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Personal exposure to particulate matter in commuters using different transport modes (bus, bicycle, car and subway) in an assigned route in downtown Santiago, Chile

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The objective of this study was to compare personal exposure to particulate matter (fine and ultrafine particles) in commuters using different transport modes (bicycle, bus, car and subway) in a busy, assigned route in downtown Santiago, Chile. Volunteers carrying personal samplers completed scheduled commutes during the morning rush hours, while central site measurements were conducted in parallel. A total of 137 valid commutes were assessed. The impact of central site, traffic and other variables was explored with regression models. $PM_{2.5}$ personal concentrations were equal to or slightly above central site measurements, while UFP personal concentrations were above them. Regression models showed impacts of both background levels and traffic emissions on personal $PM_{2.5}$ and UFP exposure. Traffic impacts varied with transport modes. Estimates of traffic impacts on personal $PM_{2.5}$ exposure were 2.0, 13.0, 16.9 and 17.5 μg m^{-3}, for car, bicycle, subway and bus, respectively; while for UFP exposure were 8400, 16 200, 25 600 and 30 100 counts per cm^3, for subway, car, bicycle and bus, respectively. After controlling the central site and transport mode, higher temperatures increased $PM_{2.5}$ exposure and decreased UFP ones, while the wind direction affected UFP personal exposure. In conclusion, we found significant impacts of both central site background measurements and traffic emissions on personal exposure of volunteer commuters in an assigned route in Santiago, with impacts varying with transport modes.

Environmental impact

An urban environment can be heavily impacted by transport emissions that include noxious pollutants such as $PM_{2.5}$ and ultrafine particles. Transport emission impacts and the impact of using different transport modes have been studied measuring personal exposure to pollutants in commuters using highly exposed routes in different cities in the world. Here we compared personal exposure to $PM_{2.5}$ and ultrafine particles in commuters travelling in different transport modes through a heavily trafficked avenue in Santiago, Chile. The impact of transport mode, background level contribution, meteorology, vehicular restriction and time variables was explored.

Introduction

It is known that traffic emissions include several pollutants, which can affect people's health, including fine particulate matter ($PM_{2.5}$), ultrafine particles (UFPs) and toxic gases, such as carbon monoxide and nitrogen oxides.[1–3] Besides the known impacts of these pollutants on human health, several recent studies have shown that proximity to traffic may increase adverse health effects. For instance, respiratory impacts in asthmatics[4] and cyclists,[5] and increased acute myocardial infarction.[6] Additionally, it has been shown that people living near highways experience increased premature mortality.[7]

People can be unequally exposed to pollutants while commuting by different transport modes. Transport mode may change how close commuters are from traffic emissions and to what extent they could be protected from ambient concentrations. For instance, bus commuters may fulfill their commutes through very busy streets with traffic jams, very close to other vehicles, while bicycle commuters may maintain a larger distance to other vehicles; on the other hand, buses have doors and windows, and even air conditioning, which may protect commuters from outdoor pollution. When comparing transport modes in terms of pollutant exposure, we address two complementary questions: (i) how exposure changes while

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keeping "external conditions" constant (*i.e.* same route); and (ii) how exposure changes when the commute is similar (similar start and end) but the route changes. Both approaches are complementary, as it is important to know whether or not the difference in exposure while commuting by a bus or a car is due to the mode itself, or to the elected route.

A standard way to compare transport modes is by assigning a fixed route. Several studies have attempted to compare transport modes considering fixed routes exposed,[8–17] while there are proportionally fewer studies controlling other variables, such as meteorology and/or central site, background levels,[11] and even fewer studies from developing countries and measuring ultrafine particles.[14,16,18] The aim of this study was to compare personal exposure to particulate matter ($PM_{2.5}$ and UFPs) in commuters using different transport modes (bicycle, bus, car and subway) in an assigned route in downtown Santiago, Chile, while controlling the impact of central site background measurements and other factors such as meteorology and vehicular restrictions.

Materials and methods

Study site

Santiago is the capital of Chile and is the center of commercial, industrial and cultural activity of the country. It has a population of over 6 million people, spread over about 100 km^2 (Fig. 1). Santiago is located in a valley crossed by the Mapocho River and surrounded by the Andes Mountains to the east and several other mountain ranges in other directions. The enclosed location inhibits ventilation, which when combined with common winter thermal inversions causes the accumulation of pollutants and frequent air pollution episodes. Due to the large population and its spread, traffic emissions are important and are one of the main contributors to the large $PM_{2.5}$ concentrations observed.[19–22] Santiago's transport system consists of a fleet of 6180 diesel buses[23] and an electrical subway system with underground and surface components. Additionally, the transport fleet includes 1 597 762 private cars, mostly gasoline powered, and light and heavy duty diesel trucks to transport materials and goods.[24] Most of the commercial and cultural activity of the city is concentrated downtown, with several mixing high rise building producing street canyons, and heavy traffic including usual traffic jams during rush hours.

