NSW HEALTH

Comparison of personal exposures to air pollutants by commuting mode in Sydney BTEX & NO_2

CSIRO images courtesy of CSIRO © September 2003.
One photo features a person wearing two BTEX samplers and another photo shows a clip-on badge with two nitrogen dioxide samplers.

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Background

Introduction

In early 2002 the Environmental Health Branch of NSW Health and the Health Promotion Unit of the Central Sydney Area Health Service sought to investigate the comparative exposure of commuters to air pollutants in different modes of transport.

A personal exposure study was identified as a suitable approach to investigate the issue. A Pilot Study was undertaken in July 2002 to consider the feasibility of a commuter exposure study using personal sampling equipment. The Pilot Study provided a basis to consider a range of planning and design issues relating to the main study, including sampling analysis aspects such as the limits of detection for each pollutant, logistical aspects for volunteer commuters, study design aspects and project planning issues.

With the benefit of the Pilot Study results, the detail of the main study was finalised. A two-week study was developed to principally measure and compare exposure levels across five selected commuting modes. This report provides information on the study, including objectives and methods applied, the results of the study and discussion of the analysis undertaken.

The results and findings of the study provide relevant information to a range of interested parties. This information is particularly relevant to urban and transport planners, infrastructure providers, transport service providers and transport user groups. The findings can inform commuters about the relative levels of exposure between different modes, and potentially the health costs and benefits associated with these travel choices. The study is therefore of broad general interest to the community as it concerns commuting activities, which are undertaken by the whole population.

Exposure to air pollutants from commuting activities

It is well established that the motor vehicle is a principle source of air pollution in a city such as Sydney [NSW EPA 2000]. There is some concern that a high proportion of personal exposure to carcinogens such as benzene is received through occupancy in motor vehicles while commuting. Investigations in a number of cities around the world have shown that exposure to air pollutants for commuters in motor vehicles is considerably higher than ambient urban concentrations, and higher than concentrations found in other urban transport modes such as train, bus, cycling and walking [Batterman et al. 2002, SCAQMD 1999, Leung and Harrison 1999, Duffy and Nelson 1997, Lawryk and Weisel 1996, Lee and Jo 2002]. Many of these investigations consider exposure to the four selected Volatile Organic Compounds (VOCs) for this study, and several studies have compared commuting exposures to nitrogen dioxide [van Wijnen et al. 1995, Farrar et al. 2001, Chan et al. 1999].

The majority of these studies used fixed travel routes to compare the personal exposure of participants using various modes of transport. The assumption that people commute using a fixed route may not necessarily reflect the usual travel patterns of the population. The approach taken in his study was to compare the personal exposure of commuters travelling to a common workplace near the Central Business District (CBD) of Sydney using five modes of transport, regardless of route taken.

Personal exposure to the pollutants benzene, toluene, ethylbenzene, xylene (BTEX) and nitrogen dioxide (NO_2) were measured using samplers worn by the participants. Concentrations of fine particles with an aerodynamic diameter of 2.5 microns ($PM_{2.5}$) were also measured for motor vehicle commuters as part of the study.

The findings of the study will be most relevant to people that commute to locations in or near the CBD during weekday peak hours, and has implications regarding their travel choices for journeying to work.

Motor vehicle emissions and health

Motor vehicles emit a variety of air pollutants that are known to be associated with adverse health impacts. Common air pollutants emitted by motor vehicles include fine particles, nitrogen oxides and volatile organic compounds (VOCs). Exposure to fine particles is associated with short and long term adverse health effects on the lungs and heart, including premature death [WHO 2000]. Exposure to nitrogen dioxide is associated with adverse effects on the lungs, particularly irritation to airways and exacerbation of asthma [WHO 2000 and 2003]. Volatile Organic Compounds (VOCs) include benzene, toluene, ethylbenzene and xylene (BTEX). These chemical compounds are associated with a range of human health effects from headaches and eye irritation to cancer [WHO 2000, NEPC 2002, Environment Australia 2001].

BTEX gases

BTEX is a term referring collectively to the volatile organic compounds benzene, toluene, ethylbenzene, and xylene. They are commonly found together in crude petroleum and petroleum products such as petrol. BTEX are also produced on the scale of megatons per year as bulk chemicals for industrial use as solvents and for the manufacture of pesticides, plastics, and synthetic fibres.

The only standards available for short-term exposure to air toxics are occupational standards. Levels in some occupational settings are many times higher than that found in roadways or other open public areas.

Benzene

Benzene is a naturally occurring organic compound found in crude oil. It is produced in large quantities by the petroleum processing industry, and is used as a component of petrol.

Exposure to benzene almost entirely arises from sources relating to human activities. For instance, benzene is formed by the combustion process of a motor engine and emitted from a motor engine's exhaust. Benzene also evaporates rapidly at room temperature, so exposure can occur due to vaporisation processes. This is well demonstrated by activities such as refuelling a motor vehicle at a petrol station, with the aromatic odour of vapour being most noticeable. In the summer months of the year, the level of evaporative emissions from petroleum distribution activities and the motor vehicle fleet can increase considerably.

Cigarette smoke contains benzene. People who smoke will have on average six times the levels of benzene in their bodies than a non-smoker [Health Canada 1998]. For smokers, cigarette smoke represents an overwhelming source of exposure to benzene. For non-smokers however, the most significant sources of exposure will occur from motor vehicle related activities and indoor air sources such as furnishings, solvents and adhesives.

Acute (short-term) inhalational exposure of humans to benzene may cause drowsiness, dizziness, headaches, as well as eye, skin, and respiratory tract irritation, and, at high levels, unconsciousness [US EPA 2002]. Acute effects have not been observed below 500 ppbv.

Benzene is a genotoxic human carcinogen, meaning that it damages the genetic material of cells. The most commonly reported adverse health effect of benzene is bone marrow depression leading to effects on blood cells such as anaemia. Long-term exposure to lower levels of benzene may increase the risk of developing certain types of leukaemia [Wadge and Salisbury 1997].

As there is concern that exposure at lower levels over a life-time could be associated with developing cancer, some countries have set a benzene standard for ambient air. As these standards relate to long-term exposure they typically use a one-year averaging period.

Toluene

Toluene is added to petrol, used to produce benzene, and used as a solvent. Acute exposure to toluene can cause respiratory or neurological irritation, which may manifest as headache. Acute effects have not been observed under 100ppm.

Ethylbenzene

The primary sources of ethylbenzene in the environment are the petroleum industry and the use of petroleum products. Ethylbenzene exposure causes eye and respiratory irritation, and neurological effects such as dizziness. High levels are required to produce these effects (1000ppm).

Xylene

Xylene is an aromatic hydrocarbon which exists in three isomeric forms: ortho, meta and para. Acute exposure to high concentrations of xylene can result in neurological effects such as headache, nausea and dizziness in humans. These seem to occur above 100ppm.

Nitrogen dioxide

Nitrogen oxides (NOx) refer to a collection of highly reactive gases containing nitrogen and oxygen, most of which are colourless and odourless. NOx gases form when fuel is burnt; motor vehicles, along with industrial, commercial and residential sources, are primary producers of nitrogen oxides. In Sydney, motor vehicles account for about 70% of emissions of nitrogen oxides, industrial facilities account for 24% and other mobile sources account for about 6% [NSW EPA 2000].

In terms of health effects, nitrogen dioxide (NO_2) is the only oxide of nitrogen of concern. NO_2 is a colourless and tasteless gas with a sharp odour. NO_2 can cause inflammation of the respiratory system and increase susceptibility to respiratory infection. Exposure to elevated levels of NO_2 has also been associated with increased mortality, particularly related to respiratory disease, and increased hospital admissions for asthma and heart disease patients [Morgan et al. 1998].

Chamber studies, where people were exposed to varying concentrations of NO_2 for 30 minutes to several hours, have demonstrated adverse impacts on asthmatics at levels over 200 ppbv. The National Environment Protection Council (NEPC) adopted a NO_2 standard of 120 ppbv or 245 $\mu g/m^3$ for a one-hour average by applying a safety factor to the 200 ppbv level found in the chamber studies [NEPC 1998]. In recent years, peak levels in metropolitan Sydney have ranged from 90 – 130 ppbv, and it has been uncommon for the daily Air NEPM standard to be exceeded [NSW EPA 2000].

Particulate matter

Particulate matter is used to describe a range of solids suspended in air. Secondary particles are formed in the atmosphere as a result of interaction of gases with other pollutants. Particles are categorised by aerodynamic diameter as respirable (0.1-2.5 microns, which is referred to as $PM_{2.5}$), or inhalable (2.5-10 microns). Estimation of PM_{10} includes all particles less than 10 microns.

Particles from the burning of petrol and diesel are a complex mixture of sulphate, nitrate, ammonium, hydrogen ions, elemental organic compounds, metals and poly nuclear aromatics amongst others. Larger particles (PM_{10}) tend to be produced by mechanical processes (eg wind erosion) as well as combustion, whereas $PM_{2.5}$ is generally produced by combustion processes such as motor vehicle exhaust and solid fuel heater emissions [NEPC 2002a].

Acute health effects of particulates include increased daily mortality, increased rates of hospital admissions for exacerbation of respiratory and heart diseases, fluctuations in the prevalence of bronchodilator use and cough and peak flow reductions [WHO 2000]. Particulate air pollution is especially harmful to people with lung disease such as asthma and chronic obstructive pulmonary disease (COPD), which includes chronic bronchitis and emphysema, as well as people with heart disease. Exposure to particulate air pollution can trigger asthma attacks and cause wheezing, coughing, and respiratory irritation in individuals with sensitive airways.

Fine particles ($PM_{2.5}$) are of particular health concern because they can be inhaled deep into the lungs where they can be absorbed into the bloodstream or remain embedded for long periods.

Study objectives

The primary aim of the study is to measure and compare the concentration levels of benzene, toluene, ethylbenzene and xylene (BTEX) and nitrogen dioxide (NO_2) for peak hour commuters in Sydney for five different commuting modes. The study provides a basis to gain a better understanding of BTEX and NO_2 personal exposure levels from commuting activities in Sydney.

The study also provides an opportunity to compare NO_2 personal exposure levels for all modes to ambient NO_2 levels, and to compare directional changes in NO_2 levels between the two sampling periods in the study.

Commuters travelling by motor vehicle also measured $PM_{2.5}$ levels inside the motor vehicle cabin while commuting. Commuters in all other modes did not sample for this pollutant. Another aim of the study is to measure the in-vehicle concentration level of $PM_{2.5}$ for peak hour car commuters in Sydney, and gain an understanding of $PM_{2.5}$ personal exposure for car commuters, and compare $PM_{2.5}$ in-vehicle exposure levels to ambient levels.

