BUSAIR Project

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URBAN BUS AIR QUALITY

A technical guide

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idaea INSTITUTE OF ENVIRONMENTAL ASSESSMENT AND WATER RESEARCH

EXCELENCIA SEVERO OCHOA

Urban Bus Air Quality:

A technical Guide based on Barcelona BUSAIR data

BUSAIR Project: AIR QUALITY INSIDE PUBLIC TRANSPORT BUSES: PHYSICO-CHEMICAL AND BIOLOGICAL CHARACTERISATION. CGL2016-79132-R

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INTRODUCTION

A technical guide based on Barcelona BUSAIR data

Urban public buses worldwide carry hundreds of millions of passengers, all of whom inhale atmospheric pollutants in the form of particles and gases during what is commonly a daily commute. These urban journeys can provide a disproportionate percentage of the individual's average daily exposure to inhalable contaminants, and recognition of this fact is reflected in a large body of scientific literature on air pollution and city transport that goes back over 50 years (e.g. Haagen-Smit, 1966; Fernández-Iriarte et al., 2020). The number of such publications has increased rapidly in recent years, accompanying the recognition of the damage to human health being inflicted by inhaling polluted urban air whilst travelling by road (e.g. Alameddine et al., 2016; Cepeda et al., 2017; Fruin et al., 2011; Hudda et al., 2011, 2012; Hudda and Fruin 2018; Jo and Yu, 2001; Leavey et al., 2017; Lee et al., 2015; Madl et al., 2015; Moreno et al., 2015, 2020; Tartakovsky et al., 2013; Xing et al., 2018; Yang et al., 2015; Zhu et al., 2007). A subset of publications dealing with air quality associated with transport microenvironments has included information specifically on buses and bus stops (e.g. Adams et al 2001; Asmi et al., 2009; Bel and Holst 2018; Chernyshev et al., 2018; Choi et al., 2018; Dales et al., 2007; Dons et a., 2012; Fernández-Iriarte 2020, 2021; Gajewski 2013; Hess et al., 2010; Li et al., 2009; Lim et al., 2015; Merritt et al., 2019; Moore et al., 2012; Moreno et al., 2015, 2020, 2021; Nogueira et al., 2019; Rivas et al., 2017; Schimek et al., 2001; Van Ryswyk et al., 2020; Velasco and Tan 2016; Wang et al., 2011). Most of these studies, whilst all providing valuable data, are based on relatively short sampling campaigns or models and commonly focused on a limited number of specific contaminants such as PM10 or PM2.5 mass, number concentrations of ultrafine particles (UFP), and/or levels of gaseous pollutants. The ambition of the Barcelona BUSAIR project was to provide a more integrated study by utilising a broad spectrum of monitoring instruments measuring particulate and gaseous pollutants simultaneously inside vehicles under normal weekday operating conditions across four seasons of the year. The sampling phase of the project took place from May 2017 to April 2018, backed up by detailed data on background city air conditions, and produced the largest freely available database on urban bus air quality to date. This Technical Guide overviews these data, identifies key influences on bus air quality, and draws conclusions and recommendations aimed to stimulate future reductions in public transport passenger exposure to urban pollutants.

BUSAIR campaign overview

The BUSAIR monitoring campaign involved placing a trolley filled with portable air monitoring equipment in the middle of a bus (in the space normally reserved for wheelchairs or baby-carts) for a full return journey along a given route. The automatic instruments used comprised a miniature diffusion size classifier (DiSCmini, Matter Aerosol) for quasi-ultrafine particle number (QUFPN 10-300nm), a mini-aethalometer (MicroAeth AE51) for black carbon (BC), a light-scattering photometer (DustTrak, Model 8533, TSI) for $PM_{2.5}$, an IAQ-Calc (Model 7547) TSI monitor for CO_2, CO, temperature and relative humidity, and a GPS (Garmin eTrex 20x) (Fig. 1). Each equipment was set to a 30 s data acquisition time. All data was corrected against reference equipment before and after the campaign except $PM_{2.5}$. This was decided as DustTrak values obtained are more reliable when the equipment is quietly measuring on a flat surface, but less optimal while being carried in movement (Moreno et al., 2015). In any case a tendency towards overestimation of PM mass values measured by DustTrak has already been demonstrated by previous works (Knibbs and de Dear, 2010), although uncorrected values can usefully show relative concentrations between different microenvironments, which is how our data are treated here rather than applying reference correction factors (cf. Quiros et al., 2013).

For $PM_{2.5}$ chemical composition determination, 37 mm quartz fibre filters (Pallflex® Air Monitoring Filters, Pall, LifeScience) were used loaded in a personal environmental monitor (761-203B PEM, SKC) connected to a personal air sampling pump (Leland Legacy, SKC) at 10 L/min. The same filter was used during 3 weekdays of sampling in order to achieve enough sample to be analysed. Once the sampling had been done, the filters were kept inside a box to maintain them in darkness before being subjected to the same procedure as for blank filters before weighing. A total of 48 $PM_{2.5}$ gravimetric samples collected using the PEMs were chemically analysed using ICP-AES and ICP-MS for major and trace elements respectively. Volatile Organic Compounds were measured in 16 of the buses using stainless steel cartridges custom packed with activated graphitized BC adsorbents, using the same methodology as detailed in Moreno et al. (2019). In addition, bioaerosol and endotoxin samples were collected (Gilair) inside 56 buses and sent to the University Institute of Cardiology and Pulmonology of Quebec—Laval University, for analysis of total bacteria and fungi concentrations and endotoxins. The bioaerosol study was widened in response to the COVID-19 pandemic, which broke after the main sampling campaign had been completed, with a supplementary investigation for the presence of SARS-CoV-2 inside Barcelona commuting buses being added to the BUSAIR database in 2020.

Figure 1. Equipment used during the BUSAIR campaigns measuring air pollutants inside public buses.

Buses were chosen to include lines representative of the newly-introduced route system that emphasises "vertical" (i.e. running to and from the coastline) and "horizontal" (parallel to the coastline) trajectories (Fig. 2). A total of 141 bus journeys were monitored during the BUSAIR campaign which ran from 10 May 2017 to 13 April 2018. Data from 4 of these journeys were unusable due to malfunction of the DiSCmini instrument (on 10th May, 12th December, 28th March, and 10th April). Of the remaining 137 journeys successfully monitored, 113 were in regular commuter buses powered by diesel (E4, E5, and Hybrid Diesel), natural gas, or electricity, and 24 were open-top tourist buses powered by E4 diesel engines (Fig. 3).

Table 1 presents mean, median and standard deviation data on quasi-ultrafine particles (QUFP: number concentrations and size modes), black carbon (BC) and $PM_{2.5}$, measured in the 113 commuter buses and from sub-groups selected by differences in route (vertical versus horizontal), and powertrain (diesel versus non-diesel), air conditioning (on or off), as well as the tourist buses upstairs (outside) and downstairs (inside). Equivalent data were collected simultaneously using SMPS equipment at the Barcelona Palau Reial urban background (UB) monitoring site (located in the southwestern side of the city, at about 500 meters away from the Diagonal Avenue, 41°23'24.01"N 02° 6'58.06"E, 80 m a.s.l.).

Figure 2. Bus routes in the Barcelona public transport system, separating vertical (V) and horizontal (H) routes (source: TMB)

Figure 3. Examples of the bus fleet in the Barcelona public transport system (source: TMB)

Table 1: *Average and median values of quasi-ultrafine particle number (QUFPN: 10-300nm) concentrations and size, and black carbon (BC) and $PM_{2.5}$ mass concentrations measured inside buses during the BUSAIR monitoring campaign. "All buses" refers to commuting buses (not tourist services) and these are subdivided into different routes, engine types, and whether the air conditioning was recorded to be on (summer months only) or off. All values corrected against reference equipment except $PM_{2.5}$.*

	n	QUFP (# /cm³)			Size (nm)			BC (µg /m³)			$PM_{2.5}$ (µg /m³)		
		Mean	Median	S.D.	Mean	Med.	S.D.	Mean	Med.	S.D.	Mean	Med.	S.D.
Urban Background		17,391	16,232	5,737	47	43	5	2.2	2.0	1.0	13	12	6
All buses	113	34,511	28,250	24,906	42	43	7	5.6	5.2	3.0	34	32	12
Vertical route	40	38,720	32,368	29,063	43	44	7	6.6	6.2	3.5	36	36	13
Horizontal route	30	28,543	22,899	21,108	43	43	7	5.1	4.6	2.7	33	32	8
Diesel non-tourist	63	37,776	29,883	29,930	41	42	7	6.1	5.6	3.1	32	31	11
Non-diesel	50	30,463	26,225	18,675	44	44	6	5.1	4.7	2.8	35	32	13
Air Con on	38	37,233	29,913	28,258	46	47	8	5.0	4.5	2.7	30	28	8
Air Con off	51	26,278	22,045	18,202	39	39	5	5.7	5.5	2.8	38	36	15
Tourist inside	12	47,092	37,142	34,315	41	42	7	6.9	6.0	3.7	40	40	9
Tourist outside	12	49,196	31,303	66,864	41	42	10	6.2	4.9	4.2	42	41	14

Mean values of the pollutants listed in Table 1 were 2 (QUFPN) to 2.6 (BC and $PM_{2.5}$) times higher than urban background concentrations measured simultaneously during each bus journey. Vertical routes and diesel (non-tourist) buses recorded highest median values of QUFPN and BC. The frequency of pollutant peaks of QUFPN and BC measured in the buses is reflected by consistently lower median values, this being most obvious in the open top of the tourist buses ("Tourist outside": mean/median=1.6) where passengers were most exposed to transient traffic-related pollutant spikes. Median values for ultrafine particle sizes were remarkably consistent at around 42-44nm, with the exception of a wider spread (39-47nm) revealed by comparing A/C on (47nm) with A/C off (39nm) conditions.

QUASI-ULTRAFINE PARTICLE NUMBER CONCENTRATIONS (N)

QUASI-ULTRAFINE PARTICLE NUMBER CONCENTRATIONS (N)

The boxplot in Figure 4 shows number concentrations of quasi-ultrafine particles (10-300nm modal diameter) measured using the DiSCmini, comparing the various groups separated in Table 1. Note the relatively low values recorded by the urban background station, the interquartile range (IQR) data from which do not overlap with that of "All buses". Lowest mean/median values measured inside buses were in the Horizontal routes sub-group (28,543 / 22,899cm^{-3}) and are 25-30% lower than mean/median values in Vertical routes (38,720/32,368cm^{-3}).

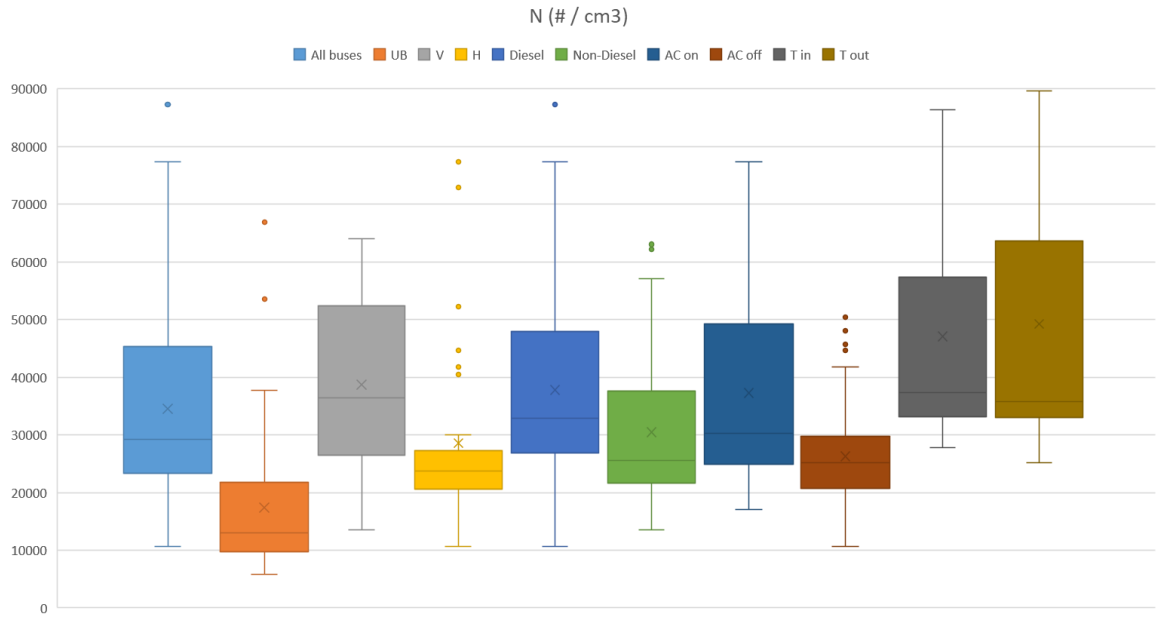


Figure 4. Boxplot for number concentrations (N) of particulate matter <300nm in diameter (quasi-ultrafine particles QUFP). Mean values marked as crosses and median values as horizontal lines. Interquartile range (IQR) represented as coloured rectangles. Outliers (mean values) marked as coloured dots. "All buses" excludes tourist buses; UB=urban background; V=vertical routes; H=horizontal routes; Tin/Tout= open-topped tourist buses inside (downstairs) and outside (upstairs).

Influence of Urban Background

The two urban background (UB) outliers recording exceptional levels of QUFP reflect abnormally polluted winter conditions in the city on 24 November and 24 January when SMPS mean values of QUFP 10-400nm were over three times normal. During both of these citywide pollution events unusually high N levels were also recorded by the DiSCmini inside the buses, as detailed below.

In the 24 November pollution episode, mean QUFPN values rose >10,000 cm^{-3}above average in both buses for that day (V3 natural gas bus 50,378cm^{-3} and V3 diesel E4 bus 45,653 cm^{-3}). In contrast, the same V3 bus pair was monitored 6 days later when urban background levels had dropped back to normal, and recorded mean N values of just 16,279cm^{-3} (natural gas) and 23,726cm^{-3} (diesel E4).

In the 24 January pollution episode, the added effect of poor outside air was even more marked as this day was used to sample in an open-topped tourist bus where mean QUFPN concentrations proved to be >20,000 cm^{-3} higher than the "All buses" average (lower floor 56,310cm^{-3}; upper floor 59,488cm^{-3}). Figure 5 compares QUFPN concentrations measured on the open top deck of a tourist bus during this 24 January event with those registered just the day before, when the city atmosphere was unusually clean.

Two other days during the monitoring campaign also registered notably high (although not boxplot outlier) urban background pollution levels, these being 1 March and 1 June. On these two days once again both buses registered outlier values recording unusually high levels of in-vehicle pollution.