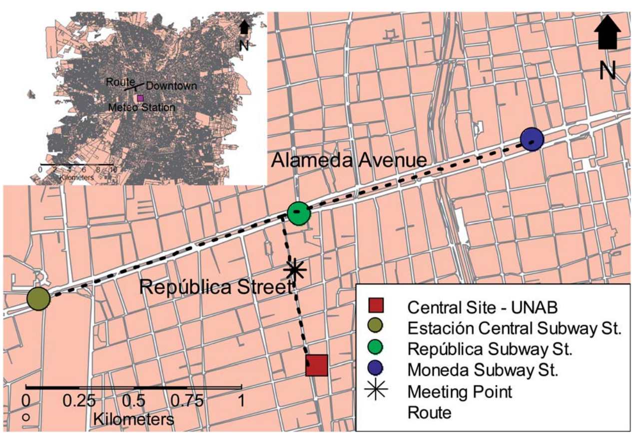

Fig. 1 Maps of the study setting.

The assigned route was located in downtown Santiago and is comprised of two major avenues: Alameda Avenue and República Street (Fig. 1b). This section of Alameda Avenue was selected because it represents a portion of many typical commutes in Santiago and includes infrastructure for all four transport modes: underground subway, several bus lines and a central promenade that includes a bicycle line. Alameda is the major commercial street in Santiago and has heavy public and private vehicular traffic that includes cars (usually gasoline powered), diesel buses and trucks; it is generally crowded with commuters of all transport modes. Traffic jams during rush hours are common.

Commutes

Volunteers carried personal samplers for $PM_{2.5}$ and ultrafine particles while background ambient measurements were performed in parallel at a central site. To ensure a variety of weather conditions, commutes were performed during winter–spring months of 2011 and summer–autumn months of 2012. All commutes were targeted to run from 8:00 am to 9:00 am, which is during the morning rush hour. The assigned route mimics a full commute for a person in the area. The route was Universidad Andrés Bello (UNAB), Alameda Avenue, "La Moneda" Subway Station, "Central Station" Subway and back to a meeting point where volunteers exchange personal samplers with the other commuter and repeated the process to finally end at the UNAB site. A sampling session consisted of two commuters performing the route twice, one carrying the $PM_{2.5}$ sampler and the other with the UFP sampler. Transport mode and order of samplers were assigned randomly. Car and bicycle commutes were performed almost completely on these transport modes. Bus and subway commutes included walking portions along República Street and bus and subway commutes along Alameda Avenue. They also included short walking sections along Alameda Avenue, including street crossing and waiting periods. Subway commutes were performed completely underground, and volunteers were asked to change the direction (*i.e.*, east to west) inside the subway station, without ascending to the street level.

During commutes, volunteers carried backpacks containing the samplers. When commuters used cars, the backpack with the sampler was located on the passenger seat next to the driver. Three different cars were used during the study: a 2006 Toyota Yaris, a 2000 Subaru Forester, and a 2005 Subary Legacy. All cars were gasoline powered and had catalytic converters. To homogenize conditions, volunteers were asked to drive the cars under the most likely cold morning conditions, *i.e.*, windows were closed and ventilation and heating were used at will, but with no recirculation. To avoid risky commutes for cyclists and not to bias the study, all measurements were cancelled during rainy days. Finally, some measurements were scheduled during the nation-wide 2011 political demonstrations regarding education. Only in a few cases measurements were rescheduled, as early morning activities did not conflict with demonstrating activities. Only volunteers (mostly researchers and some students) participated as commuters. All participants read and signed a consent form. All procedures were approved by the University of Chile, Faculty of Medicine Ethics Committee.

Measurements

Personal $PM_{2.5}$ particle concentrations were measured using a handheld optical particle counter (DUST-TRAK II, Model 8532, TSI, Shoreview, MN, USA), while personal UFP concentrations were measured using a handheld condensational particle counter (P-TRAK Model 8525, TSI). Samplers were placed in backpacks and powered with batteries. A conductive inlet tubing provided by the factory was connected to the samplers, taken out of the backpack and placed on the belts of the backpack with the inlet about 10 cm below the shoulder of the commuter. Samplers were set to register and average data every 10 seconds.