Methodology

We undertook a cross-sectional analytical study to compare exposure to benzene, toluene, ethylbenzene and xylene (BTEX) and nitrogen dioxide (NO_2) by five common travel modes – car, train, bus, bicycle and walking. Participants wore BTEX and NO_2 passive samplers during their travel to and from work for two weeks following a specific sampling protocol. Participants commuted to work on their usual route therefore travel distances did vary between commuters and between modes. Commuting took place at the same time of day however, during morning and afternoon peak hours, so actual time of measurement was the same for all.

At the end of the first week, the BTEX and NO_2 samplers were collected for analysis and replaced by new samplers. The study was undertaken over two consecutive weeks from 13-27 September 2002, thereby representing two sampling periods. Each week's sample comprised five in-bound and five out-bound journey to work trips, representing a weekly-averaged exposure level for each commuter.

Sample population

A convenience sample of 44 participants who commuted to work using one of the five modes of transport was recruited for the study. Study participants were staff of the Central Sydney Area Health Service based at or near the Royal Prince Alfred Hospital. Participants were required to be non-smokers, travel for a minimum of 30 minutes to and from work, and to follow specific instructions in using the samplers.

The Royal Prince Alfred Hospital is located in the suburb of Camperdown, three kilometres from the Sydney CBD. This reference location for the study was regarded as highly suitable as it was accessible by all transport modes to be considered in the study, and is a large employer.

Sampling protocol

Volunteer participants were required to travel directly to and from work for the period of the study, and use one mode of transport for the entire period. Volunteers were trained in the use of sampling equipment and provided written information on how to activate and deactivate the passive samplers and secure and store the samplers when not in use. Sampling equipment was only activated while the participant was commuting by their selected mode. For instance, a train commuter deactivated their samplers when arriving at the station platform, thereby not exposing the samplers for the connecting walk from platform to work or home.

All volunteers were provided with clips and fastening devices to attach the two passive samplers to a secure place on their person while commuting. Air-tight plastic vials were provided to seal and store the NO_2 samplers, and Teflon caps to seal the BTEX samplers. Zip-lock bags and baked foil to secure and store samplers were also provided to volunteers. Volunteers kept diary sheets to record start and end time of journeys and were encouraged to record any unusual circumstances in their journey (see Appendix A).

Volunteers commuting by motor vehicle also had an active sampler fitted inside the cabin of their car by study investigators for fine particle monitoring. Fine particles with a mean aerodynamic diameter less than two and a half microns ($PM_{2.5}$) were measured using a Micro-Vol© low volume aerosol sampler (Ecotech, Australia) with a $PM_{2.5}$ size selective inlet and active flow control of 3 litres/minute.

Sample analysis

All samplers were developed and provided by the CSIRO – Atmospheric Research (CSIRO-AR). At the completion of each sampling period, passive samplers and Micro-Vol© filters identified only by their sample number were couriered to CSIRO-AR for analysis. The field blanks were used in accordance with the International Standard, *ISO 6879 Air quality – Performance characteristics and related concepts for air quality monitoring methods*.

The BTEX personal sampling tubes used a passive diffusion method to sample the air. These methodologies have been previously described [Environment Australia 2003].

We used passive samplers based upon the well-characterised design of Ferm to measure NO_2 [Ferm 1991]. These passive gas samplers operate on the principle of molecular diffusion of a gas onto a filter coated with a sorbent species, integrated over the time of exposure. These methodologies have been previously described [Keywood et al. 1998, Ayers et al. 1998].

CSIRO-AR provided time-averaged pollutant levels for each commuter per sampling period.

Statistical analysis

The distribution of BTEX and NO_2 results for the entire study period indicated that the data was skewed. Logarithmic transformation of the raw data produced more normally distributed data, and the initial analysis used the log-transformed data, and the geometric means calculated by $e^{[\sum \{\ln (x1), \ln(x2), \ldots \ln(xn)\} /n]}$. A repeated measures generalised linear model was used to analyse the data, with SPSS v10.1 for Windows statistical software package.

The data was examined for possible outliers by identifying data that were three standard deviations away from the mean. The data was also visually examined using boxplots and any data points at 1.5 interquartiles away from the 1st and 3rd quartile were identified. Data points, which were common to both criteria, were defined as outliers and excluded from subsequent analyses.

A second statistical analysis method was applied to consider exposure level changes from the first sampling period (Week 1) to the second (Week 2). The valid data for the initial analysis described above was utilised. The data was then subject to further review. Commuters with valid results for both sampling periods were retained; while commuters without valid sampling period paired results were discarded. This provided a dataset with a greater level of validity in which to undertake comparisons in exposure levels between the two sampling periods.

Ambient air quality data

Ambient air quality data was obtained from the Sydney metropolitan air quality monitoring network (AQMN). The AQMN consists of 20 sites covering three regions in the Sydney metropolitan area. Data was available from 14 AQMN sites for NO_2, and from five AQMN sites for $PM_{2.5}$ in the form of one-hour mean concentrations. The closest AQMN sites to Camperdown, the reference location for the study, are Rozelle for NO_2 and Earlwood for $PM_{2.5}$ data. The AQMN is operated by the NSW Department of Environment and Conservation. Further information on the AQMN can be found at Appendix C.

We averaged the 9am and 5pm one-hour measurements for monitoring sites in each AQMN region to derive a sampling period (weekly) estimate of the average NO_2 and $PM_{2.5}$ ambient concentrations encountered by study participants during actual commuting time for each AQMN region. Further, we calculated a real time ambient exposure estimate for $PM_{2.5}$ by matching travel diary times with the closest AQMN site for each commuter for each journey to work trip. This made available an indicative commuting time ambient level for comparison purposes with commuter mode exposure levels. See Appendix F for the methodology applied to generate this ambient exposure estimate for $PM_{2.5}$.

Meteorological data

Meteorological data was obtained from the Sydney Office of the Commonwealth Bureau of Meteorology. Temperature, dew point, relative humidity, barometric pressure and rainfall data from three meteorological monitoring sites across the study area were provided – Observatory Hill, Homebush and Mascot. Wind data was also provided from the Homebush and Mascot monitoring sites.

A summary of average temperature, dew point, relative humidity and wind for the study period was derived by averaging four readings per day (8.00am, 9.00am, 4.30pm and 5.30pm) representative of commuting time for each site in the study area.

Commuting mode fleets

Motor vehicles used in the study were a range of petrol-fuelled sedan models manufactured from 1997. Train mode commuting was undertaken on the CityRail network and bus mode commuting on the State Transit Authority service.

Results

Pollutant concentrations, including outliers, for each of the five commuting modes for the study period are shown in Table 1. The study period comprised two separate sampling periods: Week 1 (13-20 September 2002) and Week 2 (20-27 September 2002). The values presented for each week represent the geometric mean of results for each pollutant by commuting mode. The range of values for each pollutant by commuting mode for the two sampling periods is also presented.

Table 1. Geometric-mean pollutant levels for all variables (includes outliers)

		Car	Bus	Bicycle	Train	Walk
		n=9,9	n=5,4	n=7,7	n=11,11	n=9,7
Benzene (ppbv)	Week 1	11.64	5.82	5.17	4.15	4.96
	Range	(3.8,80.2)	(4.3,10.9)	(1.7,13.0)	(1.4,15.6)	(2.8,13.5)
	Week 2	21.85	8.44	6.61	3.41	6.45
	Range	(8.2,203.8)	(7.4,10.0)	(2.9,13.7)	(1.9,6.1)	(3.6,40.1)
Toluene (ppbv)	Week 1	29.85	14.53	16.83	12.72	15.42
	Range	(9.6,339.1)	(9.1,34.5)	(5.8,36.7)	(3.9,56.4)	(6.4,81.3)
	Week 2	54.58	33.07	31.02	12.17	21.93
	Range	(26.0,1096.9)	(18.6,49.6)	(10.0,149.8)	(7.9,26.0)	(8.9,170.8)
Ethyl-benzene (ppbv)	Week 1	4.10	2.99	2.06	1.85	2.54
	Range	(1.6,30.1)	(1.7,5.4)	(0.8,4.7)	(0.7,7.0)	(1.5,8.1)
	Week 2	7.75	5.84	3.35	1.62	3.02
	Range	(2.4,60.3)	(3.1,9.7)	(1.6,11.2)	(0.9,3.0)	(1.5,18.8)
Xylene (ppbv)	Week 1	20.01	13.16	9.39	7.88	11.00
	Range	(6.7,165.3)	(7.4,33.2)	(3.5,25.4)	(3.0,40.4)	(5.2,45.7)
	Week 2	35.04	20.31	14.22	6.69	14.33
	Range	(12.6,406.5)	(14.1,27.1)	(6.8,36.2)	(4.8,12.1)	(5.8,92.3)
NO_2 (ppbv)	Week 1	24.58	31.03	21.40	12.11	23.50
	Range	(18.7,38.7)	(18.3,67.0)	(14.8,26.1)	(8.1,18.2)	(14.8,50.1)
	Week 2	35.88	38.63	28.59	18.21	46.11
	Range	(24.4,70.4)	(29.9,56.4)	(18.9,35.3)	(13.4,22.8)	(18.8,269.3)
$PM_{2.5}$ * ($\mu g/m^3$)	Week 1	20.75	Note: Only car commuters sampled for $PM_{2.5}$, * n=8,8			
	Range	(9.1,32.8)				
	Week 2	29.61				
	Range	(21.4,45.2)				

Only two commuters (a car and a walk commuter) in the study were found to have outlier results for any of the pollutants measured. After excluding outlier results and adjusting the data for minor differences between the two sampling periods, significant differences between commuting modes for all pollutants except toluene were found. We demonstrated significant differences for benzene and NO_2 results between the five commuting modes. The concentration levels found for train mode were significantly lower than the reference mode for all pollutants except toluene. These results are shown over page at Table 2.

Table 2. Adjusted geometric means by transport mode (BTEX and NO_2)

	Benzene (ppbv)	Sig.	Toluene (ppbv)	Sig.	E-benzene (ppbv)	Sig.	Xylene (ppbv)	Sig.	NO_2 (ppbv)	Sig.
Car	12.29	Ref	28.76	Ref	4.38	Ref	19.91	Ref	29.70	0.042
Bus	6.94		22.47		4.00		15.18		44.30	Ref
Bicycle	6.17	0.032	24.56		2.72		12.16		24.58	0.005
Train	3.77	<0.000	12.44		1.73	0.002	7.26	0.001	14.85	<0.000
Walk	5.70	0.014	19.71		2.96		13.11		26.08	0.011
Overall F-test	5.062	0.003	1.825	No	3.467	0.019	3.367	0.022	15.895	<0.000

Ref = reference value for statistical significance testing

Note: E-benzene = Ethylbenzene

Car commuters received the highest average exposure to benzene, toluene, ethylbenzene and xylene of any of the commuting modes. Bus commuters had the highest average exposure levels to NO_2. Train commuters recorded the lowest exposure levels for all four BTEX pollutants and NO_2. Walking and cycling commuters had significantly lower levels of exposure to benzene compared with motor vehicle commuters and significantly lower levels of NO_2 than bus commuters.

