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Concentrations of Submicrometre Particles from Vehicle Emissions near a Major Road

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Abstract

As part of a program of study to assess the exposure risks related to particulate matter in the outdoor environment, number concentrations of particles from vehicle emissions were measured at increasing distances from a major road. Particles in the size range from 0.015 – 0.697 μm were measured with the Scanning Mobility Particle Sizer (SMPS) and in the size range from 0.5 – 20 μm, with the Aerodynamic Particle Sizer (APS). In addition to number concentration measurements, an approximation of $PM_{2.5}$ fraction was obtained using a DustTrak (simple photometer).

The measurements conducted at distances from the road ranging from 15 to 375 m showed, that for conditions where the wind is blowing directly from the road, the concentration of fine and ultrafine particles decays to around half of the maximum (measured at the closest point to the road) at a distance of approximately 100 - 150 m from the road. For the wind blowing parallel to the road, the reduction to half of the concentration occurs at 50 – 100 m. There is no effect on total particle number

concentration at a distance greater than 15 m from the road when the wind is blowing towards the road and away from the sampling points.

Total number concentrations of larger particles measured were not significantly higher than the average values for the urban environment, and decrease with distance from the road, reaching about 60% at 150 m from the road for wind from the road. $PM_{2.5}$ levels also decrease with distance to around 75% for wind from the road and to 65% for wind parallel to the road, at a distance of 375 m.

Keywords: Ultrafine particles, fine particles, particle number concentration, $PM_{2.5}$, horizontal profiles, traffic, vehicle emissions.

Introduction

There is an increasing recognition that adverse health effects due to the exposure to airborne particulate matter could be more significant than due to the exposure to many other airborne pollutants. Throughout the last thirty years, there have been a number of scientific studies indicating that particulate air pollution can have an acute effect on human health, (review by Vedal, 1997). Standards for monitoring this pollution have been established; however, as technology improves in measurement techniques and more information becomes available on the relationship between exposure and health effects, it has become more apparent that existing standards may need to be revised to include monitoring of a finer particle size range.

Currently there are standards in the United States of America for the mass of particulate matter less than 10 μm in aerodynamic diameter (PM_{10}, - coarse particles), and less than 2.5 μm ($PM_{2.5}$, - fine particles). $PM_{2.5}$ was only recently introduced as a standard to the US in 1997, following the findings from epidemiological studies on the relationship between exposure to $PM_{2.5}$ and health effects, and thus reflecting the growing recognition of the importance of fine particles in relation to health effects.

In an urban environment over 80% of particulate matter in terms of number is related to ultrafine particles (Morawska, *et al.*, 1998b), although their total mass is usually insignificant in comparison with the mass of the small number of larger particles. Ultrafine particles are considered here as those below 0.1 μm. Fine and even more ultrafine particles, typically contain a mixture of components including soot, acid condensates, sulfates and nitrates, as well as trace metals and other toxins. The information about these very small particles is not recorded when mass samples are taken during conventional PM_{10} and $PM_{2.5}$ measurements; in fact, a majority presence of finer particles can be completely obscured by only a few larger, more massive particles. This can lead to a misrepresentation of the quantity of pollutants present and hence of the air quality and the potential health effects.

There is still very little information available on the production rate, airborne concentrations and fate of fine and ultrafine particles in the air. In an urban environment, motor vehicle emissions usually constitute the most significant source of fine and ultrafine particles. Thus for exposure assessment, it is necessary to quantify particle emission levels, and also to determine particle behaviour after emissions, as they are transported away from the emission source – the road. There

have been some studies conducted on behaviour of gaseous emissions at an increasing distance from the road, as well as on behaviour of mass concentrations of particles in terms of PM_{10} or $PM_{2.5}$, but very limited studies on particle number concentration. A study focused on the nitrogen oxides and ozone close to a motorway was conducted by Kuhler, *et al.,* 1994. In the study the dispersion of NO, NO_2, CO, and O_3 concentrations was modelled, and concentrations of the same gases were measured at three distances from a motorway (50, 100, and 600 m). The model predicted gas levels (except for ozone), to increase to a maximum at a distance of 50 m, and to decrease from 50 to 600 m. This was confirmed by the data measured at 100 m and at 600 m, however the accuracy of the model at 50 m was not shown, as those concentrations were not included in the concentration versus distance graph. Another study examined PM_{10}, $PM_{2.5}$, NO_2, black smoke, and benzene at four different distances from a major motorway (Roorda-Knape, *et al.,* 1998). In this study, monitoring sites were set up at approximately 50, 100, 150, and 300 m from a major motorway at two different locations. It was concluded that NO_2 and black smoke concentrations decrease with increased distance from a road, whereas there is no significant decrease in concentrations of PM_{10}, $PM_{2.5}$, and benzene.

Janssen, *et al.,* (1997) compared the mass concentration and elemental composition of particles sampled near major roads and at background locations. The authors concluded that PM_{10} and $PM_{2.5}$ concentrations were on average only 1.3 times higher near the road compared with the background readings, and black smoke (elemental carbon) readings were 2.6 times higher. These findings indicate that black smoke is more closely related to motor vehicle emissions than PM_{10} or $PM_{2.5}$ fractions. In addition, the levels of Fe and Si (both elements are associated mainly with natural

emission sources) were significantly higher in PM_{10}, and to a lesser extent in $PM_{2.5}$ samples near the road. This finding indicates a contribution from suspended road dust, which means that vehicle exhaust emissions may not be the main source for PM_{10} and $PM_{2.5}$ in proximity to a busy road.