Central site measurements were acquired in parallel using a pair of the same samplers used for personal monitoring. Samplers were located in a balcony at the second floor of a UNAB building (Fig. 1b), with the inlets extended about 30 cm from the edge of the balcony using the same tubing as the personal samplers. As Dust-Trak measurements cannot be used as an absolute value, in parallel, integrated $PM_{2.5}$ filter samples were collected (as previously performed[25]). $PM_{2.5}$ filter samples were collected using a personal environmental monitor (model 761-203A, SKC, Eighty Four, PA) operating at 4 liters per minute with 37 mm pre-weighed Teflon filters. Collected mass was determined by gravimetry at Chester LabNet Laboratory (Tigard, OR, USA). Blank filters were acquired in parallel and in a similar filter sampler that was not connected to a pump.

Details of the commute regarding congestion, traffic conditions, times entering transport modes and some special events during the commute were recorded using personal voice recorders. All instruments were synchronized. Meteorological variables were downloaded from the Ministry of Environment site,[26] including wind speed and direction, temperature and relative humidity. Also, during winter months a vehicular restriction takes place as an air pollution control measure. Restriction takes place during April to August, and during this period 4 out of 10 conventional cars without catalytic converters and mechanical injection (according to license plates) cannot circulate.

Each session commenced and terminated with quality control (QC) activities for both continuous PM samplers, including zeroing the instrument using a filter, and collocating the samplers for 3 minutes at the central site both at the beginning and the end of the commutes. Collocations showed good correlations, but there were usually differences in responses between samplers. Therefore, personal measurements were corrected each day using the central site as the reference. Also, $PM_{2.5}$ measurements at the central site were calibrated against filter samples as done previously.[25] About eight commutes were integrated in one filter to ensure sufficient mass was collected (about 2 m^3 sampled). Blank filters showed small values, therefore they were not considered.

Data analysis

For each sampling day, four personal/central site pair observations were generated, in two transport modes using $PM_{2.5}$ and UFP samplers. Each commute was plotted against time and visually inspected to detect data losses, sampler clogging and large outliers. Commutes with systematic problems were removed, including one $PM_{2.5}$ and three UFP commutes. Each commute was collapsed to its mean concentration value. Summary statistics, boxplots, and histograms were calculated separately by transport modes.

To determine the impact of different parameters on personal samples, regressions models were fitted as done previously.[11] The response variable was always either $PM_{2.5}$ or UFP mean personal exposures for each commute. Variables were tested untransformed to ease interpretation and provide more physical meaning to the results.[11] However, model residuals were checked, and although they showed some skewedness, regression analysis is robust to mild deviations from normality.[11]

Three models were built with increasing complexity for each pollutant. Model 1 included only the central site as the main predictor, Model 2 also included different intercepts for each transport mode, and finally Model 3 included additionally all significant parameters (meteorological, temporal and vehicular restriction variables). In Model 1 the slope was interpreted as the contribution of background pollution to personal exposure while the intercept was interpreted as an aggregate contribution of traffic emissions to personal exposure. In Model 2 the intercepts are interpreted as specific traffic contributions differentiated by transport mode. Model 3 was constructed by testing each variable at a time using Model 2 as a base. Tested variables included meteorology (temperature, relative humidity, wind speed and direction), temporal (days of week and months) and days with vehicular restriction. Variables were tested continuously, whenever possible, or as dummies one at a time. Significant variables were added to Model 2, and only variables that remained significant thereafter, including the others, were retained in Model 3. Besides the impact of the specific variables under study, output from Model 3 can be interpreted as the impact of central site and traffic emissions by transport modes controlling by the other variables. Statistical contrast between the different transport modes was done using Scheffé tests. All tests were considered significant at the 0.05 level. All data analysis was done using the SAS 9.3 statistical package (SAS Institute Inc., Cary, NC) and R statistical package (R Foundation for Statistical Computing: Vienna, Austria, 2009).

Results

Summary statistics

Commutes were performed from June 13th to October 13th, 2011 and from March 6th to May 15th, 2012. A total of 139 commutes were performed, with 68 and 67 commutes having valid data for $PM_{2.5}$ and UFPs, respectively (Table 1). Almost the same number of commutes was performed using the different transport modes. Examples of temporal observed concentrations by transport mode and pollutants are shown in Fig. 2 and 3. Usually, central site data appeared much smoother as compared to personal exposure, which showed acute peaks above central site measurements. For personal measurements, larger and more frequent peaks were observed for UFP measurements than

Table 1 Summary statistics for variables associated with the commutes

	Commutes	
Variable	$PM_{2.5}$	UFPs
Transport mode		
Bicycle	14	16
Bus	18	17
Car	18	17
Subway	18	17
Total	68	67
Dates		
Jun–Oct 2011	43	42
Mar–May 2012	25	25
Temperature (°C)		
<0	4	3
0–5	20	20
5–10	19	19
>10	25	25
Relative humidity (%)		
<40	2	2
40–60	11	11
60–80	32	31
>80	23	23
Wind speed (m s^{-1})		
0.0–0.5	21	21
0.5–1.0	31	30
>1.0	16	16
Wind direction		
East	19	18
South	29	30
West	20	19
North	0	0
Exception days		
No restriction	19	19
4 plate restriction[a]	49	48

[a] For cars with no catalytic converter.

for $PM_{2.5}$, and for bicycle and bus commutes than for car and subway ones. Finally, car measurements showed the smoothest behavior, with peaks that were broader and with several time-periods yielding concentrations lower than the central site. Concentrations below the central site were usually observed for subway commutes as well.

