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INDOOR AIR PROJECT

PART 1: MAIN REPORT

Indoor Air in Typical Australian Dwellings

A report to the
Air Quality Section, Environment Standards Branch,
Department of the Environment, Water, Heritage and
the Arts
COMMONWEALTH OF AUSTRALIA



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Contents

PART 1: MAIN REPORT

EXECUTIVE SUMMARY	6
PROJECT TEAM	10
ACKNOWLEDGEMENTS.....	10
GLOSSARY	11
1. BACKGROUND.....	17
2. THE SAMPLING AND DWELLINGS	18
2.1 Statistics of Dwellings Sampled.....	18
2.2 Measurement Design	22
2.3 Measurements of Air Quality	22
2.4 Household Surveys and Diaries	23
2.5 The Incidence of Smoking Indoors	24
2.6 Meteorology during the Study Period	25
2.7 Air Quality during the Study Period	28
3. INDOOR AIR IN TYPICAL AUSTRALIAN DWELLINGS.....	32
3.1 Continuous Measurements (Winter/Spring & Summer/Autumn).....	32
3.1.1 Activities from Diaries	32
3.1.2 Temperature, Water Vapour and Relative Humidity.....	33
3.1.3 Carbon Dioxide	34
3.1.4 Carbon Monoxide.....	35
3.1.5 Particulates: PM2.5.....	35
3.2 The Statistics of Indoor Air Quality in Typical Australian Dwellings	45
3.3 Seasonal Variations in Indoor Air Quality	51
3.4 Comparison of Indoor Air in Typical Australian Dwellings with Previous Indoor Measurements in Australia	54
4. THE INFLUENCE OF ROADS ON INDOOR AIR	58
4.1 Results.....	58
4.1.1 First Analysis Using Entire Data Set	59
4.1.2 Second Analysis Using the Reduced Data Set	67
4.2 Other Studies.....	70
4.3 Confounding Variables	72
4.4 Conclusion – the Influence of Roads on Indoor Air	73
5. THE INFLUENCE OF THE BUILDING CHARACTERISTICS, MATERIALS AND ACTIVITIES ON INDOOR AIR	76
5.1 Weekly Average Correlation Analysis	76
5.2 Survey Analysis	79

5.3	A Review of Other Studies of Emissions from Indoor Activities and their Relationships to the Results of This Study	87
5.4	Summary of the influences of Building Characteristics, Materials and Activities on Indoor Air Quality	89
6.	CONCLUSIONS.....	91
7.	REFERENCES.....	95

EXECUTIVE SUMMARY

The Department of Environment, Water, Heritage and the Arts commissioned CSIRO to carry out a study that will provide information on the indoor air quality of the “average” private dwelling in Australia, as well as the concentration of a range of specific chemicals within and outside of private dwellings. The study has measured the concentration of a range of pollutants indoors and outdoors, and associated variables and gathered data on the building characteristics and on potential sources of indoor air pollutants, including outdoor air.

The study was conducted in Winter/Spring of 2008 and Summer/Autumn of 2009 and involved sampling in 40 dwellings for 7 days during each period. The dwellings were chosen to represent the stock of Australian dwellings, in as far as that was possible with the numbers sampled. Approximately 20 of the dwellings were located close to busy roads and 20 were far from such roads. The dwellings were located in the south-eastern suburbs of Melbourne spread over an area of approximately 800 km².

The meteorological conditions experienced during this study were representative of those experienced by most of Australia’s population. However some differences were observed. These were: the rainfall during January 2009 was lower than the long term average; and the relative humidity during August 2008 was slightly higher than the long term average. These differences are not expected to impact on the study.

Air quality during this sampling program can be considered typical for Melbourne, except during January and February 2009 when bushfires in the Melbourne surrounds resulted in ambient particle concentrations enhanced by about 20% during these months.

The first purpose of this study was to determine indoor air quality in typical Australian dwellings.

This study of indoor air quality was conducted because there are no other extensive studies of indoor air quality in typical dwellings in Australia. This limits the comparisons that can be made with the data to, in many cases, comparisons against measurements in dwellings that have indoor air quality issues.

The concentrations of indoor air pollutants observed in this study are either lower than or comparable with the concentrations of these compounds observed in previous studies in Australia. In particular:

- CO₂, CO and NO₂ concentrations in these typical dwellings are less than those observed in previous studies of dwellings with unflued gas heaters. Unflued gas heaters are known sources of these pollutants. In Victoria unflued gas heaters are only permitted to operate on bottled liquid petroleum gas, which is predominantly used in rural areas with no access to natural gas. There were no dwellings with unflued gas heaters included in this study.
- The formaldehyde concentrations in these typical dwellings are less than those observed in previous studies of mobile homes and caravans. These results are not unexpected due to the high usage in caravans and mobile homes of materials that release formaldehyde. According to ABS statistics, mobile homes and caravans make

up only a very small proportion of private dwellings in Australia, and as such, none have been included in the sample of dwellings used for this study.

- The PM_{2.5} concentrations in these typical dwellings are less than those observed in previous studies of “cooking events”. Various types of cooking are known to be significant sources of PM_{2.5}. This study took measurements of PM_{2.5} inside private dwellings continuously over 7 day periods, which included many lengthy periods where “cooking events” did not occur. While peaks might be expected during “cooking events”, it is not unexpected that the seven day average is less than that observed in previous studies where “cooking events” were targeted.
- This indoor data on PM_{2.5} indicates that there are 15 days where the one day average concentration of PM_{2.5} was equal to or exceeded 25 µg m⁻³ inside a dwelling, out of a total data set of 465 days made up from measurements on 40 dwellings. The National Environment Protection (Ambient Air Quality) Measure has an Advisory Reporting Standard for the monitoring for particles as PM_{2.5}. The outdoor advisory limit for PM_{2.5} is 25 µg m⁻³ over a one day averaging period. There is no Australian indoor guideline for exposure to PM_{2.5}.
- TVOC concentrations measured in this study are comparable with those observed previously for non-complaint buildings.
- The fungi concentrations in these typical dwellings are comparable with those observed in previous studies of dwellings in Australia.

The weekly average concentrations (or parameter values) measured show that temperature, water vapour mixing ratio, carbon dioxide, carbon monoxide, nitrogen dioxide, formaldehyde, other carbonyls, TVOCs and BTEX have higher concentrations indoors compared with outdoors. Previous studies indicate that all these species have indoor sources.

The results of the weekly average measurements showed that bacteria, fungi, PM_{2.5} and PM₁₀ had no significant difference between the indoor and outdoor concentrations. Previous studies indicate that all these species have indoor sources. For these constituents in this study, the indoor removal processes appear to be sufficient to keep balance with the indoor sources at concentrations comparable with those outdoors.

The elevated NO₂ concentrations observed indoors in Winter/Spring and outdoors in Summer/Autumn have a pattern consistent with a NO₂ source from unflued combustion processes, which have a similar large change in incidence between these two seasonal periods. There is also a contribution to indoor concentrations arising from the proximity to a busy road, discussed below.

The ozone concentrations are lower indoors than outdoors in these measurements. These results for ozone are expected since there are not large sources of ozone indoors in Australian dwellings and the inside surface materials on walls, flooring and furniture are very effective in removing ozone from the air.

The absence of guidelines for indoor air quality in Australia prevents a more definitive rating of the results.

The second purpose of this study was to determine whether the proximity of dwellings to busy roads has an influence on indoor air quality.

As part of the experimental design there was selection of two sets of dwellings, Near-Road and Far-Road. A number of statistical analyses were carried out to determine whether proximity to busy roads had an influence on indoor air quality. NO₂ was found to be the only pollutant for which the proximity to busy roads resulted in enhanced concentrations both outdoors and indoors. Other vehicle pollutants – CO, TVOCs, benzene, PM10 and PM2.5 showed no statistically significant and logical connection to proximity to roads indicating that there were probably several important confounding factors that influenced the indoor levels of these pollutants in dwellings during this study; proximity to busy roads may have been one of these factors, but it was not a dominating factor.

The third purpose of the study was to relate indoor air quality to the characteristics of the dwelling, materials and indoor activities.

Dwelling age showed significant negative correlations with concentrations of formaldehyde, other carbonyls, TVOCs and several of the aromatic compounds. There is a strong positive correlation between dwelling age and the closed ventilation or leakiness of a dwelling (see Appendix C). Increased leakiness (with dwelling age) would tend to reduce the indoor concentrations of these compounds when the dwelling is in its closed-state, as these compounds all have indoor sources and average indoor concentrations higher than outdoors concentrations.

The presence of an attached garage with internal door to the dwelling caused significant increases in indoor concentrations of PM10, benzene and m-xylene. This most likely arises due to vehicle exhaust emissions that enter the dwelling via the garage.

The elevated CO₂ observed indoors has a diurnal pattern similar to that of domestic activity. The number of occupants in a dwelling is positively correlated with concentrations of CO₂, PM10 and NO₂. A related positive correlation is that of occupant density (occupants per unit volume of the dwelling) with CO₂. The major source of CO₂ in dwellings is human respiration. PM10 can be resuspended from human movements, and NO₂ has been already associated with unflued combustion.

The level of ventilation, measured as the average number of external windows and doors opened throughout the week, is negatively correlated with CO₂ and formaldehyde because these gases have indoor sources and are transported outdoors in a well ventilated dwelling. The level of ventilation is positively correlated with ozone, which indicates higher ozone penetration into a well ventilated dwelling.

The elevated CO observed indoors has a diurnal pattern similar to that of domestic activity. The daily maximum that occurs indoors around 07:00 to 08:00 is due to elevated concentrations outside, presumably due to vehicle exhaust emissions. Combustion events (any form of burning in the dwelling) were positively correlated with CO₂, CO and PM2.5 and weakly correlated with NO₂, which are all products of combustion. In particular cooking with a gas stove compared with an all electric stove and oven resulted in elevated concentrations of NO₂, CO₂, PM2.5, formaldehyde, TVOC, benzene, and CO. In approximately 10% of the homes in Winter/Spring there was a 4 fold increase in PM2.5 concentration in the early evening at around 19:00 to 20:00, at the time of the peak in combustion activity.

Activities that cause mechanical generation of particles (vacuuming, sweeping, dusting) did not significantly influence the weekly indoor concentration of particles (PM10 or PM2.5).

In Winter/Spring, the dwellings with renovations, new flooring surfaces or new furniture had significantly higher temperature and PM10 than dwellings that did not report renovations, indoor painting, flooring surfaces polishing or new furniture. The reason for the difference in PM10 is not known but may be due to residual dust or reduced minimum ventilation rates from the renovation. The reason for the higher temperature may be due to more efficient heating and insulation, and reduced minimum ventilation rates in recently-renovated dwellings. In Summer/Autumn no statistically significant differences were found between the two subsets of dwellings (renovations and no renovations) for any of the pollutants.

Solvent use was positively correlated with TVOC concentrations, as would be expected because of the vaporization of the organic chemicals when the solvents are used.

The weekly average concentrations of Nicotine were below the detection limit of the measurements, consistent with the absence of smoking from the dwellings under consideration (or in the case of the only indoors smoker in this study, the isolation of the smoking area from the general dwelling living area).

The emissions from materials used, activities undertaken and types of chemical products used within dwellings are reviewed. An examination of the available information on the chemical composition of these products was undertaken, but with little useful information unearthed.

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GLOSSARY

Simple definitions of various technical terms are given here to assist the reader. If required, the reader should look to other sources for more formal and technical definitions.

ABS	Australian Bureau of Statistics (http://www.abs.gov.au/)
Accuracy	(Air quality measuring methods) Closeness of agreement between a single measured value and the value of the air quality characteristic itself, or the accepted reference value.
Active sampling	Continuous collection of sample through a collection media for a specific period of time normally at a specific air flow rate using a pump.
Aerosol	A suspension of fine solid, liquid or mixed-phase particles in air.
AGL	Height Above Ground Level
Ambient air quality	The prevailing quality of the surrounding air in a given area in terms of the types and amounts of various air pollutants present.
AQMS	Air Quality Monitoring System
Bacteria	Bacteria are single-celled prokaryotic organisms and these occur naturally in the air.
BTEX	Benzene, Toluene, Ethylbenzene and the three isomers of Xylene
Bias	(Air quality measuring methods) Consistent deviation of the measured value from the value of the air quality characteristic itself, or the accepted reference value.
Bioaerosol	Airborne micro-organisms or their constituent parts (bioaerosols) are the airborne particles that are biological in origin. The two most prevalent viable bioaerosols are fungi spores and airborne bacteria.
Biomass Burning	Burning of vegetation in prescribed burns and wildfires
Breakthrough Volume (BV)	The volume of air containing a constant concentration of analyte which may be passed through a sorbent tube before a detectable level (typically 5%) of the analyte concentration elutes from the non-sampling end. Alternatively, the volume sampled when the amount of analyte collected in a back-up sorbent tube reaches a certain percentage (typically 5%) of the total amount collected by both sorbent tubes. These methods do not give identical results. For purposes in this document the latter definition will be used.

Carbonyls	The group of organic compounds that include the aldehydes and the ketones
CAS	The CAS Registry number is a unique substance identifier assigned by the American Chemical Society/Chemical Abstracts Service that is independent of any system of chemical nomenclature. CAS Registry numbers are internationally recognised. (http://www.cas.org/EO/regsys.html)
cfu/m ³	Colony-forming unit per cubic metre of air is a measure of viable bacterial or fungal numbers per cubic metre of air
CMAR	CSIRO Marine and Atmospheric Research (http://www.cmar.csiro.au).
CO	Carbon monoxide
Continuous sampling	Ongoing, (unbroken in time except for standard instrument checks) measurements of the concentration of air pollutant(s) over a time which is typically any period between days and years. This monitoring is often undertaken to establish compliance with licence conditions.
CSIRO	Commonwealth Scientific and Industrial Research Organisation (http://www.csiro.au)
Diffusion	In air pollution meteorology the words dispersion and diffusion are often used interchangeably and diffusion refers to turbulent diffusion not molecular diffusion. This is also the case in this report. However, strictly speaking dispersion and diffusion mean different things. Diffusion refers to dilution of pollutants by turbulent eddies in the atmosphere whose dimensions are smaller than that of a pollutant plume or a puff (see also Dispersion).
Dispersion	Dispersion refers to the movement or transport of pollutants horizontally or vertically by the wind field and their dilution by atmospheric turbulence. Dispersion includes both transport and diffusion of pollutants (see also Diffusion).
DNPH	2,4-Dinitrophenylhydrazine (used for trapping carbonyls)
Enhancement	This term is applied to the concentration of compounds during events and indicates the increase in concentration above background levels at some time during the event
Far-Road	The boundary of the property, typically the front or back fence, greater than 300 m from the edge of a busy road.
Fungi	Fungi form a kingdom of eukaryotic organisms, occurring in soil, in and on plants and animals, in air, and indoors. In general, fungi actively growing indoors can exist as yeasts or moulds.
Integrated sampling	Taking a sample over an extended period of time, e.g. 1 day or 7 days, to obtain a single concentration or other measure that

	represents the mean value for the whole time of the entire sampling period.
Inversion	An atmospheric layer in which potential temperature increases with altitude (e.g. Nocturnal Inversion). These layers are stable and resistant to vertical mixing and hence may restrict the vertical dispersion of pollutants. Properly described as a temperature inversion. The term is often used to refer to the bottom of an inversion layer, i.e. the lowest altitude at which the potential temperature starts increasing.
LOD	Limit Of Detection. The smallest concentration detectable by a measurement system as the concentration of the substance being measured approaches zero.
MDL	Minimum Detectable Limit. The lowest measured concentration in a sample that can be regarded as statistically significant [ISO6879].
mg	Milligram (1 mg = 10 ⁻³ gram = 0.001 gram). One thousandth of a gram
mg m ⁻³	Milligram per cubic metre. 1 mg m ⁻³ = 1000 µg m ⁻³
Mould	A common name for fungi found both indoors and outdoors.
NATA	National Association of Testing Authorities
n/a	Not applicable
n/r	Not recorded
Near-Road	The boundary of the property, typically the front or back fence, within 150 m from the edge of a busy road.
ng	Nanogram (1 ng = 10 ⁻⁹ gram = 0.000000001 gram). One billionth of a gram
Nm ³	Normal cubic metres. Volume of a gas sample in cubic metres expressed at 0 degrees Celsius and 1.0 atmosphere (101.325 kilopascals).
NO ₂	Nitrogen dioxide
NPI	National Pollutant Inventory (see http://www.npi.gov.au/)
Nocturnal Inversion	A layer of stable air (see Inversion) of the order of 10m to several 100m depth adjacent to the earth's surface that can form at night over land due to infrared radiative cooling of the surface particularly under the meteorological conditions of a cloudless sky and light winds, the nocturnal inversion typically erodes quickly after sunrise.

Other carbonyls	A term used in this report representing the total sum of carbonyl concentrations less the amount of formaldehyde.
Passive sampling	Continuous collection of sample through a diffusive surface on to a collection media for a specific period of time without the use of pump.
Precision	The closeness of agreement between independent-test results obtained under stipulated conditions. [ISO 3534-1]
PM2.5	Mass of particles with aerodynamic diameter less than 2.5 μm .
PM10	Mass of particles with aerodynamic diameter less than 10 μm .
ppb	Parts per billion (by volume): 1 ppb = 1/1000 ppm.
ppm	Parts per million (by volume): a unit for the concentration of a gas in the atmosphere based on the mixing ratio approach. A concentration of 1 ppm is equivalent to either a volume of 1 cubic metre of pure undiluted gas in 1 million cubic metres of air, or one mole of pure undiluted gas in 1 million moles of air. These two measures are slightly different due to discrepancies from the ideal gas law. The expression ppm (or ppb) is without dimensions. The ppm (or ppb) unit is useful because its value is unaffected by changes in temperature and pressure, and also because many sampling techniques are based on volume concentrations. Concentrations of gaseous compounds can be converted from mixing ratio units, e.g. ppm units (volumetric), to density units, e.g. mg m^{-3} (mass/volume), using the following formula:
	$C(\text{mg m}^{-3}) = \frac{273.15 \times M_w \times C(\text{ppm})}{22.4136 \times (273.15 + T)}$
	where C is the concentration, M_w is the molecular weight of the gas, and T is the ambient temperature in degrees Celsius.
	At a temperature of 0 degrees Celsius, the conversion factors from 1 ppm to mg m^{-3} are: benzene (C_6H_6) 3.490; carbon monoxide (CO) 1.250; formaldehyde (HCHO) 1.340; nitrogen dioxide (NO_2) 2.050; nitric oxide (NO) 1.340; ozone (O_3) 2.140; sulfur dioxide (SO_2) 2.860; toluene (C_7H_8) 4.113; xylene (C_8H_{10}) 4.740.
Primary air pollutant	Pollutant entering the atmosphere directly from a source. A primary air pollutant may react to form a secondary air pollutant (see definition below).
Relative humidity	The ratio of the air's actual mixing ratio to its mixing ratio if saturated at the same temperature and pressure.

Repeatability	Precision under repeatability conditions [ISO 3534-1]
Quantiles	The fraction (or percent) of points below the given value. That is, the 0.3 (or 30%) quantile is the point at which 30% percent of the data fall below and 70% fall above that value. Certain quantiles have special names. The 0.25-, 0.50-, and 0.75-quantiles are called the first, second and third quartiles. The 0.01-, 0.02-, 0.03, ... , 0.98-, 0.99-quantiles are called the first, second, third, ... , ninety-eighth, and ninety-ninth percentiles.
sccm	Standard cubic centimetres (of gas) per minute
Spot sampling	To collect a sample directly into a sampling device at a specific time or over as short a period as feasible.
Summer/Autumn	The period between 12 th January and the 4 th of May 2009 when sampling was conducted.
TO-11A	US EPA Compendium Method TO-11A. Determination of Formaldehyde in Ambient Air Using Adsorbent Cartridge Followed by High Performance Liquid Chromatography (HPLC) [Active Sampling Methodology]. (http://www.epa.gov/ttn/amtic/files/ambient/airtox/to-11a.pdf)
TNTC	Too Numerous to Count – an expression used in the measurement of bioaerosols.
TVOCs	Total Volatile Organic Compounds – the total amount of all individual volatile organic compounds measured in an air sample. In this report, TVOC was measured as the sum of all gas chromatograph flame ionization detector peaks from early eluters (typically C6 alkanes, e.g. dimethylbutane at boiling point about 50°C) to late eluters (typically pentadecane at boiling point about 260°C), expressed as a toluene-equivalent concentration.
Typical	Serving as a representative specimen of a class or kind (Shorter Oxford English Dictionary).
VOCs	Volatile Organic Compounds. These organic compounds have relatively low boiling points and, therefore, readily evaporate into the atmosphere under conditions of ambient temperature and pressure.
Water vapour mixing ratio	The ratio of the mass of water vapour per kg of dry air.
µg	Microgram (1 µg = 10 ⁻⁶ gram = 0.000001 gram). One millionth of a gram
µm	Micrometre (1 µm = 10 ⁻⁶ metre = 0.000001 metre). One millionth of a metre
µg m ⁻³	Microgram per cubic metre: a unit for the concentration of a gas or particulate matter in the atmosphere based on the density approach (mass per unit volume of air). Concentrations of

gaseous compounds can be converted from density units, e.g. mg m⁻³ (mass/volume), to mixing ratio units, e.g. ppm units (volumetric), using the following formula:

$$C(\text{ppm}) = \frac{22.4136 \times (273.15 + T) \times C(\text{mg} / \text{m}^3)}{273.15 \times M_w},$$

where C is the concentration, M_w is the molecular weight of the gas, and T is the ambient temperature in degrees Celsius.

At a temperature of 0 degrees Celsius, the conversion factors from 1 mg m⁻³ to ppm are: benzene (C₆H₆) 0.287; carbon monoxide (CO) 0.800; formaldehyde (HCHO) 0.746; nitrogen dioxide (NO₂) 0.488; nitric oxide (NO) 0.746; ozone (O₃) 0.467; sulfur dioxide (SO₂) 0.350; toluene (C₇H₈) 0.243; xylene (C₈H₁₀) 0.211.

Winter/Spring

The period between 28th August and 4th December 2008 when sampling was conducted.

1. BACKGROUND

The Department of Environment, Water, Heritage and the Arts has commissioned CSIRO to carry out a study to provide information on the indoor air quality of the typical private dwelling in Australia, as well as the concentration of a range of specific chemicals within and outside of private dwellings. The study measured the concentration of a range of pollutants indoors and outdoors, and associated variables and gathered data on the building characteristics and on potential sources of indoor air pollutants, including outdoor air.

This is the Final Report of the project. The report is presented in four main sections. These cover:

- the statistics of the dwellings sampled and measurements obtained (Section 2)
- the indoor air measurements in typical Australian dwellings (Section 3)
- the influence of proximity to busy road on indoor air quality (Section 4) and
- the relationship of indoor air quality to the materials of the dwelling and indoor activities (Section 5).

As well as these, there are Appendices on the selection process for dwellings (Appendix A), instrumentation used in the study (Appendix B), measurements of ventilation on 15 of these dwellings (Appendix C), emission factors and household chemicals (Appendix D) and an accompanying CD with data summaries. There is a separate report on Persistent Organic Pollutants and Metals in Australian dwellings.

In this report the following questions are addressed.

- What is the indoor air quality of a typical Australian dwelling?
- What is the effect of busy roads on indoor air quality of a typical Australian dwelling?
- What is the effect of building construction, materials and activities on the indoor air quality of a typical Australian dwelling?

2. THE SAMPLING AND DWELLINGS

The study design required Winter/Spring and Summer/Autumn sampling in 30 typical Australian dwellings. The Winter/Spring sampling was conducted between 28th August and 4th December 2008, with equipment installed in 41 dwellings, and sampling completed in 40 dwellings (one resident asked for the equipment to be removed after one night). The Summer/Autumn sampling was conducted between the 12th January and the 4th of May 2009 and sampling was completed in 40 dwellings. Of the 40 dwellings from which Winter/Spring sampling was completed, 39 dwellings were sampled again in the Summer/Autumn period – one participant declined to participate in the second round of sampling for personal reasons and a backup dwelling was selected which had similar characteristics as the original dwelling.

2.1 Statistics of Dwellings Sampled

The locations of dwellings sampled are shown in Figure 1. Dwellings with a green marker in Figure 1 are Far-Road dwellings, and dwellings with a blue marker are Near-Road dwellings (as discussed in Section 4). The EPA Air Quality stations are shown, as well as Moorabbin Airport meteorological station. The dwellings selected for sampling were within the area defined by the EPA Air Monitoring Stations in Alphington, RMIT, Footscray, Richmond, Brighton, Box Hill and Dandenong, and the CSIRO Bayside Air Quality Station in Aspendale, or as in the case of one house (which was initially selected for trialling the equipment), within 10 km of this boundary. The sampling area comprised approximately 800 square kilometres and included inner suburbs <5 km from the city centre in westerly, easterly and southerly directions, suburbs between 5–20 km from the city centre in easterly, south easterly and southerly directions, and outer suburbs 20–40 km from the city centre in the south eastern and southern directions.

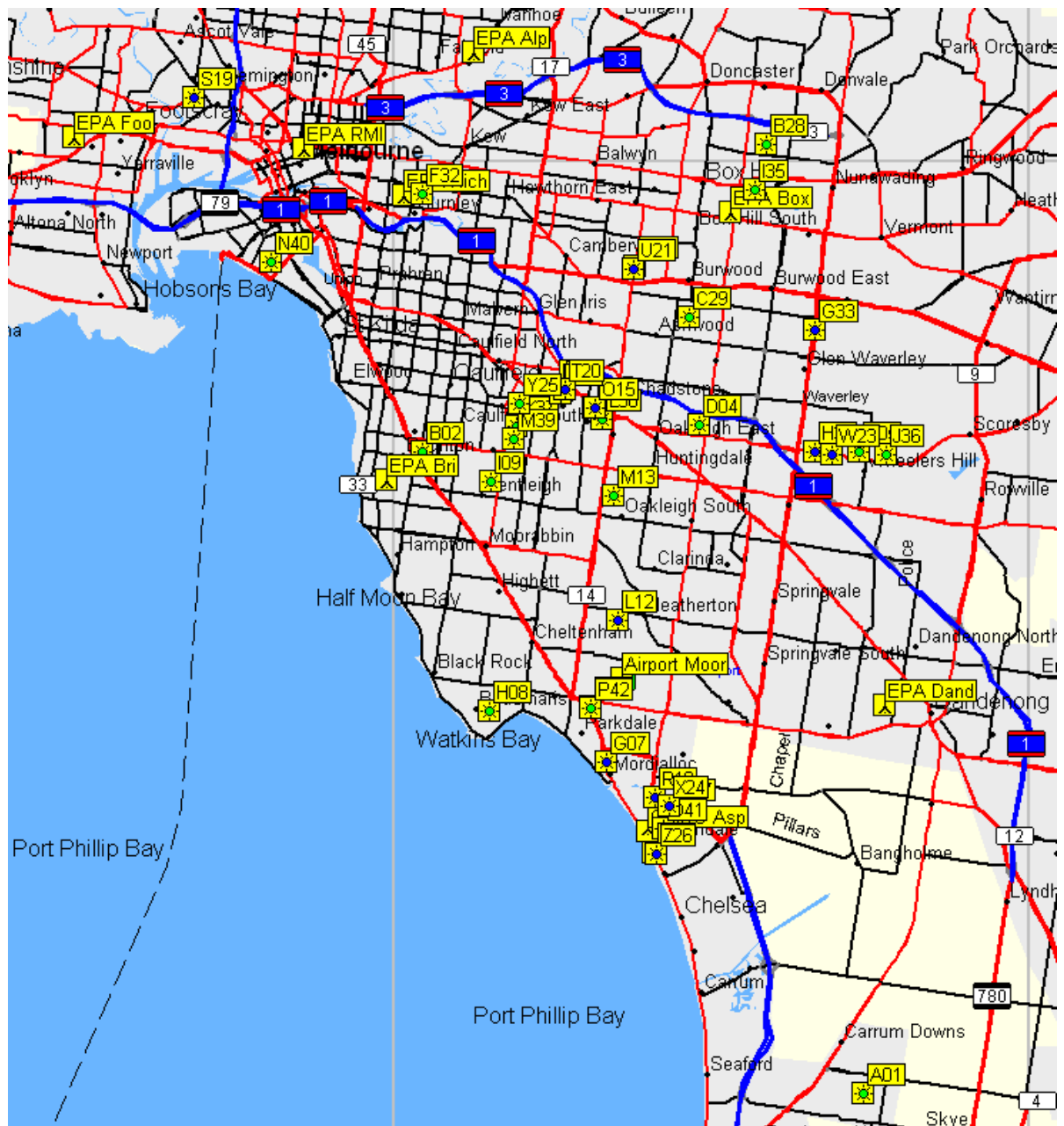


Figure 1 . Location of the dwellings sampled in this study. The yellow boxes with a letter and a two digit number are the dwellings studied. Those dwellings accompanied by a yellow square with a green sun are far road dwellings, those accompanied by a blue sun are near road dwellings. The locations of the EPAV air quality monitoring stations, the CSIRO Aspendale air quality monitoring station, and the Morabbin Airport meteorological observing site are marked.