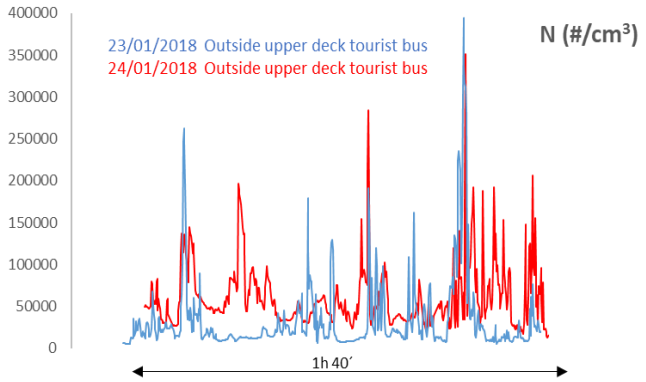


Figure 5. Comparison between mean number concentrations (N) of quasi ultrafine particles measured on the upper deck of an open topped tourist bus (Barcelona Blue Route) during days of low (23 January) and high (24 January) urban background levels. The peaks rising to N>100,000 record traffic congestion hotspots. The less polluted outdoor conditions on the 23 January are reflected in the lower baseline N concentrations recorded on the top deck of the bus.

On 1 March Route H12 buses (41,815cm^{-3} hybrid diesel and 40,478cm^{-3} natural gas) N levels were around 15,000cm^{-3} higher than the mean for their subgroup. On 1 June Route V3 both buses recorded N values of QUFP also much high than average (63,015cm^{-3} natural gas and 52,240cm^{-3} diesel E5).

Air quality measured as number concentrations of QUFP inside buses can be noticeably influenced by city background levels in outside air.

Influence of Traffic Hotspots

Other exceptional "outlier" N concentrations of QUFP shown on Figure 4 are always associated with extreme peaks produced by traffic hotspots such as proximity to the urban motorways that both encircle and traverse the city (Ronda de Dalt, Meridiana, Diagonal, Ronda de Mig, Gran Via, Ronda Litoral), or major node points such as Plaça D'Espanya and Plaça de les Glòries Catalanes. The three most prominent of these outlier values recorded by the BUSAIR data all occurred in the warmer months of the year from May to September and are detailed in the examples below.

Example 1: 87,254cm^{-3} Route 34 on 25 May. Hybrid diesel bus recorded frequent N exceedance >100,000, several >200,000 and one exceptional peak of 631,000cm^{-3}. The peaks always coincide with busy traffic hotspots, notably crossing the Meridiana urban highway, points along the Diagonal and Avenida Sarrià, and for the extreme peak of 631,000cm^{-3}, the area around the Ronda de Mig. This hybrid diesel bus was much more polluted in QUFP than the electric bus (N= 45,259cm^{-3}) running along the same route 10 minutes behind and which showed only one 100,000 peak exceedances (Fig. 6). The reason for this is deduced to be linked to the fact that the electric bus had a more closed indoor environment (no windows can be opened and therefore all glass is fully sealed), reflected by median CO_2 levels being higher than in the hybrid diesel (Fig. 6). Another marked difference was in QUFP size, which averaged 31nm in the hybrid diesel bus but 44nm in the electric bus, suggesting the presence of more fresh exhaust in the former.

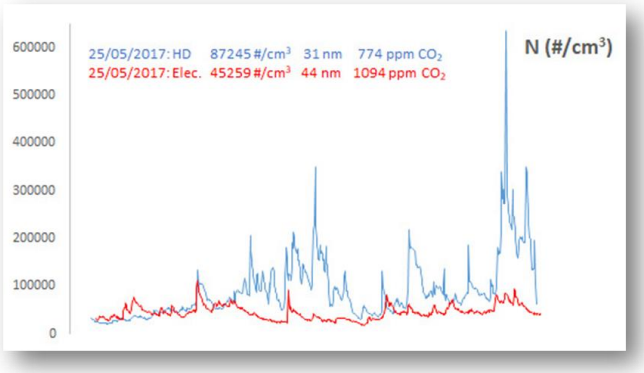


Figure 6. Comparison between number concentrations (N) of QUFP recorded inside a Route 34 bus pair monitored on 25 May (timings adjusted to coincide approximately with first 100,000cm^{-3} peak: in reality the HD bus started the journey 9 minutes ahead of the electric bus). The hybrid diesel (HD) bus data record greater infiltration of outside ultrafine traffic pollutants, especially at traffic hotspots crossing the Meridiana, Diagonal, Avenida Sarrià and Ronda del Mig, but lower levels of CO_2 due to greater outside air exchange. The windowless indoor environment of the electric bus, and possibly the lack of self-pollution from exhaust emissions, suppress N levels for most of the journey (initially higher N values inside the electric bus may be related to the logsheet stating that someone was smoking adjacent to the bus waiting at the initial stop).

It is possible that the hybrid diesel bus was at least in part self-polluted by its own exhaust plume entering as the doors opened at bus stops. Similar observations were repeated for the two other hybrid diesel/electric bus pairs on Route 34 monitored that week (23 and 24 May), with the electric bus again recording lower N values and higher UFP sizes than the hybrid diesel.

Example 2: 52-77000cm^{-3} Route H12 on 18-20 July. Cluster of three hybrid diesel buses on consecutive days sampling during typically very busy traffic along the Gran Via urban highway, especially around Plaça D'Espanya and Plaça de les Glòries Catalanes. 18 July: mean N value 77,321cm^{-3} with several peaks exceeding 100,000cm^{-3} including one with an 848,000cm^{-3} extreme value.

19 July: mean N value 52,234cm^{-3} with four peaks exceeding 100,000cm^{-3} and a maximum peak of 161,000cm^{-3}. 20 July: 72,912cm^{-3} with N>100,000cm^{-3} recorded during much of the journey along the Gran Via through the city centre, reaching extreme peaks of 62,6000 cm^{-3} (outward) and 719,000cm^{-3} (return). All these three buses were paired with natural gas-powered buses, all three of which showed much lower N values (24-28,000cm^{-3}) and larger UFP sizes (46-53nm versus 34-39nm in hybrid diesel), as seen in the 25 May bus pair (Figs. 6 and 7). The outward journey for the 18 July bus pair is depicted on Figure 7 which demonstrates how the hybrid diesel bus interior was more contaminated by traffic emission infiltration, as reflected by higher N, smaller UFP sizes and lower CO_2 concentrations. As with the previous example shown on Figure 6, there is the possibility of self-pollution by the hybrid diesel bus.

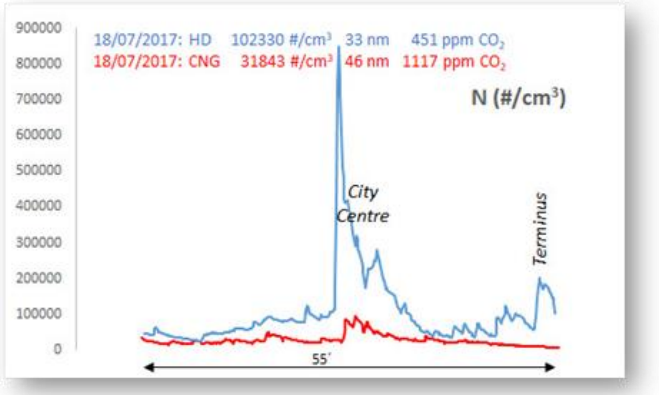


Figure 7. Comparison between two H12 buses (hybrid diesel HD and compressed natural gas CNG) on outward journey through city centre to terminus at Besòs-Verneda. Traffic particle emission infiltration into the HD bus at the busy city centre (Gran Via crossing Balmes and Passeig de Gracia) is most obviously reflected in a strong peak (848,000cm^{-3}) which is much more subdued in the NG bus. At the terminus the HD bus was left with engine running while waiting with A/C on for 11 minutes, producing an increase in QUFP concentrations that briefly peaked at >200,000cm^{-3}. In contrast the NG bus was running late and stopped at the terminus for only 2 minutes.

Example 3: 62,152cm^{-3} route V11 on 28 September. Natural gas bus with peaks of N>100,000cm^{-3} at busy traffic hotspots in Via Augusta (out and back) and the Drassanes area, plus a 17 minute period of high N (peaking at 271,000cm^{-3}) during the uphill route along Carrer Compte d'Urgell (Fig. 8).

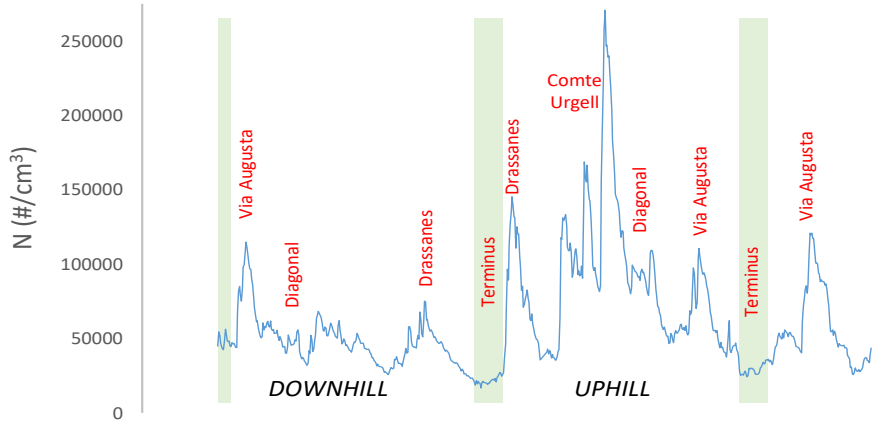


Figure 8. Concentrations of quasi ultrafine particles measured during a return journey on the "vertical" route in natural gas bus V11 (28 September, bus windows open). Note repetition of N peaks at traffic hotspots such as around Via Augusta, the low values of N at the termini, and the more polluted nature of the uphill journey climbing away from the sea level terminus near Drassanes to the Diagonal.

Transient peaks in ultrafine particle number concentrations of 100,000-1,000,000cm^{-3} can be produced frequently inside buses due to the infiltration of traffic emissions at highly polluted locations such as the proximity to urban motorways, busy intersection crossings and roundabouts, and uphill stretches of relatively narrow, canyon-like roads.

ULTRAFINE PARTICLE SIZE (nm)

ULTRAFINE PARTICLE SIZE

All data groups record overlapping IQR values for UFP sizes between 34 and 50nm, with little difference between mean and median concentrations (Table 1; Fig. 9). This size range seems to be typical of the peak size distribution of airborne ultrafine particles found inside buses (compare Moreno et al., 2020) and is sometimes referred to as "aged traffic" PM to distinguish it from finer "fresh traffic" size modes <25nm.

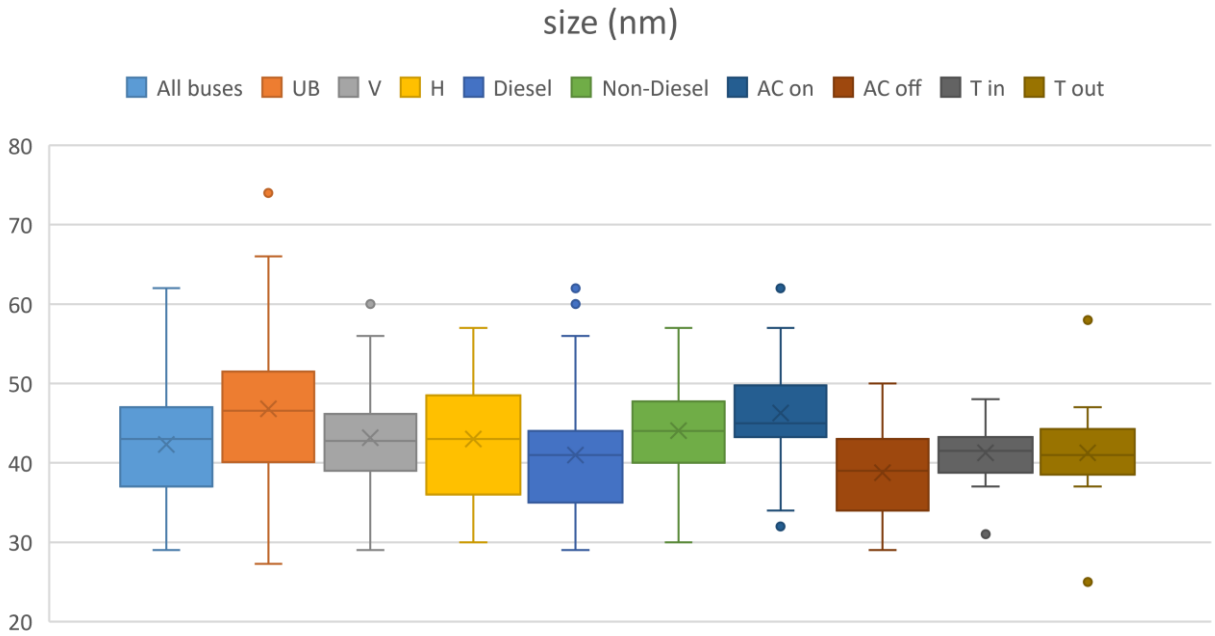


Figure 9: Average sizes of particulate matter <300nm. Outliers marked as coloured dots are as follows: Urban Background 8 June 74nm; Vertical route, diesel, A/C on 17 May E5 60nm; A/C on 23 May bus 34 hybrid diesel 32nm; Tourist inside downstairs (in) 28 June 31nm, Tourist outside upstairs (out) 28 June 25nm and 26 June 58nm.

As the number concentration of ultrafine particles rises due to infiltration of pollutants from outside so the size mode defines a corresponding trough. An example of this is illustrated in Figure 10 on which a hybrid diesel bus running along the Gran Via urban highway (Route H12) records an extreme concentration peak (>800,000cm^{-3}) and size trough (<15nm) coinciding at a major traffic hotspot in the city centre.

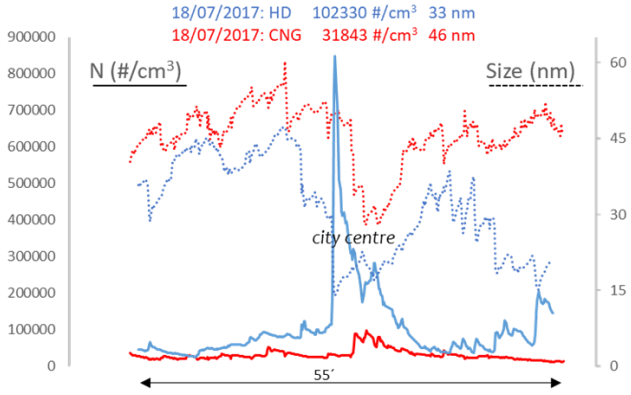


Figure 10. Comparison between number concentrations (N) and sizes (in nm) of ultrafine particles recorded during a return journey along the Gran Via in an H12 hybrid diesel bus. The data record very high N in the city centre on the outward journey but not on the return route on the other side of the road. This difference is attributed to the wind blowing at 15km/hr from east to west across the multilane highway, contaminating the west side (outward) with traffic emissions far more than the eastern side return). Ultrafine particle sizes vary inversely with N, falling from 45nm to 15nm at the city centre traffic hotspot.

