This is author version of article published as:

Morawska, Lidia and Jayaratne, Rohan and Mengersen, Kerrie L. and Jamriska, Milan and Thomas, Stephen B. (2002) Differences in airborne particle and gaseous concentrations in urban air between weekdays and weekends. *Atmospheric Environment* 36(27):pp. 4375-4383.

Differences in Airborne Particle and Gaseous Concentrations in Urban Air Between Weekdays and Weekends

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Differences in Airborne Particle and Gaseous Concentrations in Urban Air Between Weekdays and Weekends

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Abstract

Airborne particle number concentrations and size distributions as well as CO and NO_x concentrations monitored at a site within the central business district of Brisbane, Australia, were correlated with the traffic flow rate on a nearby freeway with the aim of investigating differences between weekday and weekend pollutant characteristics. Observations over a five-year monitoring period showed that the mean number particle concentration on weekdays was $(8.8 \pm 0.1) \times 10^3$ cm^{-3} and on weekends $(5.9 \pm 0.2) \times 10^3$ cm^{-3} – a difference of 47%. The corresponding mean particle number median diameters during weekdays and weekends were 44.2 ± 0.3 nm and 50.2 ± 0.2 nm respectively. The differences in mean particle number concentration and size between weekdays and weekends were found to be statistically significant at confidence levels of over 99%. During a one-year period of observation, the mean traffic flow rate on the freeway was 14.2×10^4 and 9.6×10^4 vehicles per weekday and weekend day respectively – a difference of 48%. The mean diurnal variations of the particle number and the gaseous concentrations closely

followed the traffic flow rate on both weekdays and weekends (correlation coefficient of 0.86 for particles). The overall conclusion as to the effect of traffic on concentration levels of pollutant concentration in the vicinity of a major road (about 100m) carrying traffic of the order of 10^5 vehicles per day is, that about a 50% increase in traffic flow rate results in similar increases of CO and NO_x concentrations, and a higher increase of about 70% in particle number concentration.

Keywords: airborne particles, particle number concentration, traffic emissions, ultra fine particles, diurnal variation of pollution, motor vehicle emissions

Introduction

In recent years the presence of fine and ultra fine particulate matter in the air has become of increasing concern after epidemiological and clinical studies demonstrated an association between exposure and adverse health effects. Recent studies have indicated that many of the pollution-related adverse health effects may be closely related to the presence of fine (<2.5 μm), and even more, to ultra fine airborne particles (<0.1μm) (Oberdorster et al, 1992, 1995; Peters et al, 1997, Schwartz et al, 1996). These particles usually contain most of the trace elements and toxins and, due to their higher diffusion coefficients, penetrate deeper into pulmonary interstitial spaces in the lungs provoking inflammation (Seaton et al, 1995). This response is hypothesised to depend less upon the mass of the particles than on their number and size distribution. Ferin et al (1992) showed that ultrafine titanium dioxide aerosol had an adverse effect on the respiratory system of rats. However, when the rats were exposed to the same mass concentration of micrometre particles there was no effect.

In highly polluted urban environments that are significantly influenced by motor vehicle emissions, number concentrations of particles may exceed 10^5 cm^{-3}. Harrison et al (1999) found that particle number concentration was 7.5 times higher than the background near a busy road in Bristol, UK. Most of the particles emitted by engines are in the ultra fine range (Kittelson, 1998) and consequently, it is not surprising that in urban environments not directly influenced by industrial emissions, over 80% of airborne particles are in this size range (Morawska et al, 1998b; Shi et al., 2001).

The particles emitted by motor vehicles are mostly black carbon soot. They range in size from 0.02-0.13 μm from diesel engines (Morawska et al, 1998a) and 0.04-0.06 μm from petrol engines (Ristovski et al, 1998). While most light vehicles operate on petrol, most heavy vehicles such as buses and other transport and construction sector vehicles generally use diesel fuel. Motor vehicle emissions also contain nitrogen oxides and due to incomplete engine combustion, hydrocarbons and carbon monoxide. Although diesel engines emit less organic compounds than petrol engines, they are higher emitters of particulate matter. Through fundamental improvements in engine design and the introduction of catalytic converters and unleaded fuels, technological advances in recent years have led to a marked reduction in gaseous and particle mass vehicular emissions. However, these advances have not resulted in a decrease in the emission rates of ultra fine particles. Quite to the contrary, the changes in the combustion process has in fact resulted in increased emissions of these particles (Bagley et al., 1996; Kittelson, 1998; Hall et al., 1998). The increased trend of emission of ultra fine particles by motor vehicle traffic is additionally compounded by the general increase in vehicle numbers and distance travelled.