The following two tables present the statistics of the dwellings sampled. Some additional notes follow Table 1.

Table 1 presents the distribution of Australian dwellings according to structure, age and material according to ABS statistics. Table 2 presents the statistics of the selected Near-Road and Far-Road dwellings compared with the ABS statistics. There was a difficulty within the small sample size (20 dwellings each for Near-Road and Far-Road) in exactly matching all three criteria simultaneously. In as far as the dwellings volunteered matched, the selection was made to meet the criteria.

The range of dwelling structures cover 98.9% of dwellings in Australia, the range of dwelling age covers 95.2% of dwellings in Australia (the balance have unknown ages), and the types of dwelling material sampled cover 84.5% of dwellings in Australia.

Table 1. The distribution of Australian dwellings according to selected structure, age and material characteristics according to ABS statistics

Population	% of dwellings from ABS statistics	Approx. no. required per 20 dwellings
Dwelling structure*		
Separate House	77.5	15
Semi-detached or flat	22.5	5
Dwelling age**		
Less than 5 years	7.8	2
5–19 years	31.9	6
20–49 years	41.5	8
50 or more years	18.9	4
Dwelling material***		
Double brick	35.4	7
Brick veneer	48.4	10
Weatherboard	16.2	3

* Dwelling structures selected cover 98.9% of Australian dwellings.

** Dwelling age ranges cover 95.2% of Australian dwellings. The balance have unknown ages.

***Dwelling materials selected cover 84.5% of Australian dwellings.

Table 2. The statistics of the selected Near-Road and Far-Road dwellings compared with the ABS statistics

Dwelling characteristic	Near-Road No. obtained	Near-Road % obtained	Far-Road No. obtained	Far-Road % obtained	% of dwellings from ABS statistics
Dwelling Structure					
Separate House	16	76.2	15	78.9	77.5
Semi-detached or flat	5	23.8	4	21.1	22.5
Dwelling Age					
Less than 5 years	1	4.8	2	10.5	7.8
5–19 years	6	28.6	4	21.1	31.9
20–49 years	6	28.6	7	36.8	41.5
50 or more years	8	38.1	6	31.6	18.9
Dwelling Material					
Double brick	8	38.1	4	21.1	35.4
Brick veneer	10	47.6	11	57.9	48.4
Weatherboard	2	9.5	3	15.8	16.2
Other	1	4.8	1	5.3	

Two dwellings did not fit into the dwelling material categories of double brick, brick veneer or weatherboard, and are marked in Table 2 as ‘Other’. These two dwellings had been renovated which had introduced an additional building material to the structure, making classification difficult. The first of these dwellings in Table 2 Near-Road is a combination of brick and rendered blueboard (Q17). The second dwelling in Table 2 Far-Road is a combination of brick veneer and double brick (E05).

A description of the selection process for dwellings is presented in Appendix A.

2.2 Measurement Design

The indoor air quality of a building is a result of the following five factors:

- concentrations of pollutants in outdoor air that can penetrate into the building by ventilation and infiltration
- sources of pollutants indoors, or within the ventilation systems of the building
- occupants and their activities that generate pollutants
- ventilation which expels indoor air pollutants and brings outdoor air into the building
- materials and processes that remove the pollutants from the air within the building.

It is important to understand the role that each of these factors may play in order to understand indoor air quality.

In this study, the indoor air quality is directly measured. As well as this, for the purpose of identifying the causes of indoor pollutants, four factors contributing to indoor air quality were also examined. These were:

- external contributions (measurements of air quality in outdoor air)
- building materials and contents
- human indoor activities and use of domestic products
- ventilation (measured on a sub-set of half the dwellings).

This information contributes to the understanding of the causes of indoor air quality in typical Australian dwellings.

2.3 Measurements of Air Quality

The concentrations of a range of pollutants indoor and outdoors were measured as part of this study. The measurements include: temperature, absolute water vapour content, relative humidity, CO₂, CO and PM_{2.5} as continuous measurements; weekly integrated measurements of O₃, NO₂ and nicotine by passive sampling; and PM₁₀, formaldehyde, other carbonyls, TVOCs, and speciated VOCs (BTEX) by active sampling. Fungi and bacteria are measured by spot sampling. A summary of the number of successful measurements made indoors and outdoors in Winter/Spring and Summer/Autumn is given in Table 3.

Table 3 Number of successful measurements made in dwellings during Summer/Autumn and Winter/Spring and indoors and outdoors

Measurement	Winter/Spring indoors	Winter/Spring outdoors	Summer/Autumn indoors	Summer/Autumn outdoors
CO	37	35	40	40
CO2	38	35	40	40
PM10	39	40	40	39
PM2.5	39	38	40	40
Carbonyl	39	39	40	40
VOCs	40	39	40	40
NO ₂ , O ₃ , Nicotine	40	40	40	40
Fungi & Bacteria	33	33	39	39

2.4 Household Surveys and Diaries

The following is an outline of information gathered about the dwellings and activities therein during the study. Data on the household occupants, their activities and the household characteristics were collected via (a) a survey and interview conducted at the time of installation of the air quality equipment in its dwelling, and (b) an activity diary filled in by the occupants during the sampling week.

The survey collects data on the characteristics of the home and some information on what typically occurs within the home. This data can be compared with the activity diary to determine if unusual activities have been performed in the home during the sampling week. The data on characteristics of the home was combined with information collected earlier in the selection questionnaire, and used to identify possible pollutant sources in or around the home, or other aspects that may affect the level of pollutants. The survey collected information in the following categories:

- Potential sources of pollutants in the nearby vicinity e.g. from construction or automotive shops
- Outdoor sources e.g. petrol fuelled garden equipment, vehicles and water sources on the property
- Indoor sources of dust, such as the use of mats at entrances to the building, the wearing of footwear indoors and possible exposure through occupants' employment
- Indoor sources of moisture e.g. from leaking pipes, heated fish tanks and clothes drying
- Pollutant sources from combustion e.g. stoves, candles, cigarettes
- Heating and cooling sources e.g. type of heater and location in the house
- Location and use of ventilation systems
- Materials and structure of the building, and any recent maintenance carried out
- Dimensions of the rooms
- Furnishings contained within the house

- Meter readings for gas, electricity and water.

The activity diary collected information on the frequency and duration of activities performed and chemicals used during the week of sampling that may impact on the level of pollutants in the home. This included a range of common activities such as:

- Number of people and animals inside the residence
- Number of windows and doors open to the outside
- The use of heating and cooling systems
- Personal care activities such as showering and the use of personal care products, e.g. deodorant
- Cooking and the methods used, e.g. grilling, boiling, microwaving, toasting
- Domestic chores e.g. ironing, vacuuming, sweeping, and chemicals used during the course of these activities e.g. dishwashing detergent
- Using chemicals associated with leisure activities and hobbies
- Outdoor activities such as the coming and going of vehicles, gardening, the use of BBQ's, and any chemicals associated with these activities, e.g. petrol for a lawn mower, paint.

The information collected in the diary gives a picture of what has happened in the house specifically during the week of sampling, which may or may not necessarily be typical for that home.

2.5 The Incidence of Smoking Indoors

Stage 1 of the Indoor Air Study reported on work that suggested that around 25% of the dwellings would have one person who smoked indoors, and that in this study a representative sample would be chosen.

During recruitment for this study only three (of approximately 80) recruitment drive respondents stated smoking occurred regularly indoors of the dwelling. For one of these the dwelling type (bedsitter) did not fit into the category for a typical Australian dwelling type so was not selected. The selection questionnaire for another one smoking dwelling was returned after the cut-off time for dwelling selection so was not chosen. Hence only one smoking dwelling was selected. In this dwelling, it turned out, smoking was conducted in a sun-room that could be opened to the outside and was normally shut off from the rest of the dwelling.

Education campaigns about smoking in homes and in cars have become a regular part of tobacco control mass media and education campaigns. Common themes include encouraging parents to either quit or smoke outside for the health and safety of their children. According to the 2004–05 National Health Survey, more than a third (37%) of Australian children aged 0–14 years live in households with one or more regular smokers, while 10% of children 0–14 years live in households where there is at least one regular smoker who smokes indoors. This fraction is decreasing. In 2006, 43% of Australian households with smokers totally banned smoking indoors (Borland et al. 2006, Scollo and Winstanley 2008). Thus it would appear

that the original statistics are no longer applicable. It was not possible to include smoking indoors as a variable in this study.

2.6 Meteorology during the Study Period

The time series for 24-hour averaged temperature, pressure, relative humidity, wind speed and water vapour mixing ratio between June 2008 and June 2009 are shown in Figure 2. Also shown are the 24-hour minimum and maximum values for each meteorological variable and the Winter/Spring and Summer/Autumn sampling periods, marked on the time series plots as shaded areas.

Daily average temperature rose steadily during the Winter/Spring sampling period by approximately 5°C from start to finish and decreased by approximately 10°C from start to finish during the Summer/Autumn period. Several high temperature days were experienced during the Summer/Autumn sampling period (4 days where the maximum temperature exceeded 40°C) and during the Winter/Spring period there were 10 days where the minimum temperature dropped below 5°C. The average 24-hour temperature during the Summer/Autumn period was significantly different from the average 24-hour Winter/Spring sampling period at the 95% confidence level, being higher in summer than winter (Table 4). However the mean difference 2.6°C is smaller than that which should be observed if only winter and summer were sampled. (This was impossible because of the timing of the study.)

Average 24-hour atmospheric pressure at sea level (MSL) fluctuated around a value of 1015 hPa during both sampling periods and displayed no significant difference between the two sampling periods.

Average 24-hour wind speed fluctuated around a value of 2 ms⁻¹ during both sampling periods and displayed no significant difference between the two sampling periods.

Average 24-hour H₂O mixing ratio (i.e. the mass of water vapour in grams per kg of dry air) rose steadily between September 2008 and February 2009, when it peaked at around 14 g kg⁻¹ and then decreased back to around 7 g kg⁻¹. There was a significant difference between the 24-hour averaged mixing ratio during the two sampling periods, with the Summer/Autumn sampling period experiencing the highest 24-hour averaged mixing ratios. Average 24-hour relative humidity (i.e. the ratio of the air's actual mixing ratio to its mixing ratio if saturated at the same temperature and pressure) also showed significantly different values during the two sampling periods with higher 24-hour averaged relative humidity occurring during the Summer/Autumn sampling period.

In summary the Winter/Spring sampling period was characterised by cooler temperatures and lower atmospheric moisture levels than the Summer/Autumn sampling period, and the significant differences in temperature, relative humidity and water vapour mixing ratios confirm that the two sampling periods occurred in different seasons.

Table 5 compares the range in mean monthly maximum temperature, mean monthly minimum temperature, mean monthly rainfall, mean monthly relative humidity at 9am and mean monthly relative humidity at 3pm measured in Australian capital cities with populations greater than 1 million with the ranges observed for the eight months included in this study

(January to April and August to November). The table shows that the maximum temperature range, the minimum temperature range and the ranges in 9am and 3pm relative humidities experienced during this study were within the long term ranges in maximum temperature observed in the most populated capital cities. In particular the maximum and minimum temperature ranges experienced during this study were similar to Melbourne's long term means. The range in monthly rainfall means differed from the long term means observed in the Australian capital cities. In particular, during January 2009 less than 2 mm of rainfall was measured at Moorabbin Airport. In addition the highest values in the maximum and minimum relative humidity range (recorded during August 2008) measured at both 9am and 3pm were greater during this study than recorded in long term average for all Australian capital cities.

In conclusion we believe that the meteorological conditions experienced during this study are representative of those experienced by most of Australia's population. The differences are:

- mean rainfall during January 2009 was lower than the long term average
- mean relative humidity observed during August 2008 was slightly higher than the long term average

These differences are not expected to impact on the study.

Table 4. Mean of the 7-day averaged meteorological variables for the 40 dwellings sampled for the two different sampling periods and t-test results to assess significance of differences in meteorological variables between the two sampling periods.

	Winter/Spring			Summer/Autumn			Winter – Summer Means comparison		
	N	Mean	SD	N	Mean	SD	t Stat	t Critical	Accepted Hypothesis P(Winter–Summer=0)
Temperature (°C)	40	15.0	2.0	40	17.6	2.9	-4.81	1.99	Winter–Summer<0 P=0.00
H ₂ O Mixing ratio (g kg ⁻¹)	40	6.4	0.8	40	8.1	1.1	-7.71	1.99	Winter–Summer<0 P=0.00
Relative Humidity (%)	40	58.7	7.8	40	63.3	8.5	-2.53	1.99	Winter–Summer<0 P=0.01
Rainfall (mm)	40	9.3	8.2	40	8.3	12.2	0.41	2.00	Winter–Summer=0 P=0.68
Pressure, MSL (hPa)	40	1014.8	5.5	40	1016.6	4.0	-1.69	1.99	Winter–Summer=0 P=0.09
Wind speed (m s ⁻¹)	40	2.2	1.2	40	1.9	1.1	1.40	1.99	Winter–Summer=0 P=0.17

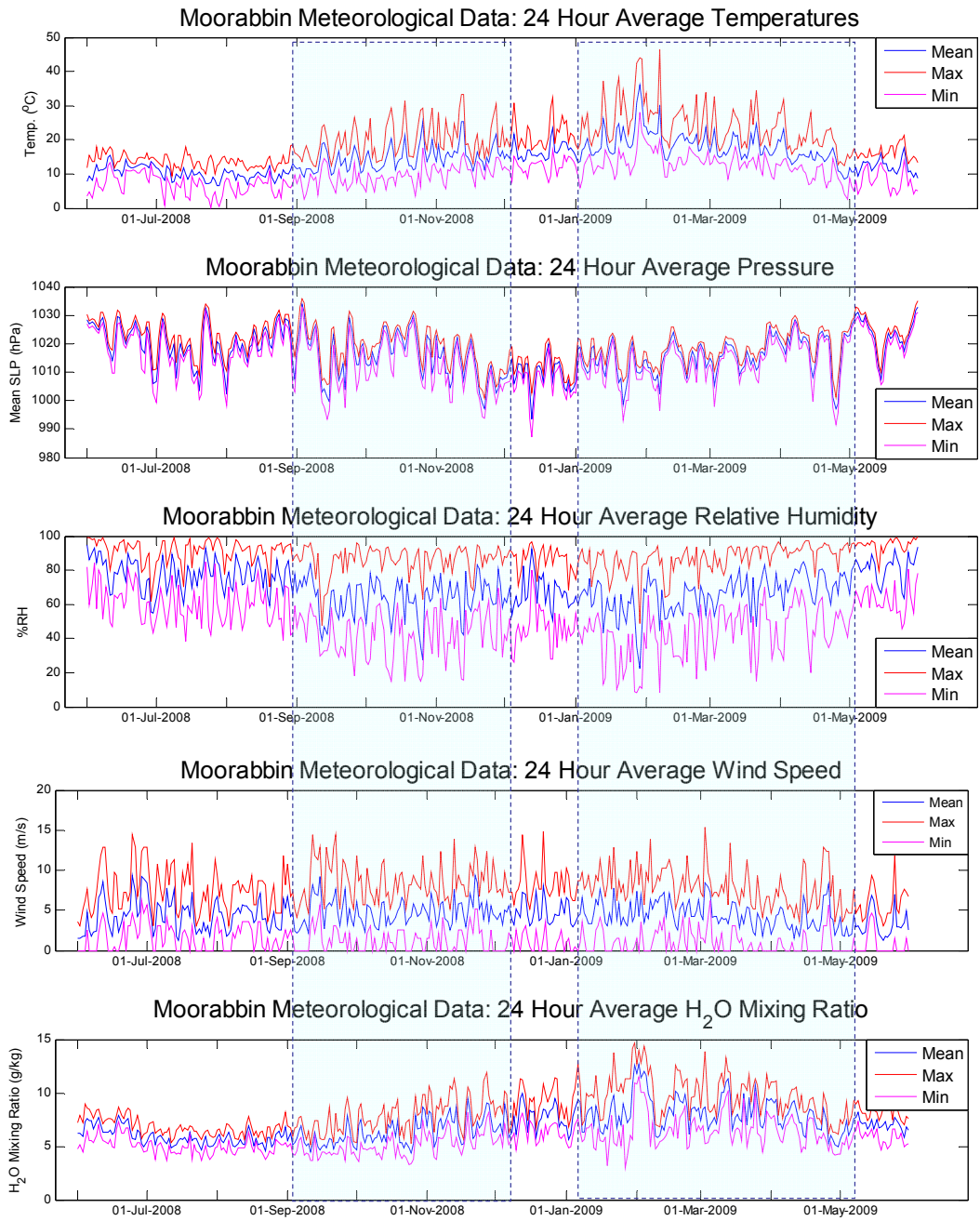


Figure 2. 24-hour average temperature, pressure, relative humidity, wind speed and water vapour mixing ratio between June 2008 and June 2009. Also shown are the 24-hour minimum and maximum values for these variables. The two shaded boxes highlight the Winter/Spring sampling period and the Summer/Autumn sampling period.

Table 5. Comparison of the range in mean monthly maximum temperature, mean monthly minimum temperature, mean monthly rainfall, mean monthly relative humidity (RH) at 9am and mean monthly relative humidity (RH) at 3pm measured in Australian capital cities with populations greater than 1 million with ranges observed for the eight months of sampling included in this study. Note that the Australian capital city data are derived from 30 year means of these variables observed during a calendar month (www.bom.gov.au/).

Variable	Sydney	Melbourne	Adelaide	Perth	Brisbane	This study
Mean Max Temp (°C)	17.8–25.9	14.9–25.8	15.9–28.0	18.0–30.0	21.8–29.4	13.4–27.3
Mean Min Temp (°C)	8.9–18.8	6.7–14.5	7.5–16.0	9.2–18.0	10.3–20.7	6.5–14.9
Mean Rainfall (mm)	69–130	48–67	18–50	9–135	46–160	2–71
Mean 9AM RH (%)	61–74	63–73	52–74	51–74	60–71	55–80
Mean 3PM RH (%)	50–64	47–56	42–61	42–57	44–60	45–66

2.7 Air Quality during the Study Period

The time series for 24-hour averaged PM₁₀, PM_{2.5}, NO₂, CO and ozone measured at Aspendale between June 2008 and June 2009 are shown in Figure 3. Also shown are the 1-hourly daily minimum and maximum values for each variable and the Winter/Spring and Summer/Autumn sampling periods, bounded by dashed lines on the plots.

Daily average PM₁₀ and PM_{2.5} both showed significant increases in concentration between late December 2008 and early March 2009. This was the period when smoke from the bushfires burning in rural areas around Melbourne impacted the Melbourne air shed. During this time the 24-hour average PM₁₀ concentration exceeded the National Environment Protection Measure (NEPM) standard for PM₁₀ of 50 µg m⁻³ on seven occasions, with the highest concentration of 168 µg m⁻³ being recorded on 3 March 2009. The PM_{2.5} NEPM advisory reporting standard of 25 µg m⁻³ was exceeded on two occasions during this period. Ozone concentrations were also high during this period. Daily average NO₂ concentrations were fairly consistent over both sampling periods, and the highest maximum daily NO₂ concentration occurred during the bushfire impacted period.

The PM₁₀ standard and PM_{2.5} advisory reporting standards were also exceeded on several occasions during April 2009. Elevated particle concentrations in Melbourne at the beginning of autumn can result from temperature inversions that trap pollutants close to the cool ground surface. Cooler temperatures during April can also promote the use of woodheaters for domestic home heating providing an additional source of pollutants throughout autumn and winter. CO concentrations also showed peaks during April 2009.

Table 6 compares the monthly averaged concentrations of PM_{2.5}, PM₁₀, CO, NO₂ and ozone measured at Aspendale during the sampling program with the average concentrations of these

pollutants for the same months between 2004 and 2008. The aim of this table is to illustrate how the air quality experienced during the sampling program compares to longer-term average air quality. In general the average monthly concentrations of the various pollutants measured at Aspendale during the sampling program are within the range of monthly concentrations measured at Aspendale between 2004 and 2008. Of the exceptions most pollutants are within 10% of the minimum or maximum values of the long term range. However, during the bushfire impacted months, PM10 was greater than the maximum value of the long term range by almost 20%.

In summary, the presence of bushfires in the Melbourne surrounds during January and February 2009 perturbed ambient air quality during this study, most particularly resulting in enhanced particle concentrations (of 20%) during these months. Otherwise, air quality during this sampling program can be considered typical for Melbourne.

Table 6. Comparison of the monthly averaged concentrations of PM2.5, PM10, CO, NO₂ and ozone measured at Aspendale during the sampling program with the average concentrations of these pollutants for the same months between 2004 and 2008. Values from this study that lie outside the 2004-2008 range are formatted bold.

Season	Month	Data source	PM2.5 µg/m ³	PM10 µg/m ³	CO ppm	NO ₂ ppb	Ozone ppb
Winter/ Spring	August	Our study	5.1	14.5	0.23	11.7	18.4
		2004–2008	7.2–11.6	13.2–16.7	0.20–0.37	10.2–15.6	10.9–18.0
	September	Our study	6.6	19.5	0.19	10.8	20.1
		2004–2008	5.1–10.4	10.8–18.7	0.19–0.24	8.3–10.8	15.0–20.0
October	Our study	6.7	21.1	0.17	8.7	21.8	
	2004–2008	5.3–11.8	18.7–22.8	0.14–0.17	6.2–8.6	19.7–22.7	
November	Our study	6.4	20.4	0.12	5.9	21.7	
	2004–2008	5.7–13.6	16.2–23.5	0.12–0.14	4.9–7.3	18.3–22.8	
Summer/ Autumn	January	Our study	9.4	30.6	0.12	6.7	19.1
		2004–2008	5.5–17.6	19.0–26.2	0.08–0.15	6.0–7.0	16.7–20.5
	February	Our study	12.1	30.8	0.14	6.1	20.9
		2004–2008	4.4–23.1	20.2–26.6	0.10–0.12	5.7–8.7	12.5–21.7
March	Our study	10.2	29.6	0.16	8.6	18.2	
	2004–2008	7.0–11.1	19.8–24.3	0.14–0.17	7.9–10.1	14.9–18.2	
April	Our study	12.9	23.4	0.26	11.5	15.7	
	2004–2008	9.2–14.8	19.9–25.6	0.19–0.38	9.4–13.6	12.6–15.0	

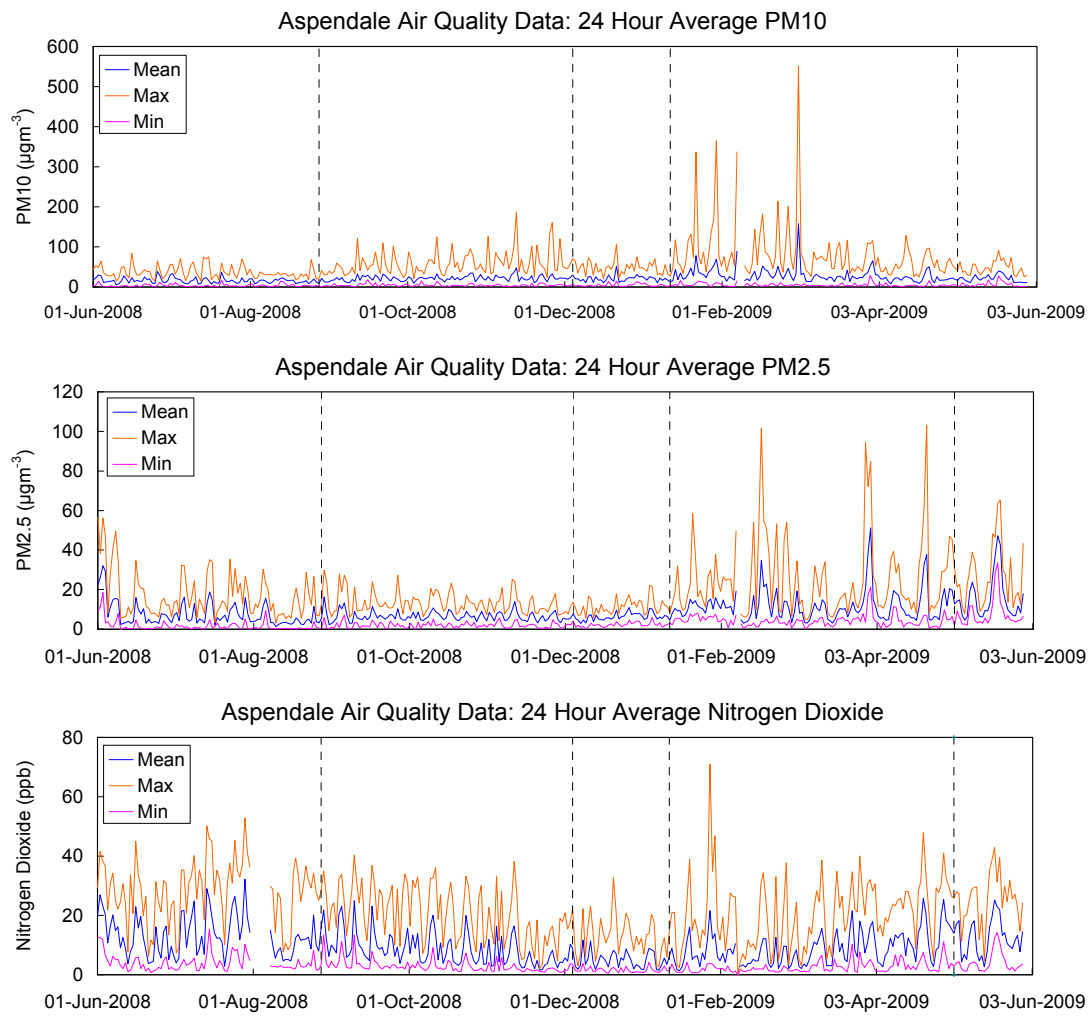


Figure 3. Time series of 24-hour averaged PM10, PM2.5 and NO₂ measured at Aspendale between June 2008 and June 2009. Also shown are the 1-hourly daily minimum and maximum values for each variable and the Winter/Spring and Summer/Autumn sampling periods, bounded by dashed lines on the plots

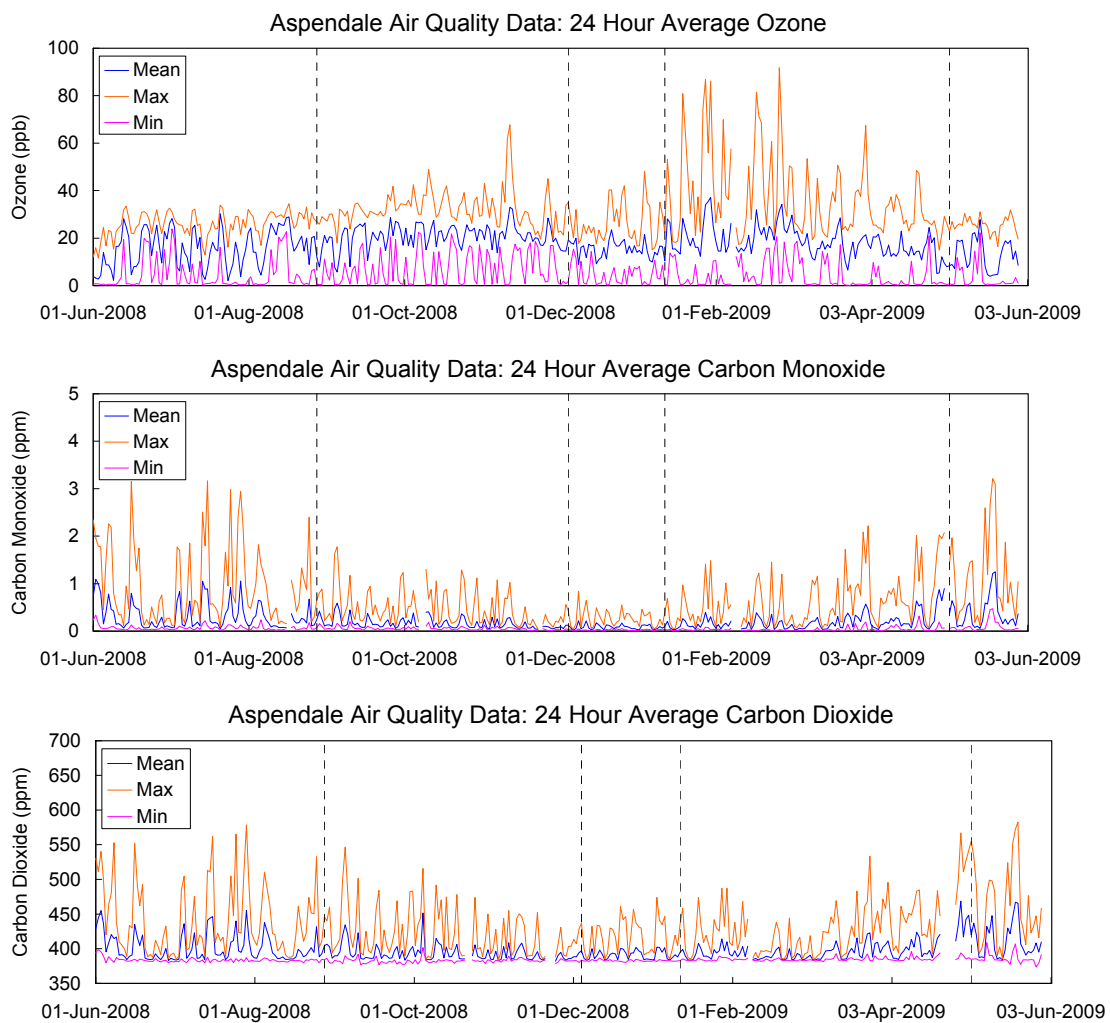


Figure 4. Time series of 24-hour averaged Ozone, CO and CO₂ measured at Aspendale between June 2008 and June 2009. Also shown are the 1-hourly daily minimum and maximum values for each variable and the Winter/Spring and Summer/Autumn sampling periods, bounded by dashed lines on the plots.