Summary statistics and box-plots of a commute's mean concentrations and time by pollutants and transport mode are shown in Table 2 and Fig. 4a. Central site $PM_{2.5}$ concentrations showed high average concentrations with a rather large SD (54.5 ± 24.1 μg m^{-3}). For personal measurements separated by mode, means ranged from 46.5 μg m^{-3} (for cars) to 62.4 μg m^{-3} (for subway), with SDs similar to the central site (around 20 μg m^{-3}). Larger SD was observed for bus commutes (24.9 μg m^{-3}) in agreement with larger peaks observed for this mode. Central site UFP concentrations were also high on average with a large dispersion (46 100 ± 38 500 counts per cm^3). Personal measurements, however, were in general significantly higher on average than the central site ranging from 42 500 counts per cm^3 (for subway) to 70 900 counts per cm^3 (for bus), but showed rather a similar SD except for bus measurements. All commutes lasted about the same amount of time (45 minutes).

Summary statistics for meteorological variables are shown in Tables 1 and 2. Most days were mildly cold (between 0 °C and 10 °C), with moderate relative humidity (around 60–80%) and very low wind speed (most days <1 m s^{-1}), with incoming wind generally from the south, never from the north. These are typical morning conditions of a city located in a semi-arid valley like Santiago. Meteorological variables showed some variability that could potentially affect personal exposure.

The impact of central site on personal exposure was explored. Fig. 4b shows boxplots of concentration differences between personal and central site measurements by mode, while Fig. 4c shows scatter plots of personal *vs.* central site measurements. The boxplot shows that the personal concentration of $PM_{2.5}$ is similar to or above the central site (by about 10 μg m^{-3}) for all modes except cars, while for UFP personal concentrations are clearly above the central site for all except subway, with difference in the range of about 20 000 counts per cm^3. Similarly, scatter plots show a strong relationship of central site measurements with personal measurements both for $PM_{2.5}$ and UFPs (Fig. 4c).

$PM_{2.5}$ models

Model 1 (Table 3) explained a large fraction of the variance ($R^2 = 0.77$, $p < 0.0001$). On average 79% of the background levels contribute to the observed personal concentrations, while a significant portion (12.4 μg m^{-3}) remained unexplained and is attributed to traffic emissions. Model 2 (Table 3) explained a larger fraction of the variability ($R^2 = 0.86$, $p < 0.0001$). Overall, the transport factor was significant, and all intercepts were significantly different from zero except for cars. The significant intercepts had a similar or a slightly larger magnitude than the intercept observed in Model 1, and ranged from 13.0 μg m^{-3} for bicycle commutes to 17.5 μg m^{-3} for bus commutes. Contrast tests showed significant differences between bicycle, bus and subway commutes *vs.* car ones, but no differences among them.

In Model 3 (Table 3), temperature as a continuous variable was the only significant variable, and no significant effects were found for wind speed or direction, relative humidity, month, day of the week, or vehicular restriction. The personal $PM_{2.5}$ exposure increased by 0.66 μg m^{-3} for each °C increment. The model including temperature further increased the variability explained ($R^2 = 0.89$, $p < 0.0001$), and increased the fraction of background $PM_{2.5}$ that impacts personal measurements (88%). Differences between modes remained similar to Model 2 results.

UFP models

As with $PM_{2.5}$, personal UFP measurements showed a strong correlation with central site measurements (Fig. 4c). Model 1 (Table 4) explained 69% of the variability, with 86% of background levels contributing to the observed personal concentrations. Traffic emissions had a significant contribution

