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Comparison of charged nanoparticle concentrations near busy roads and overhead high-voltage power lines

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Summary

Overhead high-voltage power lines are known sources of corona ions. These ions rapidly attach to aerosols to form charged particles in the environment. Although the effect of ions and charged particles on human health is largely unknown, much attention has focused on the increasing exposure as a result of the expanding power network in urban residential areas. However, it is not widely known that a large number of charged particles in urban environments originate from motor vehicle emissions. In this study, for the first time, we compare the concentrations of charged nanoparticles near busy roads and overhead power lines. We show that large concentrations of both positive and negative charged nanoparticles are present near busy roadways and that these concentrations commonly exceed those under high-voltage power lines. We estimate that the concentration of charged nanoparticles found near two freeways carrying around 120 vehicles per minute exceeded the corresponding maximum concentrations under two corona-emitting overhead power lines by as much as a factor of 5. The difference was most pronounced when a significant fraction of traffic consisted of heavy-duty diesel vehicles which typically have high particle and charge emission rates.

Keywords: *Ion, charged particle, power line, vehicle emission, pollution, dispersion*

1. Introduction

In the natural environment, air molecules are ionized by interaction with radiation in the form of galactic cosmic rays and terrestrial radioactivity. This gives rise to air ions which are essentially charged molecules or charged molecular clusters(Isräel, 1970). Air ions have a short lifetime of about 100 s as they are quickly lost through recombination, attachment and deposition (Hirsikko et al., 2011; Isräel, 1970). In stable air, this results in a uniform background air ion concentration of between 200 and 2500 cm^{-3}, the concentrations being mainly determined by the level of particle pollution in the environment (Hirsikko et al., 2011; Retalis et al., 2009). Anthropogenic sources of ions, such as corona discharge in overhead high-voltage power lines (OHVPL), may significantly affect concentrations of ions and charged particles in the urban environment (Buckley et al., 2008; Fews et al., 1999; Fews et al., 2002; Jayaratne et al., 2008; Jayaratne et al., 2011). We have monitored air ion concentrations at 41 OHVPL sites in Australia, and shown that the concentration at 76% of these sites exceeded the mean background value (Jayaratne et al., 2008). Around 25% of the sites showed concentrations that were more than twice the mean background value.

Although air ions are inhaled into our lungs during breathing, there is no evidence that the charge itself constitutes a health risk. For example, ion generators are commonly used in homes and offices to improve air quality with no reports of adverse respiratory problems to the occupants (Grinshpun et al., 2005). On the other hand, Several studies have demonstrated a link between particulate pollution and adverse health effects

(Russell and Brunekreef, 2009; Seaton et al., 1995). This link is stronger in urban environments, where the majority of particulate matter originates from motor vehicle emissions that are known to be harmful to human health (Morawska et al., 2008). For example, diesel emissions contain a range of toxic chemicals and have recently been classified as ‘probably carcinogenic to humans’ (IARC, 2012). While motor vehicles are known to emit large numbers of particles, it is less well known that many of these particles are electrically charged (Jayaratne et al., 2010; Maricq, 2006; Yu et al., 2004). This charge is created during the combustion process within the engine itself. Thus, for example, it has been shown that 60-80% of the soot particles emitted by a diesel engine are charged with nearly equal numbers of positive and negative charges (Maricq, 2006). Measurements near busy freeways have shown elevated concentrations of ions and charged particles. For example, in a recent study near two busy freeways in Los Angeles, USA, it was shown that the fraction of charged particles in each of the four sizes – 30, 50, 80 and 100 nm, was significantly higher than in the background as measured on the upwind side of the freeway (Lee et al., 2012). However, the concentration of charged particles in the air was not quantified. Measurements 10 m downwind of a road carrying between 6000 and 16,000 vehicles per day in Kuopio, Finland, showed a mean charged particle concentration of 1920 particles cm^{-3} in the size range 2-40 nm (Titta et al., 2007).