Since most of the ultra fine particles in an urban environment originate in motor vehicles, these emissions are expected to have a higher impact on human health than emissions from other sources, and it is therefore important to develop a quantitative understanding of their contributions to particle concentrations in urban environments. Routine monitoring of airborne particulate matter is generally conducted in terms of particle mass, recently either in terms of the PM_{10} or $PM_{2.5}$ concentrations (mass of particulate matter smaller than 10 μm and 2.5 μm in aerodynamic diameter, respectively) providing little information on particle number or sizes. It is important to focus on particle number as one of the main characteristics of motor vehicle emissions, as most of the emitted particles are very small and do not contribute significantly to particle mass.

Emitted particle size is affected by the type of fuel used. Thus, the particle size distributions must depend on the traffic fleet composition, that is the relative numbers of vehicles on the road using each type of fuel. These parameters vary with the day of week and thus particle concentrations and sizes are expected to be different on weekdays and weekends. Therefore, studies on the differences in particle number concentration between weekdays and weekends, could provide insight into the impact of motor vehicle emissions on particle concentrations in urban air.

This formed the main objective of this study, which was conducted in the subtropical city of Brisbane, the capital of the state of Queensland, Australia. The city lies on the eastern seaboard of the continent, on the South East Queensland (SEQ) coastal plain. It is ringed on the western flank by a range of low hills rising up to about 700m at a distance of about 35 km from the coast. The populated area around the city extends to approximately 35-40 km, the total population being about 1.3 million. During the mornings, land breezes tend to blow most of the urban pollution over the sea but a steady sea breeze, which builds up during the day, blows much of the pollutants into the coastal plain and further inland. Late evening and night time land breezes may sometimes recirculate this polluted air back into the city. The SEQ air shed, centred on Brisbane, is the fastest growing urban region in Australia and its population is expected to increase from about 3 million to 4 million by the year 2011. At present, the SEQ passenger fleet comprises 2.1 million vehicles with an average age of approximately 10.5 years. Although diesel engines are usually higher emitters of particulate matter, owing to their greater numbers and distances travelled, petrol-powered passenger vehicles give rise to most of the transport sector emissions. In the 10-year period from 1991 to 2000, the total number of vehicle kilometres travelled in Brisbane increased from 1.0×10^{10} to 1.3×10^{10}. Continued population growth and greater reliance on motor vehicles are likely to threaten air quality significantly in the coming years. It is estimated that, at present, motor vehicles contribute about 57% of total air emissions in SEQ including about 70% and 83% of the nitrogen oxides (NO_x) and carbon monoxide (CO) respectively and to approximately 18% of airborne particulate matter by mass (Queensland EPA, 1999). The contribution of motor vehicles to the concentration levels of ultra fine particles has not been quantified, however it is expected to be substantial. Results of a two year study conducted in Brisbane over the period from July 1995 to April 1997 and summarised by Morawska et al (1998b), showed that the concentration of submicrometre particles was strongly correlated with the concentrations of NO_x and CO and therefore suggested that motor vehicle emissions constituted the main source of ultra fine particles in the study area.

The aim of this study was to investigate the differences in particle number and gaseous concentration levels between weekdays and weekends using long term monitoring data from a city monitoring station, and to relate them to the respective mean traffic flow rates.

Methods and Techniques

1. Air quality and traffic volume data

The monitoring data used for this analysis was collected through long-term monitoring conducted at the Air Monitoring Research Station (AMRS) situated on the roof of a six-floor building at the Queensland University of Technology (QUT) Gardens Point Campus in the heart of the central business district (CBD) of Brisbane. The Station is a joint venture between QUT and the Environmental Protection Agency and is part of the South East Queensland Monitoring Network. It is located approximately 100 metres to the north-east of a busy freeway, the other side being open to the city botanic gardens (see map in Figure 1). The location of the station was chosen to collect representative samples of air parcels in the Brisbane CBD and complies with appropriate standards for urban air quality monitoring. The Station has been operating since 1995 and the monitored parameters include size distribution of atmospheric aerosols, PM_{10}, NO_x, CO, O_3 and meteorological parameters such as wind speed and direction, air temperature and humidity. A summary of the first two years of observations was provided by Morawska et al (1998b).

The size characteristics of aerosol particles were measured using a Scanning Mobility Particle Sizer (SMPS) in the size range from 0.016 to 0.7 μm. A description of the operating procedure of the instruments has been provided elsewhere (Wang and Flagan, 1990; Morawska et al, 1998a). Between September 1995 and December 1997, the SMPS was used for regular "grab sampling" of number size distributions (NSD) in triplicate every day at 9:30h and 16:30h. On days characterised by notable atmospheric and/or meteorological conditions, for instance hazard reduction burning, haziness, fog etc., measurements were made at regular intervals throughout the day. Since January 1998 the instrument has been used to collect particle number size distributions at hourly intervals on a continuous basis. The data collected at the Station has been used for the analyses presented in this paper.

