less predictable trends, which means that the coarse particle exchanges between in-vehicle air and the immediate outdoor atmosphere only play a limited role with respect to in-vehicle or outdoor particle generation/removal mechanisms. Another possible explanation would be that the coarse particulate concentrations at stations hardly account for these estimates between stations: inter-station values are calculated as the mean of values measured at surrounding stations. Altogether possible, a series of measurements conducted between stations (i.e. along the public transit corridors) shows that in a given urban context and in the absence of localized sources, the overall PM variations lie in the low-to-moderate range. As mentioned above, larger variations in coarse particle levels are observed with distance from the corridors used by PTV or the nearby heavily-trafficked roads. Inter-station variability in air quality thus barely accounts for observed deviations from the $y = x$ line.

Most upward deviations actually reflect in-vehicle coarse particulate generation processes (case of PN, PM_{Inh}, PM_{Tho} and PM_{Alv} in PBW vehicles), whereas downward deviations are associated with areas where road traffic particulate emissions accumulate in the atmosphere at the neighborhood scale (case of PM_{Inh}, PM_{Tho} and PM_{Alv} concentrations between Stations 6 and 7 and PN near TW Station 11). As regards PBW data, significant ($p > 0.05$) correlations are only found for PAHp and d/D. For both parameters, the slope of the best-fitting line (using Pearson's r^2) linking the measurements conducted in PBW vehicles with corresponding inter-station data yield values in the 0.6-0.7 range, which means that when traveling into contaminated areas, only a fraction of the outdoor PAHp pollution reaches the in-vehicle air. This finding further suggests that compared to variations in the immediate atmosphere, changes in the proportion of particles < 1 µm in diameter are less marked in PBW vehicles than between stations. In other words, air quality in PBW vehicles exhibits relative stagnancy in relation to the contamination with fines and PAHp-laden particles. Alternatively, this stagnancy in air quality results in sluggish decreases in the proportion of fines and PAH-laden particle concentrations when vehicles leave any highly polluted area.