Ultrafine particles from vehicle emissions penetrate deep into the respiratory system and a large fraction of them are retained in the lungs (Morawska et al., 2005). The important question that arises in this respect is whether the presence of charge on inhaled particles can influence their effect on human health. Several studies have shown that the deposition rate of particles in the lungs is enhanced when they carry an electric charge. Unipolar charged aerosols are driven by mutual repulsion toward the airway walls where they are attracted by electrostatic image forces and deposited on the surfaces (Hinds, 1999). This phenomenon has also been used to increase the deposition of aerosol in the lung enabling the amount of drugs administered to patients to be controlled (Bailey, 1997). Measurements of particle deposition in hollow cast models of human airways have shown that the deposition of 20 nm and 125 nm particles was enhanced by factors of 3.4 and 2.3, respectively, when they carried a single charge (Cohen et al., 1998). Experiments on live animals have shown that the deposition of particles in the lungs of rats was enhanced by about 20% when the particles carried an electric charge (Ferin et al., 1983). Systematic measurements with unipolar charged monodisperse aerosols of both polarities on human volunteers have demonstrated that the electrostatic charge carried by aerosol particles greatly enhanced their deposition in the airways (Melandri et al., 1983; Prodi and Mularoni, 1985). Adverse health effects are determined by particle dose, not exposure, so these observations suggest that the real danger to human health may not be from air ions but from charged particles in the air.

Monitoring studies under alternating current (AC) OHVPLs have reported air ion concentration (Jayaratne et al., 2008; Jayaratne et al., 2011; Ling et al., 2010) or total space charge concentration (Bracken et al., 2005; Grabarczyk and Berlinski, 2004). While air ions do not include charged particles, space charge includes both air ions and charged particles. Ion mobility spectra have been reported but these have not presented the actual charged particle concentrations under the lines (Buckley et al., 2008; Wright et al., 2014). Total net space charge concentrations have also been estimated using direct current (DC) electric field measurements (Fews et al., 1999;

Fews et al., 2002; Matthews et al., 2012; Matthews et al., 2010). Studies using the aerosol electrometer have provided net charged particle concentrations (J-Fatokun et al., 2010; Jayaratne et al., 2011; Ling et al., 2010). However, there have not been any direct measurements of total charged particle concentrations under OHVPLs.

In this study, for the first time, we investigate charged nanoparticle concentrations of both positive and negative polarities under OHVPLs as a function of distance from the lines. Using these results, we show that the total charged nanoparticle concentration near busy freeways carrying diesel trucks is significantly higher than near OHVPLs to a distance of as far as 200 m away from the traffic.

2. Methods

2.1 Instrumentation

In this study, we used a neutral cluster and air ion spectrometer (NAIS) to monitor neutral and charged nanoparticle concentrations. The NAIS was developed by Airel Ltd, Estonia, and measures charged and uncharged nanoparticles and molecular clusters of both polarities in the size range from about 0.5 nm to 42 nm, the upper limit restricting particle detection to approximately the nanoparticle size range (Morawska et al., 2009). For a detailed description of its operation, please refer to Manninen et al. (2009) and Mirme and Mirme (2013). The results in this paper have been obtained with the measurement cycle of the NAIS set to ions for 2 min and particles for 1 min, with a reading every 1 s.

2.2 Site description and measurement techniques

In a recent study, we showed that ion emission does not occur uniformly along OHVPLs but only from discrete corona points on the lines, generally on insulators and spacers (Jayaratne et al., 2011). Long stretches of the lines are often corona-free and the charged particle concentrations in these vicinities are not higher than the background values. For the purpose of this study, it was important to differentiate between these sites and, therefore, we define an OHVPL site as either one where there is a strong corona source (PSC), a weak corona source (PWC) or no corona source (PNC). We arbitrarily defined these three classes of OHVPL sites as where, more than 40%, 20%-40% and less than 20%, respectively, of the nanoparticles carried an electric charge.