Another study (Clairborn, *et al.,* 1995) evaluated the PM_{10} emission rates from paved and unpaved roads out to distances of approximately 80 m using the tracer gas SF_6. The assumption was that SF_6 simulates particulate matter transport for the distances used in the experiment. There was a clear decreasing trend for concentrations of SF_6 as distance increased.

In a pilot study, horizontal and vertical profiles of submicrometre particulates in relation to busy roads were examined by Morawska, *et al.,* (1999). The study selected two sites within the city area of Brisbane, one at a distance from the freeway of up to 210 m, and the other located at the junction of several major transport routes in the central business district (distance from freeway up to 73 m). Concentration measurements were made at a reference point close to the freeway and at increasing distances with two SMPS' for the first site, and with one SMPS for the second site. There was no significant decrease in particle number concentration with distance from the road for the first site, but there was a decrease in concentration at the second site. This difference was thought to be due to the topography at the sites. Further investigation into a more open topography was recommended.

In view of the increasing importance of fine and ultrafine particles for exposure assessment, the aim of this study was to measure particle size distribution and

concentration in the size range from 0.015 – 20 μm, at increasing distances from a road, and to conclude on the trends in particle characteristics for different wind conditions in relationship to the road.

Previous major studies at the Environmental Aerosol Laboratory (EAL) of the Queensland University of Technology (QUT) focused on direct vehicle emissions and included comprehensive examination of the gaseous and particle phases of city council bus exhaust (diesel fuel) (Morawska, *et al.,* 1998a), and of car exhaust (petrol and LPG fuel) (Ristovski, *et al.,* 1998). These studies presented information on the concentration and size distributions of particles in the exhausts of both cars and buses for different load and speed conditions for the test fuel used in the measurements. The majority of particles from the exhaust were found to be in the range 0.02-0.13 μm (diesel) and 0.04-0.06 μm (petrol). Thus the lower particle size range chosen for the measurements presented here ensured that most of the particles which are directly related to motor vehicle emissions were detected. The upper particle size range enabled detection of particles which have little contribution to the total particle number, but a significant contribution to particle mass, and thus to PM_{10} and $PM_{2.5}$ fractions.

Experimental Techniques and Procedures

The study design for the project included measurements of particle number concentration in the range from 0.015 – 0.697 μm, and from 0.5 – 20 μm taken using a Scanning Mobility Particle Sizer, and an Aerodynamic Particle Sizer, respectively, at increasing distances from a major road. An approximation of $PM_{2.5}$ was also

measured at the same distances using a DustTrak. Measurements were made under different recorded wind conditions while temperature and relative humidity were also recorded.

Instrumentation

Scanning Mobility Particle Sizer (SMPS)

The SMPS (TSI Model 3934) consists of an Electrostatic Classifier (EC) and a Condensation Particle Counter (CPC). The instrument enables measurements of particle number distribution in the size range from 0.005 to 0.9 μm using the electrical mobility detection technique. The SMPS uses a bipolar charger in the EC to charge particles to a known charge distribution. The particles are classified according to their ability to traverse an electrical field and are counted by the CPC. Physical settings on the SMPS include adjustments of the flow rates for the monodisperse and polydisperse aerosol, and for the excess and sheath air. These flow rates determine the measurable size range for a given sampling time. A complete sample may be taken in as little as 2 minutes or as long as 8 minutes, depending on conditions and requirements.

The entire system is automated and data analysis is performed by an IBM compatible computer system with customised software. The output data is in the form of graphs and tables of the number, surface area and volume concentration versus particle diameter. For this study, the SMPS size range used was 0.015 – 0.697 μm, and the duration of each sample was 135 s.

Aerodynamic Particle Sizer (APS)

The APS (Model 3310A) measures particle size distribution and concentration in real time, in the size range from 0.5 to 20 μm and up to the order of 10^2 or 10^3 particles.cm^{-3} for coincidence errors of 1% and 5% respectively. The instrument operates on the principle that particles of different sizes, after being accelerated in a flow field, achieve different velocities. A laser scan technique allows measurement of these velocities that are later used for calculation of particle diameter. The sheath flow rate of the APS is adjusted at 4 $L.min^{-1}$,and the sample flow rate at 1 $L.min^{-1}$, giving a total flow rate of 5 $L.min^{-1}$. Sampling time can be chosen from 1 - 65535 s, and was set to be 20 s for these experiments.

DustTrak

The DustTrak, TSI Model 8520 Aerosol Monitor, is a real time device for the determination of aerosol mass concentrations in the range 0.001 to 100 $mg.m^{-3}$, for particles ranging in size from 0.1 μm to 10 μm. Different impactors are available for the inlet of the DustTrak allowing measurements of PM_{10}, $PM_{2.5}$, and PM_1. The measurement is performed using a light scattering technique where the amount of scattered light is proportional to the volume concentration of the aerosol. For particles smaller than one third the wavelength of the laser (780 nm), the scattered light decreases as a function of the sixth power of the diameter, thus limiting the smallest detectable particles to approximately 0.1 μm. The $PM_{2.5}$ values obtained in this study using the DustTrak, are not actual gravimetric values, as the instrument was calibrated for Arizona dust particles by the manufacturer, and would need to be re-calibrated for the vehicle emission aerosol at the road site. It was used in this study to provide relative readings.

DustTrak data can be logged at user defined intervals and gives an average reading of mass concentration over the specified interval. The logged data can be analysed using the TrakPro Data Analysis Software provided with the instrument. For this work, readings were logged every minute and averaged over 10 – 15 mins.