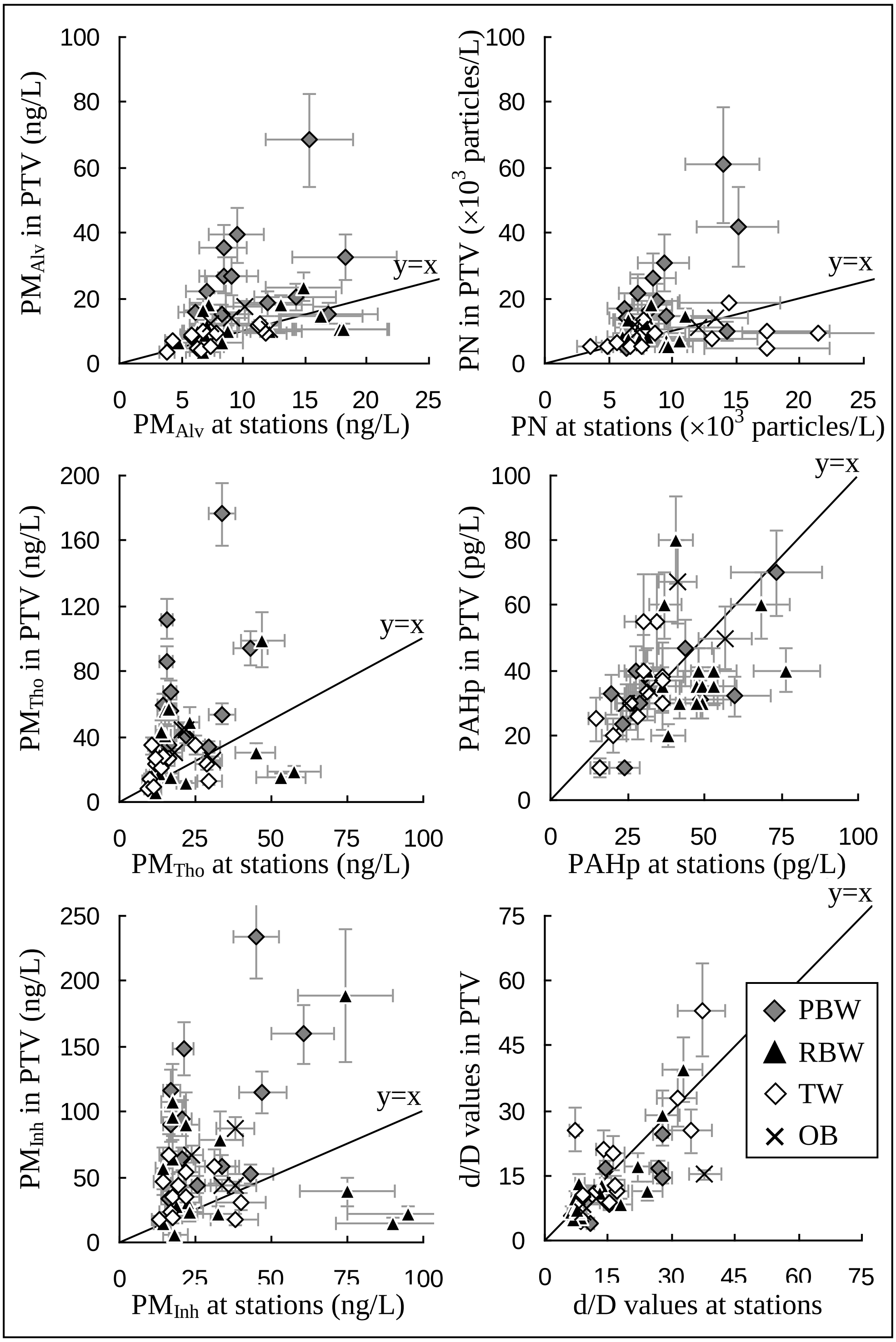

Figure 3: Mean particulate concentrations (resp. d/D values) in PTV plotted versus the average mean concentrations (resp. d/D values) in surrounding stations. Distinction is drawn among the tested public transport modes

Based on the recorded variations in PAHp and d/D PBW profiles and depending on trip duration in polluted areas as well as on the corresponding mean air contamination, it would take from < 1 to 2 stations for the in-vehicle PAHp and d/D levels to balance with external air values. The calculated equilibration distance is rather short, which would limit the exposure of passengers beyond the polluted areas. This is less the case for the initial contaminations with PM_{Inh}, PM_{Tho} or PM_{Alv}, which are thought to be internally generated before PBW vehicles leave terminal stations. Following the vehicles' departure, PM_{Inh}, PM_{Tho} or PM_{Alv} concentrations gradually decrease yet remain significant until reaching the end of the line. Providing any extra contributions of other internal or external PM sources can be neglected, equilibrium with the outdoor atmosphere would be attained after 20-35 stations, which is longer than the PBW line itself (comprising a total of 13 stations).

Two categories of particles can be clearly identified for the RBW line; they differ in the inter-station coarse particulate (mostly PM_{Tho} and PM_{Inh}) concentrations (Figure 3). The category with the highest inter-station PM_{Tho} (i.e. > 40 ng/L) and PM_{Inh} (i.e. > 70 ng/L) concentrations is also apparent for TW and PBW modes. The relating measurements correspond to the morning rush hour during a sunny weather period following several days of heavy rains. Comparisons between homogeneous urban areas (in terms of urban texture and land use) reveal significantly lower PM_{Tho} and PM_{Inh} concentrations (i.e. 17±4 ng/L and 21±8 ng/L, respectively) in lighter traffic zones. It is highly probable therefore that the high inter-station PM_{Tho} and PM_{Inh} levels originate from localized remobilization processes, i.e. through the wear of asphalt concrete, automotive parts and/or (re)suspension of remnant particles as well as of newly deposited dust. Moreover, due to the relatively low d/D values (i.e. 15±3) and PAHp concentrations (30±10 pg/L), the (re)suspension of coarse dust, plus the wear of aggregate in asphalt and/or of metal automotive parts, appears to be more likely. When excluding RBW data associated with in-vehicle coarse particle generation, the moderate in-vehicle PM_{Tho} (20±8 ng/L) and PM_{Inh} (30±20 ng/L) concentrations indicate that the suspected wear/(re)suspension particles are barely being transferred into PTV. Knowing the exact origin and fate of this particulate category would require further investigation. As for the second particulate category, i.e. lower inter-station PM_{Tho} (i.e. < 30 ng/L) and PM_{Inh} (i.e. < 45 ng/L) concentrations, most in-vehicle PN and PM data lie above the y = x line, thus acknowledging the predominance of in-vehicle particulate pollution over outdoor pollution along the RBW line. The few RBW data points (n = 3) below the y = x line exclusively stem from measurements performed within the heavily-trafficked corridor between Stations 6 and 7. Lastly, it is worth noting that unlike PN and PM, most PAHp and d/D data lie below the y = x line, which supports the notion that PAHp and fines from the adjacent heavily-trafficked road contribute to a limited extent to the pollution increase in RBW vehicles (as is also apparent in Figure 2). The ratio of the cumulative PAHp increase in vehicles to that at stations ranges from 1/6 to 1/4. It would take > 4 stations for the in-vehicle PAHp levels to be equivalent to external air values. PAHp concentrations in RBW vehicles thus exhibit a more pronounced stagnancy than in PBW. The limited PAHp increase in vehicles is further justified by the previous data on the reduced propagation and/or rapid deposition of PAH-laden fines near stations.