3. INDOOR AIR IN TYPICAL AUSTRALIAN DWELLINGS

The results of the study on indoor air in typical Australian dwellings are presented in three parts:

- the daily cycle derived from continuous measurements of temperature, water vapour mixing ratio, relative humidity, CO₂, CO, and PM_{2.5} (Section 3.1). This is preceded by a description of the observations of activities in these dwellings
- the statistics in tabular and graphical form of the weekly average concentrations of temperature, water vapour mixing ratio, relative humidity, CO₂, CO, PM_{2.5}, PM₁₀, NO₂, O₃, formaldehyde, other carbonyls, TVOCs, benzene and other aromatics (Section 3.2)
- comparison of these weekly indoor concentrations with previous measurements and indicative guidelines for indoor air (Section 3.3).

3.1 Continuous Measurements (Winter/Spring & Summer/Autumn)

The following figures (5–11) present the continuous data for temperature, absolute water vapour mixing ratio, relative humidity, CO₂, CO, PM_{2.5} and domestic activities as quantiles of concentrations (or other parameters) according to time of day for all data (combined Winter/Spring and Summer/Autumn), Winter/Spring and Summer/Autumn for indoors, outdoors and indoors–outdoors. The data presented in these summary plots represent nearly 560 days of both indoor and outdoor measurements and diaries, allowing for the small data loss, see Table 3. The comparisons of Winter/Spring versus Summer/Autumn, and Near-road versus Far-Road have nearly 280 days of measurements in each category.

It should be noted that (a) relative humidity is the appropriate variable to indicate water condensation and associated issues, and (b) water vapour mixing ratio is the appropriate variable to analyse the water balance of the dwelling including comparisons of concentrations in indoor versus outdoor air.

A synopsis of the following results is that the temperature and water vapour mixing ratio show a minimum in early morning and a maximum in early evening. Water vapour is released in the dwelling by respiration, cooking, washing etc. The indoor CO₂, CO and PM_{2.5} all show peaks in the morning and early evening that most likely correspond to peak times in domestic activities. The CO₂, CO and PM_{2.5} have indoor sources such that the indoor concentrations are greater than those outdoors. Sections 3.1.1 to 3.1.5 provide a more detailed description of this behaviour.

3.1.1 ACTIVITIES FROM DIARIES

For each dwelling that participated in the study, the occupants kept a diary of household activities recorded at 30-minute intervals for the 7 days of sampling. The various activities are combined together into 10 categories, as listed in Appendix E. The average diurnal variations of

key activities are shown in Figure 5. Reviewing Figure 5 from the top left hand panel across and down to the bottom right hand panel, the following are observed:

- The number of persons in the dwelling is minimum during the daytime and maximum at night.
- The number of external windows and doors open in the house peaks during the afternoon in winter and in the evening during summer.
- The total of all domestic activities has two daily peaks of comparable magnitude around 09:00 and 20:00 each day and very low levels from midnight to 06:00 reflecting the period when most occupants are sleeping.
- Unflued combustion activities have a distinct daily peak at around 18:00, and remain high until around 21:00.
- Heating activities have a secondary peak in the morning between 06:00 and 09:00 and a major peak between 18:00 and 22:00.
- Cooking activities show three daily peaks, a minor peak slightly after midday and two major peaks between 06:00 and 09:00 in the morning and between 17:00 and 20:00 in the evening.

These patterns of domestic activity are of use in explaining diurnal variations in indoor air quality in the dwellings.

3.1.2 TEMPERATURE, WATER VAPOUR AND RELATIVE HUMIDITY

Figure 6 shows the air temperature according to the time of day indoors, outdoors and the indoor-outdoor ratio. The indoor air temperature follows the same pattern throughout the day in both Summer/Autumn and Winter/Spring, with a minimum value in the morning at around 06:00 to 08:00, increasing throughout the day and peaking late afternoon (16:00 – 18:00), then decreasing gradually overnight.

The outdoor temperatures are also lowest around 06:00 in both seasons. The overnight cooling is driven by radiative cooling in the absence of sunlight overnight (the loss of infrared radiation from the surface to space). Solar radiation causes the temperature increase during the daytime, which peaks at around 14:00 to 16:00.

The indoor-outdoor plots show that the median temperatures are higher indoors than outdoors during the night and throughout the day in both seasons, though the temperature difference approaches zero around midday. This indicates that net heating (from electrical and combustion heaters and/or incoming solar radiation through fenestration) occurs indoors in these dwellings in both Winter/Spring and Summer/Autumn.

Figure 7 shows the water vapour mixing ratio according to the time of day. The indoor water vapour mixing ratios follow the same pattern throughout the day in both Summer/Autumn and Winter/Spring, with minimum values in the morning at around 06:00 – 07:00, increasing throughout the day and peaking in the late afternoon or early evening (15:00 – 19:00) then decreasing gradually overnight. This diurnal pattern suggests that water vapour is released in the dwelling by respiration, cooking, washing etc.

The outdoor water vapour mixing ratio shows no systematic diurnal variation. The outdoors water vapour mixing ratio is not closely related to temperature as it is indoors since the well mixed nature of the atmospheric boundary layer provides a buffer against the type of short term changes observed indoors.

The indoor-outdoor plots show that water vapour mixing ratio is higher indoors than outdoors throughout the day in both seasons, except at around 08:00 – 09:00 when the water vapour mixing ratio in the air is the same indoors as outdoors in Winter/Spring and slightly less in Summer/Autumn. This could be due (in part) to the ventilation of the house associated with activities that occur after the occupants arise in the morning. The maximum indoor-outdoor difference occurs in the late afternoon and early evening around 16:00 to 19:00.

The relative humidity (Figure 8) has an inverse relationship with temperature when there is relative constancy of the water vapour mixing ratio of the air. The indoor relative humidity is highest during the morning hours (06:00 – 08:00) in both seasons and declines as the air temperature increases until around 16:00 – 17:00. The outdoor relative humidity shows a similar pattern though the afternoon minimum is slightly earlier.

3.1.3 CARBON DIOXIDE

Indoor CO₂ displays a peak in the morning hours in both Summer/Autumn and Winter/Spring, in all the quantiles (Figure 9). The indoors CO₂ concentrations begin to rise at about 06:00, and peak at 09:00. The magnitude of the increase is about 30 ppm in both seasons. This morning increase in CO₂ reflects an additional source within the dwelling – likely to be increased exhalation from occupants as they arise from sleep and commence daily activities, and increased combustion processes in the home such as heating and cooking. Indoor CO₂ in both seasons decrease from the peak at 09:00 to a minimum concentration at around 15:00 – 16:00 and this slow decrease during the day may reflect the slow exchange between inside and outside air in these dwellings since daytime is the period of lowest occupancy of these dwellings (Figure 5).

The peak in indoor CO₂ concentrations in both Summer/Autumn and Winter/Spring during the evening hours can be observed in all quantiles. The concentration increase begins at around 17:00, peaks at about 21:00, (with median concentrations of 570 ppm in Winter/Spring and 510 ppm in Summer/Autumn), then decreases until about 01:00. The peak is similar to that seen in the morning hours, although the evening peak has higher concentrations and extends for longer periods. By about 01:00 – 02:00 concentrations of CO₂ have stabilised and then remain steady (in Summer/Autumn), or decay very slowly (Winter/Spring) until 06:00 when the morning peak begins. This overnight behaviour of CO₂ concentrations is due to a constant source such as exhaled breath of the sleeping occupants, and a constant removal, such as the slow and continuous ventilation from the house. The CO₂ remains approximately 50ppm higher indoors than outdoors in both seasons from 00:00 – 06:00.

The outdoor CO₂ concentrations remain relatively constant throughout the day. Between 06:00 and 09:00 a very slight peak is observed in all quantiles (except 10%) peaking at around 07:30. This may be due to the nocturnal build up of CO₂ from soil and plant respiration and combustion sources in the near surface that become diluted as mixing begins with solar heating after sunrise. Lowest outdoor CO₂ concentrations, observed between midday and late afternoon, may be due to a combination of the well mixed atmosphere and plant uptake of CO₂ during the

daytime. A gradual increase in outdoor CO₂ during the evening hours in both Summer/Autumn and Winter/Spring may be due to CO₂ emissions from traffic or local vehicles as well as soil and plant respiration of CO₂, and the decreased mixing of the atmosphere overnight.

The indoor-outdoor plots for both seasons show positive differences of about 100 ppm (Winter/Spring median) and 70 ppm (Summer/Autumn median). The positive differences in both seasons suggest indoor sources of CO₂ (see above) dominate over the infiltration of outdoor sources. The larger positive difference between indoor and outdoor concentrations in Winter/Spring may be due to lower rates of ventilation in the dwelling in Winter/Spring when houses were typically in a 'closed' state (Figure 5) as well as differences in the CO₂ production by indoor sources and activities in Winter/Spring compared to Summer/Autumn, for example the use of CO₂ emitting heaters is more likely in the lower temperatures during the Winter/Spring period.

3.1.4 CARBON MONOXIDE

Indoor CO concentrations in the morning hours are similar in Winter/Spring and Summer/Autumn (Figure 10). CO shows a daily maximum at about 09:00 and a daily minimum at 12:00. There is a small increase between 18:00 – 21:00 with concentrations persisting until midnight, from which they then slowly decline to a secondary minimum at 06:00. For both the morning and evening peaks the Summer/Autumn patterns show slightly higher CO concentrations at the 90% quantile than the Winter/Spring evening peak.

The outdoor CO concentrations are similar in Summer/Autumn and Winter/Spring showing the daily maximum during the morning peak hour period of 07:00 – 08:00 with concentrations at the 90% quantile of around 0.9 ppm. This peak is probably due to emissions from vehicles. The CO concentration declines to a daily minimum between 12:00 and 15:00 and then gradually increases until midnight. This may be due to CO from motor vehicles and woodsmoke accumulating in the stable boundary layer which forms at night, leading to increasing concentrations. Outdoor CO concentrations remain stable or slowly decline during the early morning hours.

The indoor-outdoor plots for both Summer/Autumn and Winter/Spring show that CO concentrations in 50% of dwellings are higher indoors compared to outdoors. The 90% quantile however indicates an indoor enhancement in concentration of about 0.7 ppm in the evening. Indoor sources of CO include combustion from cooking and heating, smoking, incense, candles etc.

3.1.5 PARTICULATES: PM2.5

Indoor PM2.5 shows an increase during the morning traffic peak hour (06:00 – 09:00) in Winter/Spring and Summer/Autumn (Figure 11). The increase is more pronounced in the 90% quantile in Summer/Autumn, which shows an increase from 14 to 27 µg m⁻³ between 06:00 – 12:00. The indoor PM2.5 concentration remains stable between 10:00 and 17:00 in both Winter/Spring and Summer/Autumn. PM2.5 concentrations then exhibit a sharp increase at around 18:00 peaking at about 19:00 before decreasing slowly over the next few hours. While the peak occurs in both Winter/Spring and Summer/Autumn, it is more pronounced in

Winter/Spring when the 90% and 75% quantiles reach almost $40 \mu\text{g m}^{-3}$ and $11 \mu\text{g m}^{-3}$ respectively in Winter/Spring. Indoor PM_{2.5} concentrations slowly decline during the early morning hours until around 06:00 in Summer/Autumn and Winter/Spring.

Outdoor PM_{2.5} shows an almost negligible change in the morning period of 06:00 to 09:00 in Winter/Spring, however in Summer/Autumn there is an increase in the 90% and 75% quantiles with concentrations peaking at 25 and $13 \mu\text{g m}^{-3}$ respectively at around 10:00. This increase is similar to the increase seen indoors in Summer/Autumn. The greater morning increase observed during the Summer/Autumn sampling period may be due to the downward mixing of bushfire smoke from aloft that impacted Melbourne during the Summer/Autumn 2009 sampling period. In both Winter/Spring and Summer/Autumn, the PM_{2.5} concentrations are at a daily minimum around 16:00.

Outdoor PM_{2.5} does not show the same striking evening peak as indoor PM_{2.5}, suggesting that indoor and outdoor air are affected by different sources, and that elevated concentration indoors are not due to outdoor air infiltrating the dwelling. The 90% quantile of outdoor PM_{2.5} does show a small trend upwards in Winter/Spring late afternoon and early evening with a peak of $17 \mu\text{g m}^{-3}$ at around 20:00 in the 90% quantile. The source of this peak in PM_{2.5} may be woodsmoke, motor vehicle emissions and lowering of the boundary layer and stabilisation of the atmosphere in the evening leading to higher concentrations. The outdoor PM_{2.5} concentration is stable from midnight to 06:00 in both Summer/Autumn and Winter/Spring.

The indoor-outdoor plot of PM_{2.5} shows that between the hours of 06:00 and 09:00, a very small increase occurs in all quantiles for Winter/Spring, whereas for Summer/Autumn, increases only occur in the 90% and 75% quantiles. The median values of indoor-outdoor PM_{2.5} for both sampling periods are slightly negative in the morning hours, indicating that PM_{2.5} levels are higher outdoors than indoors during this period. The increases that are then observed during the morning hours suggest an indoor source or activity that produces PM_{2.5} in some dwellings, or that infiltration of outdoor air into these dwellings may become more efficient during the morning hours. Indoor PM_{2.5} sources could include cooking or fuel combustion due to heating (Figure 5).

The indoor-outdoor plots show a slightly elevated concentration of PM_{2.5} at midday for the 75% and 90% quantiles, suggesting a source of PM_{2.5} indoors. This may be due to cooking and heating in dwellings that are occupied during the day. The indoor-outdoor differences in both Summer/Autumn and Winter/Spring around 19:00 show a clear peak in the 90% quantile ($21 \mu\text{g m}^{-3}$ in Winter/Spring and $15 \mu\text{g m}^{-3}$ in Summer/Autumn). This suggests a PM_{2.5} producing activity that occurs indoors in the evening in both Summer/Autumn and Winter/Spring, and creates higher particle concentration in Winter/Spring in some dwellings. Possible sources and activities include cooking and fuel combustion, environmental tobacco smoke, vacuuming and burning of consumer products like candles and incense materials. The most likely candidate from Figure 5 is unflued combustion activities. PM_{2.5} concentrations may be higher in Winter/Spring than Summer/Autumn due to a combination of the type of cooking favoured in Winter/Spring, the tendency to cook outside more in Summer/Autumn, the use of combustive heater types in Winter/Spring and less ventilation of the dwellings in Winter/Spring leading to higher concentrations. The indoor-outdoor plot shows that in the early morning hours until 06:00 the concentrations of PM_{2.5} are slightly higher outdoors compared to indoors in both Summer/Autumn and Winter/Spring.

The one day average PM_{2.5} concentrations were derived from this data set of 465 days made up from measurements on 40 dwellings. This was done using the real time (light scattering) measurement of PM_{2.5} normalised to the weekly integrated gravimetric measurement of PM_{2.5}. From this indoor data, there are 15 days where the one day average concentration of PM_{2.5} was equal to or exceeded 25 µg m⁻³ inside a dwelling out of the total data set. On 12 of these 15 days the outside PM_{2.5} concentration was less than 25 µg m⁻³ over a one day averaging period, indicating an indoor source of PM_{2.5}. The National Environment Protection (Ambient Air Quality) Measure has an Advisory Reporting Standard for the monitoring for particles as PM_{2.5}. The outdoor advisory limit for PM_{2.5} is 25 µg m⁻³ over a one day averaging period. There is no Australian indoor guideline for exposure to PM_{2.5}.

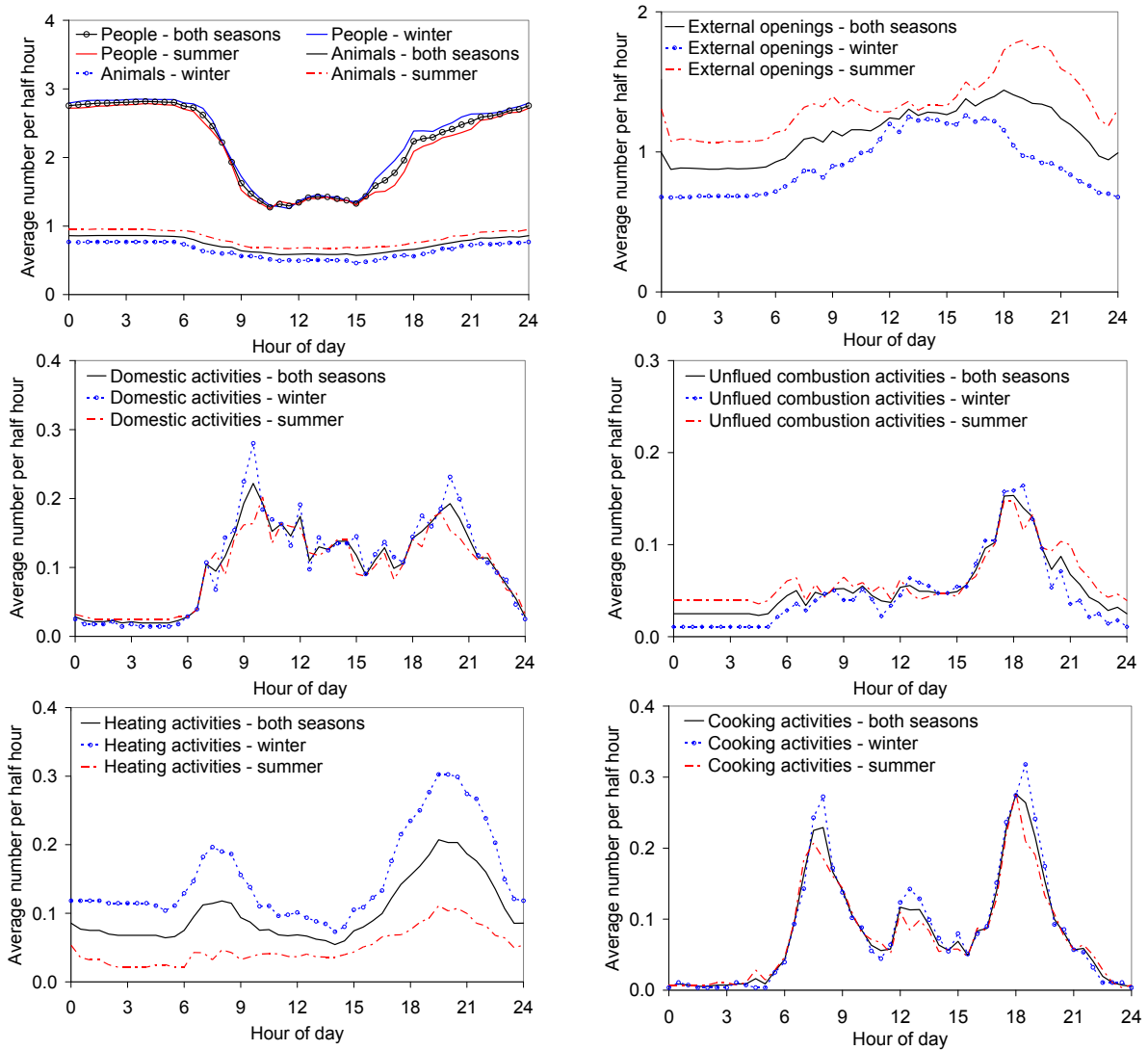


Figure 5. Activity according to time of day for Winter/Spring, Summer/Autumn and both seasons combined. Activities include (top left) number of people and animals in dwelling, (top right) number of windows and doors open (middle left) all domestic activities, (middle right) unflued combustion, (bottom left) heating and (bottom right) cooking.

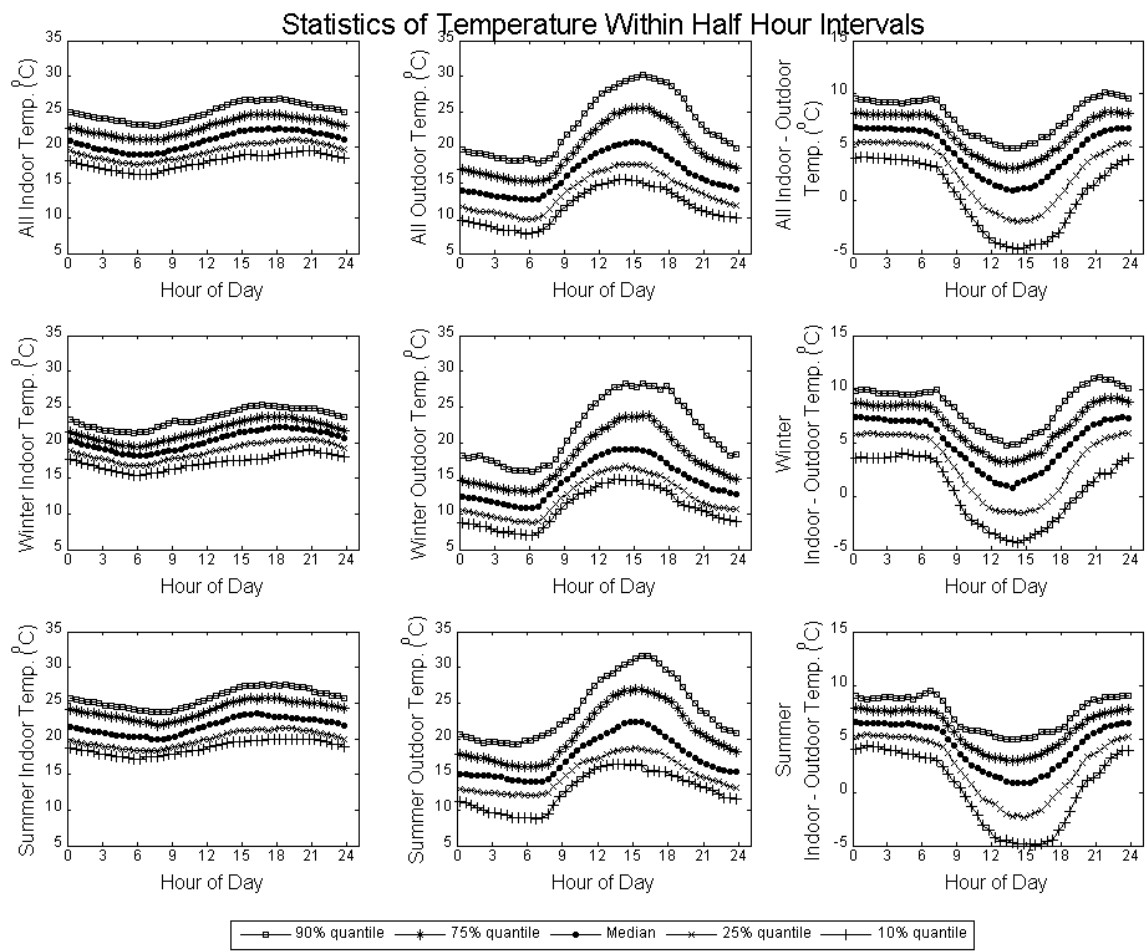


Figure 6. Air temperature as quantiles according to time of day for all data, Winter/Spring and Summer/Autumn for indoors, outdoors and indoors-outdoors

Statistics of H₂O Mixing Ratios Within Half Hour Intervals

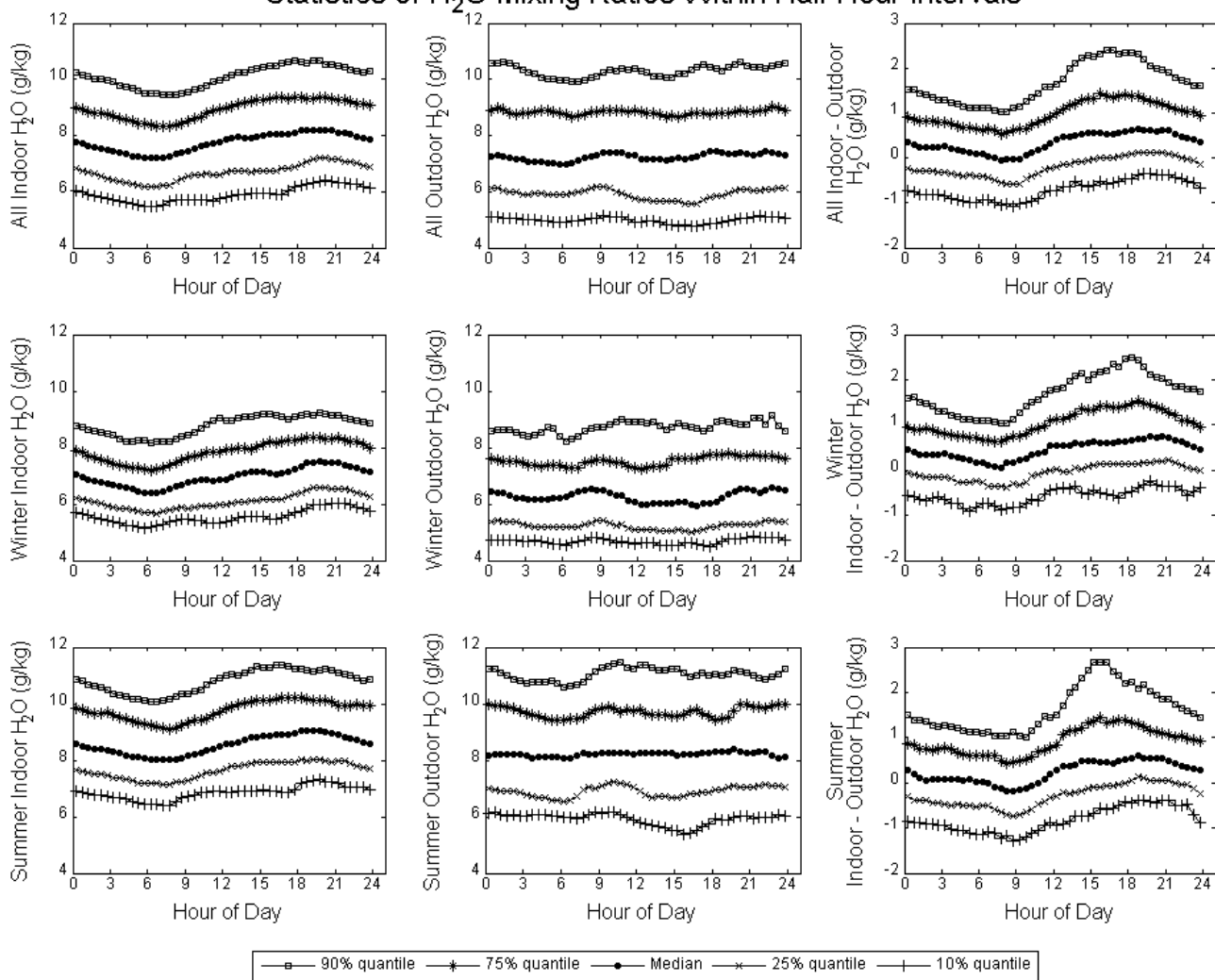


Figure 7. Water vapour mixing ratio as quantiles according to time of day for all data, Winter/Spring and Summer/Autumn for indoors, outdoors and indoors-outdoors