Ambient air pollutant levels for NO_2 were consistently higher in Week 2 than Week 1, as was similarly observed in the commuter exposure level results. Similarly, $PM_{2.5}$ measurements for car commuters were higher in Week 2 than Week 1. Actual commuting time ambient pollutant levels representative of peak hour commuting times were used to derive an average ambient pollutant concentration for both NO_2 and $PM_{2.5}$ for the study period. These values for each AQMN region are shown below at Table 3. NO_2 concentrations from a peak AQMN monitoring site in the CBD are also shown.

Table 3. Actual commuting time average ambient concentrations of NO_2 and $PM_{2.5}$ by AQMN region*

AQMN region	Average ambient pollutant concentrations by sampling period					
	NO_2 (ppbv) 1-hr averaging time			$PM_{2.5}$ (µg/m^3) 1-hr averaging time		
	Week 1	Week 2	Study	Week 1	Week 2	Study
Central East**	13.43	21.74	17.59	8.27	18.29	13.28
North West	7.42	12.31	9.86	8.89	16.31	12.60
South West	6.39	13.08	9.74	12.22	25.58	18.90
Sydney CBD	*42.17*	*53.03*	*47.60*			

* Actual concentrations (non-peak AQMN sites) representative of peak hour commuting: 8am-9am and 4pm-5pm (1-hour).

** Excludes Sydney CBD peak site (NO_2)

Note: Study means Study Period average – represents the average ambient level estimate to compare with Table 2 NO_2 commuter exposure results.

Table 3 demonstrates that differences in ambient air concentrations were observed across the study area – metropolitan Sydney. In particular, the Central East AQMN region showed the highest NO_2 ambient concentration levels for the three regions (see Appendix D for more detail).

Meteorological data showed that during commuting hours, week 2 was on average hotter (20°C versus 18°C) and less windy (9 knots versus 14 knots) than week 1. Three days in Week 2 recorded maximum daily temperatures above 25°C, with 30°C recorded on one of those days, whereas only one day above 25°C was recorded in Week 1. A summary of meteorological data providing the estimated average value for each variable during actual commuting time aggregated from three meteorological stations in Sydney, for each sampling period, is shown at Table 4.

Table 4. Meteorological summary – Actual commuting time averages*

Sampling period	Temp. °*C*	Dew pt. °*C*	Rel. Humidity *%*	Wind** *knots*
Week 1	17.8	5.6	46.9	13.8
Week 2	20.2	8.6	52.3	8.7

* Three stations: Observatory Hill, Homebush and Sydney Airport

Averaged 4 readings/day = 20 readings/week (8am, 9am, 4.30pm, 5.30pm)

** Two stations only: Homebush and Sydney Airport

Study period – Further analyses

The results presented in Table 2 provide a basis for further comparative analysis of the average personal exposure levels between commuting modes. Further analyses of comparative BTEX exposure for the study period and variations between sampling periods were undertaken.

To further investigate comparative BTEX exposure levels we used the train mode as the reference mode. Figure 1 shows the ratios or relative concentrations of BTEX levels across the modes with the train mode as the reference. ‘Total’ BTEX concentrations demonstrate well the elevated levels found in the cabins of cars, compared with other modes. Interestingly, the next lowest value for any BTEX pollutant for any other mode is at least 50% higher than that found for train commuters.

To further investigate the result demonstrated at Figure 1, especially for benzene, we looked at the relative proportions of each BTEX pollutant as a fraction of total BTEX mass for each commuting mode. The result of this analysis is given in Table 5. We found that the relative proportion of benzene exposure for car commuter as a fraction of total BTEX mass was higher than all other modes.

Figure 1. Relative BTEX concentrations across modes with 'Train' mode as reference

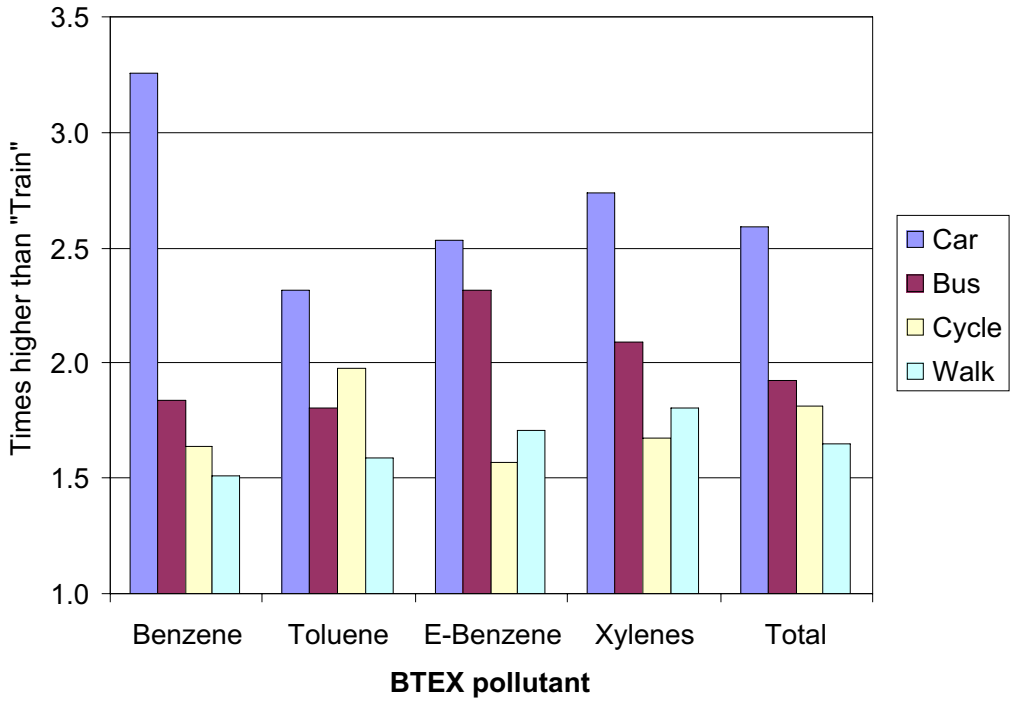


Table 5. Relative proportions of BTEX pollutant by mode

Mode	Benzene	Toluene	E-Benz	Xylene
Car	0.19	0.44	0.07	0.30
Bus	0.14	0.44	0.08	0.33
Bicycle	0.15	0.51	0.06	0.28
Train	0.15	0.49	0.07	0.29
Walk	0.15	0.46	0.07	0.32
Average	**0.15**	**0.47**	**0.07**	**0.31**

Total BTEX mass =1 (baseline), E-Benz = Ethylbenzene

Due to the wide variation in ambient NO_2 levels across the study area, as presented at Table 3 and Appendix C, it was somewhat problematic to undertake a reasonable comparison between modes for this pollutant. Nevertheless, the results should be best viewed as indicative of the relative pollutant exposure levels experienced by peak hour commuters journeying to and from work to a location in or near the CBD. Table 6 provides some descriptive comments on this issue.

Table 6. Nitrogen dioxide (NO_2) exposure levels by mode and comments

Mode	Conc. (ppbv)	Comments
Car	29.7	Generally longer distance journeys from low to high (am), or high to low (pm), ambient levels. Sample covered all AQMN regions. Result is approx. 100% higher than train mode result.
Bus	44.3	Small sample, shorter commutes entirely in Central East AQMN region, traversing major arterial roads such as Parramatta Rd, Prince's Highway and through CBD. In peak hour buses can closely trail one another on busy routes such as Parramatta Rd; can impact on in-cabin AQ. Possible urban canyon effects closer to CBD.
Bicycle	24.6	Shorter commutes entirely in Central East AQMN region. Exposure levels similar to recent Perth Study, ie 22 ppbv (Farrar et al. 2001). Similar result to walk mode.
Train	14.8	Generally longer distance commutes from low to high (am), or high to low (pm), ambient levels. Sample covered all AQMN regions. Result is within the ambient range for the AQMN, ie 9.7 to 17.6 ppbv. This was an anticipated result because trains are well-removed from major roadways. Result also tends to validate the accuracy of the NO_2 diffusion sampler.
Walk	26.1	Very short distance commutes mainly in and around the CBD where the highest NO_2 levels in the metropolitan area are found at peak hour. Possible urban canyon effects closer to CBD. Result is lower than CBD ambient AQMN peak site, ie 47.6 ppbv. Similar result to bicycle mode.

Sampling periods (Week 1 v Week 2) – Analyses

Analyses of the variations between modes for the two sampling periods focus on the two pollutants, NO_2 and $PM_{2.5}$. Further comparison of commuter exposure levels with NO_2 and $PM_{2.5}$ ambient levels was also possible.

Ambient pollutant levels and the rate of dispersion of pollutants from roadway microenvironments, which is related to meteorological conditions and other factors, may influence the relationship between car commuting and benzene exposure. It is not possible to test this assertion any further as we do not have ambient BTEX data and more detailed meteorological data. In addition, sampling periods consisted of ten journeys over a week, whereas a single journey or single day sampling protocol would have provided a better basis for such further investigation.

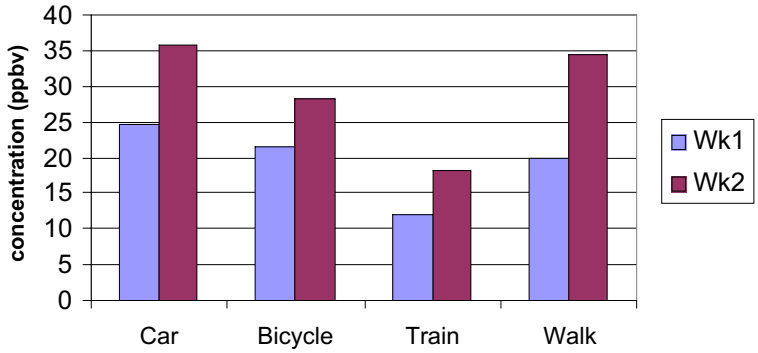
To investigate variations in exposure concentration levels between weeks for commuters further treatment of the dataset was undertaken. We rationalised the dataset to undertake week-to-week comparisons so that only paired results were utilised. This slightly reduced the dataset to 35-paired results for both BTEX and NO_2. The number of sampling period pairs for each mode can be found below at Table 7. The remainder of the analysis presented below is based on the dataset of 35-paired results.

Table 7. Summary of data points used in analyses

Mode	BTEX			NO_2		
	Week		Pairs	Week		Pairs
	1	2		1	2	
Car	8	8	8	9	9	9
Bus	5	4	3	5	3	2
Bicycle	7	7	6	7	8	7
Train	11	11	11	11	11	11
Walk	9	7	7	9	6	6
Total	**40**	**37**	**35**	**41**	**37**	**35**

Comparing pollutant levels for commuters who participated in both weeks, there was a highly significant increase in NO_2 levels from Week 1 to Week 2 for all modes except bus mode (Car: p=0.018, Bicycle: p=0.014, Train: p<0.000, Walk: p=0.010). This is presented below at Figure 2.