The traffic information was obtained from the Queensland Department of Transport and consisted of hourly total numbers of vehicles in both directions passing a point on the freeway nearest to the monitoring station.

2. Statistical Analysis

The monitoring and traffic count data were separated into two groups: the weekday (Mon-Fri) and the weekend (Sat-Sun) groups. The means and standard errors of the particle number concentrations and number median diameters were computed for each group. A two-sample students heteroscedastic two-tailed t-test was then performed to determine significant differences between the group means. The test statistic, distributed as t on number of degrees of freedom df, was determined from

$$t = \frac{\bar{x} - \bar{y}}{\sqrt{\frac{s_1^2}{m} + \frac{s_2^2}{n}}}$$

$$df = \frac{\left(\frac{s_1^2}{m} + \frac{s_2^2}{n}\right)^2}{\frac{(s_1^2/m)^2}{(m-1)} + \frac{(s_2^2/n)^2}{(n-1)}}$$

where $\bar{x}$ and $\bar{y}$ are the sample means, s_1 and s_2 are the sample standard deviations and m and n are the number of observations in each of the two groups.

The correlation between traffic count data and particle numbers was estimated by

$$\rho_{x,y} = \frac{\mathrm{cov}(x,y)}{\sigma_x \sigma_y}$$

where the standard deviations, σ_x and σ_y, of the two distributions were estimated by s_1^2 and s_2^2.

Results

Figure 2 presents the mean particle number concentration and the mean number median particle diameter (NMD) for each day of the week as computed from the number size distribution spectra measured by the SMPS. Each point is the mean of between 600 and 1300 separate readings covering the entire five-year period of observation 1995-99. The error bars represent the respective standard errors of all readings corresponding to each day of the week. The overall means of particle concentration for weekdays and for weekends were $(8.8 \pm 0.1) \times 10^3$ and $(5.9 \pm 0.2) \times 10^3$ particles cm^{-3} , respectively and of NMD 44.2 ± 0.2 nm and 50.2 ± 0.3 nm, respectively.

Figures 3 a and b present the diurnal variation of the mean particle number concentration and the NMD for weekdays and weekends, respectively. All readings have been rounded to the nearest hour and each point shows the mean of all readings obtained at that hour during the five-year period of observation.

Figures 4 a and b present mean diurnal variation of the measured concentration of CO in 1999 for weekdays and weekends, respectively. The concentrations are expressed in ppm. These measurements were obtained at half-hour intervals and the graphical representations are x-y plots of concentration versus time of day. Figures 4 c and d present similar graphs for NO_x. The concentrations are expressed in pphm, where 1 pphm = 10^2 ppm.

An important feature of diurnal variation in the wind direction at the station is the general change of direction between the morning (wind blowing from the freeway to the station) to the afternoon (wind blowing from the station towards the freeway). This is a general meteorological trend in the monitoring area, owing to the opposite directions of sea and land breezes and has significant implications for interpretation of the monitoring data from the station. While pollutants from vehicular emissions are blown from the freeway towards the monitoring station during the morning traffic hours, this effect is lessened considerably during the evening traffic hours. This is clearly noticeable in the diurnal weekday records of particle concentration (Figure 3a), CO (Figure 4a) and NO_x (Figure 4c). It can be seen from these figures that significantly higher concentrations were measured during the morning peak traffic at 8-9h while there were no corresponding peaks in the late afternoon at 16-17h. In an attempt to overcome the problem of the effect of varying wind direction on the particle concentrations measured, the analysis was repeated using only the data obtained at times when the wind was blowing from the freeway towards the monitoring station (180° to 270° clockwise from N in Figure 1). The corresponding diurnal variations of the particle concentration for weekdays showed a distinctly bimodal distribution, with peak concentrations occurring at both morning and afternoon high traffic volume times. However, the weekend distribution did not show a similar bimodality, with a single peak concentration observed during the middle of the day when the traffic flow rate was greatest.

The next task was to investigate the correlation between particle and gaseous data with the traffic flow rate on the freeway. The diurnal variation of the mean hourly traffic flow rate in both directions of the freeway traffic monitoring point nearest the monitoring station during the year 1999 is presented in Figure 5 for weekdays and weekends. Each point on the graphs is the mean of the values for all relevant days during the year at that particular time. The data is presented in such a form that times shown on the x axis are inception times of each hourly period, meaning that the traffic flow rate value at a particular hour T refers to the time interval T + 1 h. The mean daily traffic flow rates were 14.2 $x10^4$ and $9.6x10^4$ vehicles per day for weekdays and weekends, respectively. The mean particle concentration and the daily total traffic flow rate during 1999 are shown as a function of day of the week in Figure 6.

