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Characterisation of airborne particles in London by computer-controlled scanning electron microscopy

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Abstract

This study assessed the personal exposure of cyclists and Underground train users in London to particulate matter below 5 μm in diameter (PM_5) and provides evidence of the number, shape, size distribution and elemental composition of collected particles. Samples were analysed using computer-controlled scanning electron microscopy (CCSEM) and energy dispersive X-ray detection (EDX), including analysis of samples for low energy elements (carbon) by open window detection. Results were processed and classified using a custom written software package (MIDAS). A total of 33 938 particles were analysed for size and 12 568 particles were classified for size and elemental composition. Samples were also collected for gravimetric analysis. Thirty volunteers cycling commuter routes into central London were selected and monitored according to particulate matter for 1 week during November 1995–February 1996. Samples were also collected by three commuters using London Underground during their daily commuter journeys as a comparison. Cassella personal sampling pumps fitted with cyclone heads incorporating filters were used to collect particles. Carbon particles are clearly the dominant particle type in the road traffic samples with mean particle fractions of 66% carbon. The size distribution of the aerosol sampled by cyclists — high numbers of the smallest sized particles — is typical of vehicle emissions. Samples from the Underground show a distinctly different size distribution and elemental composition. Samples exhibited a higher loading of coarse mode particles with a more even distribution across the particle sizes collected. The most abundant particles in the Underground are Fe/Si-rich particles with 53% (56% in the 20-kV range) of the total number of particles. The average Fe concentration in this particle class was 22.8% and the Si concentration 17.4% together with C, Ca and K. The particle mass concentration in the London Underground trains proved to be almost 10 times higher than those measured by cyclists in traffic generated aerosol.

Keywords: Computer-controlled scanning electron microscopy (CCSEM); Particle classification; Respirable particles; Personal monitoring; Particle size distribution

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1. Introduction

London is historically infamous for urban smoke pollution events. Since the smog and resultant Clean Air acts of the 1950s, massive reductions in airborne smoke and SO_2 concentrations have been achieved. Today the UK urban aerosol of London is dominated by traffic-generated particles, which differ in size, composition, shape and number concentration compared to historically important particulate pollution. City-wide stationary monitoring of particulate matter and co-pollutants is now extensive (Department of Planning and Environment, Westminster Council, 1995) and this has illustrated the fact that the fine fraction of particulate matter — specifically PM_{10} and $PM_{2.5}$ — contributes significantly to mass concentration of airborne particulate.

The London Underground is an integral part of the London Transport system and public transport on London Underground is enormous. The distance travelled by passengers is approximately 6.5 billion km with a 5% increase per year (Transport Statistics for London, 1998). The particle mass concentration is known to be almost 10 times higher than those at the roadside (Mean, 1991; Seaborn, 1996) due to the numbers of particulate sources, restricted ventilation and significant particle resuspension during train movements.

Monitoring of personal exposure (Bevan, 1991; van Wijnen Joop, 1995) and analysis of single particles by CCSEM (Katrinak et al., 1995; De Bock et al., 1994) has not been used extensively due to the inherent difficulties of personal sampling and subsequent CCSEM analysis. However, by identifying individual particle types in a sample, the technique is able to resolve different particle sources, based on their individual emission chemistry. Such detailed analysis is also able to provide important information for health risk assessments of particles based on particle characteristics other than mass concentration. The technique is therefore potentially very important in ambient particle characterisation and health risk assessment of particulate matter.