Measurements were carried out at a number of different sites that may be classified into three main types. These were as follows: (1) Four background sites, well away from anthropogenic ion and particle sources. These four sites were located outside the city centre and consisted of open grassy areas away from trees. They were at least 200 m away from the nearest vehicular traffic and residential areas with no power lines in the vicinity. (2) AC OHVPL sites including two PSC sites and two PWC sites. As stated before, long stretches of the lines were corona free. Therefore, for our analysis, to be consistent in number with the other two types of power line sites, we selected two PNC sites where no corona were observed, giving in total six power line sites (3) Three sites near two busy freeways. More details of all these monitoring sites may be found in Ling et al. (2010). Some of the results from one of the two PSC OHVPL sites and one of the three freeway sites have been reported before in Jayaratne et al.

(2011) and Jayaratne et al. (2014), respectively. The analysis in this paper extends these results to several other sites so that the results are more representative of each type of site and provides much better comparison.

Measurements were restricted to sunny days with minimum cloud cover and carried out for at least two hours at each site. At all OHVPL and freeway sites, measurements were restricted to time periods when the wind direction remained along a line at an angle greater than 45º with the OHVPL or road. The wind direction was noted with a portable wind vane. At each site, the NAIS was placed on a low trolley with the sampling inlet at a height of 0.8 m above the ground. It was powered by a portable power generator which was placed at least 15 m away from the NAIS in the down wind direction from the road or the power line at all times. Background monitoring was conducted in open parks, well away from all ion and particle sources such as OHVPLs, roads and houses. At the freeway sites, during each 2-hour monitoring period, the numbers of light and heavy duty vehicles passing in both directions were manually counted for two successive 1 min periods every 10 min. Each of the freeways carried 100-140 vehicles min^{-1} on two lanes in each direction, of which 10-15% were heavy duty diesel trucks. The speed limit on the freeways was 100 km h^{-1}. The OHVPL sites contained 1, 2 or 3 parallel lines of voltage 275 kV ac double circuit. The lines were about 20 m above the ground.

2.3 Data Analysis

Means and standard deviations of the charged nanoparticle concentrations were calculated and the Student t-test was used to test for significant differences between sample means at the confidence level of 95%. The standard deviations are shown as error bars in each of the graphs provided.

3. Results and Discussion

3.1 Time Series

In Fig 1, we show typical short time series of the negative and positive charged nanoparticle concentrations measured (a) at the ground, 30 m downwind of a triple 275 kV AC OHVPL with a strong corona source and (b) at a distance of 2m from the kerb on the downwind side of a busy freeway carrying 120±20 vehicles min^{-1} on two lanes in each direction. The large fluctuations in Fig 1(b) are due to passing vehicles, especially heavy-duty diesel trucks, which comprised about 15% of the traffic count at this site at the time of the measurements. The two time series in Fig 1(b) showed a near-perfect mirror image pattern, indicating that there were nearly equal numbers of positive and negative charged nanoparticles near the road. This was observed at all the freeway sites. However, the nanoparticles at all four OHVPL sites with corona showed a significantly higher positive than negative charge. Although net negative space charge have been observed at some AC OHVPL sites (Fews et al., 1999; Jayaratne et al., 2008), in the majority of studies the net sign of charge has been positive (Fews et al., 2002; Grabarczyk and Berlinski, 2004; J-Fatokun et al., 2010; Jayaratne et al., 2011; Matthews et al., 2008). At present, there is no viable explanation for this observation.

Fig 1 shows a significantly higher concentration of charged nanoparticles of each sign near the freeway than the OHVPL. Since this was an OHVPL with a strong corona source, we conclude that this observation was true for all the power line sites. The mean charge nanoparticle concentrations at each of the two PSC OHVPL sites was significantly lower than at each of the three freeway sites.