Qtrak

The TSI Model 8551 IAQ monitor measures temperature, relative humidity, CO and CO_2 concurrently, and data can be automatically logged at user defined intervals. Each data point is an average over this time interval and is recorded for later retrieval using the TrakPro Data Analysis Software. Only temperature and relative humidity were used for this work as the sensitivities of CO and CO_2 were not appropriate in this case.

Sites and Procedures

Two sites were selected for these measurements. The sites were near major roads (Gateway Motorway at Tingalpa – Site 1, and Wynnum Rd at Murrarie – Site 2), and both consisted of a small bitumen road running perpendicular to the main road. Both small roads were to provide access to parklands and had a negligible amount of traffic (an estimated one car per hour). Schematic representations of the two sites chosen for measurements are shown in Figures 1 and 2.

The traffic flow on the main road was estimated by counting the numbers of cars, light trucks, and heavy trucks passing by in random five-minute periods during the measurements. The average traffic densities per hour during the measurements for

Site 1 were: cars 2550, light trucks 320, heavy trucks 520, total vehicles 3400; and for Site 2 were: cars 1990, light trucks 100, heavy trucks 40, total vehicles 2130.

Measurements were made under three wind conditions:

a) wind blowing directly from the road towards the sampling points, (within a 45° arc of the normal to the road),
b) wind blowing away from the sampling points, towards the road, (within a 45° arc of the normal to the road), and
c) wind blowing parallel to the road, (within a 45° arc of a line parallel to the road).

Wind conditions were monitored continuously on site and the data were later matched and analysed according to the corresponding conditions a, b, or c. In all cases except one, where winds switched from north-east to north-west halfway through the day, the wind remained steady in a constant direction throughout each measurement day.

Measurements were made at distances of 15, 55, 95, 135, 215, 295, and 375 m from the road at Site 1. To minimise the effect of fluctuations in the source with time, the closest point to the source (at 15 m) was used as a reference point. Samples were then taken alternately from this point and from each of the more distant points ie. every second measurement was taken from the reference point. A second site (Site 2) was chosen for validation of these measurements and the distances from the road were 15, 40, 80, 120, 160, 200, 240 and 280 m.

All measurements were taken with the instrumentation inside the EAL vehicle. Sampling tubes were extended vertically from the window for each instrument (SMPS, APS and DustTrak) and the vehicle was driven to each point, and then the engine stopped. At least two minutes elapsed before measurement commenced, and this was assessed to be sufficient time for the van emissions to be dispersed. Qtrak measurements of temperature and relative humidity were taken outside throughout the measurement period. The weather station was erected at approximately 30 m and 160 m from the main road for Sites 1 and 2, respectively, and recorded data continuously at 6 min intervals. Five samples were taken at each point with the SMPS and also with the APS. In total, sampling time at each point lasted 15 mins, and approximately 4 h was required for one complete set of measurements (sampling at all distances) at the site. Seven sets of measurements were done at Site 1, while one set of complete measurements was made at Site 2 for validation.

Results

The results presented here relate to measurements of total particle concentration in the SMPS and the APS size ranges for different wind characteristics, and to changes in the particle size distribution for wind from the road. Wind categories on the presented figures represent the range of wind speeds which occurred on the day of measurement.

Wind from the road towards the sampling points

Figures 3 a to d show the resulting normalised concentrations for the cases where the wind was blowing from the road towards the sampling points. Concentrations were normalised by calculating the ratio of the concentration at a particular distance, to the immediately preceding measurement of concentration at 15 m (conducted not more than 20 mins previously). The average value of all concentrations at 15 m was then used to normalise these ratios, and the concentrations at each distance were recalculated. Figure 3a shows SMPS and APS data for wind speed between 3.4 and 6.5 $km.h^{-1}$, 3b shows SMPS and DustTrak data for wind speed between 5.4 and 8.0 $km.h^{-1}$, and 3c shows SMPS and DustTrak data for wind speed between 8.0 and 8.9 $km.h^{-1}$. From Figures 3 a to c, it is clear that there is a significant decrease in the concentration of particle number smaller than 0.7 μm (SMPS) as the distance from the road increases. At a distance of around 150 m, the concentration decays to around 50% of the maximum occurring at 15 m from the road (the closest measurement point from the road). Concentrations close to the road are higher for the lower wind speeds and lower for the higher wind speeds. This is due to faster mixing and thus greater dilution at higher wind speeds. The $PM_{2.5}$ levels also trend the same way but the relative decrease over the total measured distance is only about 25%. Concentration levels are also lower for higher wind speeds. Some $PM_{2.5}$ curves exhibit a “dip” around the 100 – 150 m distance, where the concentrations are 50 – 60% the maximum; the reasons for this have not been investigated, but most likely relate to the change in ground cover. APS data show a decrease with distance to about 60% of the maximum after 150 m, but the concentration levels were close to average values measured at the Air Monitoring Research Station (AMRS) at the EAL.

The results of measurements conducted at Site 2 are presented in Figure 3d. This supports the finding from Site 1 measurements, showing a similar trend of decrease in concentration with distance, although the decrease is not as obvious, probably due to a larger variability in wind velocity (4.6 to 10.3 $km.h^{-1}$) during the measurements.

The normalised average count median diameters (CMD's) of the submicrometre size distributions for each distance were analysed and are shown in Figure 4. There is no obvious trend in this data.