2. Sample collection and preparation

Following an advert in a London cycling magazine, 30 volunteer cyclists cycling commuter routes into central London were selected and monitored for approximately 1.5 h/day for 1 week between November 1995 and February 1996. Furthermore, three commuters using the London Underground (Piccadilly Line) were monitored on the way to and from work only in the tunnel system (i.e. no overground trains and no walk on the road) (Table 1). The Piccadilly line runs at a number of depths during its route and the implications for addition and mixing of particles are hard to estimate. The integrated sample taken was considered interesting for preliminary comparison with the traffic samples. A total number of 60 samples were selected for analysis from 76 collected filters, following sampling errors and fluctuating flow rates. Commuting for 1.5 h/day is common in the London area (Transport Statistics for London, 1998) and thus the daily personal exposure of volunteers is likely to estimate the daily exposure of a large proportion of the London population to particles on their journey to and from work.

Samples were collected using Casella personal

Table 1
Summary for all samples analysed

Analytical method	Filter type	Samples		Particles	
		Tube	Road	Tube	Road
CCSEM-EDX	Millipore HTTP	4	6	1828	3174
CCSEM-EDX + low atomic number X-ray detection	Whatman Anodisc®	2	5	2090	5476
CCSEM for particle sizing	Millipore HTTP	6	31	3440	30 498
Gravimetry	Whatman Glass Fibre	2	4	–	–

samplers fitted with a cyclone head at a flow rate of 1.9 l/min attached at shoulder height. Two cyclists per week were supplied with five pre-prepared cassettes containing the filters which were changed daily. For particle analysis by CCSEM without carbon, Millipore polycarbonate HTTP filters with a pore size of 0.4 μm were used. Whatman Anodisc membrane filters (a ceramic material which contributes X-rays from aluminium and oxygen to the SEM analysis) with pore size of 0.2 μm were used for single particle classification with low atomic number X-ray detection and glass fibre filters (Whatman, 1.6 μm) for gravimetric analysis. Flow rates of samplers were checked daily by participants using a rotameter. Samples were stored at −20°C until analysis (Sverdrup, 1990; Vartianes, 1994). Samples were carefully cut into four pieces and mounted on an aluminium stub with conductive carbon cement then coated with approximately 20 nm of gold to improve conductivity and prevent thermal damage.

3. Analytical methods

3.1. Computer-controlled scanning electron microscopy

Samples were analysed using a Stereoscan 240 (Cambridge Instruments Inc) interfaced with a Link Analytical AN-10 000 X-ray analysis system and an interchangeable window Si(Li) detector. Interpretation and classification was performed using custom written software, MIDAS (Watt, 1990).

Approximately 300 particles per sample were analysed and X-ray count data were stored, together with size and shape data for each particle. Fine and coarse fractions were identified using ×3000 and ×1000 magnifications, respectively, resulting in frame size of 31 × 31 μm for the fine fraction and 94 × 94 μm for the coarse fraction. The system was configured to detect particles with projected diameters > 0.2 μm via their backscattered electron (BSE) signal. The BSE threshold settings were standardised to ensure comparability between samples using C and Pb standards, representing the highest and lowest BSE signal that might be expected in this type of sample. A standard beam current was also set using an iron standard. Two different X-ray spectra were used: 0–10 kV for the low atomic number X-ray detection on the Anodisc filters; and 0–20 kV for samples on Millipore filters, corresponding to an accelerating voltage of 20 kV (10 kV for low atomic number X-ray detection). The low accelerating voltage for low atomic number X-ray detection was chosen to reduce the X-rays from elements present in the background (Al and O) and increase the signal from the actual particles (Hamilton et al., 1994).

Signals were recorded for 20 elements in the energy range of 0–10 kV: C, N, F, Cu, Na, Mg, Si, S, Cl, Cd, K, Sn, Ca, Ti, V, Cr, Mn, Fe, Co and Ni. In the energy range of 0–20 kV Pb, Al, Zn, Pt and Mo were also analysed but not C, N, or F. Simple ratio corrections for background shape and overlap were performed using software that had previously been custom written for the purpose, MIDAS (Watt, 1990). Analysis of N and F