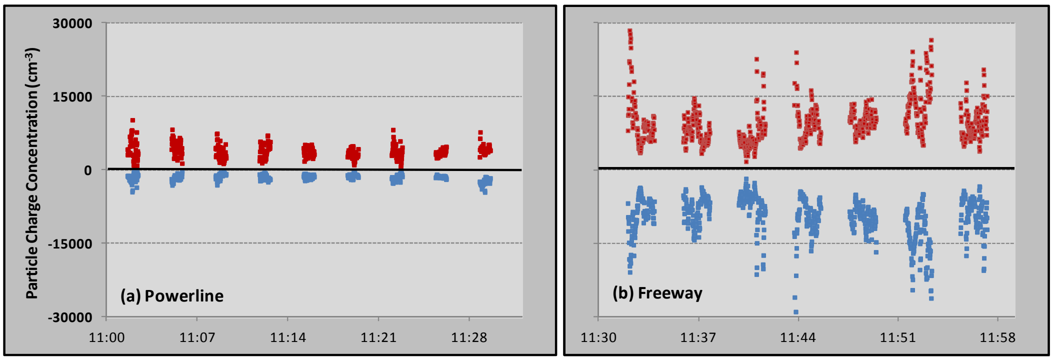

Figure 1: Typical time series of the positive and negative charged nanoparticle concentrations measured under an OHVPL (a) and near a freeway (b). The breaks in the data occur due to the NAIS measurement cycle. The apparent continuation of real time across the two frames was coincidental.

3.2 Site Comparison

The means and standard deviations of the negative, positive and total charged nanoparticle concentrations observed at the various sites are shown in Table 1. Fig 2 shows the negative and positive mean values of all 13 sites graphically. The mean background total nanoparticle number concentration was in the range (1.26 ± 0.43) x 10^4 cm^{-3}, while the corresponding total charged nanoparticle concentrations were consistently in the range (2.2 ± 0.6) x 10^3 cm^{-3}, suggesting that approximately 17% of the nanoparticles in the background were charged. There was a 10-20% excess of positive over negative charge. There was no significant increase in charged nanoparticle number concentration over background at OHVPL sites with no corona (PNC). Our observations in the study area showed that over 80% of the length of the lines was corona-free, that is there was no significant increase of charged nanoparticle number concentration over background. At sites where a weak corona source was present (PWC), the concentrations were still significantly higher than the background and the PNC sites, with the positive charge dominating. At the two OHVPL sites with strong corona sources (PSC), the positive charge concentration was significantly higher than the negative charge concentration. The mean positive charge concentration at these two PSC sites was more than three times higher than in the background. The mean nanoparticle number concentration at the two PSC sites was 1.19×10^4 cm^{-3}, showing that 46% of the nanoparticles carried a charge. The three freeway sites (F) showed very high nanoparticle number and charged nanoparticle concentrations. In agreement with previous measurements of charged particle emissions in motor vehicle exhaust in which the concentrations of negative and positive charges were roughly the same (Jayaratne et al., 2010; Maricq, 2006). The mean nanoparticle number concentration during the period of measurement was $(1.07 \pm 0.81) \times 10^5$ cm^{-3}. The large variation is symptomatic of the passage of heavy duty vehicles (Jayaratne et al., 2010). The negative and positive charge nanoparticle concentrations are given in Table 1 and they show that about 18% of the nanoparticles were charged. However, the total number of charged nanoparticles (1.90×10^4 cm^{-3}) was significantly higher than at any of the other types of sites including that under OHVPLs with strong corona sources (5.58×10^3 cm^{-3}). This is the key important finding of this study.

	B	PNC	PWC	PSC	F
MEAN					
Neg	1065	1120	1601	1627	9350
Pos	1191	1201	2706	3953	9676
Total	2256	2321	4306	5579	19026
STD DEV					
Neg	400	498	676	844	4586
Pos	426	509	1009	1883	4801
Total	584	712	1214	2064	6640

Table 1: The mean and standard deviation of the negative, positive and total charged nanoparticle concentrations (cm^{-3}) observed at the various sites. Background (B), OHVPL with no corona source (PNC), a weak corona source (PWC) and a strong corona source (PSC), as defined in the text, and Freeway (F).