Figure 2. Commuting mode NO_2 levels – Week 1 and 2



Commuter exposure to NO_2 between weeks was reasonably similar to the difference in ambient pollutant levels, which were also found to be significantly different between weeks (p=0.009). While bus, bicycle and train commuters measured increases similar to the AQMN ambient concentrations for the regions, car and walk commuters measured increases similar to the CBD and Rozelle AQMN sites. See Figure 3 over page. For BTEX pollutants, only benzene in car commuters was significantly different between weeks (9.1 ppbv and 16.5 ppbv in Weeks 1 and 2 respectively, p=0.049). No further comparative sampling period analysis for BTEX pollutants was undertaken.

Figure 3. Increase in NO_2 concentration levels from Week 1 to Week 2 for all modes, AQMN regions and AQMN sites (Rozelle and Sydney CBD)

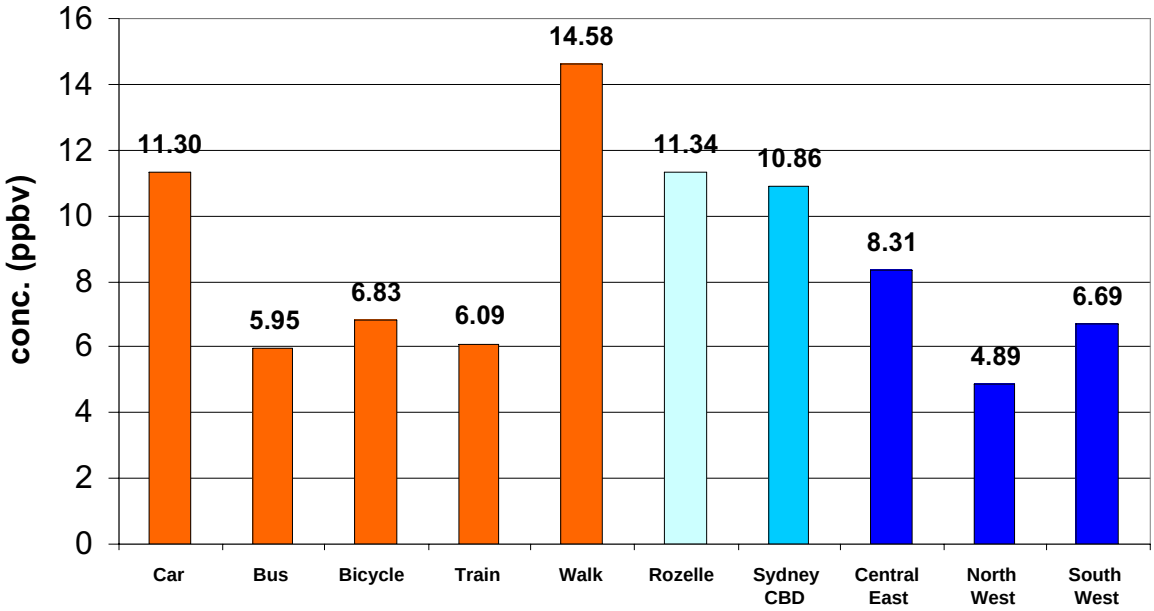
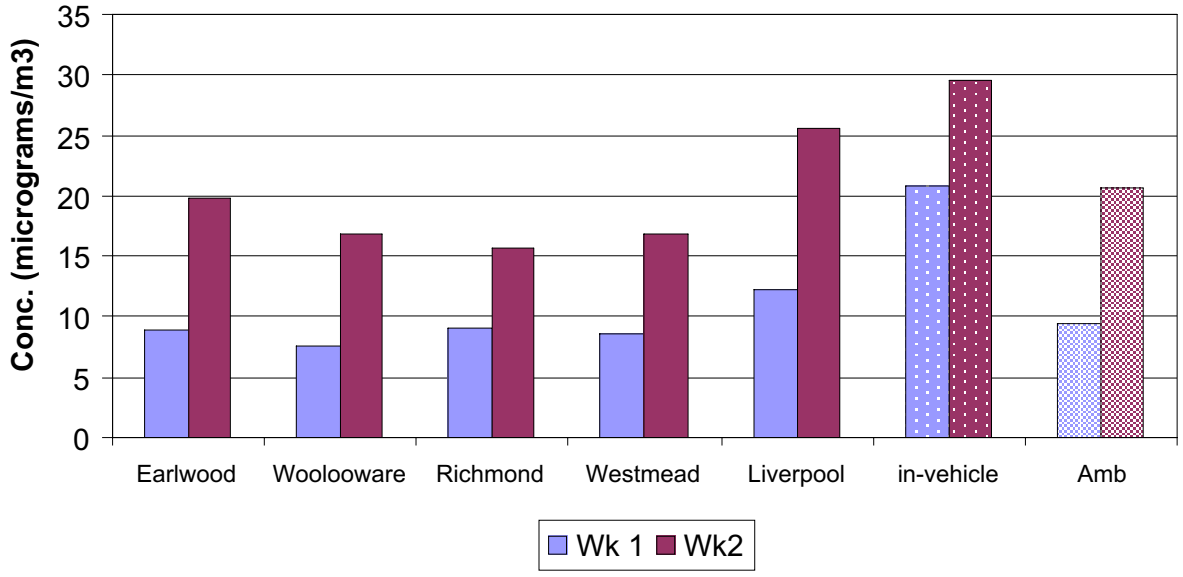


Figure 4 provides a comparison of average weekly peak hour ambient $PM_{2.5}$ levels by AQMN site with in-vehicle car commuter levels and a commute time ambient estimate (Amb) for car commuters based on best available information. The ambient estimate is reasonably similar to the Earlwood AQMN site, the reference site for Camperdown. Further detail on how this estimate was derived is available at Appendix F.

Figure 4. Comparative $PM_{2.5}$ concentration levels: AQMN site, in-vehicle and actual time ambient exposure estimate (Amb) for car commuters



Discussion and findings

We have confirmed the findings from other cities that average BTEX concentration levels in motor vehicles are higher than in other commuting modes. Benzene concentration levels measured in motor vehicles were more than three times higher than that measured in trains. While the levels of BTEX found in motor vehicles are unlikely to be associated with acute health effects, there is some concern related to long-term exposure to these chemicals [WHO 2000]. Benzene in particular is a carcinogen, and it is recommended that exposure to carcinogens is as low as possible. Estimating benzene exposure over 40 years of typical commuting [TDC 2003] a motorist would inhale 411mg of benzene compared to 126 mg for a train commuter.[a]

We have also estimated the proportion of benzene exposure attributable to the activity of weekday peak hour car commuting as a percentage of total weekday exposure, making use of recent data from a national BTEX study in four cities [EA 2003 p.38]. Based on the average personal exposure for a Sydney participant in the national study for a 24-hour period, we calculated that a car commuter received 62% of total daily exposure to benzene from the activity of journeying to work in the morning peak and journeying home in the afternoon peak hour. The result suggests that for those commuters who regularly undertake weekday peak hour car commuting in metropolitan Sydney, this could be the most significant source of benzene exposure for these people. Further information on this issue is given in Appendix H.

Elevated BTEX exposure – Car mode commuters

There are a number of potential explanations as to why BTEX levels are significantly higher in motor vehicles compared to other modes. Some authors have suggested it is attributable to the car travelling in a 'tunnel of pollutants', as the source of air intake to the car is located in the high concentration of these pollutants from the exhaust of all the vehicles on the road [Chan et al 1999]. Another well discussed explanation is direct contamination from the motor vehicle itself [Ilgen et al. 2001, Leung and Harrison 1999, Duffy and Nelson 1997, Lawryk and Weisel 1996, Lofgren et al 1991]. The differential effect we found for peak BTEX (in cars) and NO_2 (in all roadway modes) tends to confirm this second point, as BTEX gases come from both evaporative and combustive emissions, whereas NO_2 is generated only after combustion. While all road users are exposed to combustive emissions, occupants of motor vehicles may have an additional exposure to evaporative emissions directly from their own car that does not directly impact on other road users [Ilgen et al. 2001 p.1274].

BTEX exposure – Roadway microenvironments

In comparing total BTEX exposure the lowest levels were clearly found for train commuters, followed by walking, cycling and bus. This suggests that a non-roadway mode and modes involving physical activity are good alternatives to the motor vehicle to reduce personal exposure to BTEX pollutants, especially benzene. The clearly lower exposure levels for train commuters are likely to have resulted from the commuter not being directly in a roadway microenvironment, and therefore this result would tend to support the 'tunnel of pollutants' finding for roadway based modes. We also observed little difference in BTEX levels for train commuters between the two sampling periods. This result would tend to further support the findings that train routes in Sydney are generally well removed from roadway microenvironments, the predominant source of BTEX.

[a] Assuming 79 mins/day, 5 days/week, 48 weeks for 40 years, adult respiratory rate 0.83 L/min (after Wadge & Salisbury, National Environmental Health Forum Monograph, 1997).

Commuting mode comparisons

In looking more closely at the results there are a number of comparisons that can be made between particular modes. Comparisons between car and train mode demonstrated the strongest levels of significance in the statistical analysis. Both modes had very similar numbers of participants, sampling times and travel distances. On this basis, these two modes were highly comparable. The results showed, that on average, car commuters are exposed to twice the concentration levels of NO_2 than train commuters, and over three times the concentration levels of benzene.

Another comparison of note is that between walking and bicycle modes. These two modes were the closest in terms of similarity of results. They recorded the lowest levels of exposure to benzene, total BTEX and NO_2 apart from train mode. It is also worth noting that a considerable amount of commuting time for these two modes was in areas with higher ambient NO_2 levels than for other commuting modes. Nitrogen dioxide exposure levels were very similar between the two modes.

Nitrogen dioxide exposure

There have previously been inconsistent results regarding comparative nitrogen dioxide exposure for different urban commuting modes. This finding was demonstrated in an Amsterdam study in the 1990s, and it generally showed small differences in NO_2 concentrations between car and bicycle modes when the same routes were travelled, with either mode returning the higher level of concentration at time of measurement [van Wijnen et al 1995]. The average concentration levels for car drivers in the Amsterdam study ranged from 31 – 90 ppbv and for bicyclists from 50 – 80 ppbv. In comparison this study found average NO_2 levels of 30 ppbv for car drivers and 25 ppbv for bicyclists. A more recent study in Perth, Australia found an average concentration level for bicyclists of 22 ppbv, which is very similar to the result in this study [Farrar et al. 2001]. Another recent study in Hong Kong showed NO_2 concentrations to be much higher than Sydney [Chan et al. 1999]. Car and bus modes measured an average of 69 ppbv each, whereas train and mass transit rail modes were lower at 35 and 25 ppbv, respectively. While the absolute levels in the Hong Kong study were higher than Sydney, the relative levels between modes, apart from bus mode, were quite similar.