Wind parallel to the road

Figures 5a to d present data for wind blowing parallel to the direction of the road. Figure 5a shows SMPS and DustTrak data for a wind speed of between 2.5 and 5.5 $km.h^{-1}$, 5b shows DustTrak data for 3.9 to 6.5 $km.h^{-1}$, 5c shows SMPS and APS data for 3.9 to 6.5 $km.h^{-1}$, and 5d shows SMPS and DustTrak data for wind speeds of 6.4 to 9.1 $km.h^{-1}$. The total particle number concentration in the SMPS size range decreases significantly with distance from the road, and approximately half of the maximum concentration levels are reached at about 50 to 100 m. The $PM_{2.5}$ data exhibit a decrease in concentration to about 65% over the total distance, again showing a dip in some curves where the concentration drops to about 50%. The APS shows a similar trend to the $PM_{2.5}$ data, but the concentration levels were again close to the average values at the AMRS.

Wind away from the road

Figure 6 shows the concentration profiles for wind blowing away from the road. The total number concentrations from both the SMPS and the APS are very low and do not show any trends. The concentrations are similar to average urban levels measured at the QUT AMRS, even at the closest distance to the road. There is no influence of vehicle emissions on number concentrations near the road under these conditions.

Compilation of data from all measurements

Figure 7 is a compilation of all of the above horizontal profiles for particles in the SMPS size range. Each bandwidth represents the variation in concentration for the particular wind direction. The arrows indicate the gradient of the wind strength. The graph indicates that as wind speed increases, the total number concentration values become smaller. This is due to the increased dilution of the air from the road with wind speed; which means that lower average wind speeds correspond to higher concentrations and vice versa. The dark band represents the data for the wind blowing directly from the road, the light band for wind parallel to the road, and the striped band is for the wind blowing towards the road.

The average of the maximum values of total number concentration for fine and ultrafine particles, for wind blowing from the road, is approximately $4.3x10^4$ particles.cm^{-3}. This is seven times higher than the average urban exposure level of $6x10^3$ particles.cm^{-3} measured at the AMRS. The average exposure at 150 m for wind blowing from the road, is three and a half times higher than normal urban exposure.

Discussion and Conclusions

The horizontal distributions of particles from vehicle emissions near a major road were investigated and total number concentrations of particles were measured for three wind directions in relation to the road. There is a clear decrease in fine and ultrafine particle number concentration (in the range 0.015 – 0.697 μm) as distance from the road increases which indicates that these particles are related to vehicle exhaust emissions. For conditions where the wind is blowing directly from the road, the concentration decays to about half that of the maximum occurring at 15 m from the road (the nearest measuring point from the road), at a distance of approximately 100 - 150 m from the road. This reduces to 50 – 100 m for wind blowing parallel to the road. There is no effect on total particle number concentration at a distance larger than 15 m from the road when the wind is blowing towards the road and away from the sampling points.

The CMD's of the submicrometre particle size distributions for wind from the road were analysed. These values are a basic indication of the change in size distribution of particles as they are transported away from the road. There is no obvious trend from this analysis which indicates that if there is any change in particle size, it is only minor. However, it is possible that the use of more complex analysis, for example of bimodal fitting functions, would provide some more information which would be useful for particle dynamics studies.

The trends for the larger particles measured separately (in the range 0.5 – 20 μm) are similar to those for small particles, with a decreasing concentration with increasing

distance from the road, reaching about 60% at 150 m from the road. It should be noted that the total number concentrations measured here (except for some of those measured at 15 m from the road) were very similar to the average values measured at the AMRS at QUT. Thus the particles could be considered as constituents of the urban background concentration, with only a small contribution from vehicle and road dust emissions.

There is also a decreasing trend in $PM_{2.5}$ levels as distance increases, with decreases to 75% of the maximum for wind from the road, and to 65% for wind parallel to the road. This decrease is even less significant than the number concentration decrease in the APS range. This may be because the APS is more sensitive to decreases of concentration in this size range than the DustTrak.

Ultrafine particles, as measured by the SMPS, are expected to behave in a similar manner to NO_2. From this study, concentrations of ultrafine particles do decrease with distance from the road, but to a greater extent than the resulting decreases in NO_2 concentrations from other studies. The results from Roorda-Knape, *et al.,* (1998), Kuhler, *et al.,* (1994), and Nitta, *et al.,* (1993), show concentrations of NO_2 declined with distance from the road by an estimated 60% after 250 m, ~50% after 600 m, and by ~75% after 150 m, respectively. Roorda-Knape suggested an exponential decay curve would fit decreasing NO_2 concentrations with distance from the road, as this corresponds to general dispersion models, and it is apparent from simple observation of the curves from the present study, that exponential decay curves would also apply to ultrafine particle dispersion.

In terms of larger particles, Roorda-Knape found no significant decrease in $PM_{2.5}$ or PM_{10}, while Janssen, *et al.,* (1997) showed PM_{10} and $PM_{2.5}$ concentrations were on average 1.3 times higher than at background locations (~75% decrease from the road). Nitta, *et al.,* (1993) also showed a weak gradient (decrease to ~80% after 150 m) for suspended particulate matter from a major road in Tokyo. Thus the $PM_{2.5}$ results from the present study are in very good agreement with the above literature references.

From the findings of this study it is clear that exposure to submicrometre particles is significantly increased within the investigated distance from 15 to 150 m from a major road, compared to the urban average exposure levels (up to approximately seven times higher at 15m, and up to approximately three and a half times higher at 150 m). On this basis, it is reasonable to assume that personnel living and working in close proximity to an urban freeway will likely be exposed to levels of submicrometre particles beyond so-called 'normal' ambient levels. With concern already expressed elsewhere regarding the effect on human health of exposure to airborne particles, future research examining the relative health risk of such levels of exposure would be well targeted.