Except for PM_{Tho}, PM_{Inh} and Station 11 data, as well as for the supposed wear/(re)suspension coarse particle category (see above), the mean PN, PM_{Alv} PAHp and D/d values in TW are homogeneously distributed around the y = x line (Figure 3). The simple linear regression slope values and related Pearson's r^2 coefficients (n > 8) equal 0.7-1.3 and 0.45-0.75, respectively, which demonstrates that in the absence of major road traffic near a TW line or particulate sources in the confined urban areas being traversed, the mean concentrations of fines and PAHp in vehicles closely match these estimated values between stations. A careful observation of the recorded signal further shows that mean contamination is the net result of a quick succession of events involving air contamination (i.e. traveling periods) and pollution removal (during stops at the stations serviced). As for PM_{Tho} and PM_{Inh}, the mean in-vehicle concentrations tend to exceed these inter-station values: the mean factors are 1.7±0.2 and 2.2±0.3, respectively. Nonetheless, the factor values remain less than in RBW (2.0±0.3 and 2.6±0.6) or PBW (3.5±0.7 and 3.7±0.8) vehicles, thus exposing an actual yet relatively limited build-up of coarse particles in TW vehicles (as is apparent on the heavily-trafficked Segment 9-10). Since the mean PM_{Tho} and PM_{Inh} levels in TW vehicles do not depend on distance traveled (Figure 2) and to just a limited extent on interstation pollution levels (Figure 3), their nature may be substantially different from these of PM_{Tho} and PM_{Inh} in PBW or RBW vehicles. The corresponding extremely low PAHp levels indicate that combustion-type particles might not be a primary component. At this time however, the nature and origin of these particles remain unclear (e.g. sand used to increase wheel/rail adhesion performance, outdoor dust and/or authigenic particles from passengers or onboard equipment). This finding calls for further research in order to examine the specific contributions of all potential sources.

Only a limited amount of OB data is available (n = 4); most concentration-related data lie above the y = x line, whereas d/D values are positioned below (Figure 3). As such, in the monitored urban area, air quality in OB vehicles is apparently lower than that between stations. Below the y = x line, d/D values also indicate that the in-vehicle air contains a relatively higher proportion of coarse particles (> 1 μm particles account for 6%-13% of PN), hence further displaying substantial mean PAHp concentrations: from 30±3 to 70±10 pg/L. A more detailed analysis of the recorded concentration signals reveals that in-vehicle PN, PM and PAHp concentrations are highest at Station 11 and then gradually decrease with travel time. Since the monitored OB vehicles locally travel from a heavily-trafficked and confined residential area towards a less-trafficked and lower-density urban/industrial zone, the recorded trends may reflect the gradual removal, presumably through dilution and/or deposition processes, of pollutants accumulated from previous segments, including Station 11. The outdoor base levels (considered at Station 0) are reached for trips exceeding 4 stations. This purging-distance, unlike the concentration signal variability (with coarser particles exhibiting more pronounced variations), does not markedly vary from PM_{Inh} to PM_{Tho} or to PM_{Alv}. Lastly, due to high in-vehicle PAHp concentrations, extra inputs from road traffic emissions (comprising OB exhausts) or contamination by internally generated particles cannot be excluded.

4 Conclusion

It is now widely accepted that in-vehicle air quality may be lower than that in the urban area being traversed. However, the extent and mechanisms of this degradation are only partially characterized in PTV and moreover in DPTS. This scarcity of information must be addressed since today many urban areas are developing quickly (in both emerging countries and mature economies), and local authorities face the urgent request by millions of commuters to implement rapid mass transit systems. Our research has shown that air quality in PTV and stations serviced cannot continue to be neglected without experiencing subsequent health effects. It is not unusual in fact to measure PM concentrations that durably and significantly exceed the short-term standards established in the EU and US (e.g. coarse particulate pollution in PBW vehicles). Besides, in the absence of data on the nature, physical characteristics and potential transformations of particles and particle-bound pollutants, any regular PM levels would not guarantee acceptable air quality (i.e. case of air contamination with PAHp-laden (ultra)fines around Stations 2 and 3, as well as in DPTS vehicles passing through these stations). All these results underscore the dynamic character of the air quality being proposed to PTU. Air quality actually depends on many external variables, including: meteorological conditions, specific emissions from distant and immediate sources, the presence of sinks (e.g. large bodies of water), and the urban texture. It is also a function of transport equipment-dependent variables, namely: the location and layout of stations, the placement of individuals at stations, presumably the proximity to in-vehicle particle generation spots, and vehicular capacity to concentrate or dilute pollutants. This panel of variables influences, to a greater or lesser extent, all the tested transport modes, thereby demonstrating that compared to conventional bus lines, DPTS lines do not systematically help improve the air quality being proposed to PTU. More detailed investigations on air quality determinants in PTV and their related stations are actually required. Until further information is available, common sense actions should be introduced to limit the exposure of PTU. Such actions may involve: positioning stations away from intersections and traffic lights; increasing the distance between heavily-trafficked roads and public transit corridors; temporarily closing the external air vents in polluted areas; turning off the engine when the PTV is idling for longer periods (e.g. during regulation time at terminals); and producing sufficient quantities of clean/filtered air for input so as to ensure the dilution or removal of contaminated air.

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