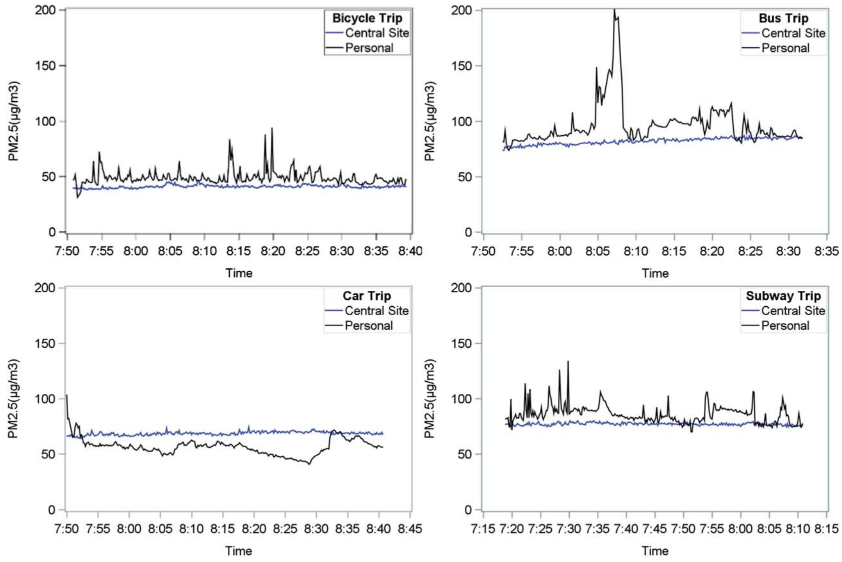

Fig. 2 Examples of temporal plots for $PM_{2.5}$ for different transport modes.

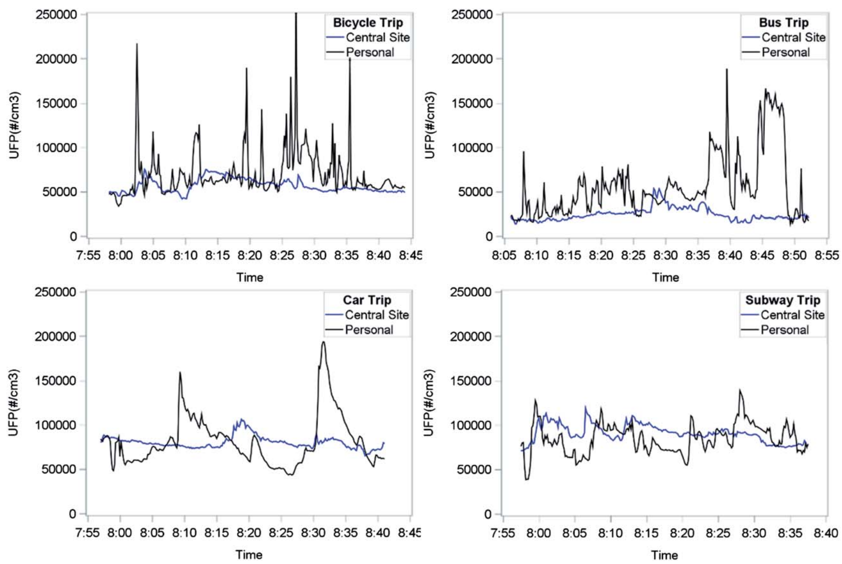

Fig. 3 Examples of temporal plots for UFPs for different transport modes.

increasing personal levels by 18 200 counts per cm^3. Model 2 (Table 4) explained a larger fraction of the variability (80%), but central site contributions to personal exposure are slightly reduced (82%) compared to Model 1. The overall transport factor was significant, but unlike $PM_{2.5}$, in UFP exposure, all intercepts were significantly above zero, and more scattered, ranging from 8400 counts per cm^3 for subway commutes to 30 100 counts per cm^3 for bus commutes. Contrast tests showed that during bus and bicycle commutes, UFP exposure was significantly higher than that during subway commutes; additionally, bus commute exposure levels were higher than those during car commutes.

Results from Model 3 (Table 4) showed that only temperature as a continuous variable and wind direction were significant. Including these variables further increased the variability explained by the model ($R^2 = 0.85$, $p < 0.0001$), but background contributions to personal exposure were decreased to 59%. The temperature showed a significant effect, increasing personal exposure in cooler days: 23 800 counts per cm^3 more for days below 0 °C, 7700 counts per cm^3 more for days between 0 °C and 5 °C, and 5200 counts per cm^3 more for days between 5 °C and 10 °C compared with days above 10 °C. The wind direction was also significant ($p < 0.01$) with UFP concentrations increasing by about 11 000 counts per cm^3 for commutes with eastern incoming winds as opposed to southern or western winds. Differences in intercepts between modes remained similar to Model 2 when adding the other variables as with $PM_{2.5}$ models.