Table 2
Classification schemes for road traffic particles

10-kV range		20-kV range	
Groups	% Net detected X-rays	Groups	% Net detected X-rays
C-rich	> 40	Zn-rich	> 7.5
Fe-rich	> 15	Fe-rich	> 10
Fe/Si-rich	> 15 < 80; > 25 < 80	Al-rich	> 11
Si-rich	> 25	Si-rich	> 21
Ca-rich	> 13	Ca-rich	> 20
S-rich	> 18	S-rich	> 19
Unclassified		Unclassified	

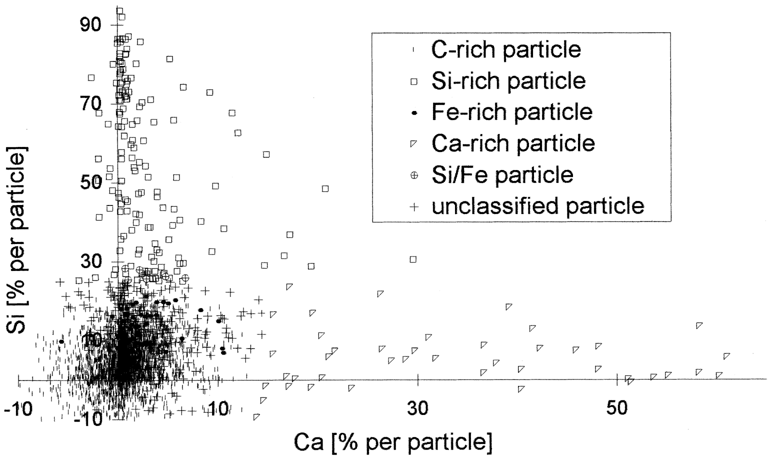

Fig. 1. Classification of road traffic particles according to Ca and Si in the 10 kV range.

proved to be particularly problematic and was therefore not included in this assessment. The results are presented as net X-rays after correction and are normalised to 100%. This semi-quantitative approach has been widely used for characterising particulate material (Watt, 1998) This study is a first attempt to include light elements in such a characterisation. A classification scheme was developed using MIDAS by manual cluster analysis from plotted composition data. All particles collected by cyclists were examined for obvious groups or associations (Fig. 1). Seven particle groups were created in this way for the samples from low energy analysis and seven groups for the samples without carbon analysis (Table 2). It is important to note that the cluster analysis method retains unclassified particles and does not attempt to assign them to the nearest group, as characteristically may happen with automatic multivariate techniques.

Particles from the Underground system were classified for seven element combinations that might be considered to reflect potential indicators of source such as brakes and electric contact material (Table 3). According to the brake producer for the London Underground the main components of the brake blocks are Fe, Si, Ca, and K (BBA Friction Ltd., Manchester, UK; Morris, 1998). The electric contacts of the trains consist of carbon with components of copper.

3.2. Gravimetric analysis

In this study a Sartorius M3 P filter-microbalance was used to weigh glass fibre filters (standard deviation ± 0.002 mg). To avoid the static

Table 3
Classification schemes for Underground particles

10-kV range		20-kV range	
Groups	% Net detected X-rays	Groups	% Net detected X-rays
Fe-rich	> 50	Fe-rich	> 70
Fe/Si-rich	> 10 < 50 (Fe)	Fe/Si-rich	> 20 < 70 (Fe)
Ca-rich	> 13	Ca-rich	> 20
K-rich	> 7.5	K-rich	> 7.5
C-rich	> 50	Al-rich	> 7.5
Si-rich	> 30	Si-rich	> 30
S-rich	> 10	S-rich	> 10

charge error associated with weighing charged filters, the filter was placed in a Faraday box during the weighing process and the balance was contacted to earth. Humidity was kept constant for weighing filter before and after loading (Weingartner, 1995); filters were conditioned before weighing.