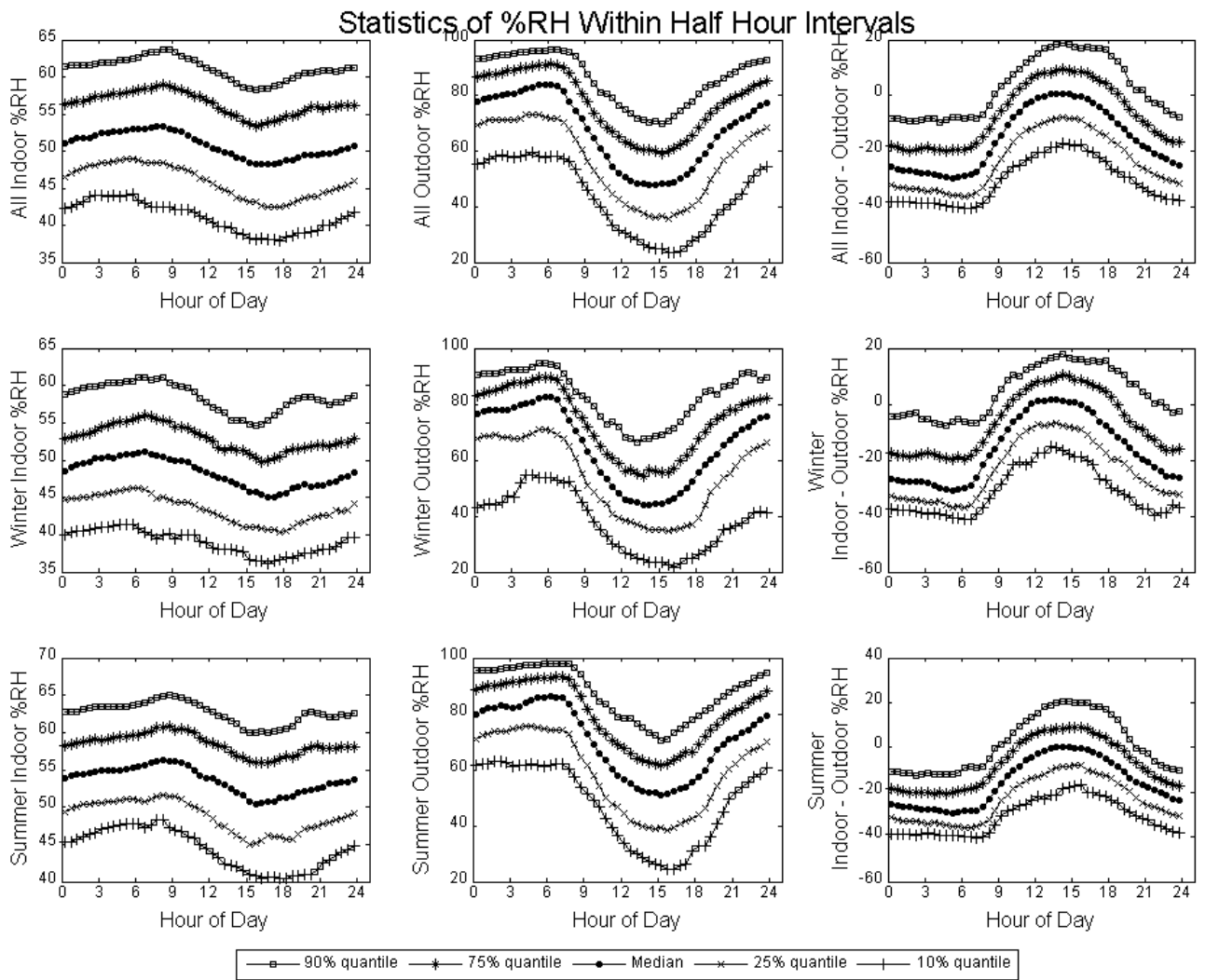


Figure 8. Relative humidity as quantiles according to time of day for all data, Winter/Spring and Summer/Autumn for indoors, outdoors and indoors-outdoors

Statistics of CO₂ Concentrations Within Half Hour Intervals

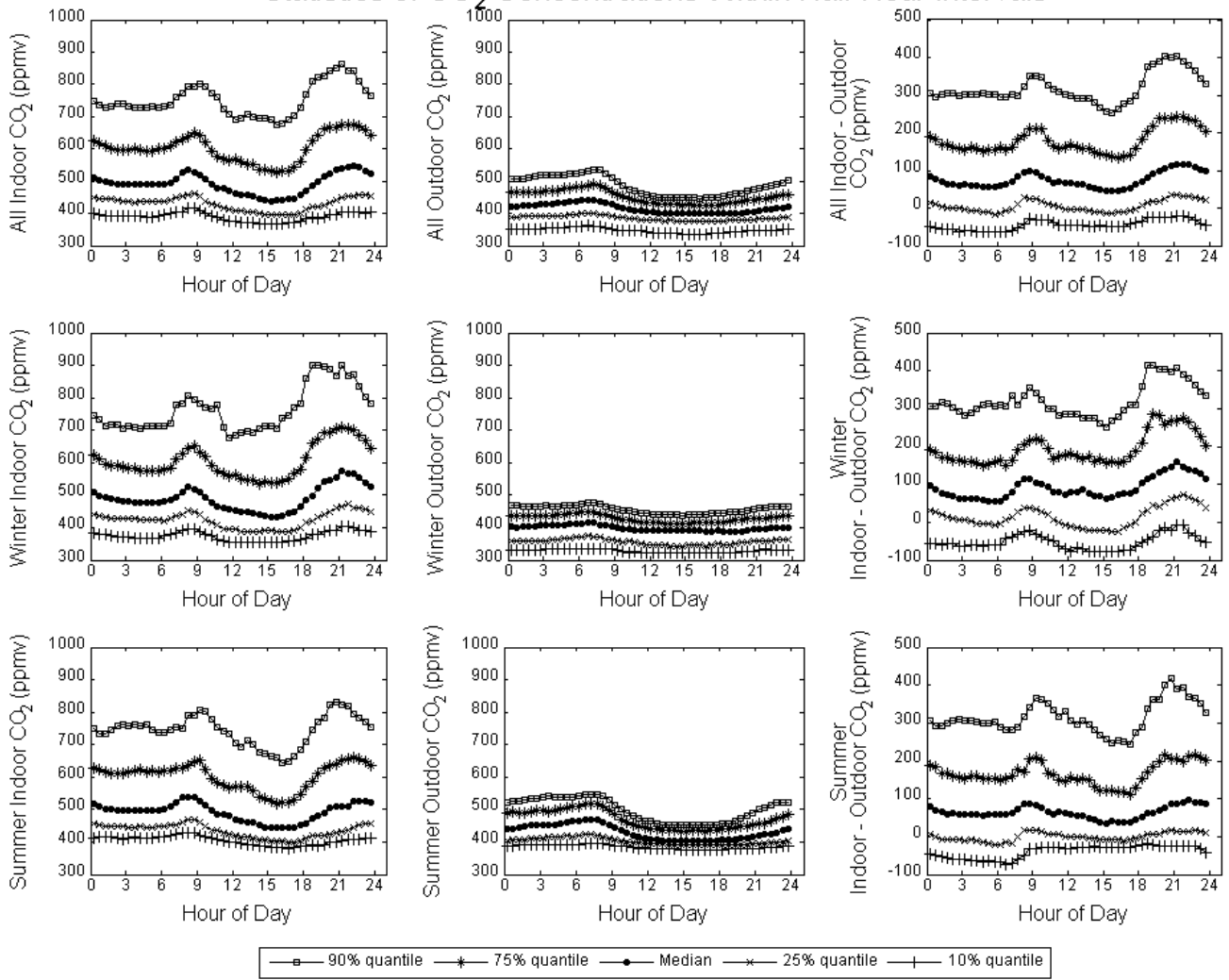


Figure 9. Carbon dioxide concentration as quantiles according to time of day for all data, Winter/Spring and Summer/Autumn for indoors, outdoors and indoors-outdoors

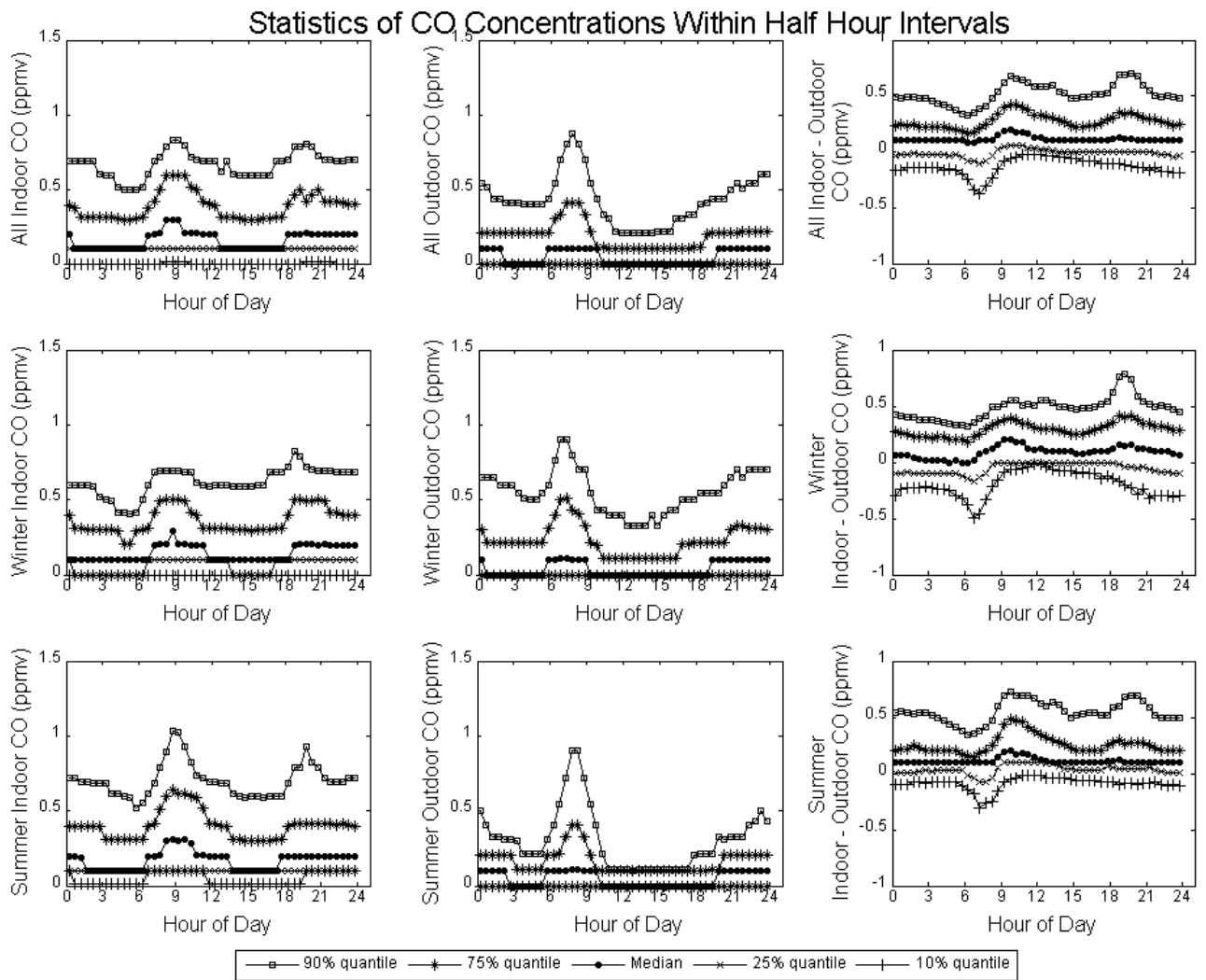


Figure 10. Carbon monoxide concentration as quantiles according to time of day for all data, Winter/Spring and Summer/Autumn for indoors, outdoors and indoors-outdoors

Statistics of PM_{2.5} Concentrations Within Half Hour Intervals

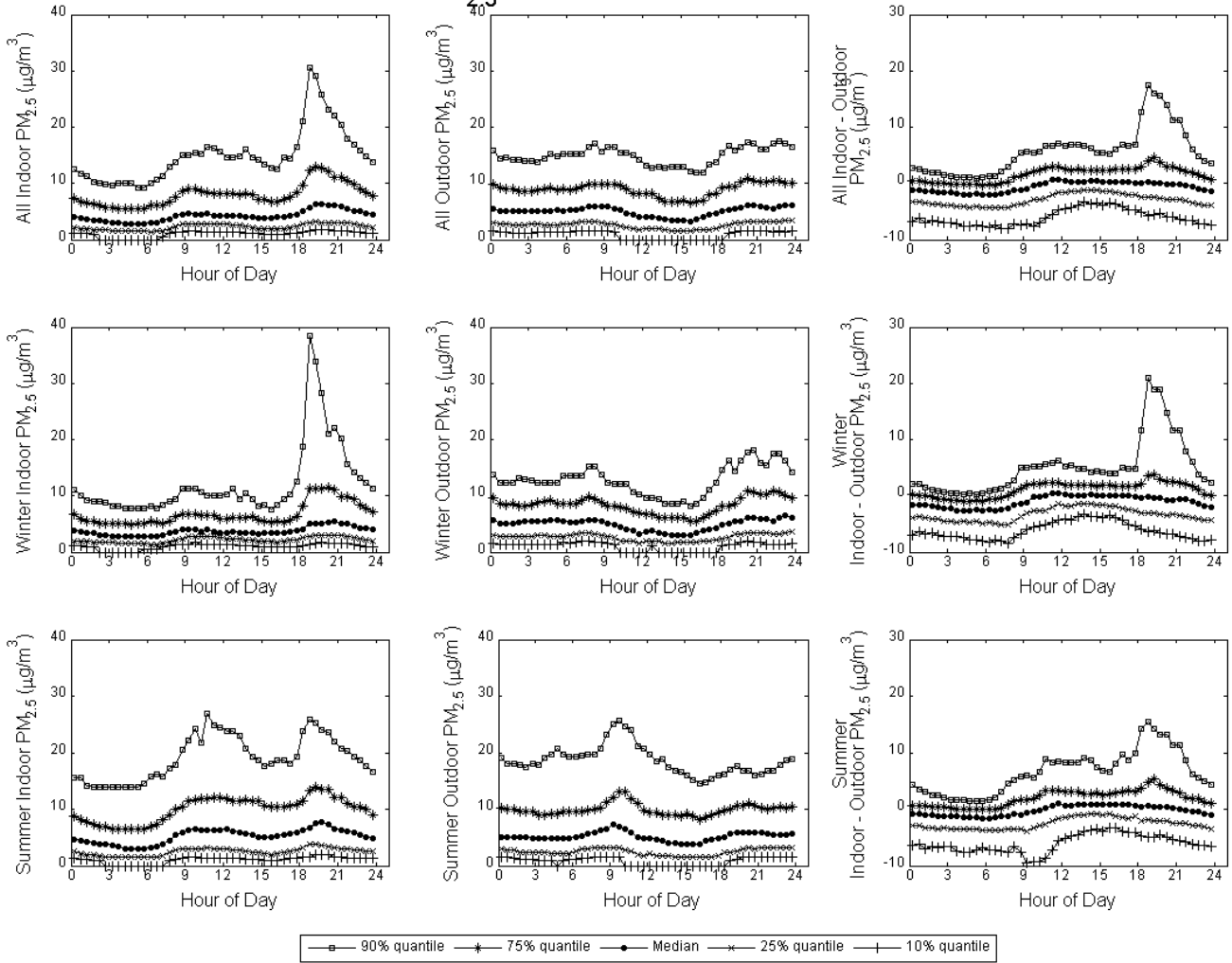


Figure 11. Particulate, PM_{2.5}, concentration as quantiles according to time of day for all data, Winter/Spring and Summer/Autumn for indoors, outdoors and indoors-outdoors

3.2 The Statistics of Indoor Air Quality in Typical Australian Dwellings

The statistics of weekly average concentrations of air quality parameters inside and outside the typical Australian dwellings sampled in this study in Winter/Spring and Summer/Autumn are given in Table 7, Table 8 and Table 9. These results are useful for comparing both the average and the variability of indoor air compared with outdoor air in Winter/Spring and Summer/Autumn. The indoor-outdoor ratios of these concentrations are also presented. A detailed set of frequency distributions of these parameters are presented in the attended CD.

The following discussion focuses on the differences between indoor and outdoor values for the species measured and the mean values for indoor concentrations during each sampling period. This discussion can be summarised as follows. In general, indoor values of the following species were greater than measured values outdoors (temperature, water vapour mixing ratio, CO₂, CO, NO₂, PM_{2.5}, formaldehyde, other carbonyls, TVOCs and BTEX). Outdoor concentrations of relative humidity, PM₁₀, O₃ and fungi were higher than indoors and concentrations of bacteria were indistinguishable between indoors and outdoors.

Indoor temperatures were significantly higher than outdoors for both sampling seasons (mean \pm standard deviation of indoors-outdoors for the Winter/Spring period were 4.7 ± 1.3 °C and for Summer/Autumn 4.0 ± 1.6 °C). Weekly average indoor temperatures were 20.3 ± 1.4 °C and 22.1 ± 2.1 °C in Winter/Spring and Summer/Autumn respectively.

Indoor water vapour mixing ratios were significantly higher than outdoors for both sampling seasons (mean \pm standard deviation of indoors-outdoors were 0.5 ± 0.4 g/kg and 0.4 ± 0.5 g kg⁻¹ in Winter/Spring and Summer/Autumn respectively). Indoor weekly average water vapour mixing ratios were 7.1 ± 0.8 g kg⁻¹ in Winter/Spring and 8.8 ± 1.1 g kg⁻¹ in Summer/Autumn.

Indoor relative humidity was significantly lower than outdoors for both sampling periods (mean \pm standard deviation of indoors-outdoors were 14.7 ± 5.3 % and 14.6 ± 6.4 % in Winter/Spring and Summer/Autumn respectively). Indoor weekly average relative humidity was 48.2 ± 4.7 in Winter/Spring and 53.5 ± 4.5 in Summer/Autumn.

Indoor carbon dioxide concentrations were significantly higher than outdoors for both sampling periods (mean \pm standard deviation of indoors-outdoors were 114 ± 109 ppm and 106 ± 123 ppm in Winter/Spring and Summer/Autumn respectively). Indoor weekly mean concentrations of carbon dioxide were 527 ± 121 ppm in Winter/Spring and 544 ± 121 ppm in Summer/Autumn.

Indoor carbon monoxide concentrations were slightly higher than outdoors for both sampling periods (mean \pm standard deviation of indoors-outdoors were 0.1 ± 0.3 ppm and 0.2 ± 0.2 ppm in Winter/Spring and Summer/Autumn respectively). Indoor weekly mean concentrations of carbon monoxide were 0.3 ± 0.2 ppm in both Winter/Spring and Summer/Autumn

Indoor ozone concentrations were significantly lower than outdoors for both sampling periods (mean \pm standard deviation of indoors-outdoors were -7.4 ± 1.2 ppb and -6.3 ± 1.8 ppb in

Winter/Spring and Summer/Autumn respectively). Indoor weekly mean concentrations were 0.4 ± 0.4 ppb in Winter/Spring and 0.9 ± 0.8 ppb in Summer/Autumn.

Indoor nitrogen dioxide concentrations were than outdoors in Winter/Spring, the difference being 1.3 ± 3.9 ppb. In Summer/Autumn the concentrations were lower indoors than outdoors, with a difference of -4.5 ± 3.3 ppb. The indoor weekly mean concentrations of nitrogen dioxide were 10.0 ± 4.5 ppb in Winter/Spring and 6.8 ± 2.2 ppb in Summer/Autumn. The slightly higher mean indoor concentration in Winter/Spring may be due to reduced ventilation caused by the house being in a more 'closed' state during the colder months (Figure 5).

Indoor PM_{2.5} concentrations were slightly higher than outdoors for both sampling periods (mean \pm standard deviation of indoors-outdoors is 1.1 ± 2.8 $\mu\text{g m}^{-3}$ and 1.3 ± 4.6 $\mu\text{g m}^{-3}$ in Winter/Spring and Summer/Autumn respectively). Indoor concentrations were 7.2 ± 2.8 $\mu\text{g m}^{-3}$ in Winter/Spring and 9.7 ± 4.6 $\mu\text{g m}^{-3}$ in Summer/Autumn.

Indoor PM₁₀ concentrations were slightly lower than outdoors for both sampling periods (mean \pm standard deviation of indoors-outdoors were -1.5 ± 7.0 $\mu\text{g m}^{-3}$ and -3.4 ± 9.8 $\mu\text{g m}^{-3}$ in Winter/Spring and Summer/Autumn respectively). Indoor weekly averages were 18.3 ± 6.6 $\mu\text{g m}^{-3}$ in Winter/Spring and 22.6 ± 9.0 $\mu\text{g m}^{-3}$ in Summer/Autumn.

The indoor fungi (mould) concentrations were lower than outdoors for both sampling periods (mean \pm standard deviation of indoors-outdoors were -630 ± 1208 cfu m^{-3} and -156 ± 1460 cfu m^{-3} in Winter/Spring and Summer/Autumn respectively). Mean indoor concentrations were 1167 ± 1233 cfu m^{-3} in Winter/Spring and 2089 ± 1642 cfu m^{-3} in Summer/Autumn. There was a great deal of variation in the indoor concentrations in both Winter/Spring and Summer/Autumn, with concentrations varying by up to a factor of 10 between the dwellings.

The bacteria concentrations were indistinguishable between indoors and outdoors in Winter/Spring (with a difference of 50 ± 1160 cfu m^{-3}) and in Summer/Autumn (with a difference of -272 ± 1295 cfu m^{-3}). The large variation in concentrations (reflected in the large standard deviations) suggests that these differences are not significant. Mean indoor concentrations were 1554 ± 1449 cfu m^{-3} in Winter/Spring and 1879 ± 1335 cfu m^{-3} in Summer/Autumn.

Indoor formaldehyde concentrations were significantly higher than the outdoor concentration for both sampling periods (mean \pm standard deviation of indoors-outdoors were 9.8 ± 4.1 ppb and 12.3 ± 5.0 ppb in Winter/Spring and Summer/Autumn respectively). Indoor concentrations of formaldehyde were 11.0 ± 3.9 ppb in Winter/Spring and 13.5 ± 5.0 ppb in Summer/Autumn.

Other carbonyls had significantly higher concentrations indoors than outdoors, the difference being 6.6 ± 2.7 ppb in Winter/Spring and 6.8 ± 2.7 ppb in Summer/Autumn (mean and standard deviation). Indoor concentrations were 7.7 ± 2.5 ppb in Winter/Spring and 8.0 ± 2.8 ppb in Summer/Autumn.

Indoor TVOCs (total volatile organic compounds) concentrations were significantly higher than outdoors for both sampling periods (mean \pm standard deviation of indoors-outdoors were 168 ± 126 $\mu\text{g m}^{-3}$ and 175 ± 119 $\mu\text{g m}^{-3}$ in Winter/Spring and Summer/Autumn respectively). While the indoor mean weekly concentrations did not vary significantly between Winter/Spring and Summer/Autumn (190 ± 127 $\mu\text{g m}^{-3}$ and 206 ± 121 $\mu\text{g m}^{-3}$ respectively) the high standard

deviations suggest large variation in concentrations between dwellings. In particular, while the majority of dwellings had concentrations clustered around the mean there were a few dwellings in both Winter/Spring and Summer/Autumn that exhibited concentrations 2–3 times greater than the mean.

Concentrations of indoor Benzene and other aromatics (Σ BTEX) were significantly higher than outdoors for both sampling periods (mean \pm standard deviation of indoors-outdoors were $10.3 \pm 15.7 \mu\text{g m}^{-3}$ and $13.4 \pm 25.1 \mu\text{g m}^{-3}$ in Winter/Spring and Summer/Autumn respectively). Indoor concentrations were $16.9 \pm 15.1 \mu\text{g m}^{-3}$ in Winter/Spring and $39.0 \pm 27.1 \mu\text{g m}^{-3}$ in Summer/Autumn.

Nicotine concentrations measured both indoors and outdoors of all dwellings were less than the analytical detection limit of 0.02 ppb and hence are not presented. These low nicotine results confirm the absence of smoking within the dwellings studied.

Table 7 Weekly statistics for all data from this study. Differences and ratios are calculated only for dwellings with both indoor and outdoor measurements.

Parameter/ Pollutant	Conc. Units	Indoor			Outdoor			Indoor minus Outdoor			Indoor/Outdoor ratio		
		N	Average	Std Dev.	N	Average	Std Dev.	N	Average	Std Dev.	N	Average	Std Dev.
Temperature	°C	78	21.2	2.0	75	16.9	2.9	73	4.3	1.5	73	1.3	0.1
Relative Humidity	%	78	50.9	5.3	75	65.6	7.6	73	-14.6	5.9	73	0.8	0.1
H ₂ O mixing ratio	g/kg	78	7.9	1.3	75	7.5	1.4	73	0.5	0.5	73	1.1	0.1
CO ₂	ppm	78	536	121	72	417	44	70	110	116	70	1.3	0.3
CO	ppm	78	0.3	0.2	75	0.1	0.2	73	0.2	0.3	73	3.3	2.9
O ₃	ppb	80	0.7	0.7	80	7.5	1.7	80	-6.8	1.6	80	0.1	0.1
NO ₂	ppb	80	8.4	3.9	80	10.0	3.6	80	-1.6	4.6	80	0.9	0.4
Nicotine	ppb	80	<0.02	N/A	80	<0.02	N/A	80	N/A	N/A	80	N/A	N/A
PM2.5	µg/m ³	80	8.6	4.2	80	7.3	3.1	80	1.1	3.8	80	1.2	0.6
PM10	µg/m ³	79	20.4	8.1	79	22.8	7.5	78	-2.5	8.5	78	0.9	0.4
Fungi	cfu/m ³	72	1666	1531	72	2040	1465	72	-373	1362	72	1.1	1.1
Bacteria	cfu/m ³	71	1733	1387	71	1859	1387	71	-127	1238	71	1.5	2.1
Formaldehyde	ppb	80	12.2	4.7	80	1.2	0.6	80	11.2	4.7	80	13.1	6.3
Other carbonyls	ppb	80	7.9	2.6	80	1.1	0.5	80	6.7	2.7	80	7.6	3.4
TVOC	µg/m ³	79	197.9	123.3	76	26.7	12.9	75	171.3	121.6	75	9.1	8.8
Benzene	µg/m ³	79	1.3	0.9	76	0.8	0.4	75	0.5	0.9	75	2.0	2.0
Toluene	µg/m ³	79	10.7	17.6	76	3.8	2.0	75	7.0	17.3	75	2.9	2.9
Ethylbenzene	µg/m ³	79	1.2	1.1	76	0.5	0.3	75	0.6	1.1	75	6.5	35.5
p-Xylene	µg/m ³	79	3.1	3.3	76	1.4	0.9	75	1.6	3.2	75	6.8	38.5
m-Xylene	µg/m ³	79	1.1	1.2	76	0.5	0.3	75	0.5	1.2	75	3.7	12.4
o-Xylene	µg/m ³	79	2.3	2.0	76	0.8	0.4	75	1.5	2.0	75	6.7	28.8
ΣXylenes	µg/m ³	79	6.5	6.3	76	2.7	1.6	75	3.7	6.2	75	5.7	26.6
ΣBTEX	µg/m ³	79	19.7	21.9	76	7.9	4.0	75	11.8	20.8	75	2.7	2.5

Table 8 Weekly statistics for Winter/Spring data. Differences and ratios are calculated only for dwellings with both indoor and outdoor measurements.

Parameter/ Pollutant	Conc. Units	Indoor			Outdoor			Indoor minus Outdoor			Indoor/Outdoor ratio		
		N	Average	Std Dev.	N	Average	Std Dev.	N	Average	Std Dev.	N	Average	Std Dev.
Temperature	°C	38	20.3	1.4	35	15.6	2.0	33	4.7	1.3	33	1.3	0.1
Relative Humidity	%	38	48.2	4.7	35	62.8	6.9	33	-14.7	5.3	33	0.8	0.1
H ₂ O mixing ratio	g/kg	38	7.1	0.8	35	6.5	0.9	33	0.5	0.4	33	1.1	0.1
CO ₂	ppm	38	527	121	32	391	45	30	114	109	30	1.3	0.3
CO	ppm	38	0.3	0.2	35	0.2	0.2	33	0.1	0.3	33	3.1	3.0
O ₃	ppb	40	0.4	0.4	40	7.8	1.4	40	-7.4	1.2	40	0.0	0.0
NO ₂	ppb	40	10.0	4.5	40	8.7	2.2	40	1.3	3.9	40	1.2	0.4
Nicotine	ppb	80	<0.02	N/A	80	<0.02	N/A	80	N/A	N/A	80	N/A	N/A
PM2.5	µg/m ³	40	7.2	2.8	40	6.3	2.3	40	1.1	2.8	40	1.2	0.4
PM10	µg/m ³	39	18.3	6.6	40	19.7	4.3	39	-1.5	7.0	39	1.0	0.4
Fungi	cfu/m ³	33	1167	1233	33	1797	1069	33	-630	1208	33	0.9	0.9
Bacteria	cfu/m ³	32	1554	1449	32	1503	942	32	50	1160	32	1.7	2.6
Formaldehyde	ppb	40	11.0	3.9	40	1.1	0.6	40	9.8	4.1	40	13.9	6.9
Other carbonyls	ppb	40	7.7	2.5	40	1.0	0.6	40	6.6	2.7	40	8.1	4.0
TVOC	µg/m ³	40	190.1	127.1	38	23.5	11.1	38	167.9	126.1	38	9.2	5.9
Benzene	µg/m ³	40	1.1	0.9	38	0.6	0.3	38	0.5	0.9	38	2.2	2.4
Toluene	µg/m ³	40	9.1	8.9	38	3.4	1.5	38	5.9	9.2	38	3.2	3.3
Ethylbenzene	µg/m ³	40	1.1	1.0	38	0.5	0.3	38	0.6	1.0	38	2.7	3.1
p-Xylene	µg/m ³	40	2.8	3.2	38	1.3	0.8	38	1.6	3.2	38	2.7	3.6
m-Xylene	µg/m ³	40	1.0	1.2	38	0.5	0.3	38	0.6	1.2	38	2.6	3.6
o-Xylene	µg/m ³	40	1.9	1.7	38	0.7	0.4	38	1.2	1.8	38	3.1	3.4
ΣXylenes	µg/m ³	40	5.7	6.0	38	2.4	1.4	38	3.3	6.2	38	2.8	3.5
ΣBTEX	µg/m ³	40	16.9	15.1	38	6.9	3.1	38	10.3	15.7	38	2.9	3.0

Table 9 Weekly statistics for Summer/Autumn data. Differences and ratios are calculated only for dwellings with both indoor and outdoor measurements.