Discussion and conclusions

Analyses of the five year monitoring data (1995-1999) from the AMRS and the related traffic flow rate data on the nearby freeway show that there is a clear difference between weekdays and weekends with respect to the measured ambient particle number concentrations, mean NMD and the concentrations of the gaseous pollutants CO and NO_x. The difference can be directly related to the traffic flow rate on the freeway.

During the five-year period of observation, the mean number concentration of particles during weekdays ($(8.8 \pm 0.1) \times 10^3$ cm^{-3}) was significantly greater than the corresponding value over weekends ((5.9 ± 0.2) x 10^3 cm^{-3}). A statistical analysis using a simple t-test showed that the two distributions were different at a confidence level of over 99%.

Analysis of particle size showed that the mean NMD during weekends (50.2 ± 0.2 nm) was significantly greater than the corresponding value during weekdays (44.2 ± 0.3 nm). Again, a t-test showed that the two distributions were different at a confidence level of over 99%. It can be seen from Figure 3b that the mean particle NMD at any given time was greater during the weekend than during weekdays. This is consistent with the fact that during the week the particle size distribution was more strongly affected by larger concentrations of fresh motor vehicle emissions that have smaller diameters than background particles in well-mixed air. It is interesting to note the higher particle NMD at night on all days of the week when there was less traffic on the roads.

The weekday diurnal variations in particles, CO and NO_x concentrations (Figures 3a, 4a and 4c) all showed distinct peaks between 8 and 9 am, which coincided with the weekday peak morning traffic (Figure 5). The close relationship between these two parameters indicated that the traffic on the freeway directly influenced particle concentrations at the station, which was distant just over 100m from the freeway. This influence is expected based on the findings of Hitchins et al (2000) who concluded that for conditions where the wind was blowing directly from the road, the particle number concentration decayed to only about half of its value at a distance of about 150m from the road. Hitchins et al (2000) did not find any effect on total particle number concentration at distances greater than 15m from the road when the wind was blowing towards the road and away from the sampling points. This supports the current interpretation that peaks in particle and gaseous concentrations were absent during the late afternoon traffic because the wind blew from the station towards the freeway. There was no evidence of a morning peak on weekends, with the concentrations increasing to their peak values between 11h and 12h, which, as presented in Figure 5, coincided with the time when the weekend traffic flow rate was relatively high. Also interesting to note were slightly higher night-time particle concentrations on weekends over weekdays. This agreed well with the corresponding increase of night traffic flow rates during the weekend (Figure 5).

Eliminating the effect of wind direction by considering only those events where the wind was blowing from the freeway towards the monitoring station provided a better insight into the relationship between the traffic flow rate and particle concentrations at the station. The weekday bimodal distribution was clearly apparent with the two peaks coinciding with times of peak traffic. There was no bimodality in the weekend diurnal variations of both the particle number concentrations and traffic flow rate. There was a distinct similarity between the mean particle concentration and daily traffic flow rates during the year 1999 as a function of day of week presented in Figure 6. Again, it was seen that the two parameters followed each other very closely with a correlation coefficient of $r = 0.86$.

A conspicuous feature of the diurnal variations shown in Figure 4 are the unusually high nocturnal values found for both gases. Closer analyses showed that almost all of these high concentration events occurred when the wind was blowing from the botanical gardens towards the monitoring station, suggesting that the pollutants were not from the freeway but rather from other sources located east of the city centre. At present, there is no viable explanation for this observation.

A summary of the particle number and gaseous concentrations measured at the station during the year 1999 as well as the traffic volume data for the same year is presented in Table 1. The results have been presented separately for all the data points irrespective of wind direction and for the data points representing wind blowing from the freeway towards the monitoring station, respectively for weekdays and weekends. Table 1 also presents the corresponding ratios of the weekday to weekend concentrations of the particles and gases. The numbers in the table may also be expressed as percentage changes. Thus, note that the mean particle number concentration during the week was 26% greater than during weekends. The corresponding values for the gases NO_x and CO were 21% and 16% respectively. Considering only the times when the wind was blowing from the freeway to the monitoring station, these values increased sharply to 69%, 55% and 50% respectively, suggesting that most of these ambient components were produced from vehicular emissions. During the same period, the total traffic flow rate during the week was 48% greater than during the weekends. Comparison of the mean particle number concentrations and mean daily total traffic flow rate on each day of the week showed that they were closely correlated with a correlation coefficient of 0.86.