4. Results and discussion

4.1. Particle morphology

Fig. 2a shows a typical filter with particles collected by a cyclist. The filter is covered by submicron carbon particles which tend to agglomerate together to form larger, highly porous particles. Such particles are typical of diesel and petrol engine vehicle emissions. The ×4 zoom shows a spherical fly-ash particle and a silicate particle surrounded by small, less-agglomerated carbon particles. The particles in Fig. 2b were collected in the London Underground (Piccadilly Line) and are typical of this sample type. Particles are more angular in shape, suggesting they resulted from friction. Particle shape is an important — although not conclusive — indicator of particle source.

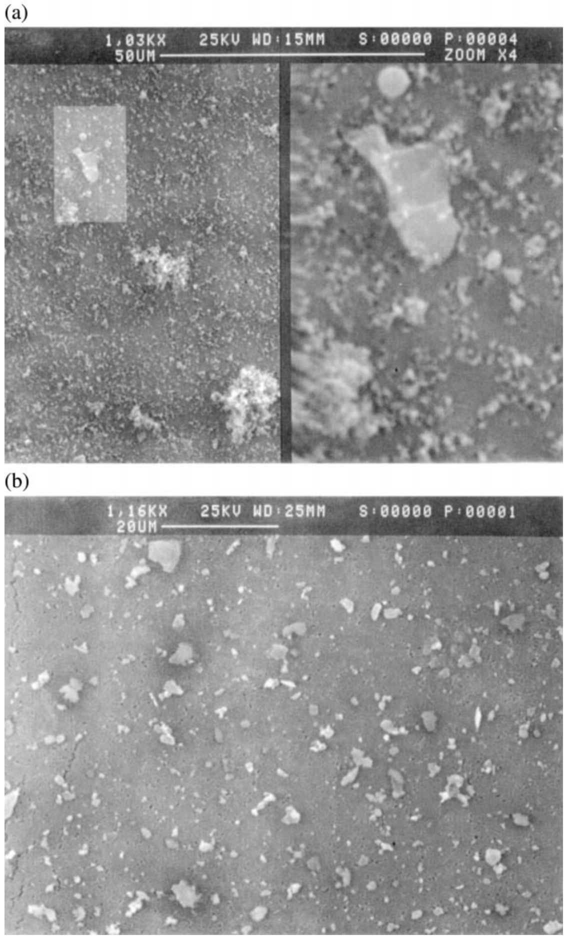

Fig. 2. (a) A Nuclepore filter loaded with particles collected by cyclist in London; (b) and particles collected by a commuter using the London Underground train system.

4.2. Results from gravimetric analysis

Table 4 lists the particle mass concentrations calculated from five samples collected for gravimetric analysis. Samples A–D were collected by cyclists, Samples E and F on the London Underground. Weather and traffic conditions were recorded by participating cyclists, although only simplistic interpretation is possible. For example, Sample A shows a high concentration, collected under low wind weather conditions and traffic

Table 4
Average mass concentrations of PM_5 samples as measured by cyclists (Samples A–D) and on London Underground (Samples E and F) during commuter journeys

Sample	PM_5 ($\mu g/m^3$)	S.D.	Week	Observations
A	88.54	6.52	8.1–12.1.96	Dry weather, no wind
B	16.28	4.72	8.1–12.1.96	Wind throughout week
C	14.00	2.34	15.1–19.1.96	Strong wind
D	16.49	4.07	15.1–19.1.96	Strong wind
E	892.84	55.18	20.5–24.5.96	London Underground
F	708.60	43.15	22.1–26.1.96	London Underground

conditions. Mass concentration ranged with differing wind speeds according the observations. The study was not large enough to begin to examine the relationship between meteorology and particle load (or type). However, it is interesting to note that comparison of the two types of sample shows that samples from the Underground (E and F) represent a far higher mass concentration than those recorded by the cyclists. These results were found to be consistent with London Transport's own air quality surveys (Mean, 1991; Seaborn, 1996).