Parameter/ Pollutant	Conc. Units	Indoor			Outdoor			Indoor minus Outdoor			Indoor/Outdoor ratio		
		N	Average	Std Dev.	N	Average	Std Dev.	N	Average	Std Dev.	N	Average	Std Dev.
Temperature	°C	40	22.1	2.1	40	18.1	3.0	40	4.0	1.6	40	1.2	0.1
Relative Humidity	%	40	53.5	4.5	40	68.1	7.3	40	-14.6	6.4	40	0.8	0.1
H ₂ O mixing ratio	g/kg	40	8.8	1.1	40	8.4	1.2	40	0.4	0.5	40	1.1	0.1
CO ₂	ppm	40	544	121	40	438	29	40	106	123	40	1.3	0.3
CO	ppm	40	0.3	0.2	40	0.1	0.1	40	0.2	0.2	40	3.4	2.9
O ₃	ppb	40	0.9	0.8	40	7.2	1.9	40	-6.3	1.8	40	0.1	0.1
NO ₂	ppb	40	6.8	2.2	40	11.3	4.2	40	-4.5	3.3	40	0.6	0.2
Nicotine	ppb	80	<0.02	N/A	80	<0.02	N/A	80	N/A	N/A	80	N/A	N/A
PM2.5	µg/m ³	40	9.7	4.6	40	8.4	3.4	40	1.3	4.6	40	1.2	0.7
PM10	µg/m ³	40	22.6	9.0	39	26.0	8.7	39	-3.4	9.8	39	0.9	0.5
Fungi	cfu/m ³	39	2089	1642	39	2245	1719	39	-156	1460	39	1.2	1.3
Bacteria	cfu/m ³	39	1879	1335	39	2151	1621	39	-272	1295	39	1.3	1.5
Formaldehyde	ppb	40	13.5	5.0	40	1.3	0.6	40	12.3	5.0	40	12.3	5.7
Other carbonyls	ppb	40	8.0	2.8	40	1.2	0.4	40	6.8	2.7	40	7.0	2.8
TVOC	µg/m ³	39	206.0	120.5	38	29.9	13.9	37	174.7	118.5	37	9.0	11.1
Benzene	µg/m ³	39	1.5	0.8	38	0.9	0.5	37	0.5	0.8	37	1.8	1.3
Toluene	µg/m ³	39	12.4	23.5	38	4.3	2.3	37	8.2	22.9	37	2.6	2.3
Ethylbenzene	µg/m ³	39	1.3	1.2	38	0.6	0.3	37	0.7	1.2	37	10.4	50.5
p-Xylene	µg/m ³	39	3.4	3.4	38	1.6	0.9	37	1.7	3.3	37	11.1	54.8
m-Xylene	µg/m ³	39	1.1	1.2	38	0.6	0.3	37	0.5	1.2	37	4.7	17.3
o-Xylene	µg/m ³	39	2.8	2.1	38	0.8	0.4	37	1.9	2.1	37	10.3	40.8
ΣXylenes	µg/m ³	39	7.3	6.5	38	3.1	1.7	37	4.1	6.3	37	8.7	37.7
ΣBTEX	µg/m ³	39	39.0	27.1	38	8.9	4.6	37	13.4	25.1	37	2.6	2.0

3.3 Seasonal Variations in Indoor Air Quality

Significant seasonal differences in the mean concentrations of a number of indoor pollutants and parameters are observed in the data. The seasonal differences were determined using the 2-sided t-test (95% confidence limits) on data measured during the Winter/Spring and Summer/Autumn sampling periods.

Table 10 shows the differences between average Winter/Spring and Summer/Autumn indoor levels of pollutants and parameters. Table 11 shows the differences between average Winter/Spring and Summer/Autumn indoor-outdoor ratios of pollutants. Parameters highlighted in bold font indicate significant seasonal variations.

Ventilation (measured as the mean number of external doors and windows open per half hour) generally has a strong influence over the contributions of indoor and outdoor sources to indoor air quality. Whilst the mean level of ventilation in Summer/Autumn (1.3) was greater than the mean level in Winter/Spring (0.9), the difference was not statistically significant in this work.

Temperature, H₂O mixing ratio and relative humidity are significantly higher both indoors and outdoors during Summer/Autumn than Winter/Spring. The seasonal differences in outdoor meteorology have been discussed in Section 2.5.

PM₁₀, PM_{2.5} and benzene are higher both indoors and outdoors during Summer/Autumn than Winter/Spring. The seasonal differences for PM₁₀ and PM_{2.5} outdoors has been discussed in Section 2.7, and resulted from bushfires in summer and periods of inversion conditions in autumn. These sources may have contributed to the indoor concentrations.

The indoor levels of fungi are significantly higher during Summer/Autumn than Winter/Spring. While outdoor levels of fungi in Summer/Autumn were also higher than Winter/Spring, the difference is not statistically significant. Also, the mean indoor-outdoor ratios are less than one for Winter/Spring and greater than one for Summer/Autumn, however this difference is not significant. An examination of fungi speciation may help to explain these differences.

Nitrogen dioxide is the only pollutant that is significantly elevated indoors in Winter/Spring compared to Summer/Autumn. Conversely, outdoor concentrations are significantly higher in Summer/Autumn than Winter/Spring, leading to a significant seasonal difference in indoor-outdoor ratios, with an average ratio of 1.2 in Summer/Autumn and 0.6 in Winter/Spring. A ratio of greater than one in winter indicates that there are indoor sources of nitrogen dioxide, most probably associated with unflued combustion sources. The decrease in the indoor-outdoor ratio in summer to 0.6 is likely to be due to a decrease in indoor combustion sources in summer and perhaps the slightly higher level of ventilation in summer.

Indoor ozone is significantly higher during Summer/Autumn than Winter/Spring. The indoor-outdoor ratio is also significantly higher whilst levels of outdoor ozone at the dwelling show no seasonal difference. Ozone is a very reactive gas so will disperse to indoor surfaces (hence the low indoor-outdoor ratio in the absence of indoor sources). The change in ventilation between Winter/Spring and Summer/Autumn, while not statistically significant, may be sufficient to cause these ozone changes.

Table 10. Analysis of the difference between indoor concentrations in Winter/Spring and Summer/Autumn from this study. Pollutants/parameters in **bold** have significantly different concentrations at 95%.

Parameter/ Pollutant	Conc. Units	Winter / Spring			Summer / Autumn			Winter–Summer Indoor Means Comparison			
		N	Mean	SD	N	Mean	SD	t Stat	t Critical	P	Accepted Hypothesis
Temperature	°C	38	20.3	1.4	40	22.1	2.1	-4.49	2.00	0.00	Winter–Summer<0
Relative Humidity	%	38	48.2	4.7	40	53.5	4.5	-5.04	1.99	0.00	Winter–Summer<0
Mixing ratio	g/kg	38	7.1	0.8	40	8.8	1.1	-7.80	1.99	0.00	Winter–Summer<0
Sea Level Pressure	hPa	38	1011	7.7	40	1012	5.4	-1.03	2.00	0.31	Winter–Summer=0
Level of ventilation	Openings [#]	40	0.9	1.2	40	1.3	2.1	-1.3	2.00	0.28	Winter–Summer=0
CO2	ppm	38	526.9	120.7	40	544.2	121.2	-0.63	1.99	0.53	Winter–Summer=0
CO	ppm	37	0.28	0.21	40	0.32	0.24	-0.86	1.99	0.39	Winter–Summer=0
O3	ppb	40	0.4	0.4	40	0.9	0.8	-3.71	2.00	0.00	Winter–Summer<0
NO2	ppb	40	10.0	4.5	40	6.8	2.2	4.13	2.00	0.00	Winter–Summer>0
PM2.5	µg/m³	40	7.2	2.8	40	9.7	4.6	-2.95	2.00	0.00	Winter–Summer<0
PM10	µg/m³	39	18.3	6.6	40	22.6	9.0	-2.43	1.99	0.02	Winter–Summer<0
Formaldehyde	ppb	40	11.0	3.9	40	13.5	5.0	-2.52	1.99	0.01	Winter–Summer<0
Other carbonyls	ppb	40	7.7	2.5	40	8.0	2.8	-0.47	1.99	0.64	Winter–Summer=0
TVOC	µg/m ³	40	190.1	127.1	39	206.0	120.5	-0.57	1.99	0.57	Winter–Summer=0
Benzene	µg/m³	40	1.1	0.9	39	1.5	0.8	-2.13	1.99	0.04	Winter–Summer<0
Toluene	µg/m ³	40	9.1	8.9	39	12.4	23.5	-0.82	2.01	0.42	Winter–Summer=0
Ethylbenzene	µg/m ³	40	1.1	1.0	39	1.3	1.2	-0.92	1.99	0.36	Winter–Summer=0
ΣXylenes	µg/m ³	40	5.7	6.0	39	7.3	6.5	-1.14	1.99	0.26	Winter–Summer=0
ΣBTEX	µg/m ³	40	16.9	15.1	39	39.0	27.1	-1.12	2.00	0.27	Winter–Summer=0
Bacteria	µg/m ³	32	1554	1449	39	1879	1335	-0.98	2.00	0.33	Winter–Summer=0
Fungi	cfu/m³	33	1167	1233	39	2089	1642	-2.72	1.99	0.01	Winter–Summer<0

[#]Units for level of ventilation are mean number of dwelling window and doors open in each 30-minute interval

Table 11. Analysis of the difference between the indoor-outdoor (I/O) ratios for Winter/Spring and I/O ratios for Summer/Autumn periods from this study. Pollutants in **bold** have significantly different concentrations at 95%.

Parameter/ Pollutant	Conc. Units	Winter / Spring			Summer / Autumn			Winter - Summer I/O Ratio Means comparison			
		N	Mean	SD	N	Mean	SD	t Stat	t Critical	P	Accepted Hypothesis
Temperature	°C	34	1.3	0.1	39	1.2	0.1	2.48	1.99	0.016	Winter–Summer>0
Mixing ratio	g/kg	34	1.1	0.1	39	1.0	0.1	2.47	2.00	0.016	Winter–Summer>0
Relative Humidity	%	34	0.8	0.1	39	0.8	0.1	-0.73	1.99	0.467	Winter–Summer=0
Sea Level Pressure	hPa	34	1.0	0.0	39	1.0	0.0	1.34	2.00	0.186	Winter–Summer=0
CO2	ppm	33	1.30	0.3	39	1.25	0.3	0.76	2.00	0.449	Winter–Summer=0
CO	ppm	32	3.12	3.00	39	3.45	2.90	-0.46	2.00	0.649	Winter–Summer=0
O3	ppb	40	0.05	0.0	40	0.13	0.1	-4.46	2.01	0.000	Winter–Summer<0
NO2	ppb	40	1.15	0.4	40	0.64	0.2	6.88	2.00	0.000	Winter–Summer>0
PM2.5	µg/m ³	40	1.19	0.4	40	1.24	0.7	-0.40	2.00	0.693	Winter–Summer=0
PM10	µg/m ³	39	0.95	0.4	39	0.93	0.5	0.25	1.99	0.804	Winter–Summer=0
Formaldehyde	ppb	40	11.87	7.2	40	12.08	5.7	-0.15	1.99	0.885	Winter–Summer=0
Other carbonyls	ppb	40	9.81	4.3	40	7.21	2.9	3.20	2.00	0.002	Winter–Summer>0
TVOC	µg/m ³	38	9.22	5.9	37	9.05	11.1	0.08	2.00	0.936	Winter–Summer=0
Benzene	µg/m ³	38	2.15	2.4	37	1.76	1.3	0.88	2.00	0.380	Winter–Summer=0
Toluene	µg/m ³	38	3.21	3.3	37	2.59	2.3	0.93	2.00	0.354	Winter–Summer=0
Ethylbenzene	µg/m ³	38	2.73	3.1	37	10.45	50.5	-0.93	2.03	0.360	Winter–Summer=0
∑Xylenes	µg/m ³	38	2.78	3.5	37	8.66	37.7	-0.94	2.03	0.351	Winter–Summer=0
∑BTEX	µg/m ³	38	2.91	3.0	37	2.58	2.0	0.56	2.00	0.578	Winter–Summer=0
Bacteria	cfu/m ³	32	1.72	2.6	39	1.33	1.5	0.74	2.01	0.461	Winter–Summer=0
Fungi	cfu/m ³	33	0.90	0.9	39	1.23	1.3	-1.26	1.99	0.210	Winter–Summer=0

3.4 Comparison of Indoor Air in Typical Australian Dwellings with Previous Indoor Measurements in Australia

The concentrations (median, minimum and maximum) of the air pollutants measured in this set of typical Australian dwellings are compared with previous studies in Australia in Table 12.

One of the difficulties in making direct comparisons between this study and other Australian studies is due to differences in sampling times. Larsen (1969) has presented an analysis relating yearly maximum concentrations observed for different averaging periods from outdoor air quality measurements. We know of no equivalent study of indoor air quality. The ratios of the yearly maximum concentrations for given sampling periods to that for a 7 day sampling period (as used in this study) are 7 for 1 hour, 3.5 for 8 hours and 2 for 1 day (Larsen 1969).

The range of concentrations of most species measured indoors in this study is similar to other Australian studies. The exceptions are:

- CO₂, NO₂ and CO which are lower in this study than reported in Sheppard et al. (2006) and DEH (2004b) where dwellings with unflued gas heaters were sampled. This is to be expected as unflued heaters fuelled by natural gas are not permitted in Victoria, where this study is conducted, and the combustion products of these heaters include CO and NO₂. In Victoria, unflued heaters can be run on liquefied petroleum gas (LPG or 'bottled' gas); these are typically used in rural regions where natural gas is unavailable.
- Fungi concentrations cover a similar range to those reported elsewhere.
- Formaldehyde concentrations measured in this study are lower than measured in caravans and mobile homes. Caravans and mobile homes make up a very small proportion of Australian dwelling, hence were not sampled in this study.
- PM_{2.5} concentrations measured in this study are lower than those observed during "cooking events".
- TVOC concentrations measured in this study are comparable with those observed previously for non-complaint buildings.

Table 12. Existing studies of indoor air quality in Australian dwellings

Pollutant	This study: Median, Min–Max (averaging period)	Previous measurements in Australia Average ^{A,G,M} , Min– Max (averaging period)	Study location	Reference
Carbon Dioxide ppm	499, 348–1089 (7-day) 499, 330–1639 (8-hr)	1700 ^A , 510–>5500 (8-hr)	149 houses operating unflued gas heaters	DEH (2004b)
Carbon Monoxide ppm	0.3, <0.1–1.5 (7-day) 0.3, <0.1–6.5 (8-hr)	2.6 ^A , <2– 22 (8-hr)	149 houses operating unflued gas heaters	DEH (2004b)
Nitrogen Dioxide ppb	7.9, 2.2–26.6 (7-day)	34–1000 (1-hr) 7.9 ^G (3-day) 9.1 ^G , 1–96 (7-day) 5.6 ^G / 15.5 (7-day) 6.2 ^A , 5.0–7.5 (7-day) 8.5 ^A , 7.6–10.0 (7-day)	149 houses operating unflued gas heaters Kitchens of 53 homes 140 living areas No unflued gas appl. / Unflued gas appl. 1 dwelling, 8-weeks, summer 1 dwelling, 8-weeks, winter	DEH (2004b) Franklin <i>et al.</i> (2006) Sheppard <i>et al.</i> , (2006a) Sheppard <i>et al.</i> (2006a) Dunne <i>et al.</i> (2006) Dunne <i>et al.</i> (2006)
Ozone ppb	0.5, 0.1–3.6 (7-day)	0.5 ^A , 0.1–1.0 (7-day) 0.1 ^A , 0.0–0.2 (7-day)	1 dwelling, 8-weeks, summer 1 dwelling, 8-weeks, winter	Dunne <i>et al.</i> , (2006) Dunne <i>et al.</i> , (2006)
PM2.5 µg m ⁻³	7.5, 3.5–22.4 (7-day) 6.0, 0.5–74.8 (24-hr*)	10.2 ^M , 0.8–71.7 (24-hr) 8.8 ^A / 19.2 ^A (24-hr) 8.5 ^A , 7.1–10.2 (24-hr) 79 ^M / 718 ^M / 745 ^M (event)	100 living areas 52 non-smoking / 14 smoking-dwellings 78 living areas, inlet height 1.4m Smoking / Grilling / Frying in 15 homes	Nguyen <i>et al.</i> (2005) Nguyen <i>et al.</i> (2005) Jones <i>et al.</i> (2007) He <i>et al.</i> (2004)
PM10 µg m ⁻³	19.7, 8.0–45.9 (7-day)	26.2 ^G , 5.4–143.8 (7-day) 15.9 ^A , 7.0–34.8 (7-day) 47.3 ^A , 23.4–84.1 (7-day) 14.2 ^A , 12.5–16.1 (24-hr)	136 living areas, winter 12 dwellings, summer, woodheater-region 12 dwellings, winter, woodheater-region 78 living areas, inlet height 1.4m	Sheppard <i>et al.</i> , (2006b) DEH (2004b) DEH (2004b) Jones <i>et al.</i> (2007)
Nicotine µg m ⁻³	<0.07, <0.07–<0.07 (7-day)	<0.1 / 8.2 (2-day) 0.0 ^A / 4.8-9.9 (7-day) 0.065 ^G , 0.001–11.4 (7-day)	1 non-smoking / 1 smoking dwelling 6 non-smoking / 3 smoking dwellings 89 living areas	Ayers <i>et al.</i> (1998) Ayers <i>et al.</i> (1999) Sheppard <i>et al.</i> (2006c)

^AArithmetic mean, ^GGeometric mean, ^MMedian, *only measurements covering entire calendar day included (n=463)

Table 12 cont. Existing studies of indoor air quality in Australian dwellings

Pollutant	This study: Median, Min–Max (averaging period)	Previous measurements in Australia Average ^{A,G,M} , Min– Max (averaging period)	Study location	Reference
Benzene ppb	0.29, 0.09–1.35 (7-day intermittent)	<8.6 ^A / 0.6 ^A (20-40 min) 0.9 ^G / 0.8 ^G (30-50 min) 0.70 ^A , 0.05–7.01 (7-day) 2.29 ^A , 0.38–10.54 (7-day) 0.5 ^A , 0.3–1.0 (7-day) 1.2 ^A , 0.8–1.8 (7-day)	Living room, new dwelling / after 8 months 22 non-complaint / 5 complaint dwellings 77 dwellings, summer, woodheater-region 77 dwellings, winter, woodheater-region 1 dwelling, 8-weeks, summer 1 dwelling, 8-weeks, winter	Brown (2001) Brown (2002) DEH (2004a) DEH (2004a) Dunne <i>et al.</i> (2006) Dunne <i>et al.</i> (2006)
Toluene ppb	1.5, 0.73–36.5 (7-day intermittent)	58.4 ^A / 1.7 ^A (20-40 min) 2.2 ^G / 1.7 ^G (30-50 min) 2.11 ^A , 0.20–21.29 (7-day) 6.37 ^A , 0.77–27.62 (7-day) 1.0 ^A , 0.7–1.6 (7-day) 1.7 ^A , 1.1–2.3 (7-day)	Living room, new dwelling / after 8 months 22 non-complaint / 5 complaint dwellings 77 dwellings, summer, woodheater-region 77 dwellings, winter, woodheater-region 1 dwelling, 8-weeks, summer 1 dwelling, 8-weeks, winter	Brown (2001) Brown (2002) DEH (2004a) DEH (2004a) Dunne <i>et al.</i> (2006) Dunne <i>et al.</i> (2006)
Ethylbenzene ppb	0.19, 0.06–1.7 (7-day intermittent)	0.26 ^A , 0.01–2.70 (7-day) 0.57 ^A , 0.12–3.20 (7-day) 0.3 ^G / 0.3 ^G (30-50 min) 1.7 ^A / 0.2 ^A (20-40 mins) 0.2 ^A , 0.1–0.3 (7-day) 0.6 ^A , 0.1–0.6 (7-day)	77 dwellings, summer, woodheater-region 77 dwellings, winter, woodheater-region 22 non-complaint / 5 complaint dwellings Living room, new dwelling / after 8 months 1 dwelling, 8-weeks, summer 1 dwelling, 8-weeks, winter	DEH (2004a) DEH (2004a) Brown (2002) Brown (2001) Dunne <i>et al.</i> (2006) Dunne <i>et al.</i> (2006)
∑Xylenes ppb	0.97, 0.4–8.7 (7-day intermittent)	1.47 ^A , 0.15–17.37 (7-day) 3.29 ^A , 0.40–19.89 (7-day) 0.9 ^{*G} / 0.5 ^{*G} (30-50 min) 6.3 ^{*A} / 0.6 ^{*A} (20-40 mins) 1.0 ^A , 0.7–1.7 (7-day) 2.5 ^A , 1.1–5.2 (7-day)	77 dwellings, summer, woodheater-region 77 dwellings, winter, woodheater-region 22 non-complaint / 5 complaint dwellings Living room, new dwelling / after 8 months 1 dwelling, 8-weeks, summer 1 dwelling, 8-weeks, winter	DEH (2004a) DEH (2004a) Brown (2002) Brown (2001) Dunne <i>et al.</i> (2006) Dunne <i>et al.</i> (2006)

^AArithmetic mean, ^GGeometric mean, ^MMedian, ^{*}m,p-Xylene only

Table 12 cont. Existing studies of indoor air quality in Australian dwellings

Pollutant	This study: Median, Min–Max (averaging period)	Previous measurements in Australia Average ^{A,G,M} , Min–Max (averaging period)	Study location	Reference
Formaldehyde ppb	11.7, 3.6–24.8 (7-day)	89.6 ^A / 34.3 ^A (1-hr) 19.7 ^G , 6–73 (90-min) 19.4 ^M , 11.9–74.6 (7-day) 3.4 ^M , 0.1–46.2 (7-day) 3.8 ^A , 1.1–25.5 (7-day) 26 ^A , 0–97 (3- to 4-day) 22.8 ^G , 3.0–92.3 (3-day) 90 ^A , 20-280 (3-4 day) 29 ^A , 8–175 (3-5 day) 346 ^A , 67-1000 (24-hr) 15.7 ^A , <0.2–109 (4-day) 2.7 ^A , 1.7–4.6 (7-day) 3.0 ^A , 1.9–4.2 (7-day)	1 new dwelling / dwelling after 8 months 40 dwellings 13 dwellings; unflued gas heaters used 139 living areas 9 dwellings 100 conventional dwellings 185 dwellings; most measured twice 6m occupied caravan occupied caravans new caravan 80 dwellings 1 dwelling, 8-weeks, summer 1 dwelling, 8-weeks, winter	Brown (2001) Godish <i>et al.</i> (1995) DEH (2004b) Sheppeard <i>et al.</i> , (2006c) Ayers <i>et al.</i> 1999 Dingle <i>et al.</i> (1992) Dingle & Franklin (2002) Dingle <i>et al.</i> (1992) Dingle <i>et al.</i> (2000) McPhail (1991) Garrett <i>et al.</i> 1997 Dunne <i>et al.</i> , (2006) Dunne <i>et al.</i> , (2006)
TVOCs $\mu\text{g m}^{-3}$	154, 56–717 (7-day intermittent)	60–162 (30-min) 43, 28, <5 (30-min) 3000 ^A / 220 ^A (20-40 min) 320 ^A / 160 ^G (30-50 min) 240 ^A / 230 ^G (30-50 min)	1 unoccupied new dwelling low-emission dwelling at 3, 5, 12 months living room, new dwelling / after 8 months 22 non-complaint established dwellings 5 complaint dwellings	Guo <i>et al.</i> 2000 Guo <i>et al.</i> 2003 Brown (2001) Brown (2002) Brown (2002)
Fungi CFU m-3	1666, 124–>5654 (2-min)	500–1500 >2000 ^A in 25% of houses >500 ^A in 50% of houses	40 dwellings 30 dwellings 485 dwellings	Garrett (1996), Godish <i>et al.</i> (1993), Dharmage <i>et al.</i> (2001)

^AArithmetic mean, ^GGeometric mean, ^MMedian

4. THE INFLUENCE OF ROADS ON INDOOR AIR

One key question in this study was: does the proximity to busy roads have an influence on indoor air quality? In order to answer this question two sets of dwellings were selected. The criteria and selection of the two sets of dwellings, Near-Road and Far-Road are presented in Appendix A. The analysis of the data for these two sets of dwellings is addressed here.

The hypothesis is that busy roads have higher traffic densities and consequently larger emissions of CO, NO, particles, TVOCs and benzene than roads with low traffic density. This leads to higher concentrations of these gases and particles in the air over the road. As the roadway air is dispersed it mixes both horizontally and vertically so that the ground level concentration of pollutants, due to the roadway emissions, decreases with distance downwind of the roadway. Hence, dwellings downwind and near the roadway are exposed to higher outdoor concentrations of these roadway pollutants than dwellings further away or upwind of the road. If the concentration outside a dwelling is elevated, provided the combination of outdoor concentrations and dwelling ventilation are significant compared with indoor sources of these pollutants, an elevation of indoor concentrations is expected. Hence, provided a dwelling is nearby and downwind of the road and the other outdoor and indoor sources of these pollutants do not have a confounding effect; there should be an observed difference in the concentration of indoor pollutants between Near-Road and Far-Road dwellings.

4.1 Results

For the analysis of the influence of roads on indoor air quality, data sets from dwellings sampled in Winter/Spring and Summer/Autumn have been combined so that potentially 80 dwelling data sets can be analysed (40 from each sampling period). Two analyses of the data are presented here – firstly an analysis of the full data set for Near-Road and Far-Road dwellings, and secondly an analysis of a reduced data set of Near-Road and Far-Road dwellings.

A number of variables can potentially impact the indoor air quality of the dwellings making the task of determining the influence of just one factor, the effect of nearby roads challenging. For example, sampling occurred in a range of meteorological conditions over several seasons. In addition, the ambient concentrations of pollutants varied temporally and spatially, influenced by factors such as local sources, pollutants being trapped in stable air during high pressure systems (or inversions), and plumes of bushfire smoke that impacted greater Melbourne in early 2009.

These factors may confound the effect, if any, of busy roads on nearby dwellings. In the following sections several techniques are used to examine this effect including comparison of mean concentrations of pollutants using the Student t-test on absolute and residual concentrations at the dwellings, correlations between indoor and outdoor concentrations of pollutants, and regression analysis.

Dwellings were selected from a range of different Melbourne suburbs in order to take a representative sample of typical Australian homes. Several busy roads were targeted with varied traffic flow and vehicle types. Dwellings were located between 12–3000 m back from these

busy roads. Traffic volumes on roads classified as busy varied from 30,000–73,000 vehicles per day.

4.1.1 FIRST ANALYSIS USING ENTIRE DATA SET

In this first analysis all 80 data sets from the 40 dwellings were used to examine possible differences in the data between Near-Road and Far-Road dwellings.

Weekly average data for Near-Road and Far-Road dwellings are shown for indoor concentrations in Table 13 and for outdoor concentrations in Table 14.

A 2-tailed Student t-test was performed on differences between the mean measurements at a 95% confidence level to determine whether there were statistically significant differences between measured concentrations in Near and Far-road dwellings. The details of the t-test were as follows: The t-test assumed the variances of the Near-Road and Far-Road measurements were unknown and could not be assumed to be equal. The numerical measure of the difference between two means was calculated as the difference between the means, divided by the sample estimate of the standard error of the difference. Table 13 and Table 14 show the calculated t value for the Near-Road–Far-Road data for each measurement, the critical t value at the 95% Confidence Level, and the Accepted Hypothesis, that states whether the calculated t value exceeds the critical t value. When the calculated t value does not exceed t critical, the Null Hypothesis is accepted, indicating no statistically significant difference between the Near (X_1) and Far (X_2) Road means for the parameter or chemical species measured. This is denoted as $X_1 - X_2 = 0$ in the Accepted Hypothesis columns of Table 13 and Table 14. When the calculated t value exceeds t critical, the Null Hypothesis is rejected indicating a statistically significant difference between the Near-Road and Far-Road means for the parameter or chemical species measured. This is denoted as $X_1 - X_2 > 0$ when the calculated t value is positive and exceeds t critical, or $X_1 - X_2 < 0$ when the calculated t value is negative and exceeds t critical. When no statistically significant difference was found, this is denoted as $X_1 - X_2 = 0$.