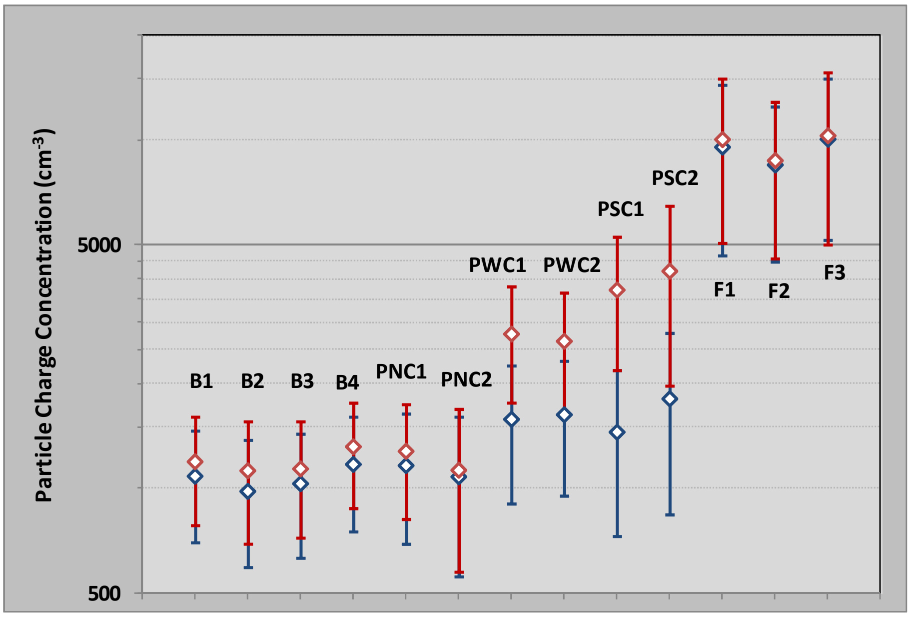

Figure 2: The mean positive and negative charged nanoparticle concentrations observed at the various sites labelled as follows: Background (B), OHVPL with no corona source (PNC), a weak corona source (PWC) and a strong corona source (PSC) and Freeway (F). The positive points are above the negative points and the error bars show the standard deviations about the respective means.

3.3 Size Distributions

Larger particles can hold a greater charge than smaller particles. In Fig 3 we show the size distribution of the total charged nanoparticle concentrations in seven size bins within the particle measurement range of the NAIS, 1.6 to 42 nm, at three site types B, PSC and F. It can be seen that the mean charged nanoparticle concentrations at F are significantly higher than at the other two types of sites in all size bins. The difference between B and PSC becomes apparent only at the larger sizes. That is, although the total nanoparticle charge concentration at PSC is significantly higher than in the background, B, particles smaller than about 10 nm carry very little excess charge. Near an OHVPL, aerosol particles are charged by the attachment of air ions formed due to corona discharge on the lines. The probability of attachment increases as the square of the particle diameter and, therefore, near a power line, most of the charge resides on the larger particles. However, at the freeway sites (F), particles right down to 2 nm carry a significantly higher charge than in the background (B). This is no surprise as particles in motor vehicle exhaust are charged within the engine before they are emitted into the environment (Jayaratne et al., 2010; Maricq, 2006; Yu et al., 2004). They do not acquire their charge by capturing air ions that are present in the environment. Thus, although most of the charge is carried by the larger particles, there is a considerable amount of charge residing on the small particles, which is significantly more than is present on particles of the same size in the environment.