The overall conclusion as to the effect of traffic on concentration levels of pollutant concentration in the vicinity of a road (about 100m) carrying traffic of the order of 10^5 vehicles per day is, that about a 50% increase in traffic flow rate results in a similar increase in CO and NO_x concentrations, and higher increases in particle number concentration under the conditions investigated.

Acknowledgment

This research was supported by an Australian Research Council Grant (SPIRT C39804407) and by the Queensland Environmental Protection Agency. The authors also wish to thank Drs David Wainwright and Ralph Riese (Queensland Environmental Protection Agency) for their vision and support of this research and the Queensland Department of Transport for providing the vehicular traffic data used in the study.

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Figure Captions

1. Schematic diagram showing the site location of the Air Monitoring and Research Station.

2. Mean particle number concentration and mean particle number median diameter NMD as a function of the day of week based on all the monitoring data obtained during 1995-99, with standard error bars on a normal y-axis

3. Mean diurnal variations of the (a) particle number concentration and (b) median particle diameter (NMD) over the period 1995-99 on weekdays (■: thick line) and weekends (▲: broken line).

4. Mean diurnal variations of the gaseous concentrations measured at the AMRS during 1999: (a) CO: weekdays (b) CO: weekends (c) NO_x: weekdays and (d) NO_x: weekends.

5. Mean diurnal variation of traffic flow rate on the freeway during weekdays (■: thick line) and weekends (▲: broken line).

6. Mean particle number concentration and mean daily traffic flow rate on each day of the week during 1999.

Table 1

Weekdays

	All Wind Directions	Wind from Freeway
Particles cm^{-3}	8010	8980
NO_x pphm	2.60	3.15
CO ppm	0.343	0.342

Weekends

	All Wind Directions	Wind from Freeway
Particles cm^{-3}	6330	5320
NO_x pphm	2.15	2.04
CO ppm	0.296	0.228

Weekday/Weekend Ratios

	All Wind Directions	Wind from Freeway
Particles	1.26	1.69
NO_x	1.21	1.55
CO	1.16	1.50

Mean Particle number, NO_x and CO concentrations measured at the QUT monitoring station during weekdays and weekends in 1999. Column 2 shows the means of all readings. Column 3 shows the means of the readings when the wind was blowing from the freeway to the station. The last block shows the corresponding weekday to weekend ratios of each parameter in each of the two cases.