We found that only train commuters had considerably lower levels of exposure to NO_2 compared to other modes. Bus commuters were found to have considerably higher levels of exposure compared to other modes. Motor vehicle, bicycle and walk modes measured NO_2 exposure concentrations of between 24 and 30 ppbv. This result may have arisen due to the study reference location being close to the Sydney CBD where levels measured are much higher than the rest of the city, especially for peak hour times. All walkers, cyclists and bus commuters undertook their entire commute in the Sydney East area of the city, which measured the highest ambient NO_2 levels for the three AQMN regions. Car and train commuters generally travelled longer distances and spent some proportion of their journey in lower ambient pollution areas of the city. Due to observed ambient variations in NO_2 levels across the study area, the results for each mode were likely to be influenced by differing background levels of NO_2 (see Appendix D for more detail).

An interesting finding is the apparent influence of ambient NO_2 levels on commuter exposure levels. The train mode mean for NO_2 of 14.8 ppbv was within Sydney's ambient range across the three monitoring regions (9.7 to 17.6 ppbv). This result also provides a level of validation for the NO_2 diffusion sampler used in the study. Mean NO_2 exposures in Week 2 were significantly higher ($p<0.000$) for all modes combined than in Week 1, which corresponded with higher ambient levels measured in Week 2. The levels of nitrogen dioxide exposure are however generally below those established as associated with health impacts, and well below the Australian National Environment Protection Measure of 120 ppbv [NEPC 1998].

Week 1 v Week 2 comparisons – Further discussion

The increase in average ambient concentration levels from Week 1 to Week 2 for NO_2 and $PM_{2.5}$ were found to be directionally consistent with the increases in commuter exposures. For NO_2 the increases in commuter exposure levels were found to be of a similar magnitude to measured ambient concentrations. This is most apparent for train commuters, with similar exposures levels compared to ambient readings, and similar increases to ambient readings from Week 1 to Week 2.

The results for $PM_{2.5}$ were significantly different between the two sampling periods and may have been strongly influenced by ambient levels. The study area was large with differences in background levels observed, and once again, a study with shorter sampling periods may be more effective in finding significance and better defining the magnitude of this relationship. A recent study in London [Adams et al. 2001] where far more numerous single journeys in a smaller area were undertaken showed a significant correlation with ambient levels. It found that road mode mean exposure levels were approximately 100% more than corresponding mean fixed site concentrations. While this study found a very similar relationship to Adams et al. for Week 1 (ie 2:1 ratio), it was not consistent in Week 2 of the study. In-vehicle exposure levels for Week 2 were elevated by a ratio of about 3:2 compared to ambient levels.

This inconsistent result with Adams et al. may have arisen due to the limitations of our study, such as the lengthier measurement periods, and the few $PM_{2.5}$ ambient monitoring sites available in the study area for comparison. Measurement methodologies differed too – Adams et al. selected three routes of around five to seven kilometres in length in close proximity to a fixed site ambient monitoring station, whereas this study had car commuters travelling unspecified routes for considerable distances (some > 40 km). It should be noted that the Adams et al. London Study, which involved over 200 participants, is the first comprehensive commuter exposure study of its kind for this pollutant. Anticipated future research internationally may shed more light on this issue and perhaps be able to support or better clarify if such a relationship between in-vehicle exposure levels and ambient concentration levels exists, and can be demonstrated in other cities around the world.

Study limitations

The study was limited by the fewer number of participants on the bus mode compared to other modes. This limitation due to sample size made it difficult to demonstrate significant differences with other modes. While the NO_2 result for bus commuters was shown to be considerably higher than other modes, the small sample size and an aged bus fleet on the routes used by our commuters may have contributed to this. Commuting journeys for this mode were all taken near the CBD on heavily trafficked roadways. Ambient NO_2 levels are highest in the CBD compared to the rest of the metropolitan area. This is somewhat supported by the aforementioned Amsterdam study, which found that NO_2 concentrations were only found to be significantly influenced by the route taken [van Wijnen et al. 1995].

A further limitation of the study is the wide variation of routes taken across modes and differing background NO_2 levels across the study area. These differences were not accounted for and integrated into the study analysis, and therefore a precise direct comparison of exposure levels between modes was not possible. Nevertheless, and quite importantly, the results are indicative of the relative pollutant exposure levels experienced by peak hour commuters journeying to and from work to a CBD location.

Overall the NO_2 results did not mirror the distinct hierarchy of results across modes found for total BTEX exposure. This may have reflected in some way the influence of substantially differing ambient levels in NO_2 that the participants in different commuting modes were generally exposed to.

Another important limitation relates to the measurement of pollutant concentrations. The use of a weekly measurement period can mean that comparisons with ambient concentration levels are less reliable than for a shorter measurement period. In this study, an aggregated reading of ambient levels was derived from source data for this comparative analysis. While this was the only way to undertake this comparison, it is recognised that a single journey measurement would provide an opportunity to directly compare with actual rather than aggregated ambient measurements.

Possible further research

To further investigate commuter exposures in and out of roadway microenvironments a comparative study for bus and bicycle modes could be undertaken for selected fixed routes. There is good opportunity to do this in Sydney due to the recent opening of the Western Sydney bus transitway – a dedicated roadway for buses. The Cooks River bicycle path to Homebush also offers a potential study location for this work.

Further research on air pollutant exposures for bus commuters would be of benefit. As discussed in the previous section, the results for this mode were the least reliable of all modes. A better understanding of exposure levels in relation to bus fleets and routes taken may be useful in characterising possible key factors that contribute to commuter exposures for this mode.

A summer/winter study may be of benefit in terms of better understanding the influence of temperature on BTEX exposure levels. This may also help us to better understand the characteristics of evaporative emissions which motor vehicle commuters are exposed to. It may also assist in understanding the impact of any changes in fuel quality standards, which can affect the emission profile of the commuting fleet. Fuel regulation changes can impact on personal exposure levels; this has been recently observed in Perth where there are stricter benzene content requirements [Environment Australia 2003].

Conclusions

We have confirmed previous results from other cities that private motor vehicle occupants are exposed to higher levels of BTEX air pollutants than commuters in other modes. The study confirmed that a high proportion of total personal exposure to benzene could potentially be received while commuting in a private motor vehicle. This finding is particularly relevant to regular peak hour motorists and those that may spend a considerable amount of time commuting in heavily trafficked or congested roadways. The results of the study suggest that personal exposure to benzene in the car cabin microenvironment is a major source of exposure to this air pollutant.

The study found that train commuters are exposed to concentrations of NO_2 similar to the levels found in ambient air. This tends to confirm that train commuters are not directly impacted by emissions from motor vehicles as train routes in Sydney are well removed from major roadways. Commuters in all other modes measured NO_2 concentrations higher than train mode levels; car commuters measuring twice the level, and bus commuters three times the level of train commuters.

All modes that involve some level of commuting in a roadway microenvironment (car, bus, bicycle and walking) showed that commuters are exposed to elevated levels of BTEX and NO_2 due to the presence of combustive emissions from motor vehicles. This finding suggests that there are implications for commuters in relation to mode choice; in that motor vehicle generated pollutants have a considerable impact on commuters in other modes that may share the use of roadways.

In addition to exposure to combustive emissions, the results of the study suggest that occupants of cars may have an additional exposure to evaporative emissions directly from their own car that does not directly impact on other road users. The results for benzene given at Table 5 tend to demonstrate this.

The study also demonstrates that exposure to benzene can be reduced by using other modes of transport for commuting activities, particularly train mode. The study confirms that policies aimed at encouraging commuting alternatives to the private motor vehicle would reduce population exposures to BTEX pollutants. In addition, we have also found that providing alternatives that are non-roadway based would further reduce population exposures to BTEX pollutants associated with commuting activities.

We have also demonstrated to a limited extent the effect of ambient pollutant levels on commuter exposures. While further research may help to improve our understanding, this study showed that directional changes in personal exposure are consistent with directional changes in ambient levels. We found that ambient NO_2 levels are a good indicator of train commuter personal exposure levels. Exposure to $PM_{2.5}$ in the vehicle of a car commuter appeared to have some relationship with ambient levels, however further research is required to better quantify this relationship.

The information provided by this study should be of particular relevance to urban and transport planners, infrastructure providers, transport service providers and transport user groups. The findings can inform commuters about the relative levels of exposure between different modes, and potentially the health costs and benefits associated with these travel choices. It is important to recognise that the findings are most relevant to people that commute to locations in or near the CBD during peak hour.

Acknowledgments

We would like to thank all participants who volunteered to be commuters in the study. We are also grateful to Jenny Powell of the CSIRO – Atmospheric Research for her ongoing assistance in the project, especially in the lead up to and during the study period. We also wish to thank Ian Weeks and Jenny Powell of CSIRO – Atmospheric Research for reviewing the manuscript. The study was also made possible through the assistance of staff at the Central Sydney Area Health Service Health Promotion and Public Health Units.

The NSW Roads and Traffic Authority funded this project.

Glossary

AQMN – Air Quality Monitoring Network

BTEX – Benzene, Toluene, Ethylbenzene, Xylene

CBD – Central Business District

CO – Carbon Monoxide

CSIRO-AR – Commonwealth Scientific and Industrial Research Organisation – Atmospheric Research

DEC – NSW Department of Environment and Conservation

EPA – Environment Protection Authority (NSW) (an agency of the DEC as of Sept. 2003)

NO_2 – Nitrogen Dioxide

NO_x – Oxides of Nitrogen

$PM_{2.5}$ – Particulate Matter less than 2.5 microns in diameter – fine particulates

PM_{10} – Particulate Matter less than 10 microns in diameter

ppbv – Parts per billion – a measure of concentration

RPAH – Royal Prince Alfred Hospital

$\mu g/m^3$ – Micrograms per cubic metre – a measure of concentration

VOCs – Volatile Organic Compounds (includes all BTEX pollutants)

WHO – World Health Organisation

Appendices

Appendix A
Information for volunteer commuters

Appendix B
Summary table of international in-vehicle/commuter BTEX exposure studies
(based on summary presented by Batterman et al. 2002)

Appendix C
Sydney Metropolitan AQMN summary

Appendix D
Ambient NO_2 levels at AQMN sites

Appendix E
Ambient $PM_{2.5}$ levels at AQMN sites

Appendix F
$PM_{2.5}$ ambient estimate calculation

Appendix G
Average time and total time travelled per mode

Appendix H
Benzene personal exposure estimate – Car

Appendix A – Information for volunteer commuters

Information provided to volunteer commuters who participated in the study:

Research study – Information for participants

Weekly diary sheet

- Week 1
- Week 2

Note: Volunteer commuters in the study were also provided with technical documentation on the use of passive samplers and sampling equipment. This information has not been included in this report.