Table 2 Summary statistics for pollutants and meteorological variables by commutes

Variable	N	Mean	Median	SD	Min	Max
$PM_{2.5}$ (μg m^{-3})						
Bicycle	14	50.9	50.2	18.8	14.3	90.1
Bus	18	60.4	57.1	24.9	22.1	108.2
Car	18	46.5	50.9	20.5	4.6	80.5
Subway	18	62.4	59.7	18.7	26.0	95.1
Central site	68	54.5	51.4	24.1	7.7	100.6
UFPs (counts per cm^3)						
Bicycle	16	63 900	62 000	22 600	20 000	107 200
Bus	17	70 900	60 000	27 300	27 500	110 100
Car	17	54 500	49 800	25 600	14 500	109 400
Subway	17	42 500	37 200	17 500	20 000	84 500
Central site	67	46 100	38 500	24 600	9800	104 400
Time (min)						
Bicycle	30	40.4	40.4	6.6	17.0	51.3
Bus	35	44.7	44.7	9.4	30.3	76.2
Car	35	42.6	43.7	7.0	25.7	57.0
Subway	35	45.3	43.2	8.9	34.5	76.3
Meteorology						
Temperature (°C)	69	8.1	8.6	6.3	−2.0	21.9
Relative humidity (%)	67	74.7	75.2	12.4	45.8	94.1
Wind speed (m s^{-1})	69	0.7	0.6	0.4	0.1	1.6

Discussion

This study compared personal exposure to traffic pollutants ($PM_{2.5}$ and UFPs) in commuters performing assigned commutes with different transport modes. We found that central site measurements, representing background ambient levels, were strong predictors of personal exposure. Additionally, there was an important contribution of traffic emissions which varied depending on transport mode. Some other covariates, such as temperature and wind direction, were important predictors of exposure levels, but did not change the main observation regarding traffic contributions and transport mode.

Impact of background and traffic

Central site observations for $PM_{2.5}$ did not differ from previous studies in Santiago, Chile,[20,27] while there is a lack of background monitoring for UFPs in Santiago. Personal traffic observations concurred with those observed in a previous study during morning rush hours,[28] however these were observed from a "curb-side" site and in a relatively shorter time frame. Traffic impacts after controlling from central site were in the order of 10 to 20 μg m^{-3} for $PM_{2.5}$ and 10 000 to 30 000 counts per cm^3 for UFPs. These observations were similar to[8,13,14] or below[29,30] those observed before for $PM_{2.5}$, and similar to[13,30] or below the rather few studies measuring UFPs at a central site. This might be explainable because the portion of Alameda Avenue under study was not a "street canyon", with rather low buildings in the surroundings (about 5–10 flights) and a relatively broad central avenue. Also, vehicular technologies used in Santiago are not considered highly polluting.

When considering a central site as a predictor of personal exposures in studies including several transport modes, only developing country studies found strong associations[14,31] for $PM_{2.5}$, while developed countries did not.[8,13] For UFPs, the two studies from developed countries that included central sites did not find an impact.[13,30] It was suggested previously that studies in developing countries might have higher background levels of pollutants, which increases the impact of them on personal exposure. Also, as it is known that pollutants, especially UFPs, might have a spatial variation, the location of the central site might be important to assess personal exposure to background levels. Sites located too far from actual measurement locations may not adequately represent background-level impacts on personal exposure.

Impact of transport modes

For $PM_{2.5}$, we found a large contribution of traffic (about 15 μg m^{-3}) for bus, bicycle and subway, while cars had a lower contribution (not significantly different from zero). It seems that under similar circumstances (the same route) these three modes are equally exposed to $PM_{2.5}$, while cars are somehow protected. The high impact on bus and subway commuters might be due to the commute itself or by being highly exposed by walking during part of the commute. Previously, it was suggested that modes closer to traffic should be more exposed.[9] While many studies have found that bus commuters are the most exposed to $PM_{2.5}$,[10,12,14–16] others have found that car commuters are among the most exposed,[17,32] and place bicycle and subway commutes generally at lower or intermediate exposure levels. Some recent studies have also found that car commuters are less exposed[14–16] suggesting that newer car designs and ventilation systems make for cleaner in-cabin environments.

For UFPs, we found larger traffic contributions for bus (30 100 counts per cm^3) and bicycle (25 600 counts per cm^3) commutes, while car (16 200 counts per cm^3) and subway (8400 counts per cm^3) commutes had relatively lower impacts. Here, it seems that proximity to traffic is important, as bus and bicycle commutes have large impacts, while subway exposure is generally lower. Car commuters seem to be protected, but not as much as for $PM_{2.5}$. The few studies that have analyzed the impact of transport modes on UFP exposure have found a high impact on car commuters[13,17] and bus commuters,[11,12] while bicycle and subway commuters usually had lower to intermediate impacts. Similarly to $PM_{2.5}$, some studies show that newer cars and buses might reduce exposure levels, as results of their newer fabrication and ventilation systems. This can also apply to subway systems that include air conditioning.