Indoors (Table 13) there were statistically significant differences between the means of Near and Far-Road average weekly NO_2 (Near – Far > 0) and PM_{10} (Near – Far > 0). This indicates enhanced concentrations of NO_2 and PM_{10} in Near-Road dwellings compared with Far-Road dwellings. There were no statistically significant differences between the means of Near and Far-Road mean weekly measurements of CO_2 , CO, Temperature, relative humidity, water vapour mixing ratio, O_3 , $\text{PM}_{2.5}$, bacteria, fungi, formaldehyde, other carbonyls and TVOC.

Outdoors (Table 14) there were statistically significant differences between Near and Far-Road means for O_3 (Near – Far < 0) and NO_2 (Near – Far > 0). This indicates enhanced concentrations of NO_2 outside Near-Road dwellings compared to Far-Road dwellings. In addition lower concentrations of O_3 occurred outside Near-Road dwellings compared to Far-Road dwellings. There were no statistically significant differences between the means of Near and Far-Road average weekly CO_2 , CO, Temperature, relative humidity, water vapour mixing ratio, $\text{PM}_{2.5}$, bacteria, fungi, formaldehyde, other carbonyls, PM_{10} and TVOCs.

Two possible explanations for these statistics exist. Either proximity to the busy road enhances indoor concentrations of NO_2 and PM_{10} , or there is a confounding variable that leads to higher indoor concentrations of NO_2 and PM_{10} in Near-Road dwellings in this data set. Elevated NO_2

concentrations outside the Near-Road dwellings support the influence of NO₂ from the busy roads. However, the absence of elevated PM₁₀ outside the Near-Road dwellings is contrary to an influence of PM₁₀ from busy roads. The wide ranges of concentrations measured at both Near and Far-Road dwellings indicates that there may be other significant influences on PM₁₀ and NO₂ concentrations as well as road proximity.

Consequently, a correlation analysis was performed to explore the issue. The analysis looked for correlations between indoor and outdoor mean concentrations for dwellings in the Near-Road category and those in the Far-Road category.

Proximity to roadways could affect weekly average concentrations indoors and outdoors of dwellings in two ways. At some dwellings the traffic density may be higher, or the duration of time that the wind blew from the roadway towards the dwelling longer, so the indoor and outdoor concentrations in that dwelling would be enhanced compared with the dataset of all Near-Road dwellings. In this case the roadway emissions would cause a correlation between indoor and outdoor concentrations. Alternatively, weekly average traffic volumes and wind direction may be relatively constant compared with other influences at all Near-Road dwellings. In this case there could be an average increase in indoor and outdoor concentrations due to roadway emissions that does not appear as a correlation between indoor and outdoor concentrations but would appear in the t-test results. In this study, given the finite data set and other influences on these pollutants, some combination of these two effects could occur and not be observable by statistical analysis.

The results of the correlation analysis between indoor and outdoor concentrations are in Table 15 for Near-Road dwellings and for Far-Road dwellings. N indicates the number of paired indoor-outdoor concentrations in the analysis for each pollutant. R indicates the level of correlation found, where ± 1 is a perfect correlation between the indoor and outdoor data, and 0 indicates no correlation. P indicates the probability of the correlation being significant at the 5% level.

For Near-Road dwellings, PM₁₀ has a significant indoor to outdoor correlation with an R value of 0.42, indicating that outdoor PM₁₀ explains only around 18% of the variance in the indoor PM₁₀ concentrations for the Near-Road dwellings and the remaining 82% of variance is due to other factors. The NO₂ concentration displays a significant correlation between indoor and outdoor concentrations. The low degree of correlation between indoor and outdoor concentrations for NO₂ and PM₁₀ indicates that outdoor air has limited impact on the variance of NO₂ and PM₁₀ concentrations in indoor air at these dwellings.

The correlations for Far-Road dwellings show a very similar picture. PM₁₀ has a significant indoor-outdoor correlation with an R of 0.43.

The correlation analysis suggests that for PM₁₀ and NO₂ measured in this study, variations in concentrations in outdoor air did not largely influence the variations in concentrations in indoor air at either the Near-Road or the Far-Road sites. The reason for the elevated NO₂ in Near-Road dwellings as detected by the t-test could be due to either a near constant increase in NO₂ due to roadway influence or alternatively activities occurring inside the home, rather than its proximity to the road. Similarly for PM₁₀, while a low degree of correlation was found between indoor

and outdoor air, over 80% of the variance in indoor concentrations for Near-Road and Far-Road is likely to be due to other sources or activities within the home.

A final exploration of the effect of proximity to busy roads involved plotting indoor and outdoor concentrations versus distance from the dwelling to the nearest busy road for the entire data set. Figure 12 shows indoor and outdoor weekly concentrations against distance to road for several pollutants for which motor vehicle exhaust is a major source in an urban area: (a) NO₂, (b) CO, (c) PM₁₀, (d) PM_{2.5}, (e) toluene and (f) TVOCs. For NO₂ there may be some indication of a decrease in concentrations with dwellings >800m from a busy road, however this is difficult to interpret because there are few observations in the range >800m and therefore the sampling uncertainty is extremely high. There does not appear to be a relationship between distance to road and concentration of CO, PM₁₀, PM_{2.5}, toluene and TVOCs.

In summary, three separate analyses were undertaken using the complete data set to determine the effect of proximity to road on nearby dwellings. There is an indication of a roadway influence of NO₂ on indoor concentrations in Near-Road dwellings, but it is not unequivocal. It appears that higher PM₁₀ in Near-Road dwellings in this data set are due to some other confounding influence. Consequently a second analysis with a reduced data set was undertaken (see Section 4.1.2).

Table 13 Indoor Near and Far-Road mean concentrations for the full data set, and t-test results. Pollutants in **bold** have significantly-different concentrations at 95%.

Parameter/ Pollutant	Conc. Units	Near-Road X ₁			Far-Road X ₂			Means Comparison X ₁ -X ₂		
		Mean	Std Dev.	N	Mean	Std Dev.	N	t	t critical	Accepted Hypothesis
Temperature	°C	21.3	1.9	40	21.1	2.1	38	0.46	1.99	X ₁ -X ₂ =0
Relative Humidity	%	50.6	5.3	40	51.2	5.4	38	-0.52	1.99	X ₁ -X ₂ =0
H ₂ O mixing ratio	g/kg	7.9	1.3	40	7.9	1.2	38	0.07	1.99	X ₁ -X ₂ =0
CO ₂	ppm	544.8	119.2	40	526.2	122.7	38	0.68	1.99	X ₁ -X ₂ =0
CO	ppm	0.3	0.3	40	0.3	0.2	37	1.14	1.99	X ₁ -X ₂ =0
PM10	µg/m³	22.8	9.0	41	17.9	6.2	38	2.85	1.99	X₁-X₂>0
PM2.5	µg/m ³	9.0	3.9	41	7.9	4.1	39	1.27	1.99	X ₁ -X ₂ =0
Other Carbonyls	ppb	8.0	2.4	41	7.7	2.9	39	0.49	1.99	X ₁ -X ₂ =0
Formaldehyde	ppb	12.6	5.1	41	11.8	4.2	39	0.82	1.99	X ₁ -X ₂ =0
TVOCs	µg/m ³	205.0	126.3	40	190.6	121.4	39	0.52	1.99	X ₁ -X ₂ =0
Benzene	µg/m ³	1.3	0.7	40	1.3	1.0	39	0.27	1.99	X ₁ -X ₂ =0
Toluene	µg/m ³	9.9	7.2	40	11.5	24.1	39	-0.41	1.99	X ₁ -X ₂ =0
Ethylbenzene	µg/m ³	1.1	0.4	40	1.2	1.5	39	-0.52	1.99	X ₁ -X ₂ =0
p-Xylene	µg/m ³	2.9	1.5	40	3.2	4.5	39	-0.37	1.99	X ₁ -X ₂ =0
m-Xylene	µg/m ³	1.0	0.5	40	1.1	1.6	39	-0.36	1.99	X ₁ -X ₂ =0
o-Xylene	µg/m ³	2.5	1.4	40	2.2	2.4	39	0.59	1.99	X ₁ -X ₂ =0
NO₂	ppb	9.9	3.3	41	6.8	3.9	39	3.77	1.99	X₁-X₂>0
O ₃	ppb	0.7	0.8	41	0.7	0.6	39	-0.29	1.99	X ₁ -X ₂ =0
Bacteria	cfu/m ³	1745.1	1547.8	40	1716.2	1172.9	31	0.09	1.99	X ₁ -X ₂ =0
Fungi	cfu/m ³	1664.7	1716.9	40	1668.7	1287.3	32	-0.01	1.99	X ₁ -X ₂ =0

Table 14 Outdoor Near and Far-Road mean concentrations for the full data set, and t-test results. Pollutants in **bold** have significantly-different concentrations at 95 %.

Parameter/ Pollutant	Conc. Units	Near-Road X ₁			Far-Road X ₂			Means Comparison X ₁ -X ₂		
		Mean	Std Dev.	N	Mean	Std Dev.	N	t	t critical	Accepted Hypothesis
Temperature	°C	17.0	2.7	38	16.8	3.1	37	0.24	1.99	X ₁ -X ₂ =0
Relative Humidity	%	65.1	7.8	38	65.7	8.0	37	-0.35	1.99	X ₁ -X ₂ =0
H ₂ O mixing ratio	g/kg	7.5	1.5	38	7.5	1.4	37	0.08	1.99	X ₁ -X ₂ =0
CO ₂	ppm	419.1	43.7	38	412.4	42.3	36	0.68	1.99	X ₁ -X ₂ =0
CO	ppm	0.1	0.1	38	0.2	0.2	36	-0.62	1.99	X ₁ -X ₂ =0
PM10	µg/m ³	23.6	7.5	40	22.0	7.6	39	0.92	1.99	X ₁ -X ₂ =0
PM2.5	µg/m ³	7.0	2.7	41	7.7	3.5	39	-0.90	1.99	X ₁ -X ₂ =0
Other Carbonyls	ppb	1.0	0.4	41	1.2	0.6	39	-1.42	1.99	X ₁ -X ₂ =0
Formaldehyde	ppb	1.2	0.5	41	1.2	0.6	39	0.17	1.99	X ₁ -X ₂ =0
TVOCs	µg/m ³	28.9	12.9	38	24.5	12.7	38	1.51	1.99	X ₁ -X ₂ =0
Benzene	µg/m ³	0.8	0.3	38	0.7	0.5	38	0.88	1.99	X ₁ -X ₂ =0
Toluene	µg/m ³	4.1	1.7	38	3.6	2.1	38	1.03	1.99	X ₁ -X ₂ =0
Ethylbenzene	µg/m ³	0.6	0.3	38	0.5	0.3	38	1.01	1.99	X ₁ -X ₂ =0
p-Xylene	µg/m ³	1.5	0.8	38	1.4	0.9	38	0.79	1.99	X ₁ -X ₂ =0
m-Xylene	µg/m ³	0.6	0.3	38	0.5	0.3	38	0.61	1.99	X ₁ -X ₂ =0
o-Xylene	µg/m ³	0.8	0.4	38	0.7	0.4	38	1.15	1.99	X ₁ -X ₂ =0
NO₂	ppb	11.0	2.9	41	9.0	3.9	39	2.53	1.99	X₁-X₂>0
O₃	ppb	7.1	1.5	41	7.9	1.8	39	-2.24	1.99	X₁-X₂<0
Bacteria	cfu/m ³	1692.5	1338.4	40	2105.9	1446.8	31	-1.23	1.99	X ₁ -X ₂ =0
Fungi	cfu/m ³	2012.0	1599.0	40	2113.9	1306.7	32	-0.30	1.99	X ₁ -X ₂ =0

Table 15. Indoor outdoor correlations for Near and Far-Road dwellings for the full data set. Correlations in **bold** are significant at 95%

Parameter/ Pollutant	Conc. Units	Near-Road Indoor/Outdoor Correlation				Far-Road Indoor/Outdoor Correlation			
		N	R	P	P<0.05	N	R	P	P<0.05
Temp	°C	38	0.86	0.00	Y	35	0.89	0.00	Y
Relative Humidity	%	38	0.66	0.00	Y	35	0.59	0.00	Y
H₂O mixing ratio	g/kg	38	0.95	0.00	Y	35	0.95	0.00	Y
CO ₂	ppm	37	0.04	0.80		33	0.14	0.44	
CO	ppm	38	0.10	0.56		34	0.34	0.05	Y
O ₃	ppb	41	0.20	0.21		39	0.30	0.06	
NO ₂	ppb	41	0.08	0.64		39	0.19	0.25	
PM2.5	µg/m³	41	0.48	0.00	Y	39	0.55	0.00	Y
Bacteria	cfu/m³	36	0.57	0.00	Y	24	0.75	0.00	Y
Fungi	cfu/m³	30	0.72	0.00	Y	23	0.81	0.00	Y
Formaldehyde	ppb	41	0.19	0.25		39	0.04	0.79	
Other Carbonyls	ppb	41	0.14	0.37		39	0.08	0.63	
PM10	µg/m³	40	0.42	0.01	Y	38	0.43	0.01	Y
TVOCs	µg/m ³	40	0.30	0.06		38	0.23	0.17	
Benzene	µg/m³	40	0.33	0.04	Y	38	0.22	0.19	
Toluene	µg/m³	40	0.11	0.52		38	0.60	0.00	Y
Ethylbenzene	µg/m ³	40	0.26	0.11		38	0.13	0.43	
p-Xylene	µg/m³	40	0.40	0.01	Y	38	0.20	0.22	
m-Xylene	µg/m³	40	0.36	0.02	Y	38	0.14	0.41	
o-Xylene	µg/m ³	40	0.03	0.86		38	0.19	0.25	

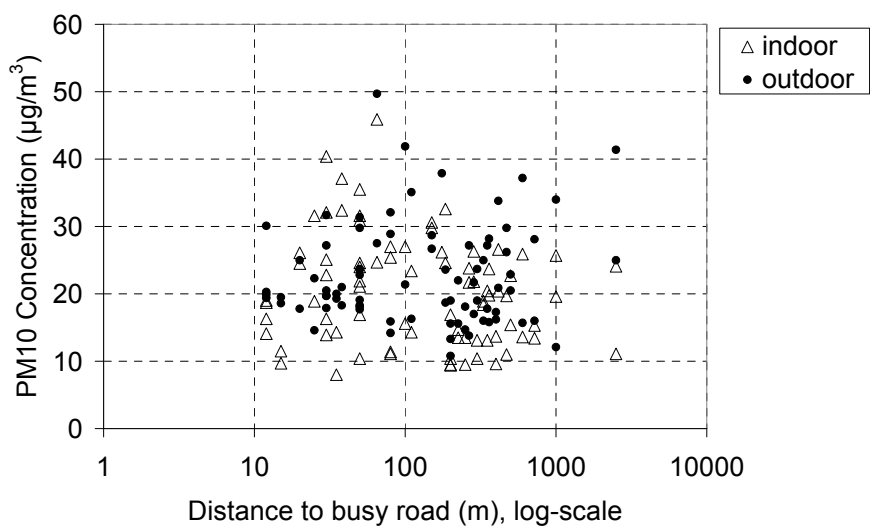
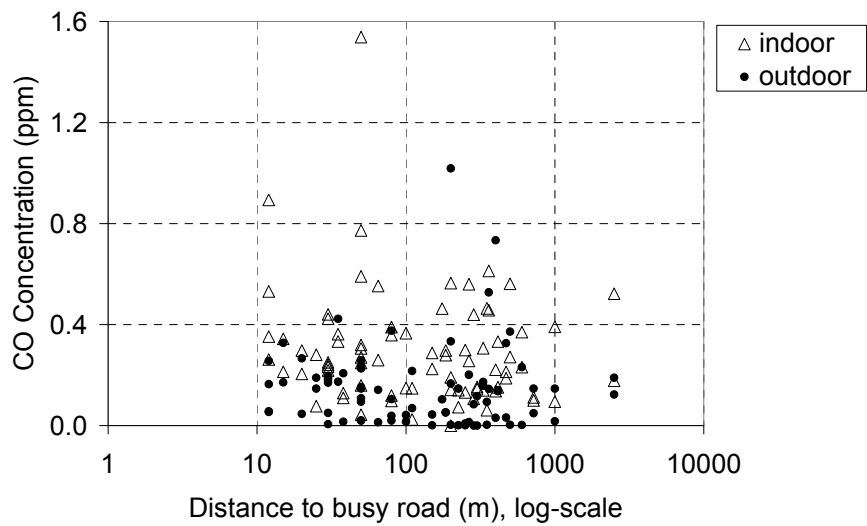
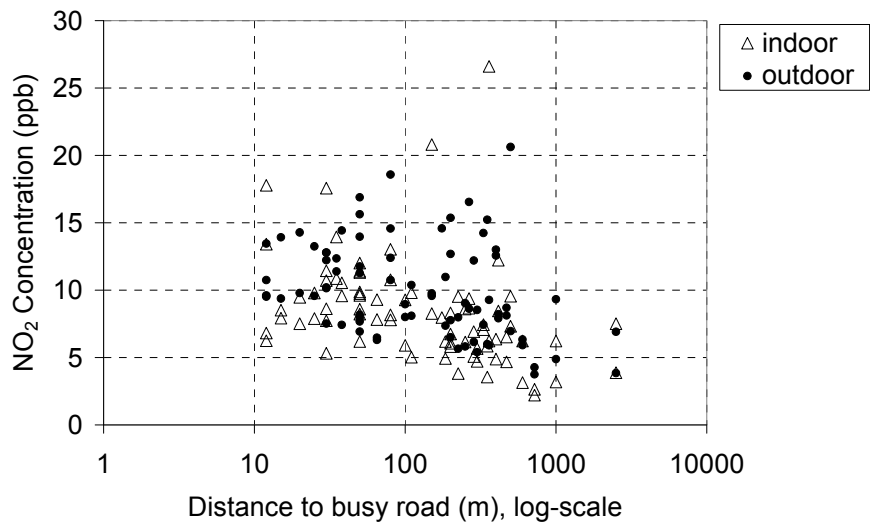


Figure 12. Indoor and outdoor weekly concentrations versus distance to busy road for the full data set. (a) NO₂, (b) CO (c) PM₁₀

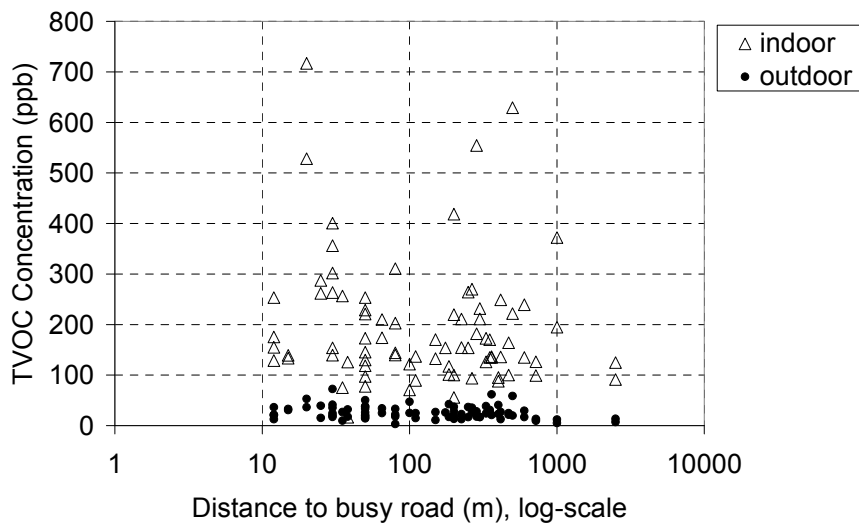
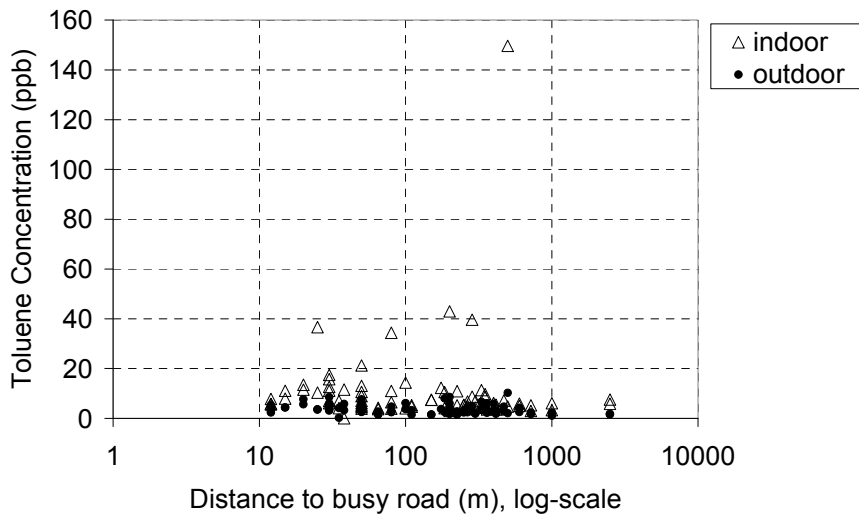
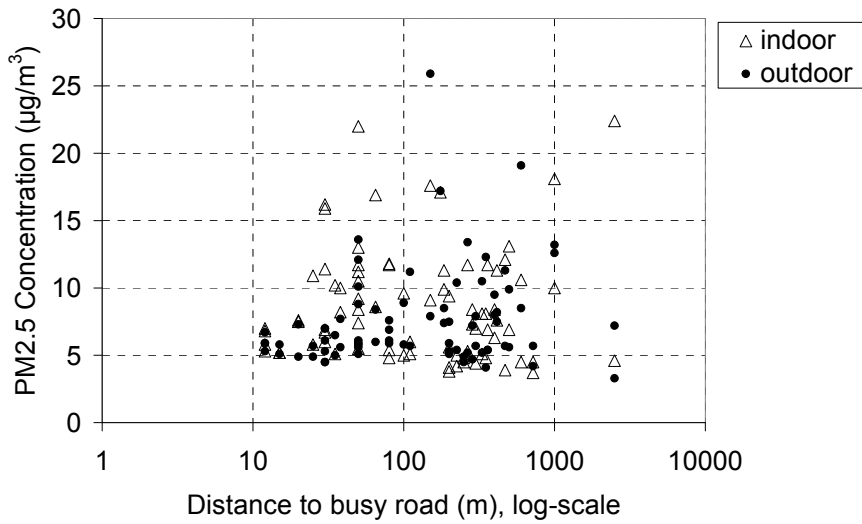


Figure 12 cont. Indoor and outdoor weekly concentrations versus distance to busy road for (d) PM2.5, (e) Toluene and (f) TVOC for the full data set.

4.1.2 SECOND ANALYSIS USING THE REDUCED DATA SET

For the second analysis of the effect of proximity to a busy road on indoor air quality, the suitability of the Near/Far-Road categorising distances was re-examined. In this second analysis dwellings were only included if they were located within 50 m of a busy road (Near-Road) or greater than 300 m from a busy road (Far-Road). These distances were selected based on other criteria presented in the literature (Ashbaugh et al., 1996; EPA Victoria, 2006; Hagler et al., 2009; Hitchins et al., 2000; Jones et al., 2000; Kwon et al., 2006; Laxen et al., 2002; Morawska et al., 1999; Naser et al., 2009; Pirjola et al., 2006; Roorda-Knape et al., 1998). The data set was decreased to 53, and comprised of 29 Near-Road and 24 Far-Road dwellings.

To address the issue of varying temporal background pollutant levels at the dwellings, including the bushfire smoke that impacted Melbourne in summer 2009, weekly ambient concentrations of CO₂, CO, PM₁₀, PM_{2.5} and O₃ were determined from regional ambient air quality data for the week corresponding to the sampling period at each of the dwellings, and subtracted from the weekly indoor and outdoor concentrations in both Winter/Spring and Summer/Autumn. The ambient measurements were made at the NATA Accredited Bayside Air Quality Station at CSIRO Aspendale. Subtraction of ambient 'background' concentrations resulted in residual concentrations of CO₂, CO, PM₁₀, PM_{2.5} and O₃ indoors and outdoors at each of the dwellings. In some cases this subtraction of background concentrations causes a negative concentration (a concentration less than the regional background).

It was not possible to constrain factors such as local meteorological conditions and traffic volumes which vary on time scales much smaller than a week.

The analysis of residual weekly average concentrations of CO₂, CO, PM₁₀, PM_{2.5} and O₃ are shown in Table 16 (indoor data) and Table 17 (outdoor data).

As with the entire data set in the first analysis, a 2-tailed Student t-test was performed on the reduced data set and looked for differences between the means of indoor and outdoor Near-Road and Far-Road residual concentrations at a 95% confidence level. The assumptions and details of the t-test used were described previously. A correlation analysis of indoor and outdoor residual concentrations for the reduced data set was not undertaken, due to an insufficient number of data points.

For the indoors measurements presented in Table 16, there was a statistically significant difference between Near and Far-Road data for PM₁₀ (Near-Road – Far-Road > 0) and NO₂, (Near-Road – Far-Road > 0). These results indicate enhanced concentrations of PM₁₀ and NO₂ in Near-Road dwellings compared with concentrations in Far-Road dwellings. There were no statistically significant differences between the mean residual concentrations of Near and Far-Road for other data. Outdoor measurements presented in Table 17 show there was a statistically significant difference between the mean residual concentration of NO₂ (Near-Road – Far-Road > 0) indicating enhanced concentrations of NO₂ outside Near-Road dwellings. There were no statistically significant differences between the mean residual Near and Far-Road concentrations for other variables.

The second t-test analysis of the reduced data set indicates the same differences between Near and Far-Road dwellings found in the t-test analysis of the full data set indoors (NO₂ and PM₁₀ enhanced in Near-Road dwellings in both cases). The second t-test analysis indicates the same

significant enhancement of NO₂ outdoors of Near-Road dwellings, but does not report the difference between O₃ outdoors to be significant as observed in the full data set.

In Far-Road dwellings, the mean indoor PM₁₀ concentration is lower than the mean ambient PM₁₀ concentration by 9.1 µg m⁻³, while at Near-Road dwellings, the indoor concentration is lower than the ambient concentration by 1.9 µg m³. While both indoor PM₁₀ concentrations are lower than ambient concentrations, the difference between Near and Far-Road is still significant at a 95% confidence limit. For NO₂ at Far-Road dwellings, mean indoor concentrations are lower than ambient concentrations by 1.5 ppb, while at Near-Road dwellings, indoor NO₂ concentrations are 1.3 ppb higher than ambient concentrations. Again this difference is significant at a 95% confidence limit.

Finally, outdoor NO₂ concentrations at Near-Road locations are on average 2.5 ppb higher than ambient concentrations, while at Far-Road locations the mean outdoor NO₂ concentrations are the same as ambient concentrations, with a difference or residual concentration of 0.0 ppb. This suggests that there is an enhancement of 2.5 ppb NO₂ outside Near-Road dwellings, compared to Far-Road dwellings. This difference is significant at a 95% confidence limit.

The enhanced NO₂ indoors and outdoors at Near-Road dwellings in both the full data set and reduced data set indicates that there are sources or processes occurring indoors and outdoors at these dwellings that are responsible for this enhancement. Similarly, it is most likely that there are processes or sources outdoors that are influencing the indoor concentration. It is probable that the enhanced NO₂ in Near-Road dwellings is due to motor vehicle exhaust from nearby busy roads.

The enhanced PM₁₀ indoors at Near-Road dwellings in both the full and reduced data set and the absence of enhanced PM₁₀ outdoors at these same dwellings indicates sources or processes occurring indoors that are responsible for the enhanced concentration of PM₁₀. The absence of enhanced PM₁₀ outdoors at Near-Road dwellings indicates that it is unlikely that nearby busy roads are responsible for enhanced PM₁₀ in these Near-Road dwellings.

Table 16. Indoor Near-Road and Far-Road measurement data for the reduced data set and t-test. Pollutants in **bold** have significantly-different concentrations at 95 %.

Pollutant	Conc. Units	Near-Road X_1			Far-Road X_2			Means Comparison X_1-X_2		
		Mean	Std Dev.	N	Mean	Std Dev.	N	t	t critical	Accepted Hypothesis
CO ₂	ppm	164.7	138.9	26	117.4	131.5	23	1.22	2.01	$X_1-X_2=0$
CO	ppm	0.2	0.3	27	0.1	0.1	22	1.57	2.02	$X_1-X_2=0$
PM10	$\mu\text{g}/\text{m}^3$	-1.9	9.8	29	-9.1	7.9	24	3.00	2.01	$X_1-X_2>0$
PM2.5	$\mu\text{g}/\text{m}^3$	0.2	3.6	29	-1.1	4.7	23	1.11	2.02	$X_1-X_2=0$
NO₂	ppb	1.3	3.8	29	-1.5	5.2	23	2.23	2.02	$X_1-X_2>0$
O ₃	ppb	-19.6	3.4	29	-19.2	4.3	23	-0.36	2.02	$X_1-X_2=0$

Table 17 Outdoor Near-Road and Far-Road residual concentrations for the reduced data set and t-test. Pollutants in **bold** have significantly-different concentrations at 95 %.