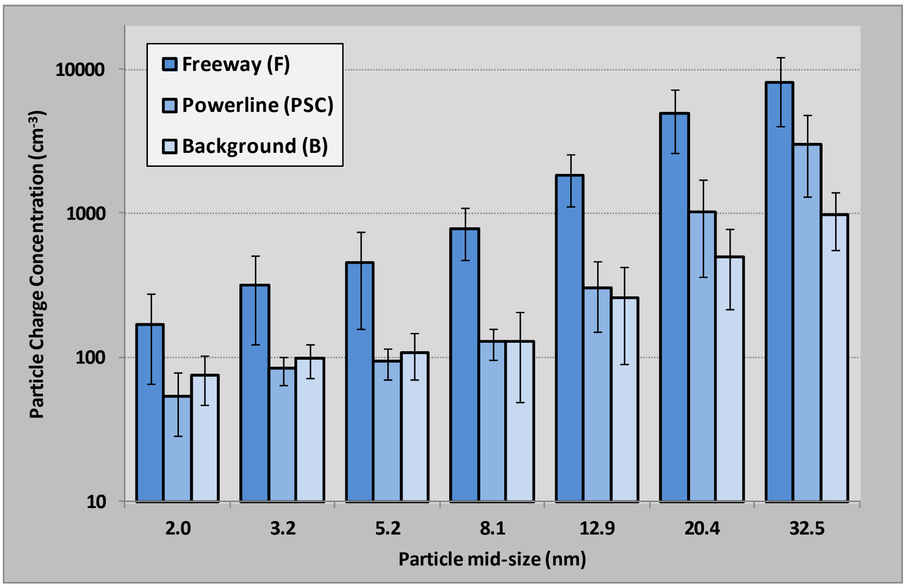

Figure 3: Size distributions of the total nanoparticle charge concentrations at three types of sites. The mean total nanoparticle charge concentrations are shown in seven size bins between 1.6 and 42 nm, mid-size values being indicated on the horizontal axis. The error bars indicate the respective standard deviations.

3.4 Variation with Distance

It should be noted that, while the source of charged nanoparticles was always at ground level near a road, it was about 20 m above ground level near an overhead power line. This resulted in the maximum charged nanoparticle concentration near a road being near the kerb. However, the concentration was not a maximum at the point on the ground directly under a power line but at some downwind distance away from this point. The data shown as PSC were obtained at ground level about 30 m away from the foot of the OHVPLs. In consistence with our previous study (Jayaratne et al., 2011), this is where the concentration of charged nanoparticles was a maximum at ground level. In Fig 4, we show the charged nanoparticle concentrations at PSC1 and F1 as a function of distance from the foot of the OHVPL and from the kerb of the freeway, respectively. Two previous studies have reported enhanced space charge concentrations at downwind distances of 2 km from a freeway (Israelsson and Lelwala, 1999) and 7 km from a 400 kV OHVPL (Fews et al., 2002). In contrast to these studies, in the present study, the charged nanoparticle concentrations were not significantly different from the background values beyond 200 m from the freeways and 100 m from the OHVPLs. We suspect that dilution resulting from turbulent mixing is the main factor that controls the decrease in concentration with distance. It is also apparent from Fig 4 that the concentration of charged nanoparticles on the downwind side of the road was greater than the maximum observed concentration under the OHVPL up to a distance of about 150 m from the road.

Considering that the concentrations decrease sharply with distance, the relative exposures to the charged nanoparticles need to be interpreted carefully. We calculated the charged nanoparticle concentrations at the same distance from the foot of the OHVPL and from the kerb of the freeway and evaluated the ratio of these two quantities, F/P, and these values are shown in Fig 4 as + symbols referenced to the secondary vertical axis. From this graph, we see, for example, that at a distance of 40 m from the freeway kerb the charged nanoparticle concentration is about twice as high as that at the same distance from the foot of the OHVPL. It is also useful to estimate the relative exposures at various ranges from the source as many people live within short distances of freeways and OHVPL. By integrating the two curves in Fig 4, we calculated the mean exposure within a given distance from the foot of the OHVPL and from the kerb of the freeway. We found that, within a distance of 10 m from a freeway, the mean charged nanoparticle exposure was approximately 15 times greater than that within the same distance from the OHVPL. Within the range from the kerb to 40 m, it was six times as great and to 100 m, it was about three times greater.