32nm Route 34. 23 May hybrid diesel. Unusually fine average UFP size appears to have resulted from the impact of two traffic pollution hotspots (with correspondingly increased N values of QUFP) around the Sagrada Familia and the Ronda de Mig (Fig. 11).

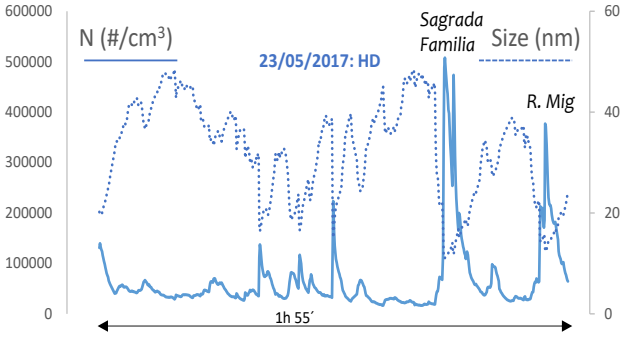


Figure 11. Comparison between number concentrations (N) and sizes (in nm) of ultrafine particles recorded during a return journey inside a hybrid diesel bus operating on Route 34. Note the inverse relationship between ultrafine particle size and number concentration N.

Exceptional cases of unusually high and low mean ultrafine particle sizes deviating from the average value of 42nm were noted in the following buses:

74nm urban background. 8 June. This unusually coarse average value of background UFP in the city coincided with very low number concentrations of QUFP (N=7,509cm^{-3}) and BC (1.1 µg/m^3) values, indicating good air quality diluted by a fresh southwesterly breeze blowing at 29km/hr across the city. This was reflected by correspondingly low N and BC values in the two buses monitored that day (natural gas 17,119cm^{-3}, 49nm and 2.7 µg/m^3; electric 20,028cm^{-3}, 47nm and 3.3 µg/m^3 respectively).

31nm route Tourist inside and 25nm Tourist outside. 28 June. This low value again coincides with unusually high N values (76,186cm^{-3}) during busy traffic and is interpreted as recording enhanced levels of fresh traffic exhaust hotspots that coincide with Plaza España, the ascent of Montjuic, descent via a tunnel (extreme peak) to the congested seafront area from Colon to Port Olympic, the ascent of Via Laietana in the medieval city, and the area around Casa Batllo in the Passeig de Gracia. Urban background values for that day are not available. Coinciding average BC and $PM_{2.5}$ values recorded during the journey were not exceptional but also punctuated by prominent traffic congestion peaks (Fig. 12).

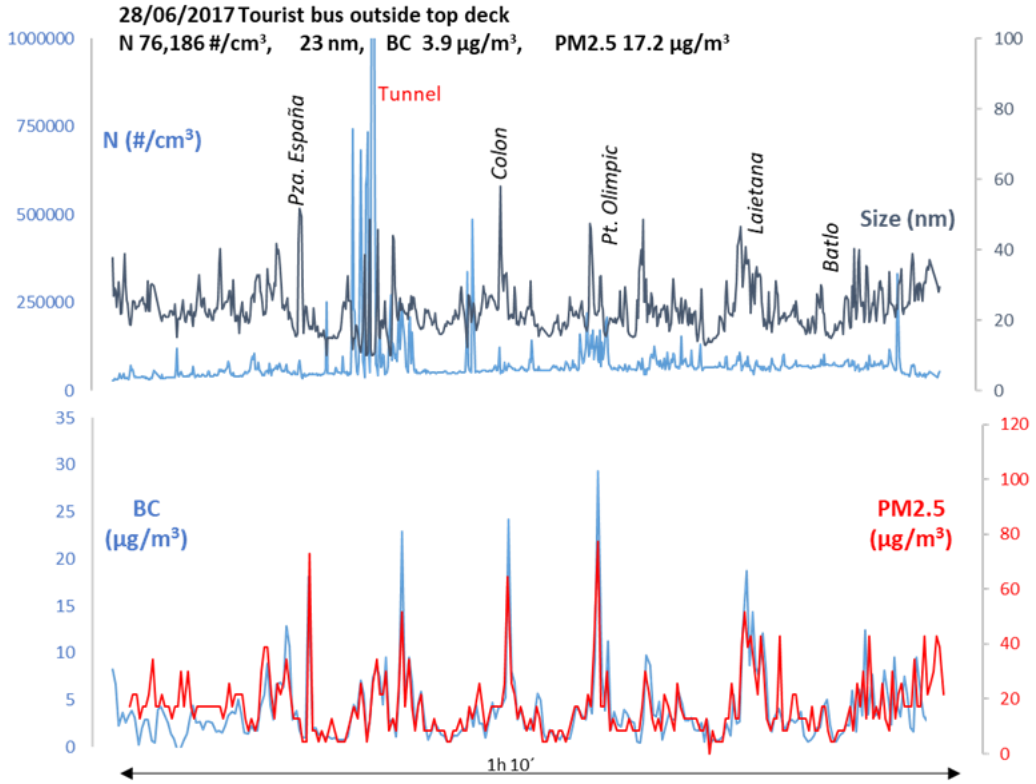


Figure 12. Levels of air pollutants recorded on the top open deck of a tourist bus (red route). An unusually extreme peak of QUFP number concentrations exceeding 2 million cm^{-3}, with corresponding trough of sizes well below 20nm, was recorded in the Montjuic tunnel. Black carbon and $PM_{2.5}$ values define similar patterns, with the peaks coinciding with traffic-congested hotspots.

Ultrafine particle size is a useful indicator for the relative amount of fresh traffic-related particle emissions inside a road vehicle, with an inverse correlation typically existing between particle size and number.

BLACK CARBON CONCENTRATIONS

BLACK CARBON CONCENTRATIONS

Levels of BC PM inside buses averaged 5.6 µg/m^3, with most measurements lying within an interquartile range of 4-7 µg/m^3 (Table 1). In contrast, equivalent measurements taken at the Palau Reial urban background site recorded average concentrations of 2.2 µg/m^3, demonstrating the important contribution of incompletely combusted hydrocarbon fuels sourced from road traffic exhaust within the city. Somewhat higher average and median BC values for vertical route and diesel bus, as compared to horizontal route and non-diesel buses, are revealed on the BC boxplot (Fig. 13), although note that there is overlap between all bus sub-group interquartile ranges.

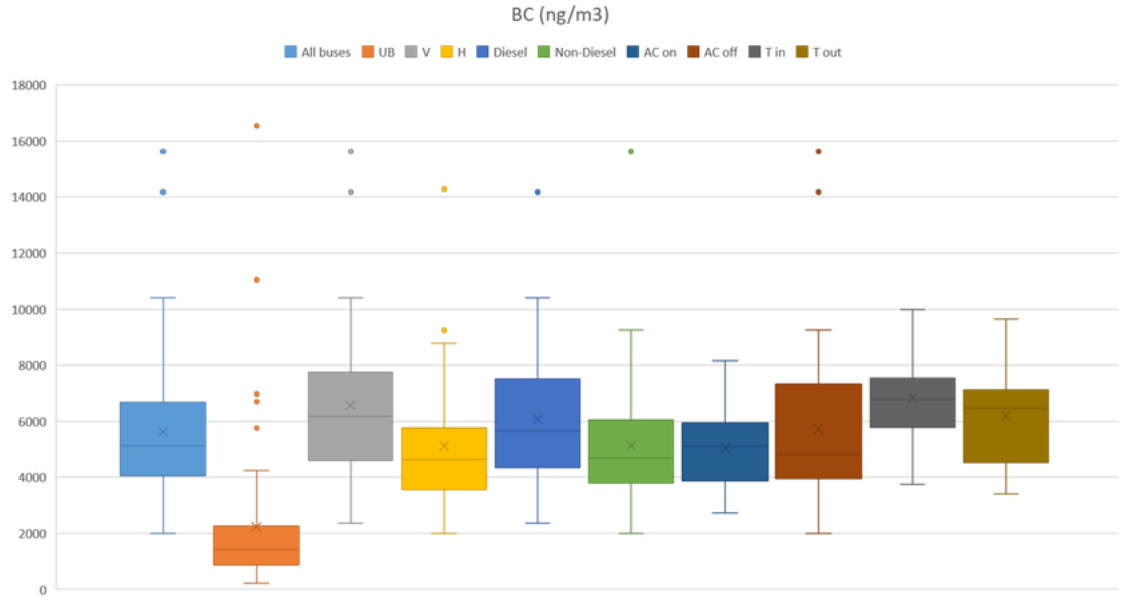


Figure 13. Ranges of black carbon concentrations measured inside buses and in urban background. Outliers marked as coloured dots are as follows: All buses: 24 Nov natural gas V3 15.6 µg/m^3; 1 Mar hybrid diesel H12 14.6 µg/m^3; 24 Nov E4 V3 14.2 µg/m^3; Urban Background: 24 November 16.5 µg/m^3; 24 January 11.0 µg/m^3, 16 November 6.7 µg/m^3; 23 November 5.8 µg/m^3; 1 March 7.0 µg/m^3; Vertical route: same as all buses; Horizontal route: same as all buses plus 1 March natural gas H12 9.6 µg/m^3; A/C off: same as all buses.

The five outliers in the urban background data on Figure 13 record days when the city air was exceptionally polluted (24 November (16.5 µg/m^3), 24 January (11.0 µg/m^3), 1 March (7.0 µg/m^3), 16 November (6.7 µg/m^3), 23 November 5.8 µg/m^3). Two of these dates coincide with outlier BC measurements in the "all buses", "vertical", and "horizontal" groups on Figure1 3, i.e. 24 November vertical route buses (natural gas 15.6 µg/m^3 and E4 diesel 14.2 µg/m^3) and 1 March horizontal route buses (hybrid diesel 14.3 µg/m^3 and natural gas 9.2 µg/m^3), all 4 of which had a/c off. Details of the bus group outliers >10 µg/m^3 shown on the boxplot Figure 13 are as follows:

15.6 µg/m³ route V3 on 24 November. Natural gas bus. The highest BC values coincide with a traffic hotspot (Diagonal) and a short tunnel entered for a few minutes in the Ronda del Mig south of the Diagonal, combined with the effect of a polluted urban background for that day. On the outward and return journeys BC values in the tunnel rose to peaks of 22 µg/m³. On the return (uphill) journey the bus entered and stopped several times in the Diagonal traffic hotspot, causing BC levels to continue to rise to a peak of 39 µg/m³. Figure 14 compares BC data from the natural gas bus with that from the same bus on the same route but 4 days later when urban background levels of BC had dropped from 16.5 µg/m³ to 1.8 µg/m³.

14.3 µg/m³ route H12 on 1 March. Hybrid diesel bus. As with the above example, high BC levels associated with tunnels and traffic hotspots were superimposed on a high urban background. Levels of BC jump to 15 µg/m³ on entering a tunnel beneath the Plaça D'Espanya, after which BC concentrations remained high (15-20 µg/m³) for most of the journey, apart from another jump at the Plaça de les Glòries Catalanes traffic hotspot (to 35 µg/m³).

14.2 µg/m³ route V3 on 24 November. E4 diesel. Similar to the other bus paired on 24 November (see above) with the tunnel again causing BC levels to reach peaks of 21-22 µg/m³. The Diagonal traffic hotspot on the return (uphill) journey is less pronounced, probably because the bus stopped fewer times.

Concentrations of BC inside buses are thus 2 or 3 times higher overall than those typically measured in Barcelona urban background air, lying within the range 4-8 µg/m³. Individual journeys record BC levels punctuated by transient peaks that can exceed 10 times average background. Such peaks in mass concentrations inside buses coincide with road traffic hotspots, tunnels, and urban background levels of outside air pollution in the city.

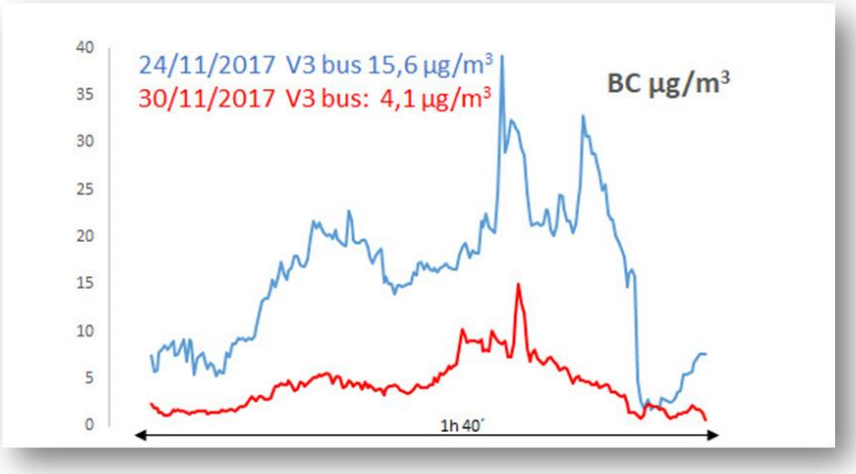


Figure 14. Comparison between BC concentrations (in µg/m³) measured inside two natural gas-powered buses running on line V3 on days with very high (24 November: 16.5 µg/m³) and low (30 November: 1.8 µg/m³) urban background BC levels. The average in-bus values for the two journeys were: 24 November 15.6 µg/m³, 30 November 4.1 µg/m³. The 24 November recorded the worst pollution event affecting the city during the BUSAIR monitoring campaign. Both buses recorded their maximum peak in the traffic hotspot intersection between 2 urban motorways (Diagonal and Carles III)

$PM_{2.5}$ MASS CONCENTRATIONS

$PM_{2.5}$ MASS CONCENTRATIONS

Average mass concentration values of $PM_{2.5}$ measured inside buses during the BUSAIR campaign were 34 µg/m³ (uncorrected values), as compared to 13 µg/m³ in the urban background recorded simultaneously at the Barcelona Palau Reial monitoring station. Similar mean values (30-38 µg/m³) were recorded in the various sub-groups of commuter buses (Table 1), although rising to 40-42 µg/m³ in the tourist buses (Fig. 15). There is typically a strong similarity between the patterns of PM2.5 and BC concentrations registered during a bus journey, with traffic pollution peaks being registered simultaneously by the two pollutants (Fig. 12).