The options for exposure control are thus either avoidance of construction of buildings within this distance from the road, installation of appropriate filtration systems with high performance for fine and ultrafine particles, or reducing vehicle particulate emissions. Control of exposure by increased filtration capability of the filtration systems, is a solution which is effective only for buildings whose occupants spend the entire time indoors, and not outside the buildings. It is not fully effective for facilities such as schools, childcare centres, or retirement villages, whose users or

occupants could spend a significant fraction of time outside. In the case of such facilities, an increased distance from a major road is the most significant solution for exposure control. Given that the primary source of these particles is however the motor vehicle engine, it is likely that a more viable social and economic solution may be found through the improvement of tailpipe emissions.

Acknowledgments

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Figure 1. Site 1 at Tingalpa – a north easterly wind blows directly from the road towards the sampling points

Figure 2. Site 2 at Murrarie – a southerly wind blows directly from the road towards the sampling points.

Figure 3. Horizontal concentration profiles of submicrometre particulate matter (Sites 1 and 2) with wind direction from the road. Error bars are calculated from the standard deviation of five samples.

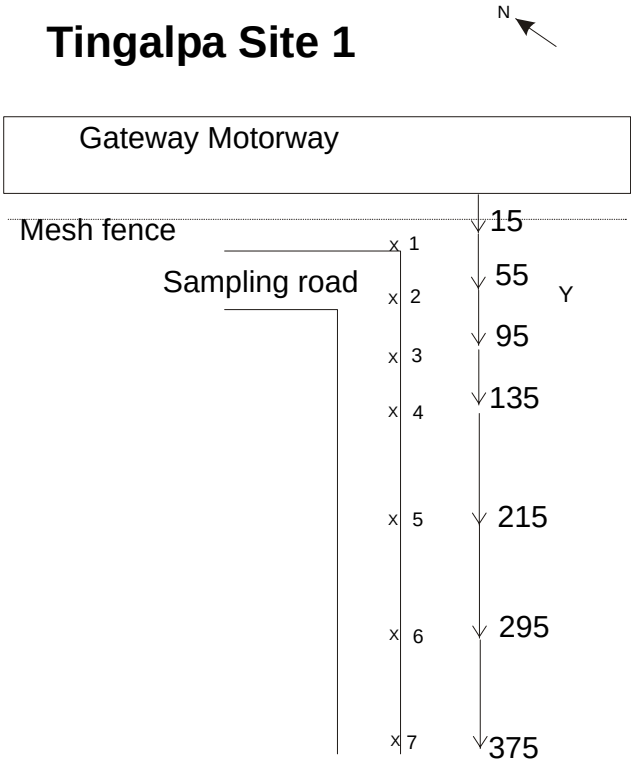
Figure 4. Horizontal profile of the count median diameters for submicrometre particles (Sites 1 and 2) with wind direction from the road.

Figure 5. Horizontal concentration profile of submicrometre particulate (Site 1) with wind direction parallel to the road. Error bars are calculated from the standard deviation of five samples.

Figure 6. Horizontal concentration profile of submicrometre particulate (Site 1) with wind direction away from the road; SMPS and APS. Error bars are calculated from the standard deviation of five samples.

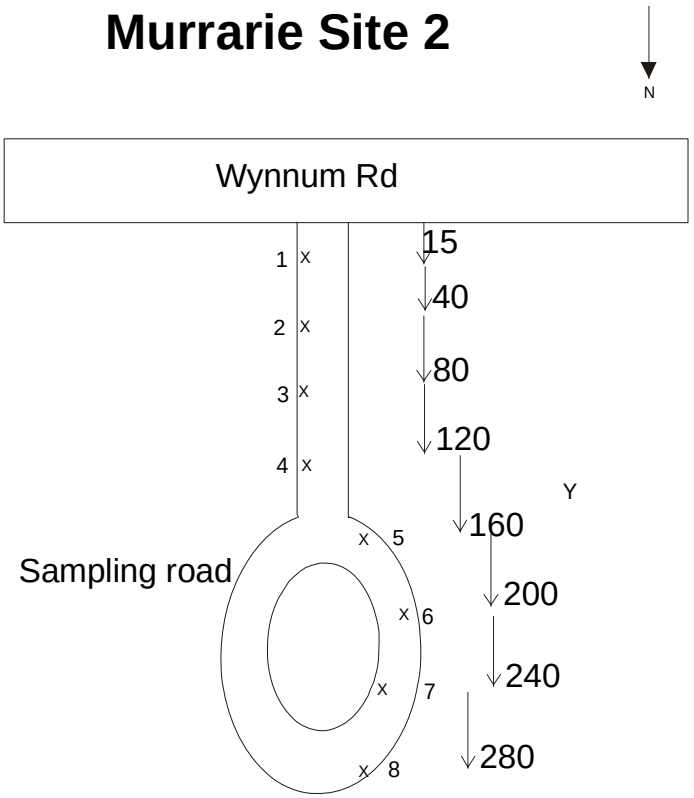
Figure 7. Compilation of total number concentration from SMPS data (14.9 – 697 nm) for horizontal profile measurements for all wind conditions and both sites.