NSW HEALTH

RESEARCH STUDY – COMPARING EXPOSURES TO AIR POLLUTANTS BY TRANSPORT MODE

INFORMATION FOR PARTICIPANTS

The NSW Department of Health is conducting a study in Sydney to determine the levels of pollutant exposure to commuters for different travel modes. With your permission we would like to include measurements from your journey to and from work in this study.

Why are we studying exposures to air pollutants from commuting?

It is widely known that air pollution can harm our health. Recent investigations in other cities provide some evidence that exposure to air pollutants is considerably higher for occupants of motor vehicles compared to users of public transport, cyclists and pedestrians, even along similar routes. We will therefore be undertaking a comparative study of pollutant exposure of commuters for each transport mode.

Why am I a volunteer commuter?

The Central Sydney Area Health Service in Camperdown is a highly suitable location for the study on the basis it's accessible by all transport modes and is a large employer. Volunteers have been exclusively sought from the employees of the Area Health Service. Volunteers will be non-smokers. Ten volunteers have been sought for each of five modes of transport. Volunteers will need to travel for at least 30 minutes to work and 30 minutes returning home on one mode of transport. The study period will cover two consecutive weeks in September. Volunteers must be available at this time to participate in the study and must use one mode of transport for their journey to and from work for the two-week period.

What are the benefits of this study?

The study is expected to provide evidence as to whether exposure to air pollutants is higher for occupants of motor vehicles compared to users of public transport, cyclists and pedestrians. The findings of the study have the potential to inform commuters about the health costs and benefits of different transport choices. It will also inform government and transport planners, and may have implications for the provision of transport infrastructure and management of transport services.

What is required if you agree to participate in this study?

All volunteers will wear samplers for nitrogen dioxide and air toxics. Both are small samplers and do not require any power to operate. They have been used in previous studies by NSW Health, and have not presented any significant difficulties for participants to wear. Volunteers travelling by car will also have a Micro-vol sampler fitted inside the cabin of their car for fine particle monitoring. Volunteers will be trained in the use of the samplers. Volunteers will be required to travel directly to and from work and record travel times and any unusual circumstances of the journey. To compensate for any inconvenience this may cause, all volunteers will have their travel costs covered and receive small incentives as part of the volunteer recruitment process.

Please complete the consent form.

We need your written consent to include you as a volunteer in the study. Please sign the form and return it to the Health Promotion Unit, Level 4 Queen Mary Building, Central Sydney Area Service, Camperdown. You can be assured that no details identifying you will be released as a result of participating in this study. Confidentiality will be observed at all times.

You can choose to receive a copy of the results.

If you would like to receive a copy of the levels of air pollution in your journey to and from work, along with a plain English explanation of their meaning, please tick the appropriate box on the consent form. If you have any concerns about these levels, Environmental Health Branch staff will be happy to discuss them with you.

For more information…

If you have any questions regarding the study, please do not hesitate to call Michael Chertok (research officer) on xxxx xxxx or Geoff Tan on xxxx xxxx or Nathan Aust on xxxx xxxx. If you feel it necessary to make a complaint about the conduct of the project, you can contact the Secretary of the Ethics Review Committee on xxxx xxxx.

Thank you for your time and cooperation in making this study possible.

Weekly diary of journey to work and home

Participant identification number:

Pollutant sample identification number:

Nitrogen dioxide

Air toxics

PM (car drivers only)

		——		

Sept. 2002 – Week 1

	Time of journey (am)		Journey Duration	**Time of journey (pm)**		Journey duration	Total duration	*
	Start	End		Start	End			
1 (13th)								
2 (16th)								
3 (17th)								
4 (18th)								
5 (19th)								
6 (20th)								
Total								

Note: For all journeys you only need to fill out the start and end time of each journey on the table above. If any unusual circumstances occur during the journey you must indicate this in the last column and provide details below.

Any unusual circumstances during the journey to work or home? If so, please provide detail below and cross-reference to table in last column (*). Please use other side of sheet if you need more space for writing.

_____

_____

_____

Weekly diary of journey to work and home

Participant identification number:

Pollutant sample identification number:

Nitrogen dioxide

Air toxics

PM (car drivers only)

		———		

Sept. 2002 – Week 2

	Time of journey (am)		Journey Duration	**Time of journey (pm)**		Journey duration	Total duration	*
	Start	End		Start	End			
1 (20th)								
2 (23th)								
3 (24th)								
4 (25th)								
5 (26th)								
6 (27th)								
Total								

Note: For all journeys you only need to fill out the start and end time of each journey on the table above. If any unusual circumstances occur during the journey you must indicate this in the last column and provide details below.

Any unusual circumstances during the journey to work or home? If so, please provide detail below and cross-reference to table in last column (*). Please use other side of sheet if you need more space for writing.

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Appendix B – Summary of in-vehicle/Commuter BTEX studies

Table B1. Summary of in-vehicle/commuter BTEX exposure studies as presented by Batterman et al (2002)

Location/Ref.	Time	Pollutants	Ave conc. ($\mu g/m^3$)	Comment
Los Angeles, USA (AQMD 1989)	Summer 1987, Winter 1988 (2 periods)	Benzene	41	Rush-hour in-vehicle concentrations measured. In 1997, measurements showed LA levels 2-4 times higher than Sacramento (smaller city) (AQMD 1999, Rodes et al 1998). Other findings: A single high polluting vehicle in front of a motorist can account for 50% of pollutants inside the car; opening or closing vents had little effect on in-vehicle concentrations; driving in a relatively uncongested carpool lane decreased pollutants by 30-50%.
		Toluene	35	
		O-xylene	32	
Raleigh, USA (Chan et al 1991)	Summer 1988	Benzene • Urban • Interstate • Rural	(median) 13.8 9.5 1.5	In-car VOC concentrations along 3 routes during morning and afternoon rush hour Total VOC = 24 VOCs reported. Other measurements: 1,3-butadiene – average concentration measured: Urban = 3.1 $\mu g/m^3$ Interstate = 2.9 $\mu g/m^3$ Total VOC *(median)* Urban = 424 $\mu g/m^3$ Interstate = 234 $\mu g/m^3$ Rural = 53 $\mu g/m^3$
		Toluene • Urban • Interstate • Rural	(median) 59 32 5	
		Ethylbenzene • Urban • Interstate • Rural	(median) 11 6.5 1.2	
		Xylene (sum) • Urban • Interstate • Rural	(median) 54 31 5.2	
Boston, USA (Chan et al 1991)	Winter 1988-89	Benzene Toluene Ethylbenzene Xylene	17 33 6 28	In-car concentrations. Levels on urban roads approx twice those on interstate highways. Use of the car's heater increased VOC levels.
Goteburg, Sweden (Lofgren et al 1991)	April/May 1989	Benzene Toluene Ethylbenzene Xylene	57 200 28 82	22 VOCs measured on a main road during 8 trips. VOC levels were high – one of the three cars studied may have leaked VOCs into the cabin

Location/Ref.	Time	Pollutants	Ave conc. ($\mu g/m^3$)	Comment
New Jersey, USA (Wiesel et al 1992)		Benzene • Suburban (l) • Suburban (h) • Heavy	 11±5 9±8 10±12	Measured concentrations in idling cars and during rush hour commutes. Three characteristic routes examined – suburban, heavily trafficked (approaching New York) and tunnel (Manhattan). Levels increased further on Suburban (h) in a tunnel to Manhattan (by 1.25 – 4 times). Ventilation conditions in car cabin also compared for suburban route: l = low ventilation, h = high ventilation. Lawryk and Wiesel (1996) undertook further measurements of VOCs in-car during 1991-1992: BTEX levels averaged (mean): Benzene = 13 $\mu g/m^3$ Toluene = 35 $\mu g/m^3$ Ethylbenzene = 6.3 $\mu g/m^3$ Xylene = 26 $\mu g/m^3$
		Toluene • Suburban (l) • Suburban (h) • Heavy	 40±27 26±21 56±54	
		Ethylbenzene • Suburban (l) • Suburban (h) • Heavy	 4.4±3.1 3.3±3.0 8±7	
		Xylene • Suburban (l) • Suburban (h) • Heavy	 32±19 24±14 32±16	
Paris, France (Dor et al 1995)	October 1991 November 1992	 Benzene Toluene Ethylbenzene Xylene	*(Range)* 38-46 178-258 28-39 122-169	Measured VOCs and CO on 49 car trips – 3 routes. Measured 1,2,4-trimethylbenzene = 41-53$\mu g/m^3$. Highest levels found on the central route. Also found strong correlation between VOC and CO levels.
Southhampton, England (Bevan et al 1991)	1991	Benzene Toluene Ethylbenzene Xylene	56 122 23 97	Measured on 16 bicycling trips – urban and suburban routes. Levels of VOCs and CO were lower on the suburban route.

Taipei, Taiwan (Chan et al 1994)	March 1992 – six consecutive days.	Benzene • Car • Bus • Motorcycle	 248 160 340	Measured personal exposure to 19 VOCs on 3 commuting routes (with similar traffic conditions), on three commuting modes – car, bus, motorcycle. Batterman: "very high VOC concentrations" – attributed to high aromatic composition of gasoline and very few cars with catalytic converters in Taipei fleet. High levels for motorcyclists – proximity to tailpipe exhaust. Total VOC (ave,max) Car 2101, 4785 µg/m^3 Bus 1274, 2814 µg/m^3 Motorcycle 3107, 6531 µg/m^3
		Toluene • Car • Bus • Motorcycle	 599 367 849	
		Ethylbenzene • Car • Bus • Motorcycle	 112 77 189	
		Xylene • Car • Bus • Motorcycle	 401 244 606	
Taegu, Korea (Jo and Choi 1996)	Winter 1994	Cars • Benzene • Toluene • Ethylbenzene • Xylene Bus • Benzene • Toluene • Ethylbenzene • Xylene	 31 100 9.1 52 20 76 6.9 40	35 rush hour trips. Measurements for urban segment of route, levels were 40-50% lower in the suburban segment. BTEX lower in buses than cars – explanation: heights of air intakes and exhausts, different evaporative emissions and ventilation rates.
Taegu, Korea (Jo and Park 1999)	Winter 1996-97	Benzene Toluene Ethylbenzene Xylene	49 115 12 44	Two cars – increase in levels from Winter 1994 attributed to higher city fleet numbers and higher fuel consumption. Air conditioning had negligible effects.