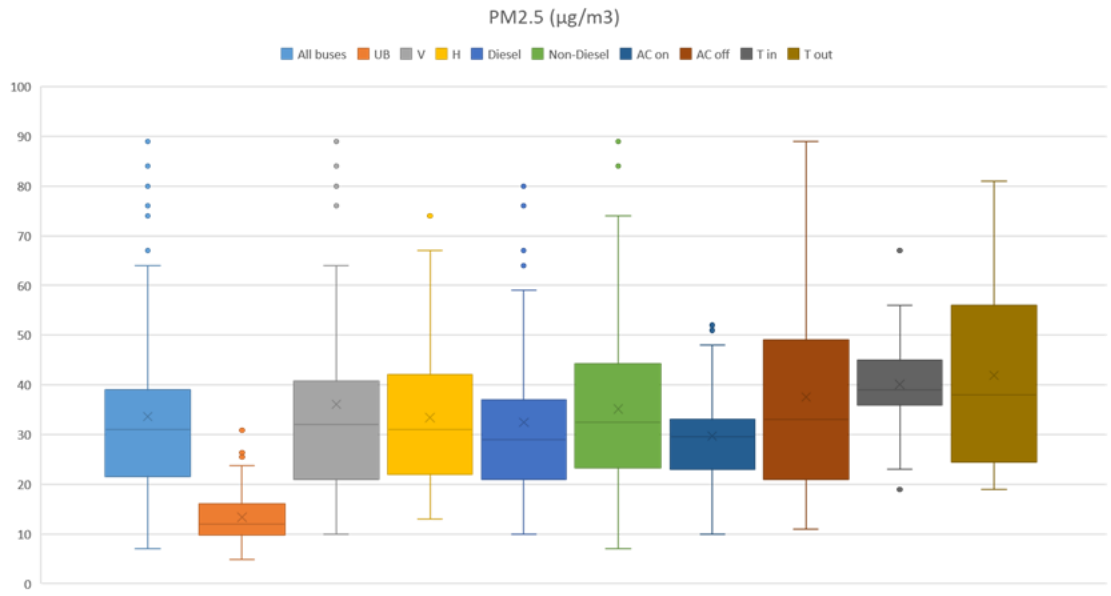


Figure 15. $PM_{2.5}$ mass concentration ranges measured during the BUSAIR project (same sub-groups as in Table 1). Note the difference between urban background levels and all other values.

Although there is little difference in interquartile ranges between the sub-groups or much deviation from the overall mean value of 34 µg/m³ (Table 1), there is considerable spread of daily average mass concentrations (<10 to >80 µg/m³). As with BC levels, the prominently polluted urban background day of 24 November tops the list of mean $PM_{2.5}$ concentrations (at 89 µg/m³). Other outlier days registering mean $PM_{2.5}$ concentrations >60 µg/m³ are 1 December, 18 January, 1 March, 23 November and 30 January. Urban background levels average 13 µg/m³, and only very rarely rise above 25 µg/m³ (26-32 µg/m³ on 22 to 24 of November).

Details for the high urban background $PM_{2.5}$ outlier days are as follows:

89 µg/m³ Route V3 on 24 November. Natural gas. Similar pattern to BC, with elevated urban background levels combined with traffic hotspot pollution around the Diagonal highway ($PM_{2.5}$ rising from 40 to 70 µg/m³) and the effect of open windows. Concentrations jumped to 100 µg/m³ after entering tunnel in Ronda del Mig after which PM levels inside the bus failed to dissipate (Fig. 16). Levels thus remained high for most of the rest of the journey, peaking at 137 µg/m³ in the Gran Via area then at 147 µg/m³ upon re-entering tunnel on the return journey, and staying at >100 µg/m³ around the Diagonal hotspot and beyond. At the upper terminus a 7 minute wait dropped $PM_{2.5}$ levels to <30 µg/m³.

84 µg/m³ Route V3 on 1 December. Natural gas. Contrasts with previous example in having all windows closed (cold weather), which slightly subdued the pollution peak associated with tunnel entry. The most notable characteristic was a prominent peak in $PM_{2.5}$ at both bus termini (>100 µg/m³), when the bus waited with engines on but doors closed, suggesting the effect of self-pollution.

80 µg/m³ on 18 January, 76 µg/m³ on 24 November, 64 µg/m³ on 23 November Route V3. Diesel E4 in all cases and all display same pollution pattern, as seen in previous examples of V3 route. High urban background pollution on both days enhanced by traffic hotspots (up to 130 µg/m³) and tunnels (up to 125 µg/m³). At the upper terminus levels can drop to <30 µg/m³, as seen on 24 November natural gas bus pair.

74 µg/m³ route H12 on 1 March. Hybrid diesel. Levels start at around 60 µg/m³ then increase to 80 µg/m³ for the first 15 minutes without stopping the bus. Levels generally high throughout journey with three peaks: when the bus started the engines at the outward terminus (jump from 62 to 98 µg/m³) a major peak at (162 µg/m³) that corresponds with Plaza España, and another at 127 µg/m³ that is Plaza Europa.

67 µg/m³ route H12 on 1 March. Natural gas. Levels begin at 40 µg/m³ and rise gradually to >60 µg/m³ with peaks at 91 (Plaza España), 95 (Gran Via/Balmes) and 97 µg/m³ (Gran Via/Ciudad de la Justicia).

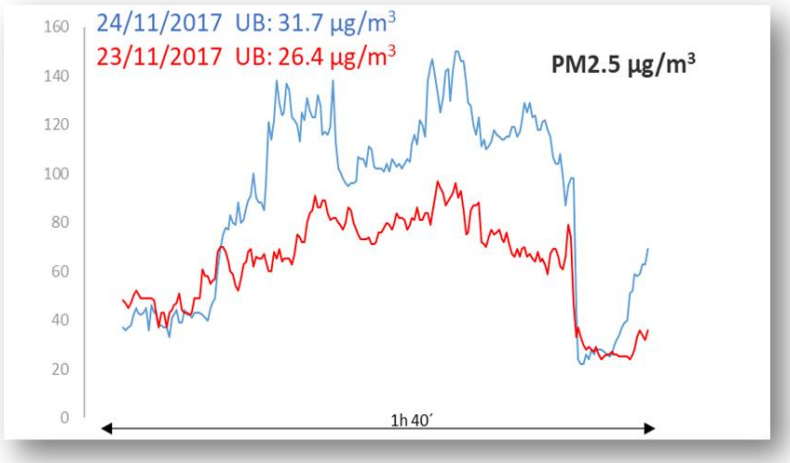


Figure 16. Comparison between $PM_{2.5}$ concentrations (in µg/m³) measured inside two natural gas-powered buses running on line V3 on days with very high (24 Nov.: 31.7 µg/m³) and lower (23 Nov.: 26.4 µg/m³) urban background $PM_{2.5}$ concentrations. The average in-bus values for the two journeys were: 24 Nov. 89 µg/m³, 23 Nov. 62 µg/m³. The 24 Nov. recorded the worst pollution event affecting the city during the BUSAIR monitoring campaign. Both buses recorded their maximum peak in the traffic hotspot intersection between two urban motorways (Diagonal and Carles III).

67 µg/m³ on 30 January. Tourist bus upper deck. PM levels increase as a result of the ascent of Montjuic, from 50 to 80 µg/m³, and stay >60 µg/m³ for the rest of the journey (Fig. 17). In contrast, average levels as low as 19 µg/m³ were recorded on 23 January during a clean, clear, sunny, cold day with excellent city AQ.

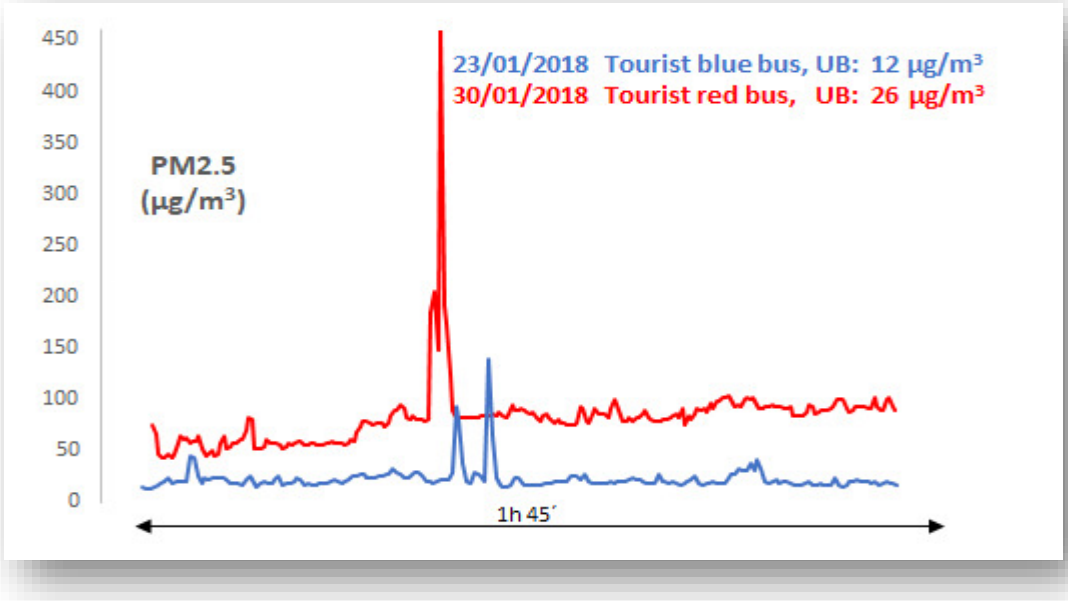


Figure 17. Comparison between $PM_{2.5}$ mass concentrations (uncorrected values in µg/m³) measured in the open deck of tourist buses in a clean (23 January) and more polluted (30 January) day.

As seen with QUFP number concentration and BC levels, average PM2.5 mass concentrations inside buses can be strongly affected by outdoor urban background air quality. PM2.5 breathed while travelling by tourist bus for example can be less than 50% below normal on clear, clean winter days with low levels of urban background pollution. Transient peaks superimposed on this background typically show a strong coincidence between BC and PM2.5 concentrations. Such pollution peaks in PM2.5 encountered inside commuter buses are associated with traffic hotspots and tunnels and typically lie within the range 75-150 µg/m³, and so can be >x10 average urban background.

POLLUTANTS AND FUEL TYPE

POLLUTANTS AND FUEL TYPE

The results recorded for the different fuel/engine bus types and are summarized in Figure 18 using median values, which reduce the effect of the numerous transient pollution peaks typically encountered during a bus journey. The data are subdivided into subgroups including fuel/engine type (diesel (E4, E5), hybrid diesel (HD), compressed natural gas (CNG), hybrid compressed natural gas (HCNG) and electric). In general, hybrid vehicles are characterized by the lowest N, BC and $PM_{2.5}$ values, whereas diesel buses show the highest values, although there are wide ranges and much interquartile overlap (Fig. 18). Median values for UQFP ranges from 22,427cm^{-3} in HCNG buses to 35,590cm^{-3} in E5 buses (HCNG<CNG<electric<HD<E4<E5), UQFP size modes vary only slightly within all the different fuel/engine bus types, between 36 (HD) and 45 nm (CNG) (HD<E5<E4<HCNG<electric<CNG), the lowest median BC concentrations (3.6 to 7.4 $\mu g/m^3$) were measured in HCNG buses (<electric<HD<CNG<E5 <E4), and finally $PM_{2.5}$ concentrations varied between 26 (HD) and 36 $\mu g/m^3$ (E4) (HD<electric<E5<HCNG <CNG<E4). Taken overall, the amount of variation exhibited by the data, combined with variability in the number of buses measured of each fuel/engine bus type, result in no clear pattern emerging.

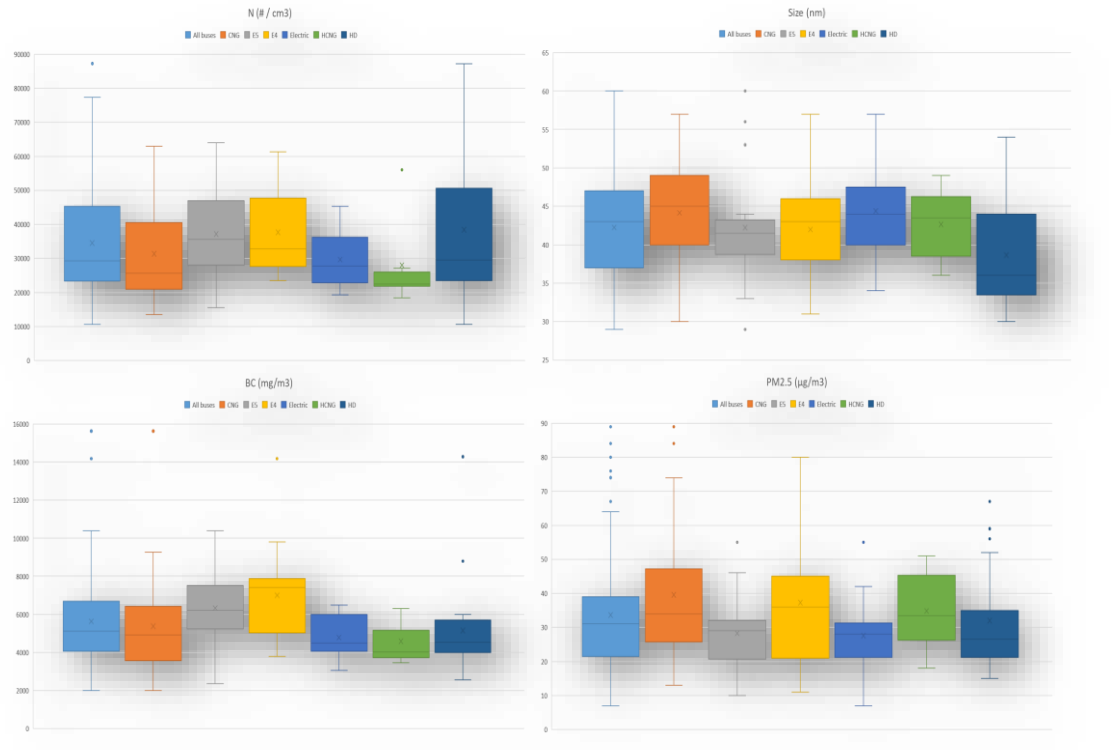


Figure 18. Box-and-Whisker plots for quasi-ultrafine particle concentrations (N) and sizes (nm), BC and PM2.5 comparing all buses and powertrain sub-groups CNG, diesel E5, diesel E4, HD, electric and HCNG. The number of monitored journeys for each sub-group is CNG= 30, E5=22, E4=20, HD= 23, Electric= 17, HCNG= 6.

The BUSAIR study did not reveal any dominant link between interior bus air quality the type of powertrain operated by the bus. Instead, the quality of the outdoor air and the extent to which such air could infiltrate and circulate around the bus appear to be the main factors influencing air quality on any given journey

INHALABLE PARTICULATE MATTER CHEMISTRY

Chemical analysis of $PM_{2.5}$ sampled during the BUSAIR campaign reveal a dominance of organic carbon (mostly 10–20 µg/m³) and elemental carbon (mostly 3–6 µg/m³; OC/EC = 3.4), followed by SO_4^{2-}, Fe, Ca, K, Al_2O_3, Mg, and Na, with calculated mineral content being around one third that of total carbon. Most bus pairs sampled in the study show little difference in major element $PM_{2.5}$ chemistry, typically varying in OC, EC and mineral content by <3 µg/m³, <2.5 µg/m³, and <2 µg/m³ respectively. In contrast, major element concentrations of $PM_{2.5}$ in bus interiors are more than double urban background levels, reflecting the polluted nature of air in the main city streets (Table 2).