Impact of other variables

The impact of other variables was explored in models already adjusted for background concentrations and transport modes. Hence, the estimates reflect their impact in the local microenvironment, and not at the general background level. We found significant impacts of meteorological variables on $PM_{2.5}$ and UFP personal exposure. For $PM_{2.5}$, concentrations increased with higher temperatures, which might be due to dryer conditions

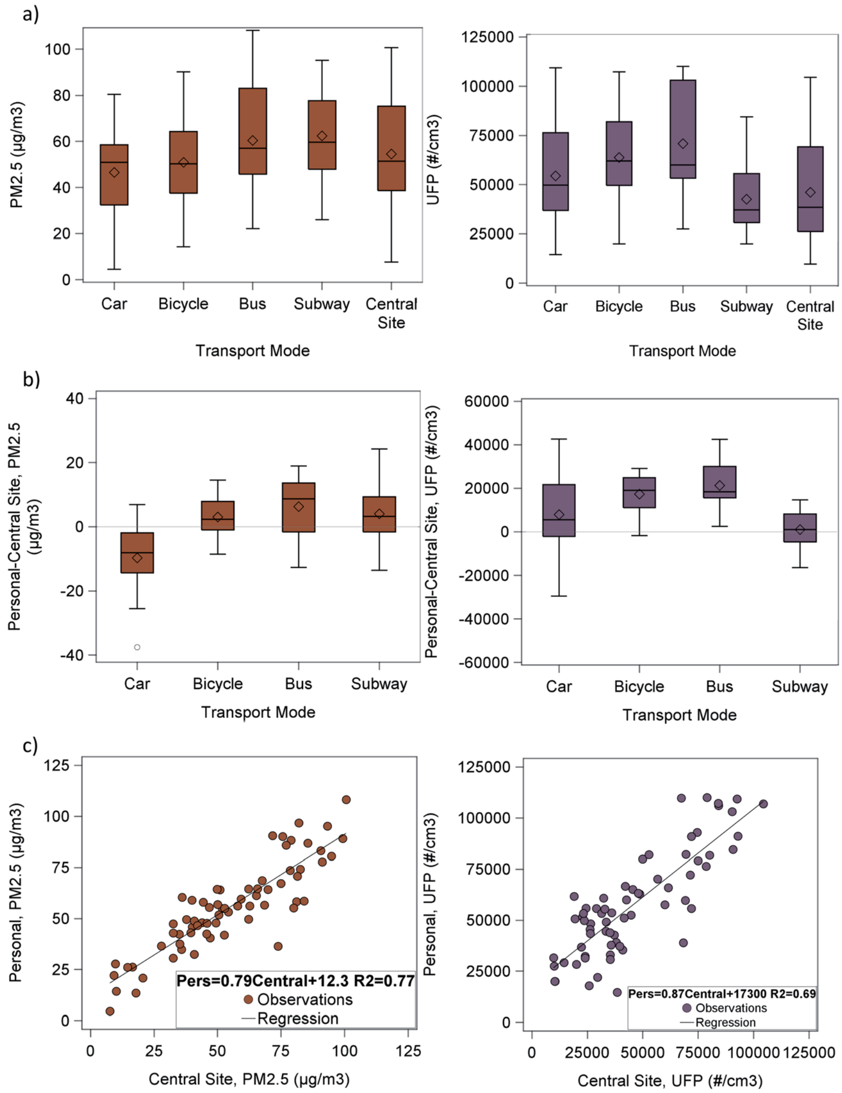

Fig. 4 Plots for personal exposure against central site exposure. (a) Boxplots for central site and personal observations by transport modes. (b) Boxplots for differences between personal and central site observations by transport mode. (c) Scatter plots for personal and central site observations.

leading to dust re-suspension and thus increasing personal exposure. For UFPs, on the other hand, lower temperatures and easterly wind sources were associated with higher exposure concentrations. This might be due to higher particle condensation and/or lower ultrafine particle evaporation in colder weather[33] as expected for a semi-volatile aerosol; while the wind direction might be locally important, as downtown is located east from the route so higher emissions are expected there.

Few studies have systematically explored the impact of meteorology on personal exposure and transport modes.[8,11,13,14] As they are not adjusted for a central site, the variables impact both background levels and personal exposure; it could be the case that the variable might affect both and may be in opposite directions. Most studies found impacts for wind speed and temperature, observing decreasing concentrations with increasing wind speed and temperature. However, these impacts should be driven by impacts on background concentrations, which is expected and is somehow trivial. We consider that modeling the impact of variables on personal exposure should separate the impact of them on background levels and on personal exposure.

Finally, apparent but insignificant exposure reductions were found for days with vehicular restriction. This may be due to the marginal impact of restricting only cars without catalytic converter and not including cars with converters, and also trucks and buses. Another factor could be that people own more than one car, so they might switch cars on the days of restriction. Finally, it is possible that pollutants accumulate on the route due to the traffic jams. Previous studies have found mild impacts of vehicular restriction on overall background levels in Santiago, Chile (less than 10%) for $PM_{2.5}$,[34] which is in agreement with our results. To our knowledge this is the first study that includes vehicular restriction impacts on personal exposure.