Taegu, Korea (Jo and Park 1998)	Winter 1997	Benzene • Cars • Buses • Roadside site MTBE • Cars • Buses • Roadside site	 60±51 21±19 7.3±6.5 74±75 16±8 5.2±4	Four cars – 55 trips, Public buses – 54 trips. Measured along a major 10-lane route.
Taegu, Korea (Lee and Jo 2002)	Summer and Winter 2000.	Benzene • Cars • Buses Toluene • Cars • Buses MTBE • Cars • Buses	 33±17 21±8 233±185 153±112 29±13 23±11	Other air toxics measured in this research, ie formaldehyde, acetalhyde, aldehyde.
Hong Kong, China (Chan et al 1999)	1995-96	Criteria Pollutants		Measured in bus, trams, trains and other vehicles. Total hydrocarbon level averaged 8.1 ppm in private cars, the highest of all vehicles tested. "Low position of the car's body and ventilation was believed to facilitate entry of freshly exhausted pollutants" (p.6017).
Birmingham, England (Leung and Harrison 1999)	May/June 1995	Benzene • Total average • Busiest • 2nd busiest • Others Toluene • Total average • Busiest • 2nd busiest • Others	 7.7 24 13 1.2 - 3.1 31 142 22 2.2 - 13	Measured VOCs during rush hour in three cars along six major routes. Others – Four other routes: Range provided.

West Yorkshire, England (Kingham et al 1998)	Autumn 1996	Benzene • Cars • Bus	 108 21	Compared benzene and PM levels in car, bus, train and bicycle commutes along a single busy route – six commutes. The study also compared roadway to non-roadway exposures for bicyclists and found that exposures were much lower for non-roadway commuting.
Sydney, Australia (Duffy and Nelson 1997)	1996	Benzene (Car) • Peak time • Midday 1,3-butadiene • Peak only Benzene (Bus) 1,3-butadiene	 70±13 17±7 12±4 31 6	Four cars and four routes. Two buses on one route. Bus: non-air conditioned, measurements in rush hour (peak time). A second bus with air conditioning measured: Benzene (Bus) = 21 µg/m^3 1,3-butadiene = 4.2 µg/m^3
Ottawa, Canada (Karman et al 2000) (Karman and Graham 2001)	21 winter and 7 summer days in 2000	Benzene • Car • Bus • Roadside site Toluene • Car • Bus • Roadside site Ethylbenzene • Car • Bus • Roadside site Xylene • Car • Bus • Roadside site	 5.1±2.1 3.4±1.4 4.2±3.2 18.1±14.5 9.6±5.2 14.4±13.7 3.1±3.2 2.6±1.2 2.5±2.6 12.3±10.8 10.0±3.5 10.2±7.8	Measured roadside and in-vehicle (car and bus) levels of VOCs and other pollutants – a city without significant industrial emissions. Sample duration: 2 hours in vehicles, 24 hours for roadside. 'In summer, levels in cars and buses were similar, but halved at the roadside sites' (p.6017).

Location/Ref.	Time	Pollutants	Ave conc. ($\mu g/m^3$)	Comment
Sydney, Australia*	September 2002	Benzene		Results represent average weekly exposure levels – Geometric means – as calculated from Table 2 with measurement units converted from ppbv to $\mu g/m^3$. Comparative Comments: In comparison to Duffy and Nelson who measured peak-hour benzene levels in cars in Sydney in the mid-1990s, this study showed a lower level of exposure (ie 40 compared to 70 $\mu g/m^3$). Similarly benzene concentrations inside buses also showed lower exposure levels from 31 to 22.5 $\mu g/m^3$. Benzene levels are roughly similar in magnitude to those found in previous Korean studies and the 1989 Los Angeles study (see above). Given that both the US and EU legislated in the mid-1990s for a 0.8% and 1.0% benzene content requirement in retail fuel respectively, it could be expected that benzene personal exposure concentrations for Sydney car commuters could be in the order of more than double in comparison to those referenced in the US and EU currently. Fuel supplied to the Sydney market currently has an average benzene content of 3% [EA 2000].
		• Car	39.9	
		• Bus	22.5	
		• Bicycle	20.0	
		• Train	12.2	
		Toluene		
		• Car	110.2	
		• Bus	86.1	
		• Bicycle	94.1	
		• Train	47.7	
		Ethylbenzene		
		• Car	19.3	
		• Bus	17.7	
		• Bicycle	12.0	
		• Train	7.6	
		Xylene		
		• Car	87.9	
		• Bus	67.0	
		• Bicycle	53.7	
		• Train	32.1	

* - in addition to studies reviewed by Batterman et al. Represents the results of this study, provided for comparison purposes with previous studies.

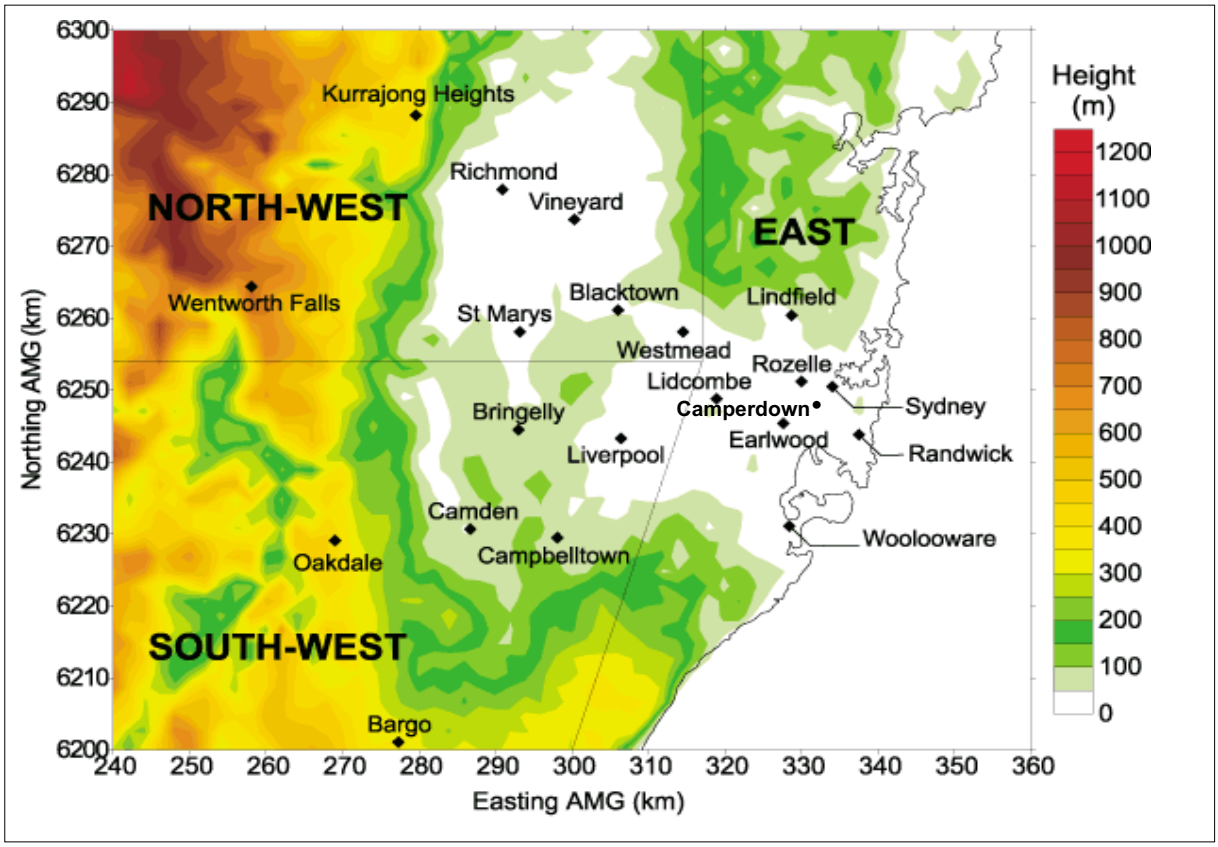
Appendix C – Ambient air quality monitoring

Sydney Metropolitan Air Quality Monitoring Network (AQMN)

Table C1. Monitoring site data used for analyses

AQMN region	Monitoring site data	
	NO_2	$PM_{2.5}$
Central East	Earlwood	Earlwood
	Woolooware	Woolooware
	Lindfield	
	Randwick	
	Rozelle	
North West	Westmead	Westmead
	Richmond	Richmond
	Blacktown	
	St Marys	
	Vineyard	
South West	Liverpool	Liverpool
	Camden	
	Bringelly	

Figure C1. Sydney Air Quality Monitoring Network – Regions and sites



(Source: DEC)

Appendix D – Ambient NO_2 levels at AQMN sites

Table D1. Peak hour ambient NO_2 levels at AQMN sites*

AQMN region	AQMN site	Week 1 (ppbv)	Week 2 (ppbv)	Study (ppbv)
Central East (CE)	**Earlwood**	16.43	25.38	20.91
	Lindfield	11.08	21.45	16.27
	Randwick	14.48	17.80	16.14
	Rozelle	14.78	26.12	20.45
	Woolooware	10.40	17.97	14.19
	Average	**13.43**	**21.74**	**17.59**
North West (NW)	**Blacktown**	9.37	14.68	12.02
	Richmond	4.33	9.10	6.72
	St Marys	8.14	12.28	10.21
	Vineyard	4.03	7.15	5.59
	Westmead	11.22	18.35	14.79
	Average	**7.42**	**12.31**	**9.86**
South West (SW)	**Bringelly**	3.85	9.19	6.52
	Camden	3.85	9.12	6.49
	Liverpool	11.47	20.94	16.21
	Average	**6.39**	**13.08**	**9.74**

* Methodology applied to derive these values previously discussed – see methods.

Table D2. Ranking of AQMN sites for NO_2

Site	Region	Conc. (ppbv)
Earlwood	CE	20.91
Rozelle	CE	20.45
Lindfield	CE	16.27
Liverpool	SW	16.21
Randwick	CE	16.14
Westmead	NW	14.79
Woolooware	CE	14.19
Blacktown	NW	12.02
St Marys	NW	10.21
Richmond	NW	6.72
Bringelly	SW	6.52
Camden	SW	6.49
Vineyard	NW	5.59

Table D2 demonstrates considerable differences in ambient NO_2 levels across the study area. Table D2 indicates which sites were more susceptible to motor vehicle related emissions at weekday peak hours.

- Sites closest to the CBD, such as Earlwood and Rozelle, ranked highest.
- Liverpool and Westmead ranked highest for sites further away from the CBD. These sites are close to business districts in Western Sydney, where significant levels of trip-generating activities are located.
- Monitoring sites at the fringe of the metropolitan area, including those located in semi-rural or 'greenfield' areas such as Camden and Bringelly, recorded the lowest levels.

Appendix E – Ambient $PM_{2.5}$ levels at AQMN sites

Table E1. Commute time ambient $PM_{2.5}$ levels at AQMN sites*

AQMN region	AQMN Site	Week 1 (µg/m^3)	Week 2 (µg/m^3)	Study (µg/m^3)
Central East	Earlwood	8.99	19.76	14.37
	Woolooware	7.55	16.83	12.19
North West	Westmead	8.62	16.92	12.77
	Richmond	9.15	15.70	12.42
South West	Liverpool	12.22	25.58	18.90
	Average (5 sites)	**9.31**	**18.96**	**14.13**

* Methodology applied to derive these values previously discussed – see Table 3 discussion.