Table 2: *Summary of chemical analyses of PM2.5: all bus average (AB), urban background (UB), and sub-groups based on bus engine types, season, and route (see Fernández-Iriarte et al., 2020 for further details).*

	URBAN BACKGROUND	ALL BUSES (AB)		BUS TYPE							SEASON		ROUTE		
	UB	AB	AB/UB	Diesel	HD	CNG	HNG	Electric	Tourist outside	Tourist inside	Summer	Winter	Vertical	Horizontal	Others
n		48		14	8	10	2	6	4	4	16	16	14	10	16
µg/m³															
OC	2.39	15.03	6.29	16.65	15.13	16.20	17.03	11.35	12.64	13.15	14.29	17.30	15.71	15.37	15.29
EC	1.04	4.81	4.61	5.15	5.52	4.90	3.90	3.93	4.94	3.56	4.54	5.41	5.29	5.42	4.28
CO3=	0.35	1.63	4.65	2.05	1.48	1.84	1.93	1.20	0.78	1.23	1.69	1.64	2.04	1.51	1.65
SiO2	0.54	3.26	6.09	3.78	2.95	3.66	4.07	2.86	2.19	2.38	3.42	3.58	3.81	2.98	3.45
Al2O3	0.18	1.09	6.09	1.26	0.98	1.22	1.36	0.95	0.73	0.79	1.14	1.19	1.27	0.99	1.15
Ca	0.23	1.08	4.65	1.37	0.99	1.23	1.29	0.80	0.52	0.82	1.12	1.09	1.36	1.00	1.10
Fe	0.19	0.99	5.33	1.13	1.02	1.27	1.11	0.56	0.68	0.64	0.73	1.51	1.26	1.23	0.77
K	0.11	0.75	6.54	0.79	0.62	0.73	0.76	0.46	0.99	1.10	0.64	0.81	0.77	0.61	0.67
Na	0.15	0.65	4.45	0.88	0.64	0.44	0.39	0.41	0.61	0.71	1.04	0.21	0.48	0.48	0.87
Mg	0.05	0.19	4.01	0.21	0.18	0.18	0.19	0.14	0.18	0.24	0.25	0.10	0.21	0.17	0.17
P	0.01	0.07	6.51	0.05	0.09	0.06	0.08	0.07	0.04	0.09	0.09	0.04	0.05	0.08	0.07
SO42-	1.72	2.09	1.21	1.88	2.31	2.04	1.90	1.82	2.46	2.61	3.30	0.94	1.79	2.51	1.86
OC+EC	3.43	19.84	5.78	21.81	20.65	21.10	20.92	15.28	17.57	16.72	18.83	22.71	21.00	20.78	19.57
Mineral	1.65	9.05	5.47	10.63	8.31	10.20	10.78	7.01	6.10	7.27	9.08	9.96	10.78	8.56	9.03
ng/m³															
Ti	6.64	28.32	4.27	35.35	22.31	31.99	70.16	20.44	18.13	16.14	12.12	48.54	30.28	23.48	36.21
V	4.04	6.08	1.51	5.93	4.74	6.11	14.10	7.11	5.49	4.47	8.65	3.40	5.91	5.44	7.24
Cr	1.53	13.65	8.94	12.90	16.37	8.57	12.21	5.55	25.06	25.48	8.24	14.06	9.31	9.43	14.36
Mn	4.10	11.78	2.87	13.20	10.32	14.20	13.05	6.57	11.78	10.86	6.67	18.27	13.69	13.77	9.09
Ni	2.38	18.71	7.87	9.86	6.59	7.02	1.84	6.00	61.72	58.29	8.56	6.00	10.29	5.76	6.11
Cu	6.70	85.91	12.82	95.42	112.92	115.28	145.17	22.79	43.64	32.51	81.31	128.56	115.52	83.36	85.52
Zn	23.70	101.50	4.28	121.74	76.70	120.13	76.80	45.66	117.10	114.23	45.99	148.88	137.32	91.35	69.43
Sr	0.88	3.57	4.06	3.48	4.69	4.71	2.77	2.88	1.01	2.41	2.77	5.05	2.87	6.50	3.15
Zr	5.08	45.33	8.92	48.06	47.21	54.11	36.47	43.03	39.49	27.01	27.27	62.80	52.53	56.33	39.26
Sn	1.78	5.08	2.86	6.07	4.71	5.31	3.57	3.83	4.86	4.58	4.18	6.47	6.17	5.57	3.99
Sb	0.94	10.71	11.45	14.05	8.37	15.79	18.75	3.99	4.18	3.55	6.07	19.95	16.22	10.75	9.28
La	0.12	0.69	5.93	0.33	0.69	1.31	0.47	0.83	0.20	0.18	0.21	1.50	0.68	1.23	0.51
Ce	0.23	1.51	6.50	0.95	1.46	2.63	0.49	1.80	0.49	1.01	0.34	3.22	1.25	2.87	1.06
Hf	0.24	1.17	4.88	1.40	1.40	1.24	0.66	1.10	1.11	0.49	1.27	1.09	1.47	1.32	1.01
Pb	3.05	4.00	1.31	3.57	4.79	4.29	4.79	3.22	3.96	3.98	2.91	5.57	3.11	6.19	3.41
OC/EC	2.29	3.13	1.37	3.23	2.74	3.31	4.37	2.89	2.56	3.69	3.15	3.19	2.97	2.84	3.57

The inorganic trace element chemistry of $PM_{2.5}$ sampled inside buses shows enhanced concentrations of specific metals and metalloids. The most notable anomaly is high levels of Cu and Sb (Fig. 19), this being attributed to the presence of brake particles entering the bus through doors and windows. In extreme cases, Sb concentrations can be >20 times that of urban background. Buses running on routes with higher gradients (e.g. "vertical" v "horizontal") tend to show this brake particle chemical signature most clearly. In contrast, electric buses which are designed to use more engine-braking and have fully sealed windows appear to be less contaminated by their own brake PM.

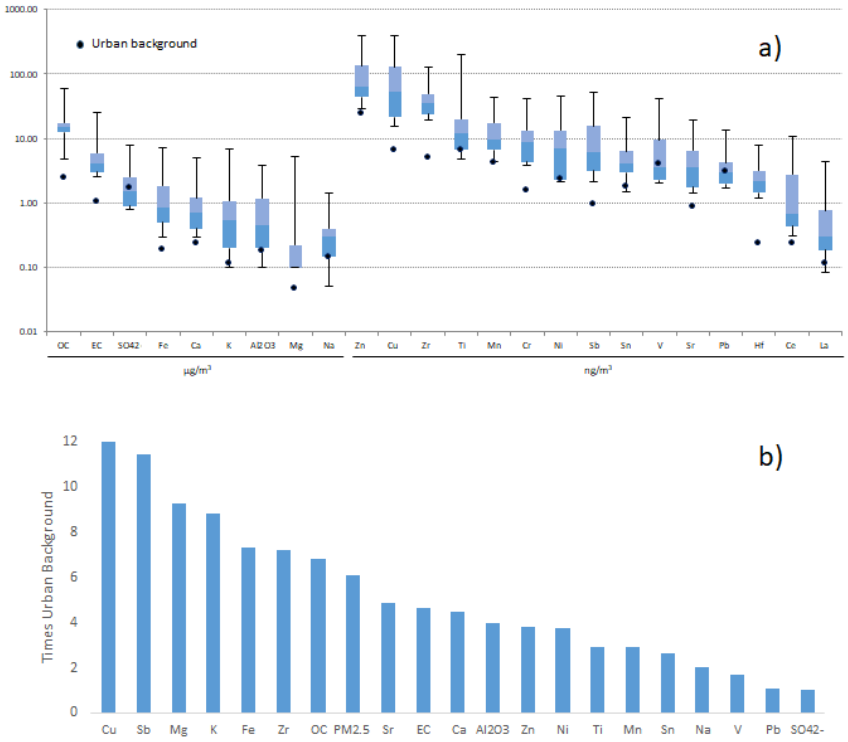


Figure 19. Elemental concentrations measured inside Barcelona buses and urban background. a) Boxplot showing concentration median, lower and upper quartiles, and ranges (vertical "whisker" bar) of major and trace elements measured from $PM_{2.5}$ sampled in buses and compared to urban background (black dot); b) Histogram demonstrating the relative enrichments of elements measured from $PM_{2.5}$ sampled in buses relative to Barcelona urban background (from Fernández-Iriarte et al., 2020).

Another observation revealed by the study of BUSAIR $PM_{2.5}$ chemistry is that there are seasonal differences, with summer samples containing higher levels of SO_4^{2-}, Na, Mg, V, Ni, and Cr, a chemical signature attributed to the ingress of outdoor marine aerosols contaminated by port emissions and the higher SO_2 summer oxidation ratio (Fernández-Iriarte et al., 2020). In winter, when air conditioning is off and city air is commonly more contaminated, the air inside the bus can be richer in mineral particles, with enhanced levels of trace metals/metalloid such as Mn, Sr, Zn, Zr, Sb and Cu.

Enhanced concentrations of certain trace metals and metalloids, notably Cu and Sb, characterize ambient aerosols inside buses and are attributed to the presence of brake particles. Seasonal differences in Barcelona ambient PM chemistry can be detected in bus interiors, with higher levels of SO_4^{2-}, Na, Mg, V, Ni, and Cr in summer, and enhanced Mn, Sr, Zn, Zr, Sb and Cu in winter.

ORGANIC POLLUTANTS

The chemical signature of volatile organic compounds (VOCs) was found to be remarkably uniform in all buses (Table 3), being dominated by alkanes and aromatics in the following: 2-methylpentane (14-36 µg/m³), toluene (10-30 µg/m³), xylenes (10-28 µg/m³, with m- >> o- > p-xylene) and n-pentane (5-15 µg/m³). This is the same mixture, although at lower concentrations, recorded inside Barcelona taxis in a previous study (Moreno et al., 2019) and is interpreted as recording the entry into the buses of mostly gasoline-sourced exhaust emissions from outside. Ambient benzene concentrations measured inside the buses were always <5 µg/m³.

Table 3: *Chemical analyses of organic aromatic, alkane, alkene and other compounds measured inside buses (see Fernández-Iriarte 2020 for details).*

Route	H4		V3		39		V3		Blue Tourist		Red Tourist		H16		H12		34	
Dates	14-16/11/17		1st, 12-13/12/17		10-12/01/18		16-18/01/18		23-25/01/18		30/01-1/02/18		21/01/18	31/01/18	26/02 & 1/03/18		27-28/03/18	
Fuel	HD	Euro V	CNG	Euro V	H-CNG	CNG	Euro IV	Euro V	Outside	Inside	Outside	Inside	Electric	CNG	CNG	HD	Electric	HD
Aromatics:																		
Benzene	2.8	2.6	2.5	1.9	3.2	3.2	2.3	2.3	3.7	3.9	2.8	2.8	3.1	3.8	3.9	2.6	2.4	4.5
Toluene	21	15	18	17	16	20	9.7	15	26	29	11	12	27	22	17	16	14	43
Ethylbenzene	3.1	2.6	2.3	2.2	2.9	3.2	2.1	2.2	4.9	6.6	4.1	3.7	4.0	3.9	3.4	2.7	2.7	95
o-Xylene	3.8	3.4	2.8	2.8	3.7	4.0	2.6	2.8	5.0	6.0	4.6	3.8	5.3	4.8	4.1	3.0	3.5	160
m-Xylene	8.7	6.8	6.0	6.1	7.3	8.4	5.5	6.0	14	17	11	9	11	10	9.5	7.3	7.5	43
p-Xylene	2.9	2.4	2.2	2.2	2.7	3.0	2.0	2.1	4.1	4.9	3.7	3.1	3.4	3.8	3.2	2.5	2.6	91
1,2,4-Trimethylbenzene	3.3	3.1	2.2	2.8	3.0	2.9	2.6	2.9	3.9	4.2	3.4	2.4	3.9	3.8	3.4	2.4	3.3	39
1,3,5-Trimethylbenzene	0.82	0.76	0.57	0.71	0.80	0.80	0.66	0.72	1.0	1.1	0.54	0.69	1.0	1.0	0.93	0.66	0.86	4.8
n-Propylbenzene	0.54	0.50	0.30	0.48	0.45	0.45	0.42	0.46	0.60	0.65	0.54	0.40	0.51	0.58	0.53	0.40	0.46	3.0
Isopropylbenzene	0.17	0.15	0.11	0.14	0.17	0.17	0.13	0.13	0.19	0.21	0.17	0.14	0.20	0.21	0.18	0.14	0.15	3.0
n-Butylbenzene	0.22	0.23	0.08	0.24	ND	<LOD	0.24	0.27	0.14	0.01	0.13	0.07	0.28	0.22	0.20	0.14	0.16	1.7
p-Cymene	0.50	0.43	0.26	0.23	0.53	0.50	0.23	0.23	0.17	0.18	0.15	0.11	0.44	0.54	0.34	0.17	0.31	1.4
sec-Butylbenzene	<LOD	0.10	<LOD	0.10	<LOD	<LOD	<LOD	0.09	0.06	0.07	0.05	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	1.3
Styrene	2.7	0.85	0.49	0.37	0.77	1.0	0.38	0.35	0.54	0.55	0.56	0.48	0.88	0.70	1.40	0.93	0.50	6.9
Branched alkanes:																		
2-Methylbutane	22	19	15	14	26	27	17	18	33	36	25	25	26	35	32	21	26	92
2,3-Dimethylpentane	0.81	0.71	0.51	0.49	0.85	0.79	0.50	0.63	1.1	1.2	0.79	0.78	0.90	1.0	1.3	0.62	0.69	9.9
Isooctane	0.51	0.41	0.45	0.14	<LOD	<LOD	1.1	2.6	0.61	0.65	0.50	0.48	0.58	0.98	0.43	ND	ND	0.57
Cycloalkanes:																		
Cyclohexane	1.1	0.99	0.69	0.82	1.7	1.7	0.62	0.64	1.4	1.4	1.3	1.3	1.7	1.7	7.6	0.80	1.0	86
n-Alkanes:																		
n-Pentane	8.1	7.3	5.7	5.2	9.0	9.3	5.6	6.1	12	13	8.6	8.8	9.9	13	15	7.1	9.3	29
n-Hexane	2.0	2.1	3.1	1.2	0.99	1.3	2.3	5.2	6.7	7.1	4.1	3.9	4.5	7.5	4.3	3.4	2.8	19
n-Octane	1.3	1.4	0.7	1.1	0.97	0.94	1.0	1.1	1.2	1.3	0.86	0.66	0.96	1.27	1.31	0.71	0.80	12
n-Heptane	2.3	2.1	1.4	1.7	2.4	2.3	1.5	1.8	2.8	3.0	2.0	1.95	2.26	2.69	3.05	1.79	1.91	10
n-Decane	2.2	3.4	1.2	3.0	2.0	2.9	1.9	2.5	3.4	9.0	1.40	1.05	1.92	6.32	4.87	1.29	1.46	63
Monoterpenes:																		
d-Limonene	2.7	11	4.2	3.6	30	65	2.0	3.1	1.6	3.2	0.94	0.49	6.4	8.6	12	1.1	2.7	5.8
alpha-Pinene	1.6	0.78	0.52	0.32	0.68	0.90	0.40	0.56	0.65	0.80	0.61	0.46	0.66	0.81	0.92	0.56	0.43	0.55
beta-Ocimene	0.20	0.26	0.24	0.12	0.27	0.36	0.13	0.23	0.03	ND	ND	ND	0.35	0.64	0.43	0.05	0.24	0.38
alpha-Ocimene	0.10	0.12	0.11	0.05	ND	ND	ND	0.10	ND	ND	ND	ND	0.18	0.30	0.20	ND	0.10	0.21
Alkenes:																		
Isoprene	2.3	6.3	5.3	1.8	6.8	8.2	2.8	1.1	1.3	0.95	0.78	0.80	8.7	10	5.9	1.2	3.4	5.6
trans-2-Pentene	1.2	1.0	0.85	0.76	1.6	1.6	0.94	1.0	2.0	2.2	1.4	1.4	1.5	1.9	1.6	1.0	0.94	3.0
1-Pentene	0.40	0.39	0.35	0.25	0.61	0.59	0.41	0.35	0.67	0.67	0.50	0.48	0.60	0.69	0.60	0.42	0.40	1.1
cis-Pentene	0.41	0.35	0.29	0.25	0.53	0.54	0.33	0.35	0.68	0.74	0.47	0.47	0.52	0.63	0.57	0.35	0.35	1.1
Oxygenated compounds:																		
Ethyl methacrylate	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3.3
Tetrahydrofuran	0.32	0.54	0.40	0.11	0.16	0.21	0.17	<LOD	0.23	0.25	0.27	0.27	0.43	0.76	0.26	0.19	0.19	3.2
Methyl methacrylate	0.15	0.64	0.28	0.13	<LOD	0.15	ND	<LOD	0.12	0.07	0.19	0.30	0.39	0.62	0.89	0.54	0.27	2.4
Isobutanol	0.07	0.33	0.24	0.19	0.14	<LOD	0.11	<LOD	0.11	<LOD	0.12	0.18	0.39	0.30	0.34	0.30	1.3	1.1
Diethyl ether	0.10	0.12	0.38	0.12	<LOD	<LOD	0.12	0.30	0.36	ND	0.27	0.20	0.16	0.60	0.21	0.15	0.36	0.21
Halocarbons:																		
Tetrachloroethylene	1.1	1.4	0.74	0.55	0.64	0.70	0.45	0.41	1.2	1.2	1.3	1.3	1.4	1.5	1.2	1.6	1.7	1.7
1,2,2-Trichlorotrifluoroethane	0.79	0.76	0.78	0.54	0.75	0.80	0.83	0.77	0.71	0.73	0.71	0.73	0.93	1.0	0.75	0.39	0.75	0.71
1,1,2-Trichloroethane	<LOD	ND	ND	ND	0.00	0.00	ND	ND	ND	ND	ND	ND	0.00	0.32	ND	ND	ND	0.66
Carbon Tetrachloride	0.32	0.48	0.62	0.44	0.34	0.38	0.46	0.41	0.43	0.35	0.43	0.46	0.67	0.82	0.60	0.31	0.59	0.43
1,2-Dichloroethane	0.09	0.15	0.14	0.10	0.00	0.00	0.14	0.12	0.18	0.10	0.27	0.26	0.65	0.54	0.28	0.24	0.33	0.33
Chloroform	0.14	0.60	0.51	0.05	0.06	0.00	0.19	0.91	0.14	0.03	0.03	0.03	0.09	0.24	0.09	0.07	0.95	0.23
Trichloroethylene	0.18	0.14	<LOD	<LOD	0.00	0.00	<LOD	0.10	0.27	0.27	0.43	0.47	0.26	<LOD	0.70	0.56	0.18	0.21
Nitriles:																		
Propionitrile	<LOD	0.07	<LOD	ND	0.00	0.16	<LOD	ND	<LOD	<LOD	0.06	<LOD	<LOD	<LOD	<LOD	<LOD	ND	0.11