Table 3 Results for personal $PM_{2.5}$ models

Parameter	Coeff.	S.E.	95% CI	*p*-Value, *t*-test	*p*-Value, *F*-test
Model 1: personal *vs.* central site ($R^2 = 0.77$)					
Intercept	12.3	3.1	6.2–18.4	0.0002	
Central site	0.79	0.05	0.69–0.89	<0.0001	<0.0001
Model 2: personal *vs.* central site + transport mode ($R^2 = 0.86$)					
Central site	0.79	0.04	0.71–0.87	<0.0001	<0.0001
Transport mode					<0.0001
Bicycle	13.0	3.0	7.1–18.9	<0.0001	
Bus	17.5	3.0	11.6–23.4	<0.0001	
Car	2.0	3.1	−4.1 to 8.1	0.5215	
Subway	16.1	3.2	9.8–22.4	<0.0001	
Model 3: personal *vs.* central site + transport mode + temp. ($R^2 = 0.89$)					
Central site	0.88	0.04	0.80–0.96	<0.0001	<0.0001
Transport mode					<0.0001
Temperature	0.66	0.17	0.33–0.99	0.0002	0.0002

Table 4 Results for personal UFP models

Parameter	Coeff.	S.E.	95% CI	*p*-Value, *t*-test	*p*-Value, *F*-test
Model 1: personal *vs.* central site ($R^2 = 0.69$)					
Intercept	18 200	3700	10 900–25 500	<0.0001	
Central site	0.86	0.07	0.72–1.00	<0.0001	<0.0001
Model 2: personal *vs.* central site + transport mode ($R^2 = 0.80$)					
Central site	0.82	0.06	0.70–0.94	<0.0001	<0.0001
Transport mode					<0.0001
Bicycle	25 600	4000	17 800–33 400	<0.0001	
Bus	30 100	4100	22 100–38 100	<0.0001	
Car	16 200	3900	8600–23 800	0.0001	
Subway	8400	3700	1100–15 700	0.027	
Model 3: central site + transport mode + Temp. + wind direction ($R^2 = 0.85$)					
Central site	0.59	0.10	0.39–0.79	<0.0001	<0.0001
Transport mode					<0.0001
Temperature					0.0229
<0	23 800	7600	8900–38 700	0.0027	
0–5	7700	4400	−902 to 16 300	0.0849	
5–10	5200	3500	−1700 to 12 100	0.1466	
>10	0	Ref.		Ref.	
Wind direction					0.0113
East	11 600	4800	2200–21 000	0.0192	
South	−700	3400	−7400 to 6000	0.8329	
West	0	Ref.		Ref.	

Strengths and limitations

The biggest strength of this study is that we have actual personal exposure data for $PM_{2.5}$ and ultrafine particles, which are seldom available in developing countries. We also included central-site measurements. An additional strength is that, with our modeling approach, we found clear impacts of central site, transport modes and meteorology that have clear physical interpretation and can be easily used to compare transport impacts between cities, and for health impact assessment studies.[35] Previous studies explored associations using log transforms or ratios, with results that are more difficult to interpret. For instance, central site impacts might be in a percent increase in personal exposure, while ratios cannot be easily used in risk assessment.

One limitation of our study is that we did not measure other traffic pollutants such as NO_2 and CO, which may be better tracers of gasoline car emissions. Also, we measured only one route at only one time of the day, and we measured an assigned route, which is common in the majority of studies. How these measurements are compared to real-life routes is an important question and should be explored.

Conclusions

In this study we analyzed personal exposure to $PM_{2.5}$ and ultrafine particles in commuters using different transport modes in Santiago, Chile. We found impacts of background levels and traffic on personal exposure that varied with transport modes and meteorological factors. Bus commuting had the stronger traffic impacts on both pollutants, while car commuting had the lower impacts for $PM_{2.5}$, and subway commuting for UFPs. Our study shows that although central site measurements are important predictors of personal exposure, these alone will likely underestimate actual concentrations, and the transport microenvironment appears heavily affected by local emissions. Effort should be made to improve commuter's conditions as follows: decreasing nearby traffic whenever possible; improving emission technologies; improving in-cabin conditions; and separating heavy polluting vehicles from commuters.

Although we found traffic impacts in almost all transport modes it is of concern that cyclists experience relatively large exposure levels as compared to the relatively low exposure levels experienced by car commuters. We highlight this inequity of the situation where the most sustainable commuters (cyclists with almost no emissions) experience a similar, or larger, burden of traffic emissions as compared to those commuters contributing to larger pollution emissions (cars). Route selection might be important to decrease cyclist exposure as has been shown in previous studies. Comparing the impact of transport modes using "real-life" routes, especially for cyclists, should be explored in future work.

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