4.3. Size distribution

Fig. 3 shows the size distributions of over 30 000 particles. The number concentration of particles/cm^3 ranged for cyclists from 7 particles/cm^3 in the early morning (04.00–05.00 h) to 157 particles/cm^3 in the rush hour. Journey observations recorded by cyclists indicate particle count to be affected by traffic density and meteorological conditions (Bevan, 1991). In contrast, the samples collected on London Underground exhibited a higher loading of coarse mode particles with a more even distribution of all sized particles. The accuracy of the estimated size distribution for very small particles is limited because of threshold settings in the backscatter image, but these results provide an indication of size distribution. Particles < 0.2 μm were therefore excluded from the analysis even though there were particles recorded in this size range. However, it is clear that the cyclist samples are dominated by very fine particles which may be expected (Hawkins, 1996).

4.4. Single particle classification

Size and elemental composition were measured for a total of 12 568 particles (Table 1). The data set includes 8650 particles collected by cyclists and 3918 particles from the Underground tunnel system. The 17 samples analysed for elemental composition came from nine commuter routes. The percentage particle number in each group detected in the 10-kV range were in good agreement with the 20-kV range. The standard deviation is 2.5%, thus results of < 2.5% must be treated with caution.

4.5. Cyclist-collected particles

Table 5 shows the classification of particles collected by the cyclists. The upper part of the table shows the average composition of the particles in each group and the bottom rows show the particle numbers and percentages recorded in each group. The main particle fraction in the road traffic samples are carbon rich particles which account for 84.4% of the total number of particles in the 10-kV range. In the 20-kV range (i.e. carbon could not be detected), 92% of the particles collected were impossible to classify and the majority of these particles are assumed to be carbon particles. Motor vehicles are the major source of carbonaceous aerosols in the urban environment, including London (Westminster

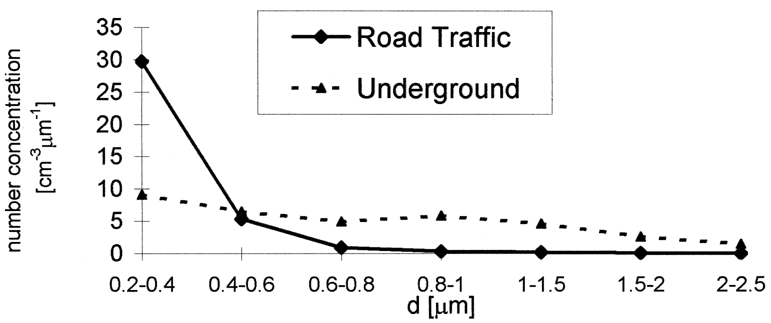

Fig. 3. Comparison of the size distributions and number density of particles collected by cyclist and London Underground commuters.

Table 5
Results from single particle classification of 8650 particles collected by cyclists in London