Concentrations of BTEX measured inside buses typically range from 25-68 µg/m3 in a hierarchy of Toluene (10-30 µg/m^3) > m-Xylene (5-17 µg/m^3) > p-Xylene (2-5 µg/m^3) > o-Xylene (3-6 µg/m^3) > Benzene (2-4 µg/m^3) and Ethylbenzene (2-7 µg/m^3). A notable exception to these normal VOCs concentrations can be observed in new buses, which record an enhanced VOC signature due to offgassing of interior coatings and materials. In the BUSAIR study one such bus (hybrid diesel route 34) recorded exceptionally high concentrations of o-Xylene (160 µg/m^3), Ethylbenzene (95 µg/m^3), 2-Methybutane (92 µg/m^3), p-Xylene (91 µg/m^3), and Cyclohexane (86 µg/m^3). These exceptional levels of VOC offgassing recorded in the new hybrid diesel bus produced interior BTEX concentrations closely approaching 0.5 mg/m^3, although benzene levels still remained below the European Union limit value of 5 µg/m^3.

Volatile Organic Compounds measured inside all Barcelona buses except one were dominated by 2- Methylpentane, Toluene, Xylene isomers (with m- >> o- > p-Xylene) and n-Pentane. This distinctive mixture of organic pollutants is interpreted as a chemical fingerprint characterising hydrocarbon burning traffic-contaminated ambient air in the city road environment.

CARBON DIOXIDE

CARBON DIOXIDE

Concentrations of CO_2 measured in the BUSAIR campaign vehicles are shown in Table 4 and Figure 20 which demonstrate how the lowest CO_2 levels were measured in open-topped tourist buses which are well ventilated by outside air and therefore provide obvious exceptions to normal "indoor" conditions inside commuter buses. In contrast, typical mean levels of CO_2 inside buses are commonly around double that of outside air although there is considerable variation, depending especially on whether windows are open (Table 4).

Table 4: *Mean and median values for CO_2 (in ppm) measured in Barcelona buses during the BUSAIR campaign. Given uncertainties over the accuracy of the measuring equipment, these data have been normalized to Barcelona background levels and are therefore best used for comparative purposes rather than as exact numbers.*

BUSAIR	CO_2 mean	CO_2 median
all commuting buses	936	865
closed windows	1030	918
open windows	787	759
tourist downstairs	470	454
tourist upstairs	452	444

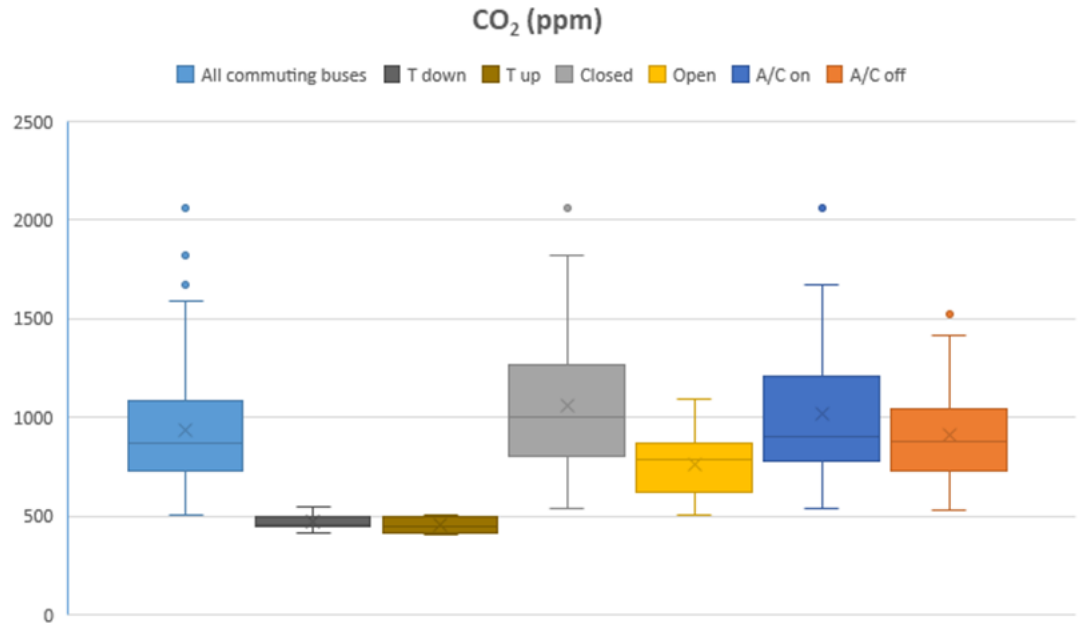


Figure 20. Boxplot for CO_2 concentrations Mean values marked as crosses and median values as horizontal lines. Interquartile range (IQR) represented as coloured rectangles. Outliers (mean values) marked as coloured dots. All commuting buses excludes tourist buses; Tdown/Tup = open-topped tourist buses inside (downstairs) and outside (upstairs); Open and Closed Windows, and air conditioning (A/C) on and off.

The concentrations of CO_2 inside a commuting bus on a weekday morning typically rise to a peak as the vehicle travels from its outward terminus to the crowded city centre and then declines as passenger numbers decrease towards the end of the route, after which the pattern is repeated on the return journey. However the height of the peak will depend on ventilation conditions. Thus the sub-group of buses recorded as having windows closed during the journey record higher mean and median CO_2 values than with those with at least one window open (Fig. 20, Table 4). To demonstrate the point we have selected a specific example which compares two buses, one operating with closed windows the other with at least one window open (16 May). Both buses stopped almost the same number of times (39, 37 stops) and ran 10-12 minutes apart the entire return journey on the same route (V13), but the bus with windows closed recorded nearly double the concentration of CO2 (Fig. 21).

Another example illustrating the controls on CO_2 levels inside buses, in this case the direct link with passenger numbers, is presented in Figure 22. This compares two journeys made on the same route (H4) on the same day (14 Nov) with one bus initially 7 minutes in front of the other. On the outward journey the front bus picked up more passengers, stopping 33 times and opening 84 doors, with CO_2 levels correspondingly peaking at over 1,500 ppm. In contrast the bus behind stopped 27 times, opened 66 doors and outward CO_2 peaked at around 1250 ppm (Fig. 22). However, it is on the return journey that a much greater difference in CO_2 levels emerged, when the rear bus was by now running progressively closer behind and thus increasingly failing to pick up passengers (it opened only 40 doors, as compared to 95 in the front bus, on this leg of the journey). Under these conditions whereas CO_2 levels in the crowded front bus showed a similar peak to the outward journey, concentrations of the gas in the near-empty rear bus failed to reach even 600ppm (Fig. 22).

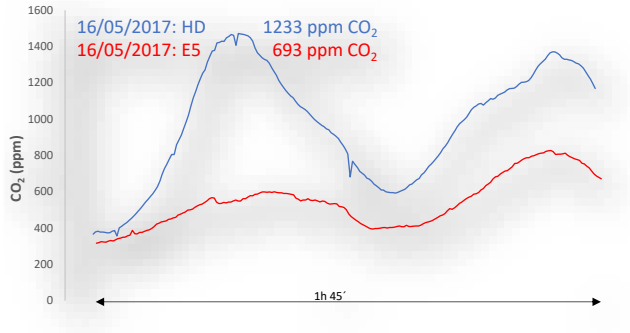


Figure 21. Comparison of CO_2 concentrations inside on two buses (diesel Euro5 and hybrid diesel) running along route V13 the same day with windows open (E5) and closed (HD).

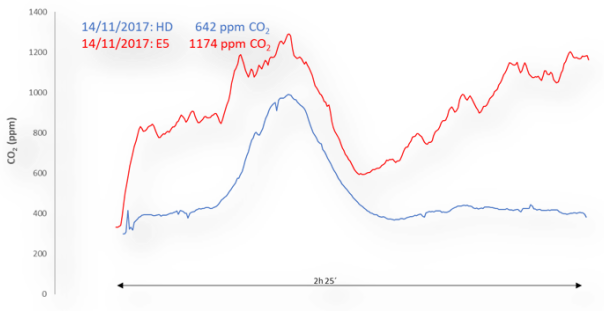


Figure 22. Comparison of CO_2 concentrations measured inside two buses running on route H4 the same day with clear differences on the number of passengers on the return journey (see text for details).

Concentrations of CO_2 inside buses depend directly on the number of passengers, outside air entry through doors and windows, and the ventilation system. As such, levels of this gas inside public transport vehicles are a good proxy for how much indoor air is being diluted from outside. In the context of the COVID-19 pandemic this criterion has assumed great importance, given the fact that unreplenished stale air indoor air represents a greater threat for airborne disease transmission. In this context, a crowded bus operating with closed windows can record CO_2 concentrations in excess of 3,000 ppm, over seven times natural background

BIOAEROSOLS

BIOAEROSOLS

The concept of air quality within the atmospheric microenviroment of a public transport vehicle encompasses the presence not only of inorganic particles, organic chemicals and gases, but also includes airborne bacteria and their endotoxins, fungi and viruses (Lee et al., 2005; Triadó-Margarit et al., 2016; Fernández-Iriarte et al., 2021; Moreno et al., 2021). Much of this airborne biological particulate matter, generally referred to as "bioaerosol", is less than 10 µm in size and therefore small enough to be inhaled by vehicle passengers. Pathogenic forms of inhalable bioaerosols can spread diseases and allergic reactions in these transport microenvironments. Thus airborne *Mycobacterium tuberculosis* can pass on tuberculosis inside buses, indoor fungal bioaerosols can induce allergic rhinitis and asthma (Lee et al., 2016), and inhaled endotoxins have been linked to a range of respiratory problems (Lehtinen et al., 2013). Most recently, the appearance of SARS-CoV-2 and the consequent COVID-19 pandemic has suddenly changed the general perception of indoor air quality issues and the importance of disease transmission by airborne respiratory pathogens.

The BUSAIR project sampling programme included the study of the microbiological composition and abundance of bacterial and fungal bioaerosols sampled inside 52 buses (44 commuting, 8 tourist). Quantitative PCR was used to quantify total bacteria, *Penicillium*/*Aspergillus* and *Cladosporium sp*. and Kinetic Chromogenic *Limulus Amebocyte Lysate* (LAL) Assay for endotoxins. In addition, in response to the COVID-19 emergency lockdown in 2020, a supplementary study was made inside buses for the possible presence of SARS-CoV-2. Polyester swabs from call buttons and holding bars in 30 buses were sampled before and after nightly cleaning procedures. To this sample group was added an analysis of 6 samples of air conditioning filters, 3 swab samples of dust deposited immediately behind the A/C filters, and 6 samples of ambient air $PM_{2.5}$ (Moreno et al., 2021). Samples were analysed for the presence of viral RNA with Real-Time Reverse-Transcription PCR (Real-Time RT-qPCR) using three target gene regions (IP2, IP4 and E).