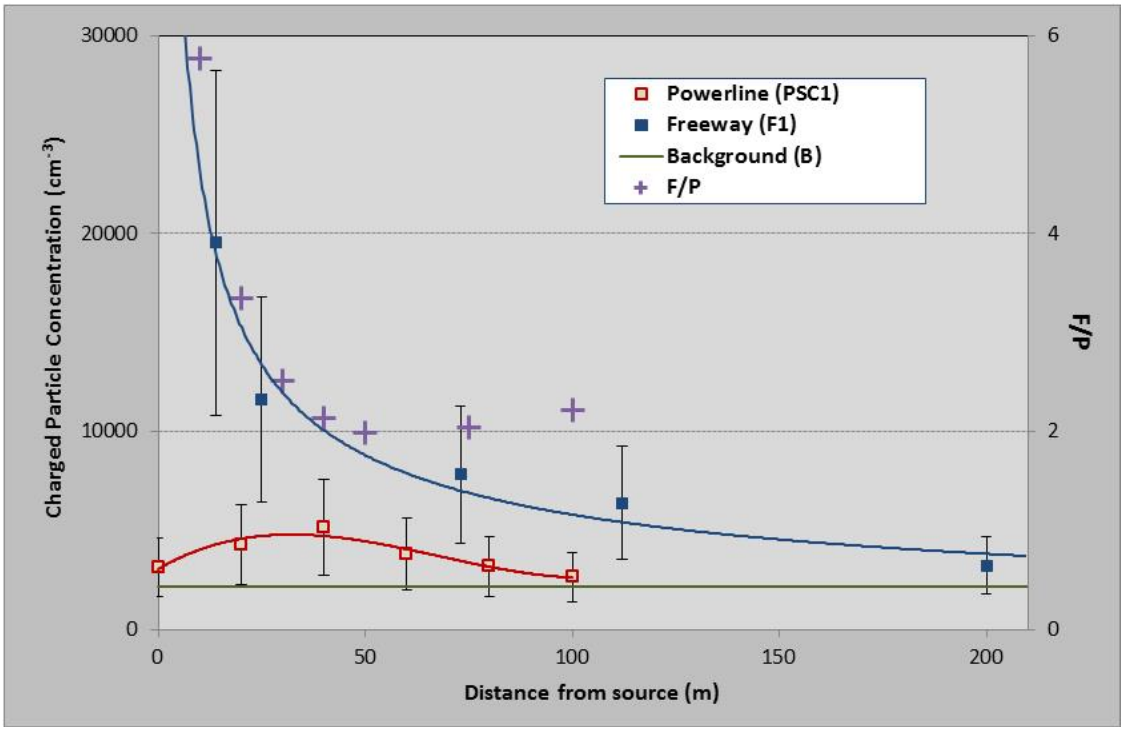

Figure 4: Charged nanoparticle concentration as a function of distance from the foot of an OHVPL (open squares) and from the kerb of a busy freeway (filled squares). The horizontal straight line shows the mean urban background concentration. The error bars represent the respective standard deviations. Also shown is the F/P Ratio (+) up to a distance of 100 m.

This study is restricted to measurements at the ground since human exposure is primarily at this level. However, it should be noted that, since overhead power lines are located at some height above the ground, nanoparticle charge concentrations in close proximity to the lines would be greater than at ground level. The variation of charged nanoparticle concentration from overhead power lines as a function of height above the ground was outside the scope of this study and will form the subject of a future paper.

With expanding urbanisation, increasing numbers of people reside closer to busy freeways. While several studies have focussed on exposure to particles near busy roads, no study has taken into account the increase in dose rate due to the charge carried by these particles. In this study, we have shown that the exposure to charged nanoparticles is many times greater near a busy freeway than under an OHVPL. These findings may have important implications for urban planning, human settlements and infrastructure development.

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