	10-kV range							20-kV range						
	C-rich	Fe-rich	Fe/Si-rich	Si-rich	Ca-rich	S-rich	Unclassified	Fe-rich	S-rich	Si-rich	Ca-rich	Al-rich	Zn-rich	Unclassified
Normalised net corrected X-rays (%)														
C[b]	66.0	30.2	27.2	25.1	40.5	27.2	32.8							
Cu	3.1	4.1	0.9	1.2	0.7	1.6	1.9	1.8	2.1	0.6	0.8	0.9	1.9	3.2
Na	1.8	0.9	1.2	1.2	1.3	1.9	2.1	0.6	1.4	1.6	1.2	1.6	4.1	3.0
Mg	2.5	2.2	3.9	2.0	2.5	3.0	5.4	1.3	1.7	1.6	1.2	2.9	2.3	4.5
Al[a]								1.4	3.8	6.3	3.3	30.0	0.7	4.9
Si	6.6	13.7	28.3	50.9	7.0	6.6	11.8	6.0	6.9	53.1	17.0	26.4	0.9	7.4
S	2.6	3.3	3.1	3.4	3.8	29.6	7.3	4.1	44.9	7.0	8.0	5.8	5.2	9.3
Cl	1.6	1.6	0.9	1.6	2.3	2.2	4.3	1.4	4.6	2.5	1.6	3.1	5.8	7.7
Cd[b]	1.3	1.0	0.8	1.1	1.3	1.8	3.3							
K	1.2	0.9	0.6	2.3	1.9	1.2	2.7	1.1	3.0	3.2	0.9	4.6	2.7	5.6
Sn	1.1	0.8	0.4	1.0	0.8	1.5	2.8	1.3	3.2	1.9	2.5	2.2	4.7	5.8
Ca	1.2	2.2	4.1	3.1	28.1	16.0	2.3	3.6	14.8	9.1	50.0	4.6	10.5	8.9
Ti	1.1	1.4	1.1	0.9	1.1	0.8	2.9	2.5	1.7	1.3	1.5	1.5	10.1	6.0
V[b]	1.1	1.0	0.5	0.6	0.5	1.0	2.5							
Cr	0.9	0.8	0.3	0.5	1.0	0.6	2.0	1.4	1.2	0.6	1.8	1.6	6.3	4.9
Mn	0.9	0.8	0.4	0.5	1.0	0.6	1.8	1.2	1.0	0.5	0.8	0.8	2.6	4.4
Fe	1.4	25.6	22.5	1.4	1.9	0.9	3.2	68.2	2.4	6.8	4.2	8.1	3.6	4.0
Co	0.7	0.8	0.6	0.3	0.5	0.3	1.5	0.9	1.1	0.3	0.9	0.9	4.4	3.7
Ni	1.0	0.7	0.2	0.4	1.1	0.9	1.8	0.8	0.9	0.6	1.0	1.2	5.4	3.4
Zn[a]								0.9	1.2	0.7	1.1	0.8	22.2	3.0
Pt[a]								0.7	0.9	1.1	1.2	1.0	1.9	4.8
Pb[a]								0.8	2.8	0.8	0.8	1.6	2.3	3.7
Mo[a]								0.2	0.6	0.5	0.2	0.4	2.5	1.7
Number of particles														
	4645	78	14	203	65	53	418	130	95	40	44	47	12	2806
(%)	84.8	1.4	0.3	3.7	1.2	1.0	7.6	4.1	3.0	1.3	1.4	1.5	0.4	88.4

[a]Only in the 20-kV range.
[b]Only in the 10-kV range.

Council, 1995). Motor vehicles emit many particles with diameter < 0.5 μm (Hawkins, 1996) and as this size range is largely excluded from the analyses conducted in this study, it is possible that motor vehicle particles are even under-represented in the data set.

Alumino-silicate material is ubiquitous in the urban environment with inputs from soil, from building materials and industrial fly ash. Al was only measured in the 20-kV range, and it is likely to be that the Si-rich and the Fe/Si-rich particle group in the 10-kV range contain aluminosilicate particle also. Particles containing Al, Si, Fe and Ca may additionally originate from friction of car tyres with the road surface (Rauterberg-Wulff et al., 1995). The Fe/Si-rich particles in samples analysed in the 10-kV range and the aluminosilicates in the 20-kV range may also originate from the abrasion of tyres. The iron-rich particle group in the London aerosol are likely to originate from industrial emissions in and around London or from the vehicles themselves, especially the exhaust system. The presence of carbon with calcium indicate limestone and marble, both natural materials also used extensively in buildings throughout London. The presence of sulphur with calcium is suggestive of gypsum or anhydrite. Both can originate from industrial and natural sources, and the weathering of building materials. The Zn particles may be paint or perhaps might be produced by industrial process in the London area. The unclassified particles in the 10-kV range contain some metal alloy particles, but the group is dominated by Si and C.