FUNGI AND BACTERIA

Results of fungal contamination inside the sampled buses, measured in terms of *Penicillium*/*Aspergillus sp.* and *Cladosporium sp*. concentrations, were below detection limits for both targets in all samples. In contrast airborne bacteria were detected in 94 out of 100 bioaerosol samples: 46 of 50 in summer (May–September) and 48 of 50 in the colder months (November–March). Total bacteria concentrations showed a range between 1.25×10^{0} and 3.49×10^{4} equivalent *E. coli* genomes/m^3 of air, which correspond to a geometric average (GA) concentration of $9.63 \times 10^{2} \pm 7.21 \times 10^{0}$ equivalent *E. coli* genomes/m^3 of air for the summer, and 1.25×10^{0} and 2.28×10^{4} equivalent *E. coli* genomes/m^3 of air, which correspond to a GA concentration of $2.63 \times 10^{3} \pm 1.31 \times 10^{1}$ equivalent *E. coli* genomes/m^3 of air in the winter (Fig. 23). A higher loading of indoor bacteria in the colder months would be consistent with the lack of air conditioning ventilation (cf. Dębek et al., 2017).

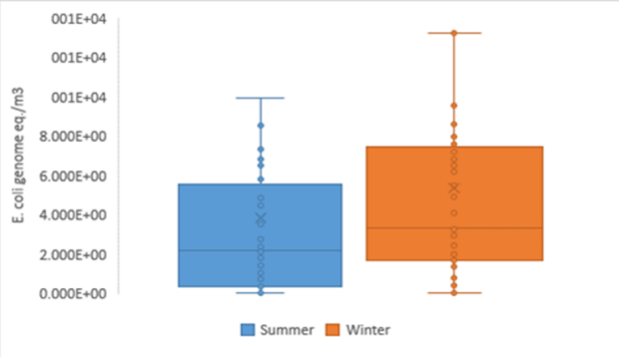


Figure 23. Concentrations of airborne Bacterial 16S rDNA gene copies determined by qPCR analyses for different seasons (Fernández-Iriarte et al., 2021).

Regarding the identified taxa at the phylum level (Fig. 24), almost 80% of the relative abundance of bacteria detected in the buses comprised Actinobacteria and Proteobacteria. Whereas Proteobacteria were more abundant in winter, *Firmicutes* was more common in summer. At the genus level, airborne bacterial communities in Barcelona bus systems were dominated by a limited number of taxa, with half of the genera (13 of 26) being detected in both warmer and colder months and comprising 70-80% of the total. Seasonal differences observed include the fact that *Corynebacterium*, *Bradyrhizobium* and *Paracoccus* were the most abundant genera in summer, whereas *Paracoccus* and *Cutibacterium* were only detected in the colder months. The relative abundances of bacterial genera noted for "summer" (May to September) and "winter" (November to March) are summarized on Figure 24. In contrast, statistical analysis of the data did not detect any significant difference between bacterial populations and the type of engine powering the bus (Fernández-Iriarte et al., 2021).

As would be expected in public transport vehicles, the biodiversity of these bacterial populations is strongly influenced by the presence of humans. *Cutibacterium* for example is a taxonomic genera related to human skin microbiota. The presence of such bacteria was predicted by an earlier chemical source apportionment study of PM inside buses which detected a significant loading of organic carbonaceous aerosols attributed to textile fibres and skin flakes (Fernández-Iriarte et al., 2020).

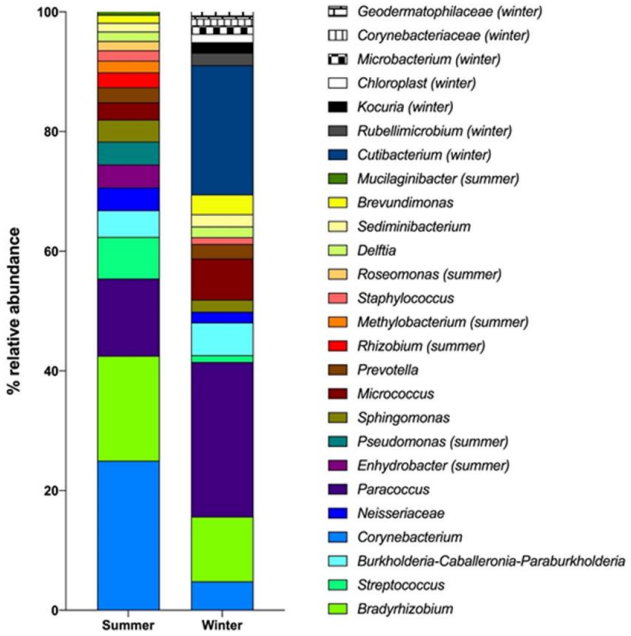


Figure 24. Relative seasonal abundance of bacterial genera sampled in Barcelona buses. Taxa that were specific to each season, controls are specified in parentheses (Fernández-Iriarte et al., 2021).

SARS-CoV-2

Polyester swab sampling of bus call buttons and support bars for the possible presence of SARS-CoV-2 took place on the night of May 25–26 (2020) in one of the four main bus depots in Barcelona before and after nightly cleaning (see Moreno et al., 2021 for details). Table 5 summarises the sample numbers, timings and type of disinfection applied. In addition, samples from air conditioning filters were taken from six buses and in three of these, samples of dust from immediately behind the a/c filter were also collected. Finally, ambient air particles ($PM_{2.5}$) were collected during the entire bus workday from a further six buses operating from June 3 to 5 2020 (two buses per day).

Table 5: *Results of the analysis of determination of SARS-CoV-2 by Real-Time RT-PCR in the bus samples using three targets of the virus genome. - negative detection result, + to ++++, positive from traces to very abundant. In brackets the quantification cycle (Cq) values obtained in the positive dilution rendering the highest positivity. D: direct (not diluted). GC: Counts of Genome (Moreno et al., 2021).*

BUS SURFACES														
Bus	Cleaning method	IP2		IP2 GC/m²		IP4		IP4 GC/m²		E		E2 GC/m²	
		A	B	A	B	A	B	A	B	A	B	A	B
SWAB1	O_3	-	-			-	-			++ (38 1/10)	++ (38 1/10)	338	342
SWAB2	NaClO	-	-			-	-			++ (39 1/10)	-	208	
SWAB3	O_3	-	-			-	-			+ (41 D)	-	5	
SWAB4	O_3	++ (39 1/10)	-	408		-	-			-	-		
SWAB5	NaClO	+ (39 D)	-	38		-	-			-	-		
SWAB6	NaClO	++ (39 1/10)	-	446		+ (40 D)	-	13		-	-		
SWAB7	O_3	+ (41 1/10)	-	86		-	-			-	-		
SWAB8	O_3	-	-			++ (38 1/10)	-	490		++ (38 1/10)	-	344	
SWAB9	O_3	+ (42 1/10)	+ (40 1/10)	48	236	-	++ (38 1/10)		745	-	++ (39 1/10)		314
SWAB10	O_3	-	-			-	-			++ (38 1/10)	++ (39 1/10)	378	270
SWAB11	O_3	-	-			+ (41 D)	-	9		++ (39 1/10)	++ (38 1/10)	210	633
SWAB12	O_3	+ (41 D)	-	14		+ (40 D)	-	11		++ (38 D)	-	37	
SWAB13	NaClO	-	-			-	-			+ 39 (D)		27	

BUS AIR						
Sample	IP2	IP2 GC/m³	IP4		E	
Air1	+/(40 D)	1.4	-		-	
Air2	-		-		-	
Air3	-		-		-	
Air4	-		-		-	
Air5	-		-		-	
Air6	-		-		-	

BUS FILTERS AIR CONDITIONING						
Sample	IP2		IP4		E	E GC/m²
AC1	-		-		++/(38 1/10)	9500
AC2	-		-		-	
AC3	-		-		++/(39 1/10)	7333
AC4	-		-		+/(38 D)	989
AC5	-		-		-	
AC6	-		-		-	
Dust behind AC1	-		-		++/38 (1/10)	--
Dust behind AC2	-		-		-	
Dust behind AC3	-		-		-	

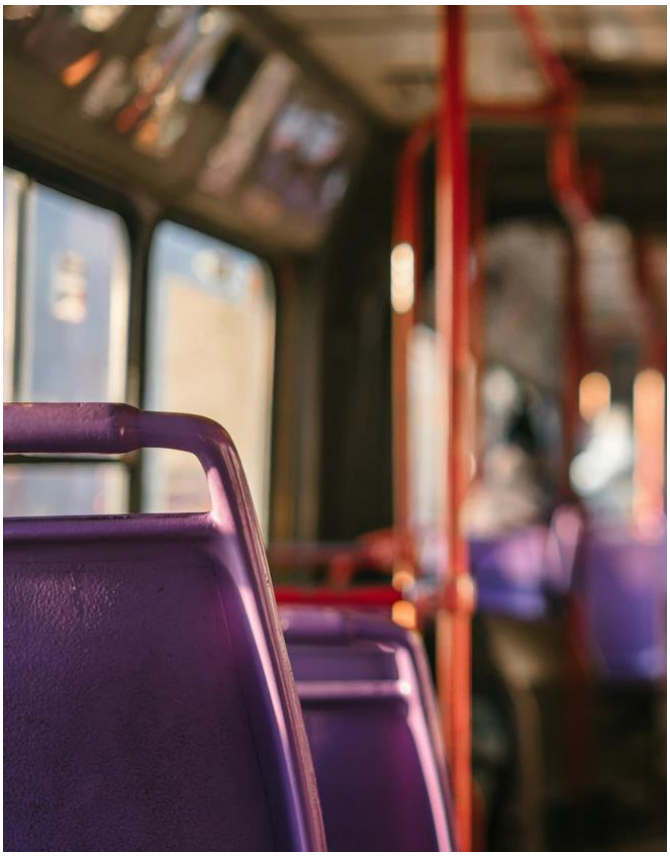
Of 30 swab surface samples taken from call buttons and support bars inside buses prior to disinfection (Sample group A), 13 detected some evidence for the presence of SARS-CoV-2 RNA traces (Table 5). In the majority of these cases (9 of 13) only 1 of the 3 target gene regions (either IP2 or E) produced a positive result. Of these 9 cases, 4 were IP2 positives and 5 E positives, but all indicated low or trace amounts of the virus (samples A, Table 5). Of the remaining results 3 were positive for 2 of the targets (IP2 and IP4 or IP4 and E), and one (sample B29) gave positive for all three targets (Table 5). Genome count values ranged between 14 and 446/m^2 for IP2, 9–490/m^2 for IP4 and 5–378/m^2 for E. After the bus nightly maintenance and cleaning, 9 out of the 13 samples that recorded RNA traces proved to be virus-free. The fact that a minority of the previously RNA positive samples still showed some RNA traces suggests that the disinfection/cleaning procedure being applied at that time (all used ozone) was not totally effective in removing the RNA.

Of the 6 $PM_{2.5}$ air samples collected in the buses (Air1-6), one gave a weak positive result in one of the target genes (IP2), with a calculated viral load of 1.44 GC/m^3 (Table 5). In the case of the six air conditioning filter samples analysed by RT-PCR, 3 of these revealed evidence for the presence of the gene target E (Table 5). Genome count values ranged between 989 and 9500/m^2 for E. The same RNA target was also detected in one of the swab dust samples taken from behind the air conditioning filter (Table 5).

It is important to emphasize that the detection of fragments of RNA belonging to SARS-CoV-2 virus does not imply infectivity of this pathogen, especially in the context of this study in which only one sample showed the presence of all of the 3 targets under investigation. Nevertheless, the findings demonstrate that traces of the SARS-CoV-2 viral genome can be detected within public transport vehicles, both on surfaces inside the vehicle and in the ambient air. Although in the case of this study evidence for concentrations of the viral genome was fragmentary, generally weak, and the chances of infectivity considered to be extremely low, the fact that viral traces were present emphasizes the need for rigorous cleaning/disinfection procedures and highlights the importance of wearing protective masks and having forced ventilation systems to dilute indoor air by introducing airflow from outside.

The biodiversity of microbial populations inside transport microenvironments is strongly influenced by the presence of humans, the time of year and any ongoing epidemics. In the case of potentially pathogenic particles, such as those carrying the SARS-CoV-2 virus, efficient cleaning and ventilation of the bus interior assume a high priority. Given the likely importance of COVID-19 airborne transmission, CO2 levels can be used as a valuable proxy for proving effective dilution of indoor bus air by air introduced from outside.

CONCLUSIONS AND RECOMMENDATIONS



- ✓ Bus interior air quality is strongly influenced by road traffic emissions. Highly transient peaks in ultrafine particle number concentrations of 100,000-1,000,000cm^{-3}, black carbon levels of >20 µg/m^3, and PM2.5 concentrations of >50 µg/m^3 can occur frequently inside buses due to the infiltration of traffic emissions.
- ✓ Outside road emission infiltration into buses is commonly most severe at highly polluted localized points within a given route, such as the proximity to urban motorways, busy intersection crossings and roundabouts, tunnels, and uphill stretches of relatively narrow, canyon-like roads. Closer attention to the atmospheric microenvironment of individual bus routes and the location of bus stops could considerably reduce passenger exposure whilst waiting and travelling.
- ✓ Ultrafine particle size is a useful indicator for the relative amount of fresh traffic-related particle emissions present inside a road vehicle, with an inverse correlation typically existing between particle size and number.
- ✓ Mean concentrations of black carbon particles inside buses are 2 to 3 times higher overall than those typically measured in Barcelona urban background air, lying within the range 4-8 µg/m^3. There is commonly a strong coincidence between black carbon and PM2.5 concentrations inside a bus.
- ✓ Air quality inside buses can also be noticeably influenced by localised wind patterns and by background levels of pollution in the air outside the vehicle. Thus a "bad air day" across a city can increase individual exposure to pollutant particles and gases whilst travelling in public transport. In contrast, on a "good air day" PM2.5 breathed while travelling by tourist bus for example can be less than 50% below normal on clear, clean winter days with low levels of urban background pollution.
- ✓ The BUSAIR study did not reveal any dominant link between interior bus air quality and the type of powertrain operated by the bus, although diesel buses were associated with higher levels in several cases. Further work is needed on this question, although the data so far indicate that the quality of the outdoor air and the extent to which such air could infiltrate and circulate around the bus appear to be the main factors influencing air quality on any given journey.