Pollutant	Conc. Units	Near-Road X_1			Far-Road X_2			Means Comparison X_1-X_2		
		Mean	Std Dev.	N	Mean	Std Dev.	N	t	t critical	Accepted Hypothesis
CO ₂	ppm	25.9	42.0	24	19.8	35.0	20	0.53	2.02	$X_1-X_2=0$
CO	ppm	0.0	0.1	25	0.0	0.2	20	-0.62	2.05	$X_1-X_2=0$
PM10	$\mu\text{g}/\text{m}^3$	-2.7	3.5	28	-2.3	4.8	24	-0.33	2.02	$X_1-X_2=0$
PM2.5	$\mu\text{g}/\text{m}^3$	-2.4	2.2	29	-1.5	3.6	23	-1.12	2.03	$X_1-X_2=0$
NO₂	ppb	2.5	2.2	29	0.0	1.8	23	4.76	2.01	$X_1-X_2>0$
O ₃	ppb	-13.1	3.0	29	-12.0	3.1	23	-1.30	2.01	$X_1-X_2=0$

4.2 Other Studies

Many studies have examined the effect of nearby busy roads on pollutant levels inside and outside dwellings (Ashbaugh et al., 1996; Barzyk et al., 2009; Beckerman et al., 2008; EPA Victoria, 2006; Hagler et al., 2009; Hitchins et al., 2000; Hoek et al., 2002; Janssen et al., 2001; Jones et al., 2000; Kwon et al., 2006; Laxen et al., 2002; Lianou et al., 2007; Morawska et al., 1999; Naser et al., 2009; O'Connell et al., 2008; Pirjola et al., 2006; Roorda-Knape et al., 1998; Sheppard et al., 2006c; Wang et al., 2006; Zhu et al., 2002). Some studies have shown that depending on the wind direction, pollutant levels drop off quickly within 50 m of the roadside (Ashbaugh et al., 1996; EPA Victoria, 2006; Jones et al., 2000; Kwon et al., 2006; Laxen et al., 2002; Morawska et al., 1999; Naser et al., 2009; Pirjola et al., 2006; Roorda-Knape et al., 1998). However in other cases pollutant levels may remain elevated above background up to 300 m downwind of the road, depending on the concentration of emissions and meteorological conditions (Hagler et al., 2009; Hitchins et al., 2000). An analysis of these studies that examined the effect of proximity to roads on indoor air quality is below and a summary of studies and their findings can be found in Table 18.

Janssen et al. (2001) measured PM_{2.5}, Elemental Carbon (EC), NO₂ and benzene inside and outside of 24 schools within 400 m of motorways in the Netherlands, to assess exposure of school children to traffic emissions. Motorways had a mean traffic density of 100,000 vehicles per day. PM_{2.5} and EC significantly decreased with distance from the motorway indoors and outdoors, and benzene decreased with distance outdoors. A relationship between percentage of time downwind and indoor NO₂ concentration was also established. Another study which assessed exposure of people to traffic near motor ways (daily traffic volume of 80,000–152,000) measured PM₁₀, PM_{2.5}, black smoke and benzene at four different distances from the roadside and measured indoor PM₁₀ and NO₂ in 12 schools in the Netherlands (Roorda-Knape et al., 1998). This study found that NO₂ concentrations in classrooms significantly correlated with car and total traffic intensity, percentage of time downwind and distance of the school from the motorway, and that outdoor NO₂ decreased with distance to the roadside. PM₁₀ concentrations in schools were high compared to outdoor concentrations and did not correlate with distance to the motorway, traffic intensity or time downwind.

Ilgen et al. (2001) measured six aromatic hydrocarbons indoors and outdoors of homes in high density traffic streets of Hannover city, Germany. The homes in the high traffic areas were five storey apartments that formed street canyons. Monitoring was carried out both inside and outside the front room of the dwelling that faced the city street, and ranged at heights from 3.5 m (first floor) to 16 m (fifth floor). The concentration of benzene, ethylbenzene and xylenes in the rooms facing the street were almost the same as the concentrations outside on the street (Indoor/Outdoor = 1), and there was a strong correlation between indoor and outdoor concentrations. Toluene was an exception, with an average I/O ratio of 3.5 and low correlation between indoor and outdoor concentrations, indicating significant indoor sources. Back rooms of the same apartments displayed a low correlation between indoor and outdoor concentrations, and higher I/O ratios (where the outdoor concentrations were measured at the back of the apartments), indicating that the traffic emissions were mainly affecting the front rooms of the apartments – indoor sources dominated in rooms further away from the road.

Fischer et al. (2000) measured PM₁₀, PM_{2.5}, PAHs and VOCs indoors and outdoors of 36 homes in Amsterdam during winter and spring, to evaluate differences in pollutant concentrations indoors and outdoors of homes near busy and quiet streets. Measurements were made on balconies and in living rooms of 18 dwellings fronting major streets (with an average traffic density of 16,000 vehicles/day) and 18 dwellings in quiet streets. Outdoor PM₁₀ and PM_{2.5} were 15–20% higher in high intensity streets, while PAHs, soot, benzene and TVOCs were 100% higher. Indoor concentrations in high traffic areas were greater than those in low traffic areas by a similar magnitude, except for VOCs. All differences between busy and quiet locations for both indoor and outdoor concentrations were significant except for indoor benzene. The study concluded that PM_{2.5} and PM₁₀ are not specific indicators of traffic emission exposure, and that benzene, VOCs and PAHs, which were highly correlated outdoors, are a more reliable indicator.

O'Connell et al. (2008) assessed respirable particle mass and number in areas of high and low traffic flow in Cardiff, UK. They found that the median indoor concentration of PM₅ in homes in high traffic locations was significantly higher (40%) than in those in low traffic locations. There was no difference in particle number concentration. Similarly, PM₅ was 45% higher outside residences in high traffic flow compared to those in low traffic flow, and the median particle number concentration was almost twice as high outside residences in high traffic areas compared to low traffic areas.

Other studies have found no effect of busy roads on the indoor air quality of nearby dwellings. An Australian study (Sheppard et al., 2006a; Sheppard et al., 2006b; Sheppard et al., 2006c) used weekly average measurements of NO₂, PM₁₀, formaldehyde and nicotine in 140 homes in NSW, Australia to investigate sources and typical levels of indoor air pollutants. Homes within 50 m of a busy road (traffic 50,000 vehicles/day) had significantly higher outdoor levels of NO₂; however there was no significant effect on indoor NO₂ or indoor and outdoor PM₁₀ due to the proximity of the busy road.

Kingham et al. (2000) monitored PM₁₀, PM_{2.5}, benzene and PAHs indoors and outdoors of homes in Huddersfield, England to investigate spatial variation in these traffic related pollutant. 24-hour measurements were made on the same day for paired 'proximity' homes (between 1–31 m from main road with peak hour traffic density of 1200–1500 vehicles/hr) and background dwellings (between 62–920 m from a main road). An analysis of spatial variations did not show a significant change in concentrations of any of the pollutants due to distance from main roads. The indoor and outdoor concentrations were correlated for all pollutants.

One important meteorological factor that has been studied is wind speed and direction and its impact on the transport of pollutants from the roadside (Barzyk et al., 2009; Hagler et al., 2009; Hitchins et al., 2000; Janssen et al., 2001; Jones et al., 2000; Pirjola et al., 2006; Roorda-Knape et al., 1998; Zhu et al., 2002). Wind direction has an important influence on the concentration of pollutants at sites near busy roads. Hitchins et al. (2000) found that when the wind is blowing parallel along the road, fine and ultra fine particle (UFP) number concentration drops with distance from the road twice as quickly as when the wind is blowing directly from the road towards the sampling points. In addition, when the wind blows towards the road and away from the sampling points, at a distance of just 15 m from the road no contribution of vehicle emissions can be measured. Hagler et al. (2009) found a similar effect with UFP, with concentrations measured at twice the background level up to 300 m downwind of the road.

When the wind was blowing from the opposite direction the observed concentrations were near background levels only 20 m from the road. In the same study CO, benzene and NO all correlated well with UFP. Barzyk et al., (2009), found that using effective distance (defined as the distance an air parcel will travel from the middle of the roadway to a site, which varies as a function of wind direction) rather than perpendicular distance from the roadway was a more accurate predictor of how VOC concentrations will vary spatially. Janssen et al., (2001) and Roorda-Knape et al. (1998) found that NO₂ concentrations in classrooms were significantly correlated with the percentage of time the school was downwind of the road.

4.3 Confounding Variables

There are several possible reasons why this study found no evidence of the effect of busy roads on nearby dwellings for pollutants other than NO₂. As discussed previously, there are many variables that affect the concentration and distribution of pollutants in an urban area, such as meteorology, local sources and background concentrations of pollutants.

The average level of ventilation of the dwelling, (as determined from the activity diaries as the numbers of doors and windows recorded to be open during half hour blocks) is positively correlated with distance of the dwelling from the road (correlation of 0.3). That is, the further the dwelling is from a busy road, the more windows and doors the occupants tended to have open. It is possible that participants closer to roads tended to have the dwelling in a more closed state due to traffic noise or concerns about traffic fumes. This may be a factor which obscures the effect (if any) of busy roads on indoor air quality.

Another possible reason that no effect of nearby busy roads was seen in the outdoor measurements for pollutants other than NO₂ and PM₁₀ may be due to the location of outdoor monitoring equipment at the dwellings. In a study in the Netherlands, Bloeman et al. (1993) found that benzene concentrations at the facade of homes along busy streets was about 70% higher at the front of the dwelling than at the back of the same dwellings. Ilgen et al. (2001) found that aromatic hydrocarbons measured outside on the street side of apartments in Hannover, Germany were twice as high as concentrations measured in the backyards of the same apartments. A high correlation between indoor and outdoor concentrations for rooms facing the street was observed, however for rooms at the backs of dwellings there was no correlation between indoor and outdoor concentration. During this study monitoring equipment was often sited at the back of homes, due to security issues associated with unfenced front gardens. This placement of the equipment may have diminished the concentrations of pollutants measured outdoors.

Another factor that made determining the effect of the road somewhat difficult was the 7 day integrated weekly average measurements. Using averaged data meant that the effects of short term changes occurring at the sample site, such as wind blowing towards the sample site from the road and increased emissions from peak hour traffic could not be isolated. It is possible that the nearby busy roads may have impacted on the indoor air quality in dwellings for short periods during the sampling week, however this effect is not evident in the weekly integrated sample, which is the combined result of all the factors impacting the site for the week.

The final factor is topography in the urban area, which influences dispersion, mixing and transport of pollutants.

In this study the busy roads had a traffic volume of between 30,000 and 73,000 vehicles per day. In studies by Roorda Knape et al. (1998) and Janssen et al. (2001) the average traffic volumes of busy roads were 80,000–152,000 and 39,737–169,637 vehicles per day respectively. Fischer et al. (2000) measured alongside busy roads with traffic volumes ranging from 5951–30974 vehicles per day. However there are other factors in Fischer's study that may have increased the roadside concentration of pollutants despite the modest traffic volume – Fischer's study was conducted in apartments in the centre of the city of Amsterdam, in canyon-type microenvironments, that may have lead to increased build up of emissions by the roadside. This is also the case for Ilgen et al. (2001) who used busy roads of 16,000 vehicles per day but measured in a street canyon environment with poor mixing, likely to lead to the build up of pollutants. Ilgen measured average concentrations outdoors facing the street of $9.6 \mu\text{g m}^{-3}$ benzene, $25.7 \mu\text{g m}^{-3}$ toluene and $27.6 \mu\text{g m}^{-3}$ xylene, whereas in this study, for the subset of dwellings within 50 m the average concentrations outdoors were only $0.74 \mu\text{g m}^{-3}$ benzene, $10.8 \mu\text{g m}^{-3}$ of toluene and $6 \mu\text{g m}^{-3}$ of xylenes, considerably lower.

4.4 Conclusion – the Influence of Roads on Indoor Air

A number of analyses were carried out in order to determine whether proximity to busy roads had an influence on indoor air quality in this study, including 2-tailed t-tests on full and reduced data sets, correlation analyses between indoor and outdoor concentrations, and an examination of the relationship between pollutant concentrations and distance from road.

Only for NO_2 was there statistical evidence of enhanced concentrations indoors in Near-Road dwellings that could be linked logically to roadway emissions. Other vehicle pollutants – CO, TVOCs, benzene, PM10 and PM2.5 showed no statistically significant and logical connection.

Many variables had the potential to impact the air quality of dwellings during this study. These include changing meteorological conditions, background pollutant levels varying both spatially and temporally, differences in road traffic flow, differing levels of dwelling ventilation and perhaps most importantly differing activities and chemicals used inside the dwelling. 7 day integrated measurements made it difficult to isolate the different factors that impacted the indoor air quality in dwellings during the week. Had proximity to a busy road dominated all the other factors for a particular pollutant, then an enhancement would likely to have been seen in the 7 day integrated sample for dwellings in the Near-Road category. However, the fact that no enhancement was seen for several pollutants indicates that there were probably several important factors that influenced the indoor concentrations of these pollutants in dwellings during this study; proximity to busy roads may have been one of these factors, but it was not a dominating factor.

Several studies in Europe and the UK have found that proximity to busy roads does impact indoor air quality in nearby dwellings, however some of these studies were conducted in locations quite different from those found in suburban Melbourne – for example in dwellings within street canyons. Another study in Australia and a study in the UK also found no effect of proximity to major roads on indoor air in nearby dwellings.

Table 18. Summary of other studies that examined the effect of proximity to busy roads on indoor air quality.

Reference	Study Location	Traffic density per day	Pollutants	Effect of nearby road on indoor air quality observed?	Key findings	Miscellaneous
This study, 2009	Melbourne, Australia	30,000–73,000 vehicles/day	PM2.5, PM10, NO ₂ , CO ₂ , CO, HCHO, , carbonyls, TVOCs, benzene, toluene, ethylbenzene, xylenes,	Yes	Indoor NO ₂ enhanced near busy roads.	Confounding influences on PM10. No effects for other pollutants
O'Connell et al., 2008	Cardiff, UK	14,790–48,310 vehicles/day	PM5	Yes	Indoor PM5 40% higher and outdoor PM5 45% higher for homes in high traffic areas	
Sheppeard et al., 2006a; Sheppeard et al., 2006b; Sheppeard et al., 2006c	NSW, Australia	>20,000 vehicles/day	NO ₂ , PM10,	No	Proximity to busy road not significant in predicting indoor levels of NO ₂ or PM10.	
Janssen et al., 2001	Netherlands	100,000 vehicles/day	PM2.5, EC, NO ₂ and benzene	Yes	Indoor and outdoor PM2.5 and EC significantly decreased with distance from motorway. Identified a relationship between indoor NO ₂ and percentage of time downwind from motorway.	Pollutants measured inside and outside schools

.Table 18 cont. Summary of other studies that examined the effect of proximity to busy roads on indoor air quality.

Reference	Study Location	Traffic density per day	Pollutants	Effect of nearby road on indoor air quality observed?	Key findings	Miscellaneous
Ilgen et al., 2001	Hannover, Northern Germany	17,500 vehicles/day	Benzene, toluene, ethylbenzene, <i>p</i> , <i>m</i> , <i>o</i> -xylene	Yes	Concentration of benzene, ethylbenzene and xylene in room facing street had same concentration as outside on the street. Strong correlation between indoor and outdoor concentrations.	5 story dwellings sampled in street canyons, this may lead to build up of emissions on roadside
Fischer et al., 2000	Amsterdam, Netherlands	5951 – 30,974 vehicles/day	PM10, PM2.5, PAHs, BaP, soot, benzene and sum VOCs	Yes	PAHs, BaP and soot were a factor of two higher indoors and outdoors for homes in high traffic streets. Difference is significant.	Study concluded PM2.5 and PM10 not specific indicators of traffic emission exposure.
Kingham et al., 2000	Huddersfield, UK	28,000 – 36,000 (based on peak hour)	PM10, PM2.5, benzene, PAHs	No	No significant change with distance from road for any of the pollutants. Indoor and outdoor concentrations correlated for all pollutants.	Measured paired 'proximity homes' (Near-Road) and 'background homes' (Far-Road).
Roorda-Knape et al., 1998	Netherlands	80,000 – 152,000 vehicles/day	PM10 and NO ₂	Yes	NO ₂ significantly correlated with car and total traffic intensity and distance to motorway. Outdoor NO ₂ decreased with distance to motorway.	Pollutants measured inside and outside schools

5. THE INFLUENCE OF THE BUILDING CHARACTERISTICS, MATERIALS AND ACTIVITIES ON INDOOR AIR

This section presents the analysis of the relationship of indoor air quality to the building characteristics, materials and indoor activities in the dwelling. This is presented in two parts. First, a correlation matrix is presented containing all the indoor air quality measurements and variables representing the characteristics, materials and activities in the dwellings. The data used are the weekly averages of each variable. The second analysis involved dividing the data set of weekly averages of indoor air quality measurements into sub-sets according to data obtained from the household survey. The differences between the sub-sets are then tested for statistical significance with a t-test. It should not be presumed, unless there is independent evidence, that there is a causal relationship between any two variables found to have a statistically significant relationship in this data since the relationship can also be caused by the confounding effect of one or more other variables. This will be discussed in the analysis.

5.1 Weekly Average Correlation Analysis

The correlations of the weekly average indoor air quality measurements with building characteristics, materials and some activities are presented here. The definitions of the building characteristics, materials and activity variables are described in detail in Appendix E. In summary, volume is the volume of the dwelling determined from the dwelling survey, number of occupants is the average number of people and animals present in the house over the 7 day period, weighted proportionately to a 75 kg adult, level of ventilation is the average number of doors and windows open to the outside over the 7 day period, space per occupant is the volume of the dwelling divided by the number of occupants, combustion events is the average number of activities that involved any combustion (e.g. cooking, heating), particles (mechanical sources) is the average number of mechanical activities known to generate particles such as sweeping and cleaning, particles (cooking sources) is the average number of cooking activities (grilling, frying, baking and toasting) known to generate particles.

Table 19 presents the correlation between indoor air quality measurements and building characteristics, materials and activities for all data. Correlation coefficients greater than 0.225 are highlighted in bold italics. For 80 pairs of values (the typical number), these correspond to 2 variables having 5% of variance in common, with less than a 5% probability of occurring by chance. It should be acknowledged that the fungi and bacteria are spot samples taken over 2 to 5 minute periods, whereas the other samples are 7-day integrated samples and so caution must be exercised in interpreting correlations involving fungi and bacteria with other parameters.

A number of significant correlations between indoor air quality measurements and building characteristics, materials and activities can be observed.

- Formaldehyde, other carbonyls, TVOCs, other aromatics and fungi all occur in lower concentrations in older dwellings. The presence of newer furniture, floor coverings and painted surfaces in newer dwellings may account for these correlations with the exception of the fungi. Newer dwellings are also ‘tighter’ and have lower infiltration

rates (when windows and doors are closed) due to building design and materials that improve the energy-efficiency of the dwelling. The relationship between infiltration and building age was quantified during a series of ventilation measurements performed on a subset of dwellings (see Appendix C). There is a significant positive correlation ($R^2=0.55$, $p < 0.001$) between dwelling age and air exchange rate (air changes per hour) when the dwelling is in a minimum ventilation (closed-up) state. Thus for pollutants with indoor sources, the removal rate of the pollutant is slower in newer dwellings due to reduced ventilation, which may result in higher indoor concentrations.

- PM10, benzene and m-xylene concentrations are higher in dwellings that have a connecting door to an attached garage (reflected in a negative correlation associated with the absence of an attached garage). This is presumably the result of infiltration of motor vehicle emissions from vehicles housed in the attached garage.
- The number of occupants is positively correlated with CO₂, PM10 and NO₂, presumably due to respiration, movement resulting in mechanical dust, and indoor combustion activities.
- CO₂ is positively correlated with occupant density, as would be expected, because occupants through their respiration are the major source of CO₂ in the dwellings.
- The level of ventilation, measured as the average number of external windows and doors opened throughout the week, is negatively correlated with CO₂ and formaldehyde. This presumably arises because these gases have an indoor source and are transported outdoors in a well ventilated dwelling. The level of ventilation is positively correlated with temperature, H₂O mixing ratio and ozone. In the case of ozone, this indicates higher ozone penetration into a well ventilated dwelling. The positive correlation of ventilation with temperature and H₂O mixing ratio presumably arises because ventilation, temperature, and H₂O mixing ratio all have a similar seasonal cycle.
- NO₂ is negatively correlated with distance from a busy road. This is discussed in Section 4.
- Combustion events (any form of burning in the dwelling) are positively correlated with CO₂, CO and PM2.5, which are all products of combustion.
- Activities that could cause mechanical generation of particles (vacuuming, sweeping, dusting) have no correlation with weekly PM10 or PM2.5.
- Cooking (grilling, frying, baking and toasting) has positive correlations with CO₂, NO₂ and bacteria. The connection between cooking and CO₂ and NO₂ is expected, see combustion events. The cause of the correlation with bacteria is unknown.
- Solvent use was positively correlated with TVOC concentrations, as would be expected because of the vaporization of the organic chemicals when the solvents are used.

Table 19 The correlation of indoor air quality measurements versus building characteristics, materials and activities for all data from this study. The correlations greater than 0.225 are presented in **bold italics**. For 80 pairs of values (the typical number), these correspond to 2 variables having 5% of variance in common, with less than a 5% probability of occurring by chance.

Parameter/ Pollutant	Age (years)	Volume	Garage w/ Internal Door	No. Occupant s	Occupant density	Level of Ventilatio n	Distance to Busy Road (m)	Combustio n Events	Particles - Mechanical Sources	Particles - Cooking Sources	Solvent Use
Temperature (°C)	-0.32	-0.04	-0.03	0.18	0.20	0.35	0.08	-0.13	0.05	0.04	0.12
Relative Humidity (%)	0.10	-0.02	0.00	-0.22	-0.14	0.10	-0.17	-0.01	0.09	-0.03	-0.14
H ₂ O mix. ratio (g/kg)	-0.18	-0.05	-0.01	0.00	0.05	0.35	-0.05	-0.11	0.11	-0.01	-0.01
CO ₂ (ppm)	-0.19	-0.05	0.10	0.23	0.27	-0.24	-0.09	0.31	-0.10	0.38	0.08
CO (ppm)	0.12	-0.05	0.10	-0.20	-0.14	-0.04	-0.05	0.52	-0.08	0.07	-0.11
PM ₁₀ (µg/m ³)	-0.10	0.15	-0.25	0.29	0.13	0.13	-0.14	0.08	0.03	0.02	0.12
PM _{2.5} (µg/m ³)	-0.12	0.21	-0.13	0.11	-0.09	-0.06	0.15	0.36	-0.04	-0.04	-0.05
Carbonyls (ppb)	-0.39	0.01	-0.06	0.08	0.09	-0.17	-0.05	0.12	0.00	0.17	0.09
HCHO (ppb)	-0.36	0.10	-0.04	0.04	0.02	-0.31	-0.04	0.15	-0.03	0.15	0.06
TVOC (µg/m ³)	-0.30	0.09	-0.07	0.13	0.15	-0.21	-0.09	0.05	0.09	-0.02	0.35
Benzene (µg/m ³)	-0.22	-0.01	-0.25	-0.08	-0.02	-0.19	-0.17	0.06	-0.08	-0.09	-0.02
Toluene (µg/m ³)	-0.03	0.13	-0.05	-0.02	-0.08	-0.11	-0.01	-0.07	-0.07	-0.07	-0.01
Ethylbenzene (µg/m ³)	-0.38	-0.01	-0.17	-0.01	0.01	-0.16	-0.03	-0.02	-0.04	-0.04	0.01
p-Xylene (µg/m ³)	-0.34	-0.01	-0.20	-0.04	-0.01	-0.16	-0.07	-0.04	-0.04	-0.04	0.00
m-Xylene (µg/m ³)	-0.35	0.00	-0.23	-0.02	-0.01	-0.15	-0.06	-0.04	-0.02	-0.05	0.00
o-Xylene (µg/m ³)	-0.32	0.02	-0.21	0.01	0.04	-0.19	-0.13	-0.05	-0.03	0.04	0.07
NO ₂ (ppb)	0.09	0.13	0.08	0.26	0.12	-0.06	-0.29	0.20	0.06	0.27	-0.05
O ₃ (ppb)	0.00	0.03	0.04	0.07	-0.01	0.51	0.12	0.14	-0.07	-0.04	0.02
Bacteria (cfu/m ³)	-0.08	-0.08	-0.02	0.07	0.12	0.02	-0.08	0.08	0.13	0.28	0.16
Fungi (cfu/m ³)	-0.24	0.04	-0.22	0.12	0.10	0.03	-0.10	-0.04	0.22	0.02	0.07

5.2 Survey Analysis

In this section, the data set was divided into subsets according to key information extracted from the Winter/Spring and Summer/Autumn household surveys from each dwelling. This information included:

- type of cooking fuel used (both stovetop and oven),
- presence of visible mould or musty odour in the dwelling
- presence of new furniture less than 6 months old (equal to or greater than the size of a 2 seater couch) and/or new carpet, flooring, renovations and/or indoor painting in the last 6 months.

This information was selected because of the potential of gas cooking appliances, mould, materials in new furniture (e. g. MDA, glues, lacquer) and activities associated with renovations to impact indoor air quality in the dwellings.

Based on the survey information, weekly average measurements from the dwellings were divided into seven subsets

- dwellings with a Gas Stove and Gas Oven
- dwellings with an Electric Stove and Electric Oven
- dwellings with a Gas Stove and Electric Oven
- dwellings in which occupants reported visible mould or musty odour
- dwellings in which occupants reported no visible mould or musty odour
- dwellings where major renovations or indoor painting occurred or new furniture was introduced in the last six months
- dwellings where no major renovations or indoor painting occurred or no new furniture was introduced in the last six months.

Two-tailed t-tests were used to explore differences in mean concentrations at a 95% confidence interval for the following correlations:

- dwellings with a Gas Stove and Gas Oven versus dwellings with an Electric Stove and Electric Oven, combining measurements from Winter/Spring and Summer/Autumn
- dwellings with a Gas Stove and Electric Oven versus dwellings with Electric Stove and Electric Oven combining measurements from Winter/Spring and Summer/Autumn
- dwellings in which occupants reported visible mould or musty odour, versus dwellings at which occupants reported no visible mould or musty odour, combining measurements from Winter/Spring and Summer/Autumn

- dwellings where major renovations or indoor painting occurred or new furniture was brought into the dwelling in the 6 months prior to sampling, versus dwellings with no major renovations, indoor painting or new furniture 6 months prior to sampling. These analyses were done firstly for Winter/Spring measurements, and secondly for Summer/Autumn measurements.

Table 20 shows weekly indoor measurement statistics for Dwellings with a Gas Stove and Gas Oven and dwellings with an Electric Stove and Electric Oven. Dwellings with a Gas Stove and Gas Oven have enhanced indoor CO and NO₂ concentrations compared with dwellings with Electric Stove and Electric oven. This is probably due to production of NO₂ and CO during gas combustion.

Table 21 shows weekly indoor measurement statistics for dwellings with a Gas Stove and Electric Oven and dwellings with an Electric Stove and Electric Oven. Dwellings with a Gas Stove and Electric Oven have enhanced indoor CO₂, PM_{2.5}, formaldehyde, TVOCs, benzene and NO₂ compared with dwellings having an Electric Stove and Electric Oven. The CO₂, NO₂, formaldehyde and TVOC are gas combustion products and may be explained by the gas stovetop. Benzene and PM_{2.5} may be from combustion of burned food during cooking.

Table 22 shows weekly measurement statistics for dwellings that reported visible mould or a musty odour and dwellings which did not report visible mould or a musty odour. Dwellings which reported visible mould or a musty odour had significantly lower fungi concentration than dwellings reporting no visible mould or musty odour. This is an unexpected result, and may be due to the relatively small number of dwellings that reported visible mould or odour and had a corresponding fungi sample (9 dwellings) compared to those that did not report visible mould or odour and had a corresponding fungi sample (63 dwellings). The relationship is not significant when it is analysed by comparing the means of indoor/outdoor ratios. Alternatively this relationship may indicate that occupants who report mould are more aware of it, and therefore tend to remove it more vigilantly. Disturbing mould during its removal is likely to increase concentration of airborne spores.

Table 23 shows weekly indoor measurement statistics in Winter/Spring for dwellings which in the 6 months prior to sampling occupants reported renovations, indoor painting, new flooring surfaces, or new furniture larger than a 2 seater couch and those dwellings that did not. Those dwellings with renovations, new flooring surfaces or new furniture had significantly higher temperature and PM₁₀ than dwellings that did not report renovations, indoor painting, flooring surfaces polishing or new furniture. The reason for the difference in PM₁₀, which is also significant when comparing the means of indoor/outdoor ratios, is not known but may be due to residual indoor dust or reduced minimum ventilation rates from the renovation. The reason for the higher temperature may be due to more efficient heating and insulation, and reduced minimum ventilation rates in recently renovated dwellings.

Table 24 shows weekly indoor measurement statistics in Summer/Autumn for dwellings which in the 6 months prior to sampling reported renovations, indoor painting, new flooring surfaces, or new furniture in the dwelling equivalent or larger than a 2 seater couch and those dwellings that did not. There are no statistically significant differences between the two subsets of measurements for any of the pollutants.