4.6. London Underground particles

The aerosol in the London Underground is dominated by particles with iron and silicate (Table 6). Of the total number of particles in the 10-kV range, 53.6% are included in the Fe/Si-rich particle group (58% in the 20-kV range). According to the London Underground brake manufacturers cast iron and glass fibres are included in the brake block, thus some of the Fe/Si-rich particles are likely to be produced by friction between the brake block and the train wheel (BBA Friction Ltd., Manchester, UK, 1998). The calcium- and potassium-rich particle groups may also have some particles that are produced in the same manner as the brake block contains calcium carbonate and potassium in the matrix. The total number of particles in the samples generated at the brake–wheel–rail interface may therefore be estimated as up to 67.9% (75.7% in the 20-kV range).

The 202 (9.7%) carbon-rich particles may also originate from abrasion of the electrical contact, which mainly consists of carbon with slight components of copper and the transfer of ambient air into the Underground ventilation system. Carbon-rich particles may also originate from the carbon inclusion in cast iron, and human debris such as clothes fibres, hair and skin. The number of iron-rich particles ranged between 2.2% (10 kV) and 14.4% (20 kV) with an average iron concentration of 58% (62% in the 20-kV range).

The only particle group likely to have originated from soil minerals, by abrasion of building materials including paint or construction work in the tunnel system are the Si-rich , the Al-rich (aluminosilicate) and the S-rich particles. The particle classified as S-rich particles also contain Ca, suggestive of gypsum or anhydrite. The presence of Si, Ca and Fe in the unclassified particle group may indicate material from the brake block also. Thus the total number of particles from friction between the brake and the wheel may be even higher than estimated above.

The presence of asbestos was not specifically examined. It may potentially be determined, by combining characteristic elemental ratios with large differences in the maximum and minimum diameter of each particle which indicates fibre material (high aspect ratio) but in practice this has never been satisfactorily achieved by automated scanning electron microscopy.

5. Conclusion

Samples collected by London commuters using bicycles and the London Underground system show great variations in size, shape, elemental composition and morphology. The number concentration in the cyclist samples is higher than

Table 6
Results from single particle classification of 3918 particles collected on London Underground