- ✓ Enhanced concentrations of certain trace metals and metalloids, notably Cu and Sb, characterize ambient aerosols inside buses and are attributed to the presence of brake particles. At least some of this contamination is likely to derive from the vehicle itself braking as it approaches bus stops before opening the doors, so that use of less potentially toxic and more environmentally friendly brake materials is recommended.
- ✓ Seasonal differences in Barcelona ambient PM chemistry can be detected in bus interiors, with higher levels of $SO4^{2-}$, Na, Mg, V, Ni, and Cr in summer, and enhanced Mn, Sr, Zn, Zr, Sb and Cu in winter. Important pollution sources in a city, such as summer cruise shipping in Barcelona, will impact what people are breathing inside public transport vehicles.
- ✓ Volatile Organic Compounds measured inside all Barcelona buses except one are typically dominated by 2- Methylpentane, Toluene, Xylene isomers (with m- >> o- > p-Xylene) and n-Pentane. This distinctive mixture of organic pollutants is interpreted as a chemical fingerprint characterising hydrocarbon burning traffic-contaminated ambient air in the city road environment.
- ✓ New buses are more likely to be strongly offgassing volatile organic compounds, and thus would benefit from greater attention to ventilation in order to minimize BTEX levels inhaled by passengers.
- ✓ Concentrations of CO2 inside buses depend directly on the number of passengers, outside air entry through doors and windows, and the ventilation system. A crowded bus operating with closed windows can record CO2 concentrations in excess of 3,000ppm, over seven times natural background. Thus, levels of this gas inside public transport vehicles are a good proxy for how much indoor air is being diluted from outside.
- ✓ The biodiversity of microbial populations inside transport microenvironments is strongly influenced by the presence of humans, the time of year and any ongoing epidemics. It is a subject about which relatively little has been written and deserves further study.
- ✓ In the context of the ongoing COVID-19 pandemic and the increasing transport hyper-mobility of much of the world population, our concept of air quality in public transport microenvironments is rapidly changing to encompass not just the health effects of traffic emissions but also those of pathogenic bioaerosols. Efficient cleaning, ventilation and use of viricides within the bus interior are suddenly assuming a high priority.

- ✓ Given the likely important role of aerosol-driven transmission in the spread of SARS-CoV-2, greater emphasis needs to be placed on continuously monitoring CO2 levels which can be used as a valuable proxy for proving effective dilution of indoor bus air by air introduced from outside. Intelligent ventilation is key to the future of bus air quality, and the challenge will be to tackle not only the critical need to dilute and refresh indoor air, but also filter out the pollutant loading introduced from contaminated outdoor air.

- ✓ As the COVID-19 pandemic has progressed, so urban commuter behavior has changed radically as individuals adapt to a new reality and learn how best to minimise their exposure to viral infection. Correctly fitted face masks are currently obligatory on public transport in most countries, and people are increasingly aware that remaining silent whilst travelling is likely to reduce the risk of aerosol transmission. Transport companies have similarly developed new strategies to protect their passengers and staff, such as offering the availability of hydroalcoholic gels, operating remote door opening so that fewer fomite surfaces need to be touched by passengers, working to maintain a high frequency of service to reduce crowding, and encourage avoidance of peak hour travel. It is to be hoped that one positive aspect of the COVID-19 tragedy could be that these current changes in passenger and operator behavior due to their enhanced understanding of air contamination issues will not be quickly forgotten but drive a push for better air quality in transport microenvironments worldwide. It would be a lesson well learnt.

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References

Adams, H. S., M. J. Nieuwenhuijsen, and R. N. Colvile. 2001. Determinants of Fine Particle (PM2. 5) Personal Exposure Levels in Transport Microenvironments, London, UK. Atmos Environ, 35, 4557–4566.

Alameddine, I., Abi Esber, L., Bou Zeid, E., Hatzopoulou, M., El-Fadel, M. 2016. Operational and environmental determinants of in-vehicle CO and PM2.5 exposure. Sci. Tot. Environ. 551–552, 42-50.

Asmi E, Antola M, Yli-Tuomi T, Jantunen M, Aarnio P, Mäkelä T, Hillamo R, Hämeri K. 2009. Driver and passenger exposure to aerosol particles in buses and trams in Helsinki, Finland. Sci Total Environ. 1;407(8):2860-7. doi: 10.1016/j.scitotenv.2009.01.004.

Bel, G., M. Holst. 2018. Evaluation of the impact of Bus Rapid Transit on air pollution in Mexico City, Transport Policy, 63, 209-220,ISSN 0967-070X, https://doi.org/10.1016/j.tranpol.2018.01.001.

Cepeda, M., Schoufour, J., Freak-Poli, R., Koolhaas, C., Dhana, K., Bramer, W., Franco, O. 2017. Levels of ambient air pollution according to mode of transport: a systematic review. The Lancet Public Health, 2, 23-34.

Chernyshev VV, Zakharenko AM, Ugay SM, Hien TT, Hai LH, Olesik SM, Kholodov AS, Zubko E, Kokkinakis M, Burykina TI, Stratidakis AK, Mezhuev YO, Sarigiannis DA, Tsatsakis A, Golokhvast KS. 2018. Morphological and chemical composition of particulate matter in buses exhaust. Toxicol Rep. 11;6:120-125. doi: 10.1016/j.toxrep.2018.12.002.

Choi W, Ranasinghe D, DeShazo JR, Kim JJ, Paulson SE. 2018. Where to locate transit stops: Cross-intersection profiles of ultrafine particles and implications for pedestrian exposure. Environ Pollut. 233:235-245. doi: 10.1016/j.envpol.2017.10.055.

Dales R, Liu L, Szyszkowicz M, Dalipaj M, Willey J, Kulka R, Ruddy TD. 2007. Particulate air pollution and vascular reactivity: the bus stop study. Int Arch Occup Environ Health. 81(2):159-64. doi: 10.1007/s00420-007-0199-7.

Dębek, N., Pawlak, B., Wlazło, H., Maksym, L., Kapica, P., Chmielowiec-Korzeniowska, J., Trawinska, A. 2017. Evaluating bioaerosol exposure among bus drivers in the public transport sector. J Occup Environ Hygiene. 14. 00-00. 10.1080/15459624.2017.1339165.

Dons, E., L. LR. Int Panis, Van Poppel, M., Theunis, J. 2012. Personal exposure to Black Carbon in transport microenvironments. Atmos Environ 55,392-398. DOI:10.1016/j.atmosenv.2012.03.020

Fernández-Iriarte, A., Amato, F., Moreno, N., Pacitto, A., Reche, C., Marco, E., Grimalt, J., Querol, X., Moreno, T. 2020. Chemistry and sources of PM2.5 and volatile organic compounds breathed inside urban commuting and tourist buses. Atmos Environ 223, 117234, ISSN 1352-2310

Fernández-Iriarte, A., Duchaine, C., Degois, J., Mbareche, H., Veillette, M., Moreno, N., Amato, F., Querol, X., Moreno, T. 2021. Bioaerosols in public and tourist buses. Aerobiologia, DOI: 10.1007/s10453-021-09704-9

Fruin, S., Hudda, N., Sioutas, C., Delfino, R.J. 2011. Predictive Model for Vehicle Air Exchange Rates Based on a Large, Representative Sample. Environ Sci Technol 45, 8, 3569-3575.

Gajewski, A. 2013. Indoor air quality in a bus. DOI:10.2495/SAFE130671. Conference: SAFE 2013Volume: 134

Haagen-Smit, A.J. 1966. Carbon monoxide levels in city driving. Archives of Environ. Health, 12, 548-551.

Hess, D.B., P.D.Ray, A.E.Stinson, J.Park. 2010. Determinants of Exposure to Fine Particulate Matter (PM2.5) for Waiting Passengers at Bus Stops. Atmos Environ 44, 5174-5182. DOI:10.1016/j.atmosenv.2010.08.046

Hudda, N., Kostenidou, E., Delfino, R., Sioutas, C., Fruin, S. 2011. Factors that Determine Ultrafine Particle Exposure in Vehicles. Environ Sci Technol 45(20), 8691–8697.

Hudda, N., Eckel, S., Knibbs, L., Sioutas, C., Delfino, R., Fruin, S. 2012. Linking In-Vehicle Ultrafine Particle Exposures to On-Road Concentrations. Atmos Environ 59, 578–586.

Hudda, N., Fruin, S. 2018. Carbon dioxide accumulation inside vehicles: the effect of ventilation and driving conditions. Sci Tot Environ 610-611, 1448-1456.

Jo, W., Yu, C. 2001. Public Bus and Taxicab Drivers' Work-Time Exposure to Aromatic Volatile Organic Compounds. Environ Res 86, 66-72

Knibbs, L.D., de Dear, R.J. 2010. Exposure to ultrafine particles and PM2.5 in four Sydney transport modes. Atmos Environ44, 3224–3227

Leavey, A., Reed, N., Patel, S., Bradley, K., Kulkarni, P., Biswas, P. 2017. Comparing on-road real-time simultaneous in-cabin and outdoor particulate and gaseous concentrations for a range of ventilation scenarios. Atmos. Environ 166, 130-141.

Lee, E., Stenstrom, M., Zhu, Y. 2015. Ultrafine particle infiltration into passenger vehicles. Part 1: Experimental evidence. Transportation Res. Part D 38, 156-165.

Lee, B., Lee, G., Joon Heo, K. 2016. Concentration of culturable bioaerosols during Winter. J Aerosol Sci 94, 1-8. doi: 10.1016/j.jaerosci.2015.12.002

Lee, Ji Hyun, and Wan Kuen Jo. 2005. Exposure to Airborne Fungi and Bacteria While Commuting in Passenger Cars and Public Buses. Atmos Environ 39, 7342–50.

Lehtinen, Jenni, Outi Tolvanen, Ulla Nivukoski, Anja Veijanen, and Kari Hänninen. 2013. Occupational Hygiene in Terms of Volatile Organic Compounds (VOCs) and Bioaerosols at Two Solid Waste Management Plants in Finland. Waste Management 33, 964–73.

Li C, Nguyen Q, Ryan PH, Lemasters GK, Spitz H, Lobaugh M, Glover S, Grinshpun SA. 2009. School bus pollution and changes in the air quality at schools: a case study. J Environ Monit 11, 1037-42.

Lim,s., K. N. Dirks, J. A. Salmond, S. Xie, 2015. Determinants of spikes in ultrafine particle concentration whilst commuting by bus, Atmos Environ 112, 1-8. https://doi.org/10.1016/j.atmosenv.2015.04.025.

Madl, P., Majid, H., Kwasny, F., Hofmann, W. 2015. In-Vehicle Exposure to Ultrafine Particles While Driving through a Tunnel System and Associated Lung Deposition Calculations. Aerosol and Air Quality Res. 15, 295–305.

Merritt, A, A. Georgellis, N. Andersson, G. B. Bedada, T. Bellander, C. Johansson. 2019. Personal exposure to black carbon in Stockholm, using different intra-urban transport modes. Sci Tot Environ 674, 279-287. https://doi.org/10.1016/j.scitotenv.2019.04.100.

Moore, A., M. G. Figliozzi, Monsere, C.M. 2012. Air Quality at Bus Stops. Research Record. J Transportation Res Board 2270(-1), 76-86. DOI:10.3141/2270-10

Moreno, T., Reche, R., Rivas, I., Minguillón, MC., Martins, V., Vargas, C., Buonanno, G. et al. 2015. Urban Air Quality Comparison for Bus, Tram, Subway and Pedestrian Commutes in Barcelona. Environ Res 142, 495–510.

Moreno, T., Pacitto, A., Fernández, A., Amato, F., Marco, E., Grimalt, J.O., Buonanno, G., Querol, X. 2019. Vehicle interior air quality conditions when travelling by taxi. Environ Res 172, 529-542.

Moreno T, Reche C, Ahn KH, Eun HR, Kim WY, Kim HS, Fernández-Iriarte A, Amato F, Querol X. 2020. Using miniaturised scanning mobility particle sizers to observe size distribution patterns of quasi-ultrafine aerosols inhaled during city commuting. Environ Res 109978. doi: 10.1016/j.envres.2020.109978.

Moreno T, Pintó RM, Bosch A, Moreno N, Alastuey A, Minguillón MC, Anfruns-Estrada E, Guix S, Fuentes C, Buonanno G, Stabile L, Morawska L, Querol X. 2021. Tracing surface and airborne SARS-CoV-2 RNA inside public buses and subway trains. Environ Int 147:106326. doi: 10.1016/j.envint.2020.106326

Nogueira T, Dominutti PA, Vieira-Filho M, Fornaro A, Andrade MdF. 2019. Evaluating Atmospheric Pollutants from Urban Buses under Real-World Conditions: Implications of the Main Public Transport Mode in São Paulo, Brazil. Atmosphere 10(3), 108. https://doi.org/10.3390/atmos10030108

Quiros, D., Lee, E., Wang, R., Zhu, Y. 2013. Ultrafine particle exposures while walking, cycling, and driving along an urban residential roadway. Atmos Environ 73, 185-194.

Rivas, I., P. Kumar, A. Hagen-Zanker. 2017. Exposure to air pollutants during commuting in London: Are there inequalities among different socio-economic groups?, Environ Int 101, 143-157.

Schimek, P. 2001. Reducing Emissions from Transit Buses. Regional Sci and Urban Econ 31, 433–451.

Tartakovsky, L., Baibikov, V., Czerwinski, J., Gutmana, M., Kasper, M., Popescu, D., Veinblata, M., Zvirina, Y. 2013. In-vehicle particle air pollution and its mitigation. Atmos Environ 64, 320–328.

Triadó-Margarit, X., M. Veillette, C. Duchaine, M. Talbot, F. Amato, M. C. Minguillón, V. Martins, E. de Miguel, E. O. Casamayor,and T. Moreno. 2016. Bioaerosols in the Barcelona Subway System. Indoor Air, no. May: 1–12.

Van Ryswyk, K., Evans, G.J., Kulka, R. et al. 2020. Personal exposures to traffic-related air pollution in three Canadian bus transit systems: the Urban Transportation Exposure Study. J Expo Sci Environ Epidemiol. https://doi.org/10.1038/s41370-020-0242-2

Velasco, E. and S. H.Tan, 2016. Particles exposure while sitting at bus stops of hot and humid Singapore, Atmos Environ 142, 251-263. https://doi.org/10.1016/j.atmosenv.2016.07.054.

Wang, L., L. Morawska, E.R. Jayaratne, K. Mengersen, D. Heuff, 2011. Characteristics of airborne particles and the factors affecting them at bus stations. Atmos Environ 45, 611-620.

Yang, F., Kaul, D., Wong, K., Westerdahl, D., Sun, L., Ho, K., Tian, L., Brimblecombe, P., Ning, Z. 2015. Heterogeneity of passenger exposure to air pollutants in public transport microenvironments. Atmos. Environ 109, 42-51.

Zhu, Y., Eiguren-Fernandez, A., Hinds, W., Miguel, A. 2007. In-cabin commuter exposure to ultrafine particles on Los Angeles freeways. Env Sci Tech 41, 2138-45

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