Tingalpa Site 1



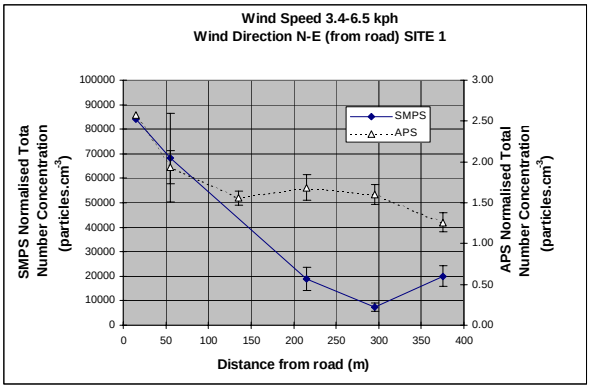
Weather station at “Y”
Dimensions in metres

Murrarie Site 2

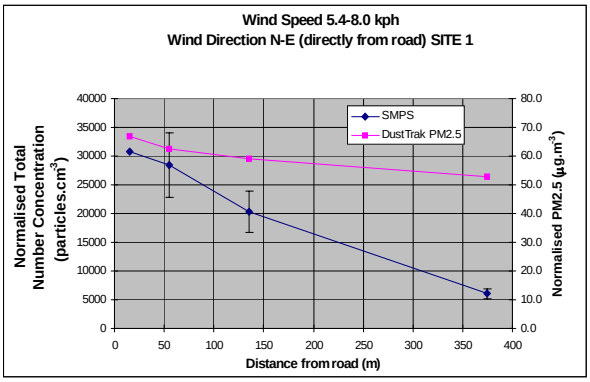


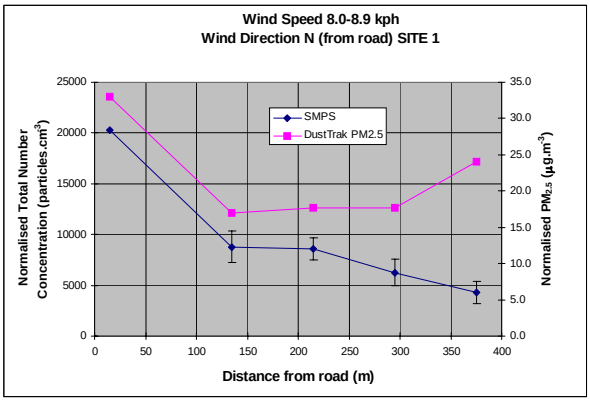
Weather station at “Y”
Dimensions in metres

a


Wind Speed 3.4-6.5 kph
Wind Direction N-E (from road) SITE 1
SMPS Normalised Tota Number Concentration (particles.cm-3)
APS Normalised Total Number Concentration (particles.cm-3)
SMPS
APS
Distance from road (m)

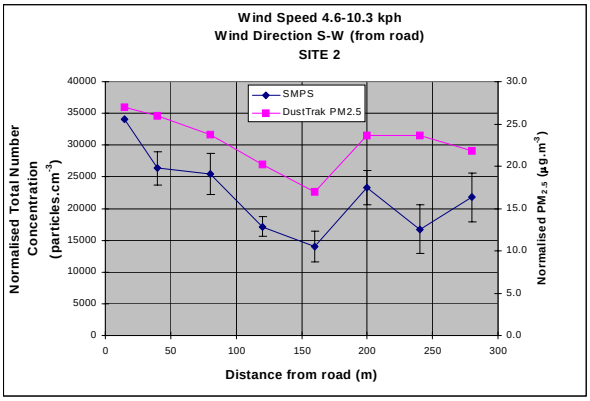
b

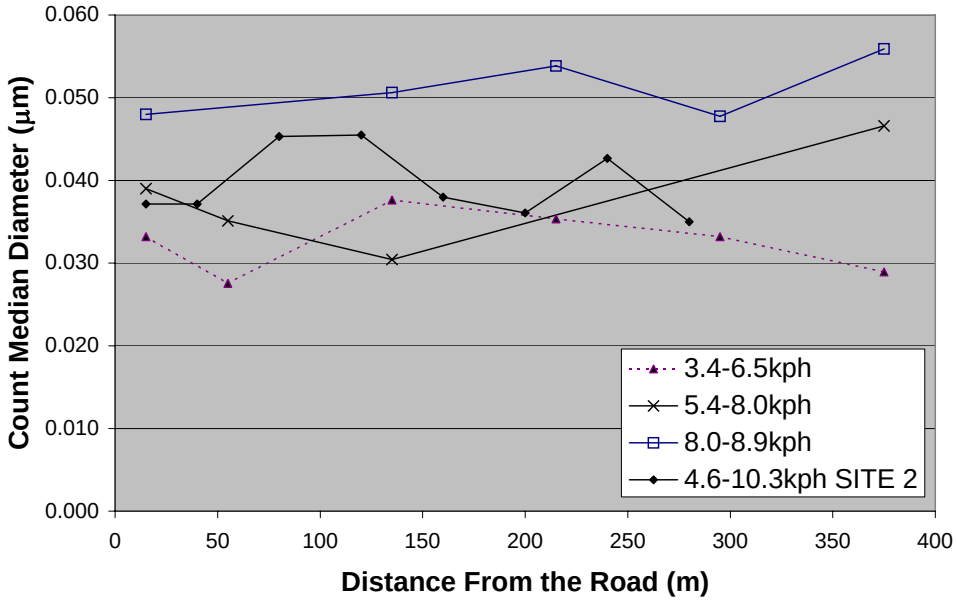

Wind Speed 5.4-8.0 kph
Wind Direction N-E (directly from road) SITE 1
Normalised Total Number Concentration (particles.cm-3)
Normalised PM2.5 (µg.m-3)
SMPS
DustTrak PM2.5
Distance from road (m)