In summary:

- NO₂ and CO were significantly enhanced in dwellings with all gas cooking (stovetop and oven) compared to all electric cooking (stovetop and oven).
- CO₂, PM_{2.5}, formaldehyde, TVOCs, benzene and NO₂ were significantly enhanced in dwellings with gas stoves and electric ovens, compared to dwellings with electric stovetops and electric ovens.
- PM₁₀ and temperature were significantly higher in Winter/Spring in dwellings where occupants reported renovation, new flooring, painting or furniture in the 6 months prior to sampling compared to dwellings that did not report renovations or new furniture.
- There were no significant differences in Summer/Autumn between dwellings where occupants reported renovation, new flooring, painting or furniture in the 6 months prior to sampling and dwellings that did not report renovations or new furniture.

Table 20 Weekly Indoor measurement data and t test comparison for dwellings with Gas Stove and Gas Oven and dwellings with Electric Stove and Electric Oven. Data from both Winter/Spring and Summer/Autumn are included here. Pollutants in **bold** have significantly different concentrations at 95%.

Parameter/ Pollutant	Units	Gas Stove, Gas Oven X ₁			Electric Stove, Electric Oven X ₂			Means Comparison X ₁ -X ₂		
		Mean	Std Dev.	N	Mean	Std Dev.	N	t	t critical	Hypothesis
Temperature	°C	20.5	1.9	20	21.1	1.8	13	-1.00	2.04	X ₁ -X ₂ =0
Relative Humidity	%	53.1	5.3	20	50.2	5.7	13	1.46	2.04	X ₁ -X ₂ =0
H ₂ O mixing ratio	g/kg	7.9	0.9	20	7.8	1.4	13	0.19	2.04	X ₁ -X ₂ =0
CO ₂	ppm	524.5	99.1	20	491.2	68.0	13	1.14	2.04	X ₁ -X ₂ =0
CO	ppm	0.4	0.3	20	0.2	0.1	12	2.62	2.04	X₁-X₂>0
PM10	µg/m ³	17.2	6.4	20	18.8	7.5	14	-0.67	2.04	X ₁ -X ₂ =0
PM2.5	µg/m ³	7.8	4.0	20	6.7	2.7	14	0.99	2.04	X ₁ -X ₂ =0
Carbonyls	ppb	7.1	2.7	20	7.2	2.7	14	-0.04	2.04	X ₁ -X ₂ =0
Formaldehyde	ppb	11.0	4.4	20	10.4	4.7	14	0.35	2.04	X ₁ -X ₂ =0
TVOC	µg/m ³	166.7	70.6	20	136.7	65.3	14	1.28	2.04	X ₁ -X ₂ =0
Benzene	µg/m ³	1.2	0.5	20	0.9	0.5	14	1.57	2.04	X ₁ -X ₂ =0
Toluene	µg/m ³	6.7	3.0	20	9.4	8.6	14	-1.14	2.04	X ₁ -X ₂ =0
Ethylbenzene	µg/m ³	0.9	0.4	20	1.0	0.5	14	-0.16	2.04	X ₁ -X ₂ =0
p-Xylene	µg/m ³	2.6	1.5	20	2.4	1.4	14	0.28	2.04	X ₁ -X ₂ =0
m-Xylene	µg/m ³	0.9	0.5	20	0.8	0.5	14	0.27	2.04	X ₁ -X ₂ =0
o-Xylene	µg/m ³	1.9	1.1	20	1.9	1.3	14	-0.21	2.04	X ₁ -X ₂ =0
NO₂	ppb	9.8	5.5	20	6.6	2.2	14	2.33	2.04	X₁-X₂>0
O ₃	ppb	0.7	0.7	20	0.6	0.4	14	0.77	2.04	X ₁ -X ₂ =0
Bacteria	cfu/m ³	1908	155	17	1947	1159	12	-0.08	2.04	X ₁ -X ₂ =0
Fungi	cfu/m ³	1601	1278	18	1608.3	1402	12	-0.01	2.04	X ₁ -X ₂ =0

Table 21 Weekly Indoor measurement data and t test comparison for dwellings with Gas Stove and Electric Oven and dwellings with Electric Stove and Electric Oven. Data from both Winter/Spring and Summer/Autumn are included here. Pollutants in **bold** have significantly different concentrations at 95%.

Parameter/ Pollutant	Units	Gas Stove, Electric Oven X ₁			Electric Stove, Electric Oven X ₂			Means Comparison X ₁ -X ₂		
		Mean	Std Dev.	N	Mean	Std Dev.	N	t	t critical	Hypothesis
Temperature	°C	21.6	2.0	43	21.1	1.8	13	0.728	2.01	X ₁ -X ₂ =0
Relative Humidity	%	50.2	5.1	43	50.2	5.7	13	-0.021	2.01	X ₁ -X ₂ =0
H ₂ O mixing ratio	g/kg	8.0	1.4	43	7.8	1.4	13	0.452	2.01	X ₁ -X ₂ =0
CO₂	ppm	553.6	140.8	43	491.2	68.0	13	2.184	2.01	X₁-X₂>0
CO	ppm	0.3	0.1	43	0.2	0.1	12	1.672	2.01	X ₁ -X ₂ =0
PM10	µg/m ³	22.2	8.7	43	18.8	7.5	14	1.400	2.01	X ₁ -X ₂ =0
PM2.5	µg/m³	9.1	4.2	44	6.7	2.7	14	2.540	2.01	X₁-X₂>0
Carbonyls	ppb	8.3	2.6	44	7.2	2.7	14	1.400	2.01	X ₁ -X ₂ =0
Formaldehyde	ppb	13.4	4.6	44	10.4	4.7	14	2.127	2.01	X₁-X₂>0
TVOC	µg/m³	229.7	147.1	43	136.7	65.3	14	3.273	2.01	X₁-X₂>0
Benzene	µg/m³	1.4	1.1	43	0.9	0.5	14	2.587	2.01	X₁-X₂>0
Toluene	µg/m ³	13.2	23.1	43	9.4	8.6	14	0.896	2.01	X ₁ -X ₂ =0
Ethylbenzene	µg/m ³	1.4	1.4	43	1.0	0.5	14	1.616	2.01	X ₁ -X ₂ =0
p-Xylene	µg/m ³	3.5	4.2	43	2.4	1.4	14	1.495	2.01	X ₁ -X ₂ =0
m-Xylene	µg/m ³	1.2	1.5	43	0.8	0.5	14	1.569	2.01	X ₁ -X ₂ =0
o-Xylene	µg/m ³	2.7	2.4	43	1.9	1.3	14	1.453	2.01	X ₁ -X ₂ =0
NO₂	ppb	8.2	3.2	44	6.6	2.2	14	2.047	2.01	X₁-X₂>0
O ₃	ppb	0.7	0.8	44	0.6	0.4	14	0.893	2.01	X ₁ -X ₂ =0
Bacteria	cfu/m ³	1595	1410	40	1947	1157	12	-0.876	2.01	X ₁ -X ₂ =0
Fungi	cfu/m ³	1719	1670	40	1608	1402	12	0.229	2.01	X ₁ -X ₂ =0

Table 22 Weekly Indoor measurement data and t-test comparison for dwellings with visible mould and/or musty odour and dwellings with no visible mould or musty odour. Data are from Winter/Spring and Summer/Autumn. Pollutants in **bold** have significantly different concentrations at 95%.

Parameter/ Pollutant	Units	Visible Mould or Odour, X ₁			No Visible Mould, Odour X ₂			Means Comparison X ₁ -X ₂		
		Mean	Std Dev.	N	Mean	Std Dev.	N	T	t critical	Hypothesis
Temperature	°C	20.6	2.4	12	21.3	1.9	66	-0.94	1.99	X ₁ -X ₂ =0
Relative Humidity	%	51.6	7.4	12	50.8	4.9	66	0.37	1.99	X ₁ -X ₂ =0
H ₂ O mixing ratio	g/kg	7.8	1.4	12	8.0	1.3	66	-0.47	1.99	X ₁ -X ₂ =0
CO ₂	ppm	550.6	108.9	12	533.1	123.1	66	0.50	1.99	X ₁ -X ₂ =0
CO	ppm	0.3	0.2	12	0.3	0.2	65	-0.81	1.99	X ₁ -X ₂ =0
PM10	µg/m ³	18.2	6.4	12	20.9	8.4	67	-1.26	1.99	X ₁ -X ₂ =0
PM2.5	µg/m ³	6.9	2.6	12	8.7	4.1	68	-1.98	1.99	X ₁ -X ₂ =0
Carbonyls	ppb	6.6	2.5	12	8.1	2.6	68	-1.83	1.99	X ₁ -X ₂ =0
Formaldehyde	ppb	10.8	5.4	12	12.5	4.5	68	-0.99	1.99	X ₁ -X ₂ =0
TVOC	µg/m ³	177.2	83.4	12	201.6	129.3	67	-0.85	1.99	X ₁ -X ₂ =0
Benzene	µg/m ³	1.6	1.2	12	1.2	0.8	67	1.05	1.99	X ₁ -X ₂ =0
Toluene	µg/m ³	10.5	9.3	12	10.7	18.8	67	-0.06	1.99	X ₁ -X ₂ =0
Ethylbenzene	µg/m ³	1.2	0.5	12	1.2	1.2	67	-0.12	1.99	X ₁ -X ₂ =0
p-Xylene	µg/m ³	3.0	1.9	12	3.1	3.5	67	-0.15	1.99	X ₁ -X ₂ =0
m-Xylene	µg/m ³	1.0	0.7	12	1.1	1.2	67	-0.14	1.99	X ₁ -X ₂ =0
o-Xylene	µg/m ³	2.3	1.8	12	2.3	2.0	67	-0.07	1.99	X ₁ -X ₂ =0
NO ₂	ppb	9.7	6.4	12	8.2	3.3	68	0.82	1.99	X ₁ -X ₂ =0
O ₃	ppb	0.5	0.4	12	0.7	0.7	68	-1.54	1.99	X ₁ -X ₂ =0
Bacteria	cfu/m ³	1578	1501	9	1755	1382	62	-0.33	1.99	X ₁ -X ₂ =0
Fungi	cfu/m³	829.6	784.2	9	1786	1577	63	-2.91	1.99	X₁-X₂<0

Table 23 Weekly Indoor measurement data and t-test comparison for dwellings with which in the 6 months prior to sampling had major renovations, indoor painting or new furniture and dwellings which did not have renovations, painting or new furniture. Data are from Winter/Spring. Pollutants in **bold** have significantly different concentrations at 95%.

Parameter/ Pollutant	Units	Renovation/new furniture X ₁			No Renovation/new furniture X ₂			Means Comparison X ₁ -X ₂		
		Mean	Std Dev.	N	Mean	Std Dev.	N	t	t critical	Hypothesis
Temp	°C	20.9	1.3	16	19.9	1.3	22	2.33	2.02	X₁-X₂>0
RH	%	46.9	4.3	16	49.2	4.9	22	-1.53	2.02	X ₁ -X ₂ =0
H ₂ O mixing ratio	g/kg	7.1	0.8	16	7.0	0.8	22	0.44	2.02	X ₁ -X ₂ =0
CO ₂	ppm	566.7	136.0	16	498.0	101.8	22	1.70	2.02	X ₁ -X ₂ =0
CO	ppm	0.2	0.2	15	0.3	0.2	22	-0.77	2.02	X ₁ -X ₂ =0
PM10	µg/m³	22.3	6.6	16	15.5	5.1	23	3.49	2.02	X₁-X₂>0
PM2.5	µg/m ³	8.2	3.1	16	6.5	2.4	24	1.92	2.02	X ₁ -X ₂ =0
Carbonyls	ppb	8.3	3.1	16	7.3	2.1	24	1.17	2.02	X ₁ -X ₂ =0
Formaldehyde	ppb	12.0	4.8	16	10.2	3.1	24	1.34	2.02	X ₁ -X ₂ =0
TVOC	µg/m ³	191.0	90.0	16	189.4	148.6	24	0.04	2.02	X ₁ -X ₂ =0
Benzene	µg/m ³	0.9	0.4	16	1.2	1.0	24	-1.13	2.02	X ₁ -X ₂ =0
Toluene	µg/m ³	8.5	8.4	16	9.5	9.3	24	-0.36	2.02	X ₁ -X ₂ =0
Ethylbenzene	µg/m ³	0.9	0.4	16	1.2	1.2	24	-0.89	2.02	X ₁ -X ₂ =0
p-Xylene	µg/m ³	2.2	1.1	16	3.2	4.0	24	-1.21	2.02	X ₁ -X ₂ =0
m-Xylene	µg/m ³	0.8	0.4	16	1.2	1.5	24	-1.19	2.02	X ₁ -X ₂ =0
o-Xylene	µg/m ³	1.5	0.7	16	2.1	2.2	24	-1.19	2.02	X ₁ -X ₂ =0
NO ₂	ppb	11.0	3.8	16	9.4	4.9	24	1.12	2.02	X ₁ -X ₂ =0
O ₃	ppb	0.5	0.4	16	0.4	0.3	24	1.12	2.02	X ₁ -X ₂ =0
Bacteria	cfu/m ³	1534	1527	14	1569	1430	18	-0.06	2.04	X ₁ -X ₂ =0
Fungi	cfu/m ³	1088	1396	14	1226	1135	19	-0.30	2.04	X ₁ -X ₂ =0

Table 24 Weekly Indoor measurement data and t-test comparison for dwellings with which in the 6 months prior to sampling had major renovations, indoor painting or new furniture and dwellings which did not have renovations, painting or new furniture. Data are from Summer/Autumn. Pollutants in **bold** have significantly different concentrations at 95%.

Parameter/ Pollutant	Units	Renovation/ new furniture X ₁			No renovation/new furniture X ₁			Means Comparison X ₁ -X ₂		
		Mean	Std Dev.	N	Mean	Std Dev.	N	t	t critical	Hypothesis
Temperature	°C	22.1	2.5	11	22.1	1.9	29	0.02	2.02	X ₁ -X ₂ =0
Relative Humidity	%	55.3	3.0	11	52.8	4.9	29	1.90	2.02	X ₁ -X ₂ =0
H ₂ O mixing ratio	g/kg	9.1	1.4	11	8.6	1.0	29	0.92	2.02	X ₁ -X ₂ =0
CO ₂	ppm	549.0	90.0	11	542.4	132.6	29	0.18	2.02	X ₁ -X ₂ =0
CO	ppm	0.3	0.1	11	0.3	0.3	29	0.42	2.02	X ₁ -X ₂ =0
PM10	µg/m ³	27.1	9.6	11	20.8	8.2	29	1.93	2.02	X ₁ -X ₂ =0
PM2.5	µg/m ³	11.7	4.3	11	8.9	4.6	29	1.81	2.02	X ₁ -X ₂ =0
Carbonyls	ppb	9.5	3.1	11	7.4	2.4	29	1.99	2.02	X ₁ -X ₂ =0
Formaldehyde	ppb	15.0	6.4	11	12.9	4.4	29	1.00	2.02	X ₁ -X ₂ =0
TVOC	µg/m ³	225.5	86.5	11	1.5	0.8	28	0.25	2.02	X ₁ -X ₂ =0
Benzene	µg/m ³	1.5	0.9	11	14.1	27.6	28	-1.16	2.02	X ₁ -X ₂ =0
Toluene	µg/m ³	8.0	3.0	11	1.3	1.4	28	0.18	2.02	X ₁ -X ₂ =0
Ethylbenzene	µg/m ³	1.3	0.7	11	3.4	4.0	28	-0.38	2.02	X ₁ -X ₂ =0
p-Xylene	µg/m ³	3.1	1.2	11	1.2	1.4	28	-0.49	2.02	X ₁ -X ₂ =0
m-Xylene	µg/m ³	1.0	0.4	11	2.7	2.3	28	0.96	2.02	X ₁ -X ₂ =0
o-Xylene	µg/m ³	3.3	1.6	11	2.6	2.3	29	1.11	2.02	X ₁ -X ₂ =0
NO ₂	ppb	6.9	2.4	11	6.7	2.2	29	0.24	2.02	X ₁ -X ₂ =0
O ₃	ppb	1.2	1.0	11	0.8	0.7	29	1.20	2.02	X ₁ -X ₂ =0
Bacteria	cfu/m ³	1330	786.7	11	2095	1452	28	-2.11	2.02	X ₁ -X ₂ =0
Fungi	cfu/m ³	2045	1619	11	2106	1681	28	-0.10	2.02	X ₁ -X ₂ =0

5.3 A Review of Other Studies of Emissions from Indoor Activities and their Relationships to the Results of This Study

The emission rates of PM_{2.5}, PM₁₀, CO, CO₂, VOCs and NO₂ for a number of common household activities from other studies are summarised in Table 25 and presented in detail in Appendix D.

The highest CO₂ emissions are associated with human breathing. Section 3 shows that the increase in CO₂ concentrations in dwellings at night was related to the return of people to the dwelling in early evening.

Cooking (particularly burning food) results in high emissions of PM_{2.5}, and frying on a gas stove top generally emits more particles than frying on an electric stove top. Frying generally emits more particles than baking.

Unflued gas heaters have the highest emission rates of CO, NO₂ and some VOCs. All gas heaters in this study were flued. One house with high NO₂ concentration had a gas oven that was not flued. Table 25 indicates that emission of NO₂ during cooking and baking can be high.

Sweeping and vacuuming cause only very low particle emission or, more correctly, re-suspension. This study finds no significant correlation of sweeping and vacuuming with PM₁₀.

Smoking results in high emissions of CO and PM_{2.5}. However, no smoking occurred indoors during this study.

Table 25. Emission rates of PM2.5, PM10, CO, CO₂, VOC and NO₂ by different activities summarised from information presented in Appendix D.

Emission rate (mg min ⁻¹)	PM2.5	PM10	CO	CO ₂	VOC	NO ₂
>100	Cooking (burning food, grilling)		Smoking Unflued gas heater	Breathing (human)	Unflued gas heater (TVOC, formaldehyde)	Unflued gas cooker Unflued gas heater
100–10	Cooking (frying on gas stove top, toasting)	Mosquito coil	Smoking	Candle	Unflued gas heater (TVOC, formaldehyde)	
10–1	Cooking (frying on gas stove top, grilling, oven) Smoking Incense, mosquito coil	Stove Mosquito coil	Mosquito coil			
1–0.1	Cooking (frying on electric stove top, grilling, toasting) Smoking Vacuuming, dusting Washing machine Candle Walking Incense, mosquito coil	BBQ Cooking (oven, toasting) Candle Mosquito coil			Mosquito coil	
<0.1	Cooking (frying on electric stove top microwave, oven, kettle) Sweeping, vacuuming, dusting Washing, shower Fan heater Hair dryer Candle	Candle	Candle		Mosquito coil	Mosquito coil

5.4 Summary of the influences of Building Characteristics, Materials and Activities on Indoor Air Quality

In this section we have investigated the effect of building characteristics, materials and activities on indoor air quality.

Dwelling age appears to influence indoor concentrations of formaldehyde, other carbonyls and TVOCs. This may be due to the presence of older surface coatings and furnishings in older dwellings that have lower emissions of these semi-volatile compounds.

The presence of an attached garage with internal door to the dwelling resulted in elevated concentrations of PM₁₀, benzene and m-xylene, presumably the result of motor vehicle emissions from vehicles housed in the attached garage.

Distance of the dwelling from the road had an influence in indoor NO₂ concentrations (discussed in detail in Section 4).

A negative correlation between dwelling age and fungi concentration is a statistically significant relationship observed between indoor air quality measurements and building characteristics that does not have a direct explanation. Such relationships highlight the complexity of the causal relationship between any two variables found to have a statistically significant relationship since the relationship can also be caused by the confounding effect of one or more other variables.

The level of ventilation is classed here as an activity since it relates to the number of doors and windows that were opened during the sampling periods. The level of ventilation effected the concentration of CO₂ and formaldehyde, presumably because these gases have indoor sources and are easily able to be vented outdoors in a well ventilated dwelling. The level of ventilation also influenced indoor temperature, moisture and ozone concentrations. In the case of ozone, this indicates higher ozone penetration into a well ventilated dwelling.

The number of occupants influenced CO₂, PM₁₀ and NO₂, presumably due to respiration, movement resulting in mechanical dust, and cooking.

A number of statistically significant relationships are observed between indoor air quality measurements and activities (e.g. CO₂ is positively correlated with occupant density).

Combustion events (any form of burning in the dwelling) were positively correlated with CO₂, CO, PM_{2.5} and NO₂, which are all products of combustion. In particular cooking with a gas stovetop and gas oven combination resulted in elevated concentrations of NO₂ and CO. CO₂, PM_{2.5}, formaldehyde, TVOC, benzene and NO₂ were significantly enhanced in dwellings with gas stoves and electric ovens, compared to dwellings with electric stovetops and electric ovens.

Activities that cause mechanical generation of particles (vacuuming, sweeping, dusting) did not significantly influence the weekly indoor concentration of particles (PM₁₀ or PM_{2.5}) but did show a positive relationship with fungi.

Airborne fungi concentrations were significantly enhanced in dwellings where occupants reported no visible mould or musty odour, compared to dwellings that reported visible mould or musty odour. However only nine dwellings reported visible mould or musty odour and the relationship was not significant when examining indoor/outdoor ratios.

Solvent use was positively correlated with TVOC as would be expected.

Elevated concentrations of PM10 were observed in dwellings where occupants reported recent renovations (within the 6 months prior to sampling) during the Winter/Spring sampling period. However this relationship was not observed in the Summer/Autumn period.

6. CONCLUSIONS

The first purpose of this study was to determine indoor air quality in typical Australian dwellings.

This study of indoor air quality was conducted because there are no other extensive studies of indoor air quality in typical dwellings in Australia. This limits the comparisons that can be made with the data to, in many cases, comparisons against measurements in dwellings that have indoor air quality issues. In general, no other comparisons with Australian dwellings can be made.

The concentrations of indoor air pollutants observed in this study are either lower than or comparable with the concentrations of these compounds observed in previous studies in Australia. In particular:

- CO₂, CO and NO₂ concentrations in these typical dwellings are less than those observed in previous studies of dwellings with unflued gas heaters. Unflued gas heaters are known sources of these pollutants. There were no unflued gas heaters included in this study because in Victoria they are only permitted to operate on bottled liquid petroleum gas, which is predominantly used in rural areas with no access to natural gas.
- The formaldehyde concentrations in these typical dwellings are less than those observed in previous studies of mobile homes and caravans. According to ABS statistics, mobile homes and caravans make up only a very small proportion of private dwellings in Australia, and as such, none have been included in the sample of dwellings used for this study. These results are not unexpected due to the high usage in caravans and mobile homes of materials that release formaldehyde.
- The PM_{2.5} concentrations in these typical dwellings are less than those observed in previous studies of “cooking events”. Various types of cooking are known to be significant sources of PM_{2.5}. This study took measurements of PM_{2.5} inside private dwellings continuously over 7 day periods, which included many lengthy periods where “cooking events” did not occur. While peaks might be expected during “cooking events”, it is not unexpected that the seven day average is less than that observed in previous studies where “cooking events” were targeted.
- This indoor data on PM_{2.5} indicates that there are 15 days where the one day average concentration of PM_{2.5} was equal to or exceeded 25 µg m⁻³ inside a dwelling, out of a total data set of 465 days made up from measurements on 40 dwellings. The National Environment Protection (Ambient Air Quality) Measure has an Advisory Reporting Standard for the monitoring for particles as PM_{2.5}. The outdoor advisory limit for PM_{2.5} is 25 µg m⁻³ over a one day averaging period. There is no Australian indoor guideline for exposure to PM_{2.5}.
- TVOC concentrations measured in this study are comparable with those observed previously for non-complaint buildings.

- The fungi concentrations in these typical dwellings are comparable with those observed in previous studies of dwellings in Australia.

The weekly average concentrations (or parameter values) measured show that temperature, water vapour mixing ratio, carbon dioxide, carbon monoxide, nitrogen dioxide, formaldehyde, other carbonyls, TVOCs and BTEX have higher concentrations indoors compared with outdoors. Previous studies indicate that all these species have indoor sources.

The results of the weekly average measurements showed that bacteria, fungi, PM_{2.5} and PM₁₀ had no significant difference between the indoor and outdoor concentrations. Previous studies indicate that all these species have indoor sources. For these constituents in this study, the indoors removal processes appear to be sufficient to keep balance with the indoor sources at concentrations comparable with those outdoors.

The elevated NO₂ concentrations observed indoors in Winter/Spring and outdoors in Summer/Autumn have a pattern consistent with a NO₂ source from unflued combustion processes, which have a similar large change in incidence between these two seasonal periods. There is also a contribution to indoor concentrations arising from the proximity to a busy road, discussed below.

The ozone concentrations are lower indoors than outdoors in these measurements. These results for ozone are expected since inside surface materials on walls, flooring and furniture are very effective in removing ozone from the air.

The absence of guidelines for indoor air quality in Australia prevents a definitive rating of the results.

The second purpose of this study was to determine whether the proximity of dwellings to busy roads have an influence on indoor air quality.

As part of the experimental design there was selection of two sets of dwellings, Near-Road and Far-Road. A number of statistical analyses were carried out to determine whether proximity to busy roads had an influence on indoor air quality and NO₂ was found to be the only pollutant for which the proximity to busy roads resulted in an enhanced concentration. The enhancement of 2.5 ppb NO₂ outdoors of dwellings close to busy roads represents approximately 20% of the NO₂ measured at these dwellings, the remaining 80% coming from other sources. Other vehicle pollutants – CO, TVOCs, benzene, PM₁₀ and PM_{2.5} showed no statistically significant and logical connection indicating that there were probably several important confounding factors that influenced the indoor levels of these pollutants in dwellings during this study; proximity to busy roads may have been one of these factors, but it was not a dominating factor.

The third purpose of the study was to relate indoor air quality to the characteristics of the dwelling, materials and indoor activities.

Dwelling age showed significant negative correlations with concentrations of formaldehyde, other carbonyls, TVOCs and several of the aromatic compounds. There is a strong positive correlation between dwelling age and the closed ventilation or leakiness of a dwelling (see Appendix C). Increased leakiness (with dwelling age) would tend to reduce the indoor

concentrations of these compounds when the dwelling is in its closed-state, as they all have indoor sources and average indoor concentrations higher inside than outside.

The presence of an attached garage with an internal door to the dwelling caused significant increases in indoor concentrations of PM10, benzene and m-xylene. This most likely arises due to vehicle exhaust emissions that enter the dwelling via the garage.

The elevated CO₂ observed indoors has a diurnal pattern similar to that of domestic activity. The number of occupants in a dwelling is positively correlated with concentrations of CO₂, PM10 and NO₂. A related positive correlation is that of occupant density (occupants per unit volume of the dwelling) with CO₂. The major source of CO₂ in dwellings is human respiration. PM10 can be resuspended from human movements, and NO₂ has already been associated with unflued combustion.

The level of ventilation, measured as the average number of external windows and doors opened throughout the week, is negatively correlated with CO₂ and formaldehyde because these gases have indoor sources and are transported outdoors in a well ventilated dwelling. The level of ventilation is positively correlated with ozone, which indicates higher ozone penetration into a well ventilated dwelling.

The elevated CO observed indoors has a diurnal pattern similar to that of domestic activity. The daily maximum that occurs indoors around 07:00 to 08:00 is due to elevated concentrations outside, presumably due to vehicle exhaust emissions. Combustion events (any form of burning in the dwelling) were positively correlated with CO₂, CO and PM2.5 and weakly correlated with NO₂, which are all products of combustion. In particular cooking with a gas stove compared with an all electric stove and oven resulted in elevated concentrations of NO₂, CO₂, PM2.5, formaldehyde, TVOC, benzene, and CO. In approximately 10% of the homes in Winter/Spring in the early evening at around 19:00 to 20:00 there was a 4 fold increase in PM2.5 concentration, at the time of the peak in combustion activity.

Activities that cause mechanical generation of particles (vacuuming, sweeping, dusting) did not significantly influence the weekly indoor concentration of particles (PM10 or PM2.5).

The dwellings with renovations, new flooring surfaces or new furniture in Winter/Spring had significantly higher temperature and PM10 than dwellings that did not report renovations, indoor painting, flooring surfaces polishing or new furniture. The reason for the difference in PM10, which is also significant when comparing the means of indoor/outdoor ratios, is not known but may be due to residual indoor dust or reduced minimum ventilation rates from the renovation. The reason for the higher temperature may be due to more efficient heating and insulation, and reduced minimum ventilation rates in recently renovated dwellings. In Summer/Autumn no statistically significant differences were found between the two subsets of measurements for any of the pollutants.

Solvent use was positively correlated with TVOC concentrations, as would be expected because of the vaporization of the organic chemicals when the solvents are used.

The weekly average concentrations of Nicotine were below the detection limit of the measurements, consistent with the absence of smoking from the dwellings under consideration

(or in the case of the only indoors smoker in this study, the isolation of the smoking area from the general dwelling living area).

The emissions from materials used and activities undertaken within dwellings are reviewed. The types of chemical products used in the dwellings are presented. An examination of the available information on the chemical composition of these products was undertaken, but with little useful information unearthed.

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