	10-kV range								20-kV range							
	C-rich	Fe-rich	Fe/Si-rich	Si-rich	Ca-rich	K-rich	S-rich	Unclassified	Fe-rich	Fe/Si-rich	Si-rich	Ca-rich	K-rich	Al-rich	S-rich	Unclassified
Normalised net corrected X-rays (%)																
C[b]	63.2	14.8	29.6	21.7	31.2	27.6	22.4	38.4								
Cu	2.0	0.0	0.8	0.6	0.6	0.4	0.6	1.7	0.2	0.6	0.4	1.0	1.0	0.5	0.9	2.5
Na	1.0	0.5	1.1	1.7	0.7	0.6	1.0	2.3	0.3	0.8	0.5	0.8	1.5	2.1	1.2	1.7
Mg	2.3	2.4	2.2	1.6	2.2	3.8	3.0	4.1	0.4	1.1	1.1	1.0	2.3	1.5	1.5	2.0
Al[a]									0.4	2.3	2.2	2.2	3.8	13.6	1.9	4.1
Si	7.3	5.4	17.4	53.0	13.8	30.4	12.5	16.3	3.4	12.9	68.0	11.4	16.3	36.0	7.8	10.9
S	0.9	0.0	0.7	0.8	1.4	1.5	19.5	1.6	0.4	1.2	1.4	1.2	2.9	1.6	25.1	2.7
Cl	1.0	0.5	1.3	1.0	1.2	1.7	1.8	2.3	0.5	1.5	1.5	1.1	4.3	2.2	2.9	4.2
Cd[b]	0.7	0.9	1.0	0.6	0.9	1.2	1.8	1.7								
K	0.8	1.3	1.2	1.2	0.9	10.1	1.4	1.4	0.4	1.5	0.8	1.1	11.7	2.3	1.4	2.2
Sn	0.7	1.1	0.9	0.6	0.9	1.2	1.3	1.2	0.4	1.3	0.9	2.4	1.4	1.8	3.2	3.9
Ca	1.9	3.4	3.9	4.9	29.5	3.4	15.8	4.0	2.1	7.4	6.0	40.6	9.4	7.6	14.1	12.3
Ti	0.7	1.2	1.1	0.5	0.6	0.5	1.4	1.3	0.3	1.1	0.7	1.3	1.9	0.6	1.1	4.2
V[b]	0.9	0.8	0.9	0.4	0.6	0.7	0.5	0.9								
Cr	0.6	0.8	0.7	0.4	0.4	0.8	0.6	0.9	0.3	1.1	0.7	1.0	1.4	0.6	1.1	5.2
Mn	0.6	0.8	0.9	0.4	0.5	0.6	0.6	0.7	0.7	1.2	0.4	1.2	1.1	0.4	0.9	3.5
Fe	5.5	58.6	22.8	4.6	6.7	9.1	10.4	6.0	88.7	62.2	12.9	29.3	34.4	26.5	32.5	25.2
Co	0.5	1.2	0.8	0.3	0.5	0.4	0.4	0.7	0.4	0.8	0.4	0.9	1.3	0.6	0.8	3.4
Ni	0.5	0.3	0.5	0.3	0.4	0.7	0.5	0.7	0.1	0.6	0.5	0.7	1.4	0.3	0.7	1.9
Zn[a]									0.2	0.6	0.4	0.6	0.8	0.8	0.6	2.1
Pt[a]									0.3	0.8	0.5	1.0	1.6	0.6	1.1	3.8
Pb[a]									0.2	0.6	0.3	0.8	1.4	0.4	0.6	3.2
Mo[a]									0.1	0.3	0.3	0.3	0.4	0.2	0.4	0.6
Number of particles																
	202	45	1120	174	268	32	53	196	264	1060	25	239	85	33	49	74
(%)	9.7	2.2	53.6	8.3	12.8	1.5	2.5	9.4	14.4	58.0	1.4	13.1	4.6	1.8	2.7	4.0

[a]Only in the 20-kV range.
[b]Only in the 10-kV range.

the Underground samples, but mass concentration is approximately ten times lower in the cyclist collected samples. The dominant element in the road traffic is carbon whereas most particles in the Underground consist of iron in combination with silicon. The low number of Pb bearing particles in the road traffic samples probably results from the reduction in the use of leaded fuel in London. Morphologies of the road traffic particles were very homogeneous, highly porous agglomerates which agglomerate into larger particles. Underground particles consist of a dense matrix, probably of mixed substances, principally originating from the brake–wheel–rail interface.

CCSEM using the MIDAS system proved to be extremely useful in identifying individual particle types in the particulate air samples collected. The technique is able to resolve individual particles from each other, based on their individual chemistry. It was therefore possible to distinguish between particles containing iron/silicate and particles of aluminosilicate, for example.

The effects of the inhalation of carbon aerosol particles remain unclear. The current model of carbonaceous particles assumes an elemental carbon core with a surface coating of hydrocarbons and other adsorbed species. These hydrocarbons include known carcinogens such as benzo[*a*]pyrene and long-term exposure to and retention in the lungs of these compounds would be expected to cause cancers (IARC, 1987). Research is currently focussing on the ability of these carbonaceous compounds to cause oxidative stress.

The implications for human health are difficult to determine since the toxic action of particles in the lung — what particle characteristics are the most important and the mechanisms by which they affect lung physiology — are still not determined. Current European research has identified increased surface area (Seaton, 1995) and the quantities of iron and silica in ambient aerosol (Ghio and Hatch, 1993; Donaldson et al., 1997; Smith and Aust, 1997) as particularly important. However, the importance of the quantities of silica and iron measured appears to be dependent on the phase of iron and age (and consequently oxidation state) of these particles.

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