Wind Speed 8.0-8.9 kph
Wind Direction N (from road) SITE 1
Normalised Total Number Concentration (particles.cm-3)
Normalised PM2.5 (µg.m-3)
SMPS
DustTrak PM2.5
Distance from road (m)

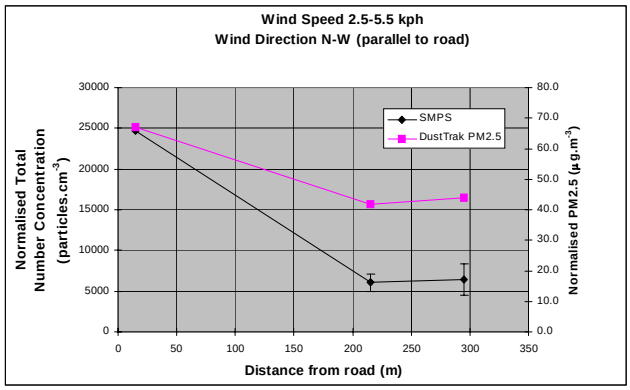
c

d

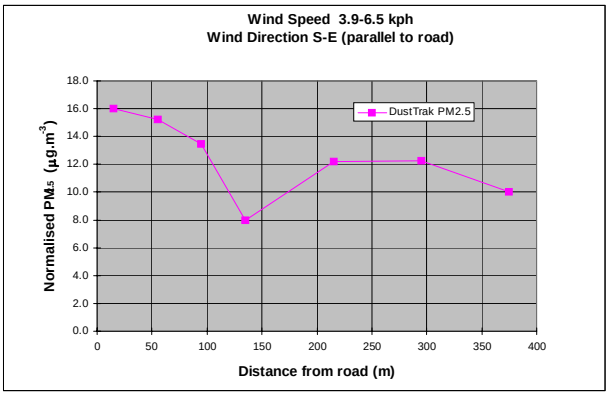

Wind Speed 4.6-10.3 kph
Wind Direction S-W (from road)
SITE 2
Normalised Total Number Concentration (particles.cm-3)
Normalised PM2.5 (µg.m-3)
SMPS
DustTrak PM2.5
Distance from road (m)

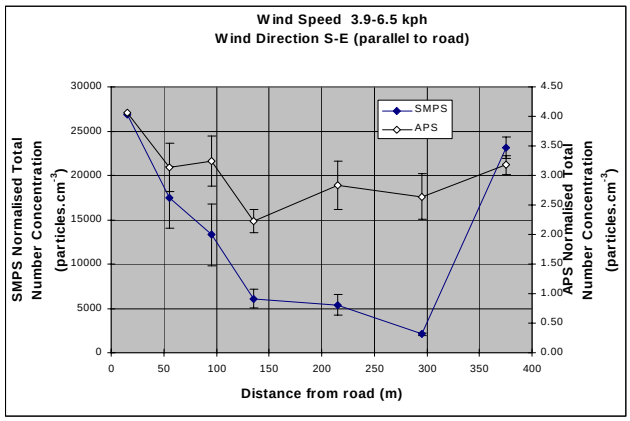

Count Median Diameter (µm)
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0
50
100
150
200
250
300
350
400
Distance From the Road (m)
3.4-6.5kph
5.4-8.0kph
8.0-8.9kph
4.6-10.3kph SITE 2

a


Wind Speed 2.5-5.5 kph
Wind Direction N-W (parallel to road)
Normalised Total Number Concentration (particles.cm-3)
Normalised PM2.5 (µg.m-3)
SMPS
DustTrak PM2.5
Distance from road (m)