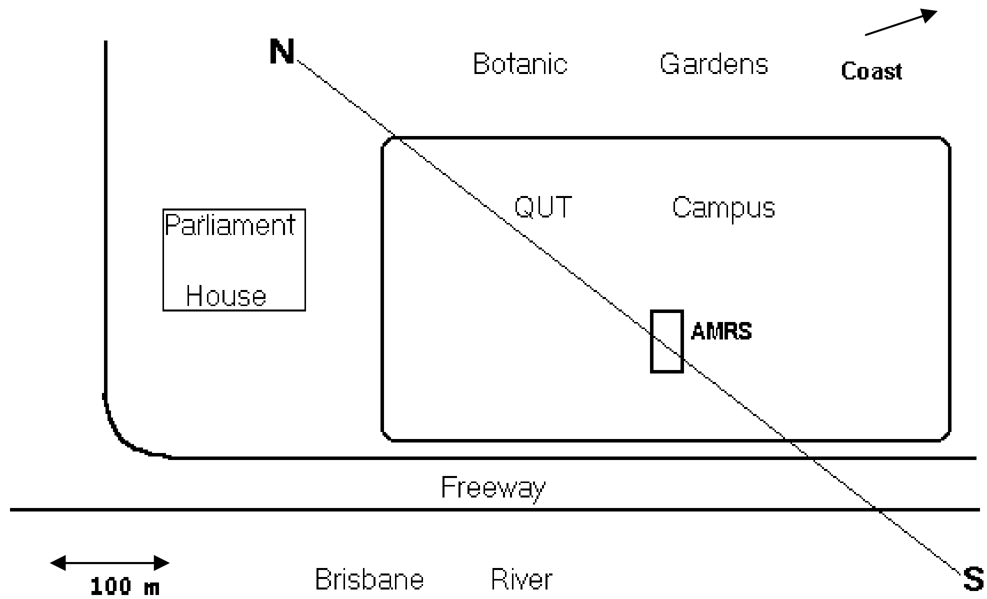
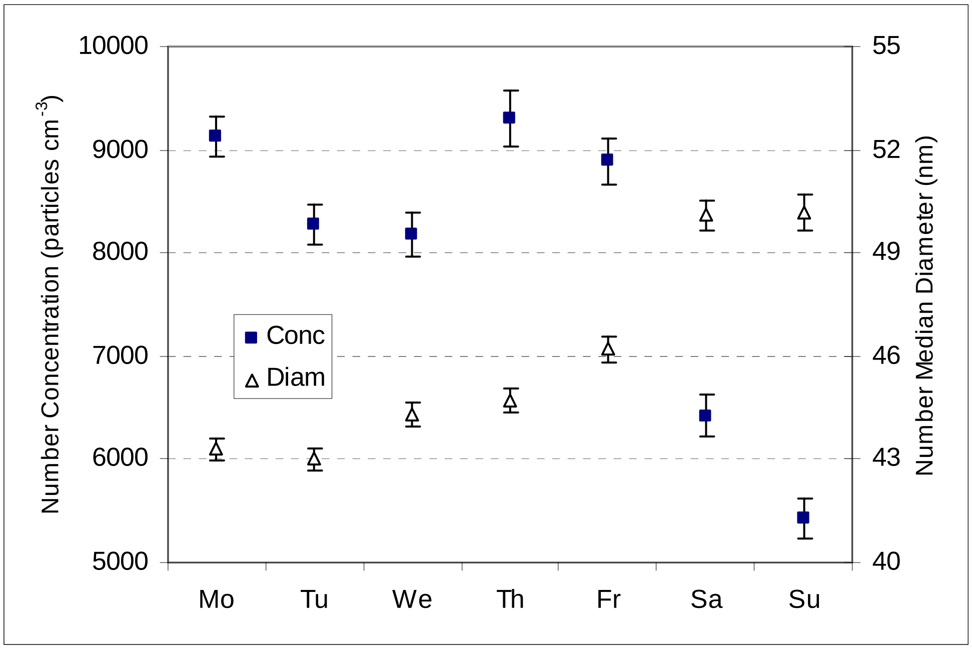
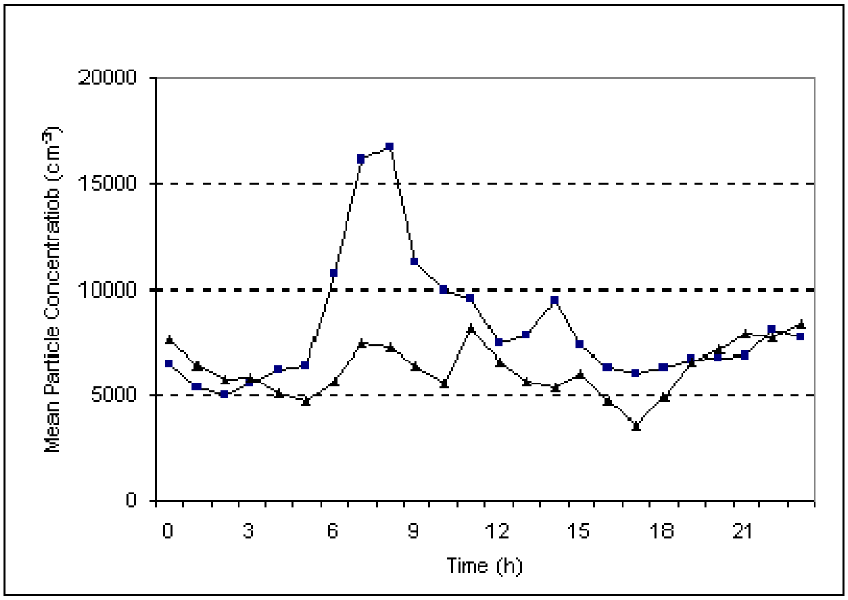

N
Botanic Gardens
Coast
QUT Campus
Parliament House
AMRS
Freeway
100 m
Brisbane River
S