Table E2. Ranking of AQMN sites for $PM_{2.5}$

Site	Region	Conc. (µg/m^3)
Liverpool	SW	18.90
Earlwood	CE	14.37
Westmead	NW	12.77
Richmond	NW	12.42
Woolooware	CE	12.19

Table E1 demonstrates small differences in ambient $PM_{2.5}$ levels across the study area. Table E2 ranks the ambient monitoring sites according to average commuting time concentration during the study period. The Liverpool AQMN site in the SW region ranked slightly higher than all other sites. In summary, background ambient concentrations were reasonably similar across the study area. There was noticeably lower spatial variability in $PM_{2.5}$ concentrations compared to NO_2.

Appendix F – Calculation of $PM_{2.5}$ ambient estimate

Method for calculating $PM_{2.5}$ ambient estimate for car commuters based on best available information

1. **Calculation of individual commuter single trip ambient exposure (STAE) estimate**
   The estimated ambient exposure component for a single journey was calculated by obtaining the time-weighted fraction of total commuting time exposure, then, multiplying by the average of two ambient readings corresponding to the closest AQMN site for start and end of journey.

   = Single Trip Time/Total Time x Conc. (AQMN_start + AQMN_end)/2

2. **Calculation of individual commuter sample period ambient exposure (SPAE) estimate**
   The estimated ambient exposure for a single sampling period was calculated by adding together the entire single trip exposure estimates for the sampling period.

   = _ {STAE (x1), STAE (x2),… STAE (xt)}

   t = total number of trips

3. **Calculation of commuter group sample period ambient estimate.**
   This is simply the average of all individual commuter sample period estimates, ie SPAEs. This derived the mode group average ambient estimate based on the best available information (ie use of ambient readings at time of journey taken at closest AQMN site).

   = _ {SPAE (x1), SPAE (x2),… SPAE (xn)}/n

   n = total number of commuters

This derived estimate was then compared to the personal exposure results, ie group average, to establish if it was possible to characterise a relationship between ambient and in-vehicle $PM_{2.5}$ levels for car commuters. This analysis was undertaken to test a recent hypothesis put forward by Adams et al. 2001 who found a 2:1 relationship between in-vehicle and ambient concentrations.

Adams HS, Nieuwenhuijsen MJ and Colville RN 2001, Determinants of fine particle ($PM_{2.5}$) personal exposure levels in transport microenvironments, London, UK, *Atmospheric Environment* 35, 4557-4566.

Appendix G – Sampling times by mode

Commuter sampling time

The amount of time in which passive samplers were exposed for by each commuting mode provides an indication of comparative sample size and contributes to a better understanding of the study results. For instance, the figures below illustrate well the sample size issues associated with bus mode, including a much lower level of commuter participation, especially for Week 2. The average trip time for Week 2 also fell well below 30 minutes. When recruiting volunteers for the study, a 30-minute minimum trip time was applied as a criterion for selection. Figure G1 also demonstrates similar sampling times for car and train modes.

Figure G1. Total sampling time by mode

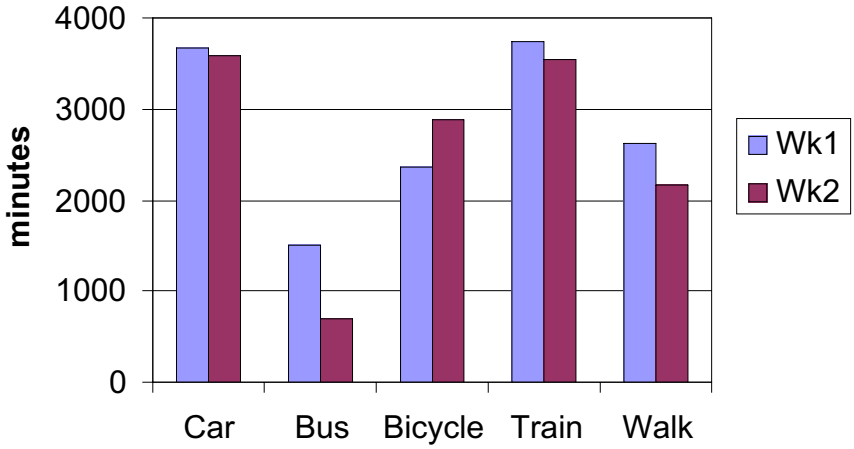
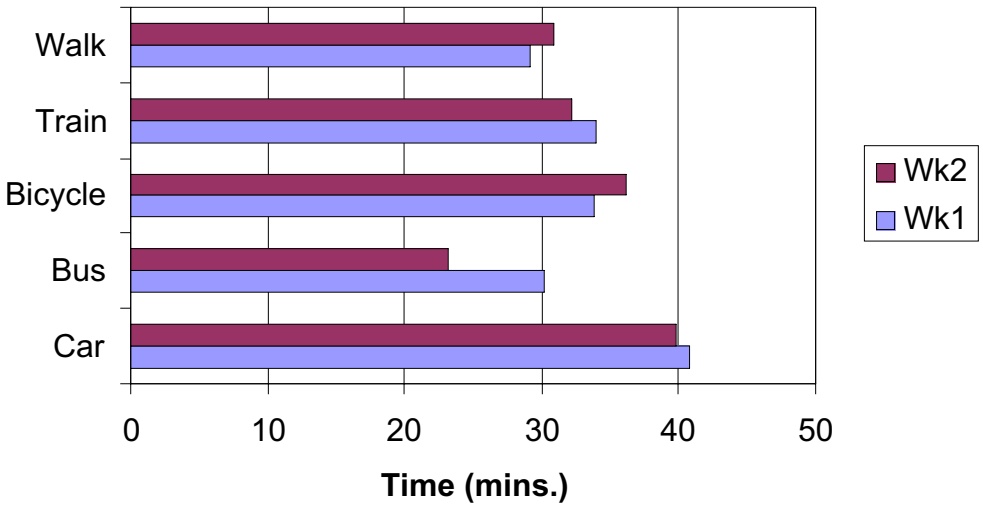


Figure G2. Average trip time by mode



Appendix H – Benzene personal exposure estimate – Car

An estimation of the proportion of total personal exposure to benzene for a weekday peak hour commuter (non-smoker) attributable to weekday peak hour commuting activity in a private motor vehicle.

Method

The recently published Environment Australia Technical Report No.6: BTEX Personal Exposure Monitoring in Four Australian Cities (BTEX-PEM) provides results for average exposure levels and daily commuting times.

The commuter study was undertaken in September so we used the average of the winter and summer geometric means from the BTEX-PEM study for Sydney to obtain a 24-hour exposure [EA 2003 p.38].

= (Benzene_winter + Benzene_summer)/2 = (1.05 + 1.11)/2 = 1.08 ppbv

This result includes all activities undertaken in the 24-hour period, so it therefore includes commuting activities in a private motor vehicle. If we undertake an analysis of total 24 hour exposure estimating the contribution of peak hour commuting from our study, we can then estimate the proportion of total benzene exposure attributable to this source.

We obtained the latest NSW Transport Data Centre [TDC April 2003] results to identify the average time spent commuting to and from work for one weekday. This amounted to 79 minutes, very similar to the result of 80 minutes for our study. We then simply multiplied the number of minutes spent commuting with the car mode average exposure to benzene and compared to the result of the four cities study.

Total 24 hour exposure (minutes) = 1.08 x 1440 = 1555.2

Estimate of commuting exposure = 12.29 x 79 = 970.9

Estimated contribution from peak hour commuting to total weekday benzene exposure = 970.9/1555.2 = 62.4%.

We then considered the mean daily commuting time result from the BTEX-PEM study. This was equal to 1.9 hours or 114 minutes [EA 2003 p.140]. This included all daily commuting activity in addition to the journey to work component.

The difference between total daily travelling time and journey to work travel time left a residual of 35 minutes. We treated this as an average daily travel time for other car commuting activity not related to journey to work. We also treated this as a non-peak hour commuting activity. To quantify, we utilised the results of a previous VOC exposure study undertaken in Sydney in 1996 [Duffy and Nelson 1997] that considered peak hour to non-peak hour (ie midday) exposures. It found that peak hour exposures were around four times higher than non-peak hour exposures (ie 4.1:1 ratio).

Non-peak commuting exposure = 12.29/4.1 = 2.98

Estimate of total non-peak hour benzene exposure = 2.98 x 35 = 104.5

Estimated contribution from non-peak hour commuting to total weekday benzene exposure = 104.5/1555.2 = 6.7%

Estimated contribution from both peak and non-peak hour commuting to total weekday benzene exposure = 69.1%

It is likely that the peak hour estimate overstates to some extent the contribution from this source activity to average daily exposure. The BTEX-PEM study included participants who travelled on different modes of transport and some did not journey to work during peak hour times. The degree to which it may overstate the exposure would require further examination of the BTEX-PEM data to derive a similar sample population that undertook weekday peak hour commuting by private motor vehicle. The comparison nevertheless highlights the high proportion of benzene exposure potentially attributable to the activity of peak hour commuting by private motor vehicle.

If associated car use activities of refuelling a motor vehicle and time in an underground car park are also considered, this figure would be higher [EA 2003]. Furthermore, warmer temperatures, particularly extreme heat, have been shown to dramatically raise in-vehicle concentrations of VOCs for cars in static mode (parked, unventilated) [Fedoruk and Kerger 2003]. Occupancy in a vehicle in these conditions without ventilating the cabin can potentially lead to even higher VOC exposures.

It is interesting to compare Sydney with the Perth mean exposure for the BTEX-PEM study. Perth results were 0.40 ppbv; almost three times lower than the other three participating Australian cities. The result has been attributed to a stricter benzene content requirement in petrol (ie 1%) that was in force at time of monitoring in that city. This compares to the current average benzene content levels in other states, including NSW, of 3% at time of monitoring [EA 2000].

This result suggests that personal exposure to benzene can be substantially reduced through stricter benzene content requirements on retail fuel supply. Legislation to regulate benzene in retail fuel to a 1% content level could potentially reduce total personal exposure by well over 50%, as is perhaps demonstrated by the Perth result. A commitment to such a regulatory policy would also be consistent with World Health Organisation (WHO) recommendations to limit exposures to benzene to as low as possible [WHO 2000]. Nationally, Australia is expected to achieve the 1% content benchmark on 1 January 2006 when new National fuel quality standards take effect.

The benzene limit in the United States has been 0.8% since January 1995. A limit of 1% has been in existence in the European Union for a similar time. An annual average standard for ambient air of 1 ppbv is expected to come into effect in Europe in 2010. The BTEX-PEM study results for Sydney showed that personal exposure levels marginally exceeded this newly proposed ambient benchmark.

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