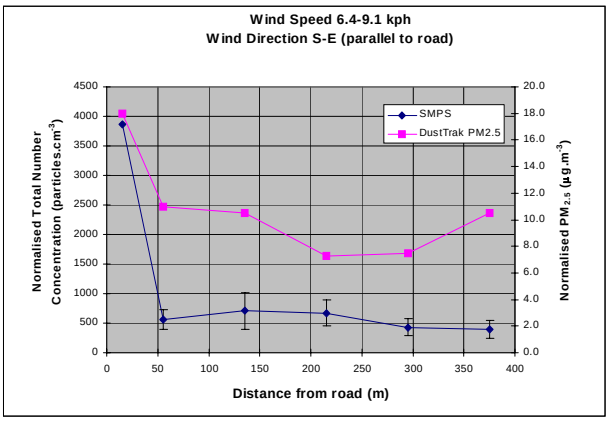
b

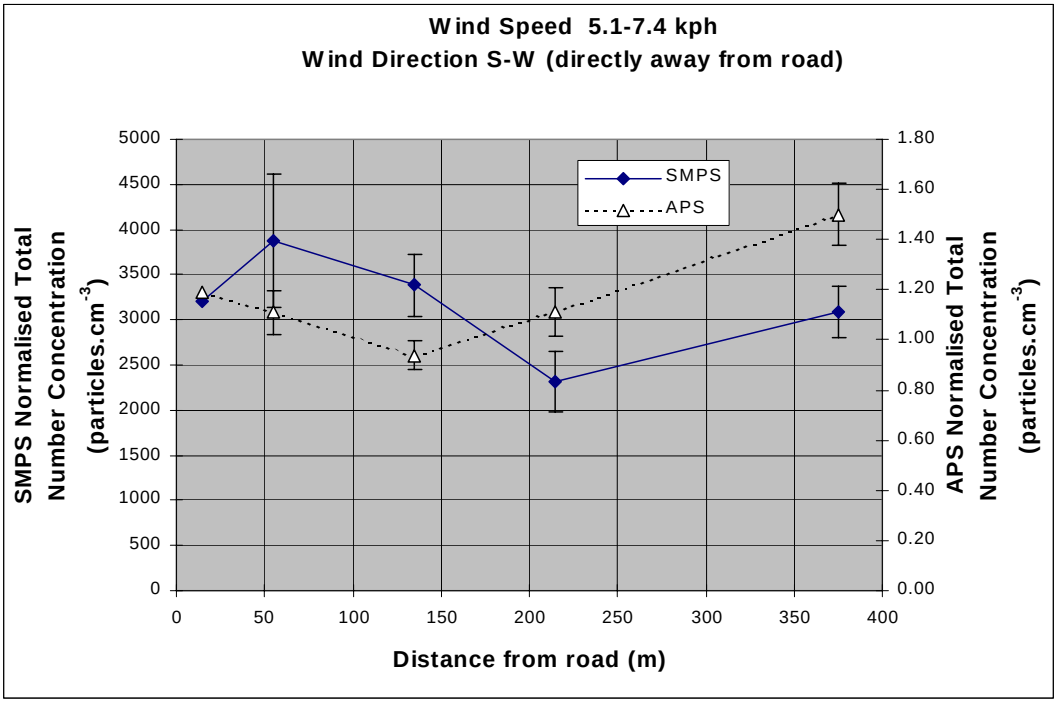

Wind Speed 3.9-6.5 kph
Wind Direction S-E (parallel to road)
Normalised PM2.5 (µg.m-3)
DustTrak PM2.5
Distance from road (m)

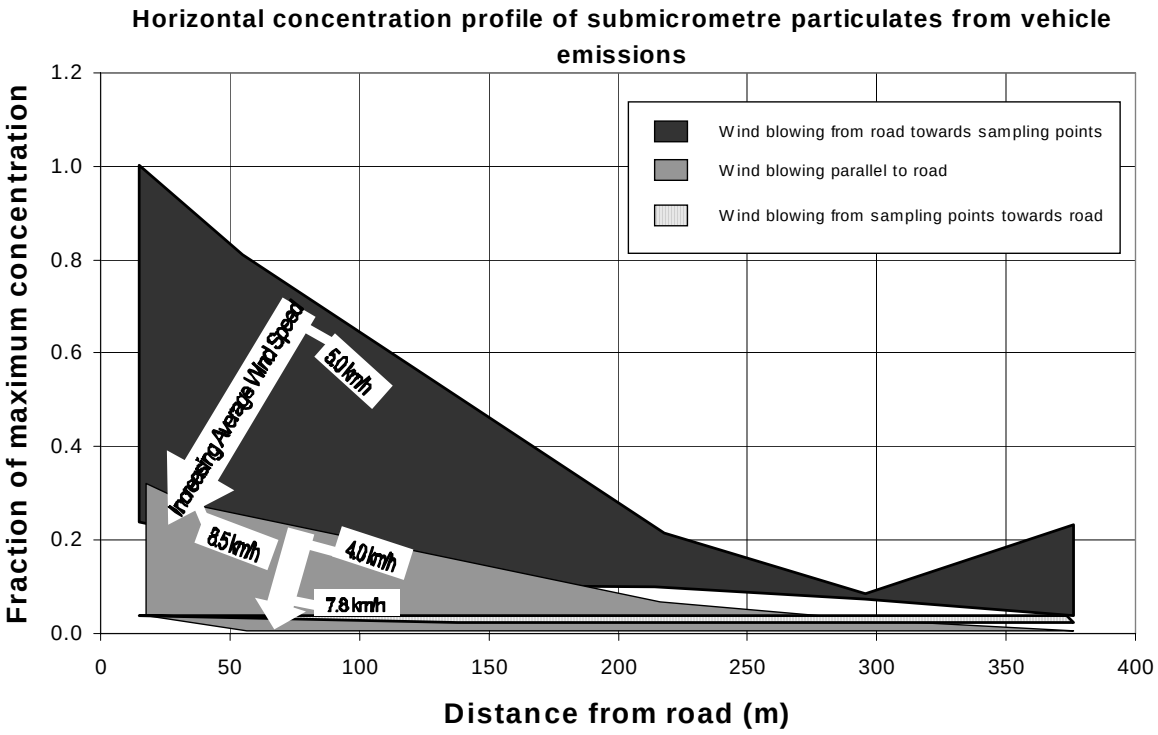

Wind Speed 3.9-6.5 kph
Wind Direction S-E (parallel to road)
SMPS Normalised Total Number Concentration (particles.cm-3)
APS Normalised Total Number Concentration (particles.cm-3)
SMPS
APS
Distance from road (m)

c

d


Wind Speed 6.4-9.1 kph
Wind Direction S-E (parallel to road)
Normalised Total Number Concentration (particles.cm-3)
Normalised PM2.5 (µg.m-3)
SMPS
DustTrak PM2.5
Distance from road (m)


Wind Speed 5.1-7.4 kph
Wind Direction S-W (directly away from road)
SMPS Normalised Total Number Concentration (particles.cm-3)
APS Normalised Total Number Concentration (particles.cm-3)
SMPS
APS
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
50
100
150
200
250
300
350
400
Distance from road (m)


Horizontal concentration profile of submicrometre particulates from vehicle emissions
Fraction of maximum concentration
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
300
350
400
Distance from road (m)
Wind blowing from road towards sampling points
Wind blowing parallel to road
Wind blowing from sampling points towards road
Increasing Average Wind Speed
5.0 km/h
8.5 km/h
4.0 km/h
7.8 km/h