Fig 1

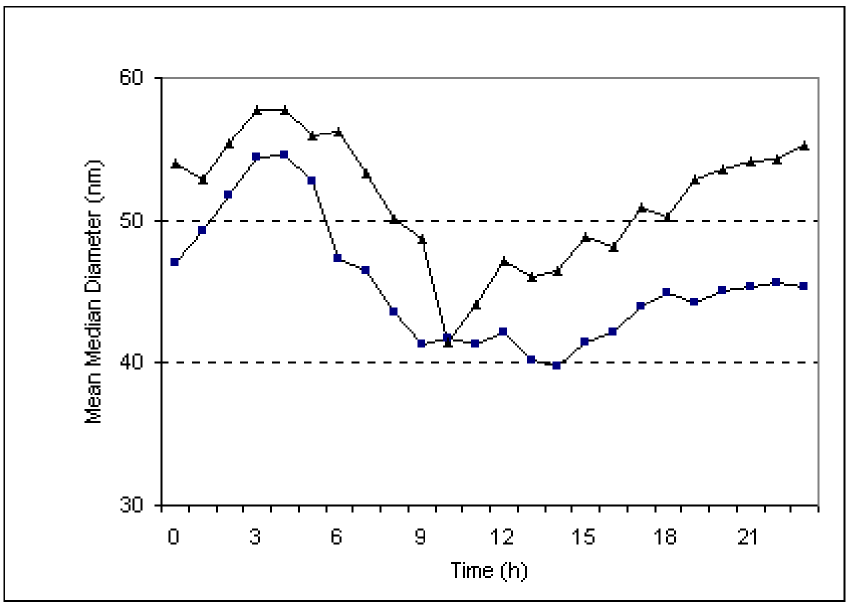


10000
9000
8000
7000
6000
5000
55
52
49
46
43
40
Number Concentration (particles cm-3)
Number Median Diameter (nm)
Conc
Diam
Mo
Tu
We
Th
Fr
Sa
Su

Fig 2

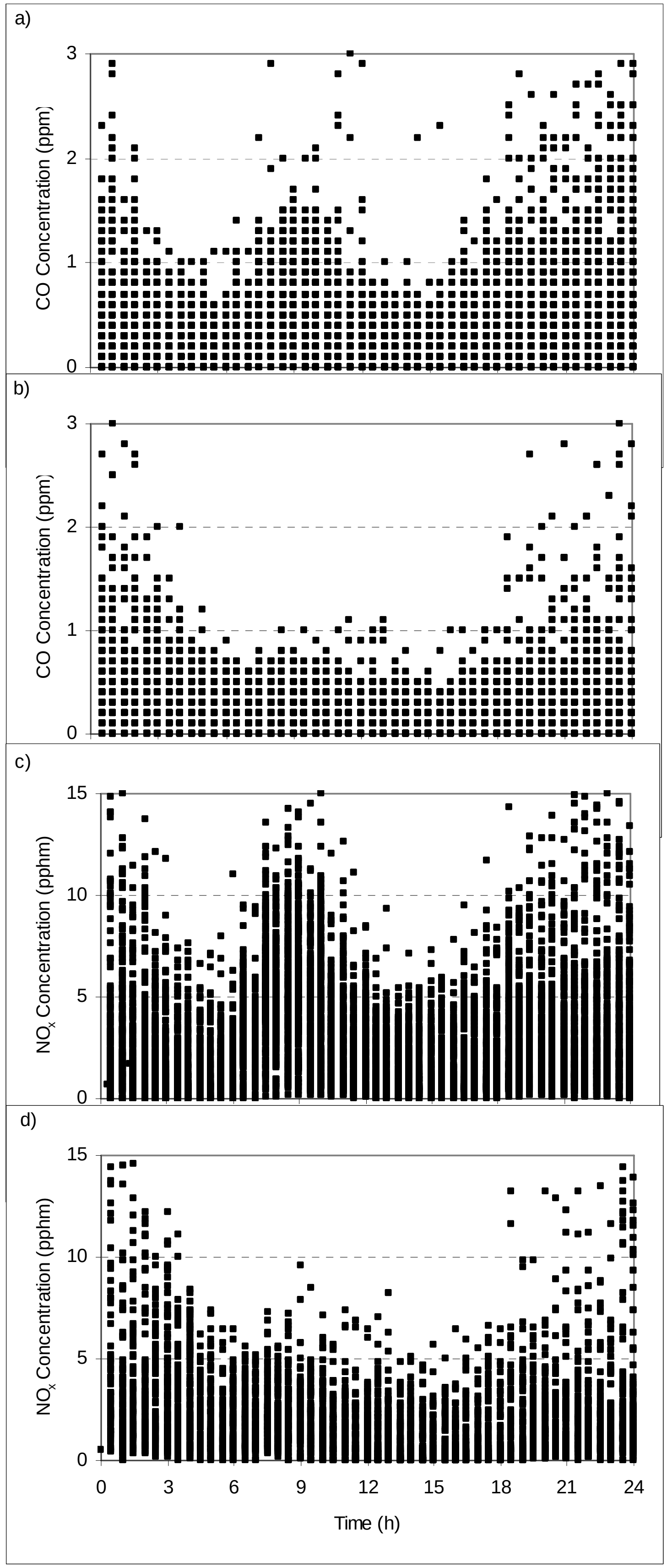

20000
15000
10000
5000
0
Mean Particle Concentratiob (cm-3)
0
3
6
9
12
15
18
21
Time (h)

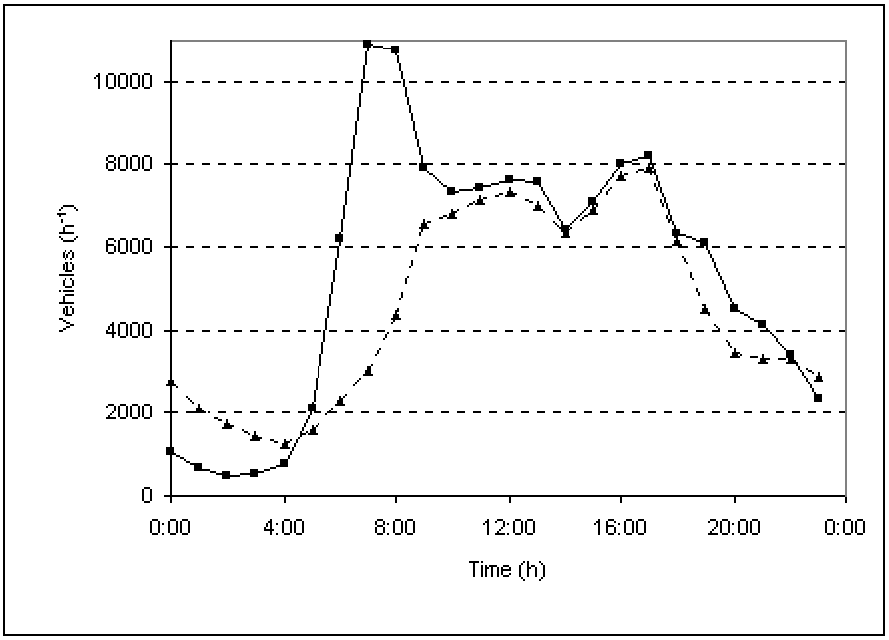
(a)


60
50
40
30
Mean Median Diameter (nm)
0
3
6
9
12
15
18
21
Time (h)

(b)

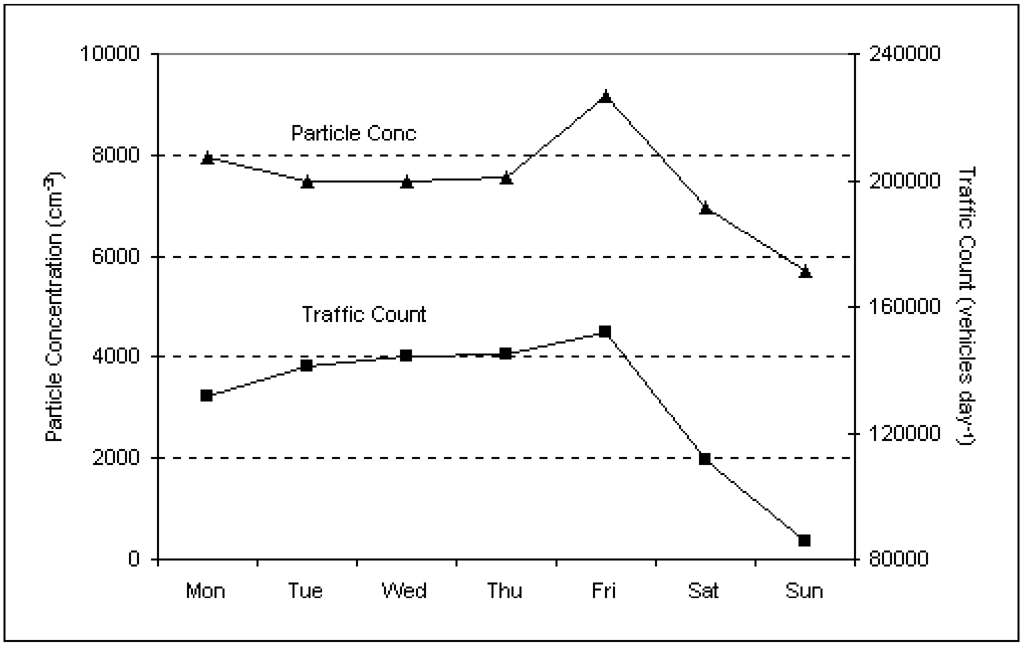
Fig 3


a)
CO Concentration (ppm)
b)
CO Concentration (ppm)
c)
NO_x Concentration (pphm)
d)
NO_x Concentration (pphm)
Time (h)



10000
8000
6000
4000
2000
0
Vehicles (h⁻¹)
0:00
4:00
8:00
12:00
16:00
20:00
0:00
Time (h)

Fig 5



Particle Conc
Traffic Count
Particle Concentration (cm-3)
Traffic Count (vehicles day-1)
10000
8000
6000
4000
2000
0
240000
200000
160000
120000
80000
Mon
Tue
Wed
Thu
Fri
Sat
Sun

Fig 6