4. RESULTS

Transit Characteristics

Monitoring dates

The main study was undertaken for 32 consecutive weekdays between 30 October and 12 December 2002. The monitoring was undertaken at a time free from school holidays and public holidays. Two additional days were used to replace the afternoon of 19 November when the tunnel was closed and the afternoon of 20 November when the NO_2 passive sampler dislodged from the vehicle during the final afternoon trip.

Vehicle ventilation

Ventilation type 1 (windows closed, recirculating air, air conditioning off) was used for a total of 10 days. Ventilation type 2 was used for 12 days (windows closed, recirculating air, air conditioning on). For 10 days we used ventilation type 3 (windows open, air conditioning off).

Travel times through the M5 tunnels

The number of trips through the tunnels each day varied from 8 to 16. Active sampling was taken during the first trip through each tunnel morning and afternoon. The mean trip time for active sampling was 6.39 minutes (Table 1).

Table 1: Time taken (minutes) to traverse a tunnel for each trip direction during active sampling

Trip Direction	N	Minimum	Maximum	Mean
Morning east	32	3.39	10.41	4.81
Afternoon west	31	3.57	18.07	9.98
Afternoon east	31	3.32	12.06	4.66

On two occasions the time taken to traverse a tunnel was greater than 15 minutes as a result of multiple vehicle breakdowns.

The daily duration monitoring time (passive sampling) through the tunnels ranged from 71 – 100 minutes. A total of 372 trips (2723 minutes) were made monitoring the air quality inside the M5 East tunnels.

Speed

A comparison of the study vehicle speeds with traffic flow is provided in Table 2. The study vehicle travelled in the left-hand lane on each trip, thus its speed was lower than the average for all vehicles.

Table 2: Average speed of the study vehicle compared with all traffic.

Trip Direction	Average actual trip speed of the study vehicle (km/hr)	Average speed of all vehicles* (km/hr) (RTA data)
Morning east	52.0	56.4
Afternoon west	27.0	41.0
Afternoon east	54.5	74.1

*Average speed of all vehicles travelling in the tunnel for the corresponding one-hour period.

Further data from the RTA (Table 3) revealed that the total number of vehicles travelling through the tunnels for the one-hour period when monitoring took place ranged from 1993 to 4106 (mean, 3137). Analysis of vehicle size showed that an average of 93.7% of vehicles were classified as short (<6m in length), 3.3% were medium in length (6-12m) and 3% were long (>12m).

Table 3: RTA traffic statistics during study monitoring periods

	Minimum	**Maximum**	**Mean**	**Std. Deviation**
Average speed of all vehicles in both lanes (km/h)	27.1	77.0	57.2	15.0
Total number of cars travelling in both lanes during 1 hr period.	1993	4106	3138	612
Total number of short vehicles (<6m)	1848	3881	2939	582
Total number of medium vehicles (6-12m)	44	204	104	31
Total number of long vehicles (>12m)	34	135	94	21

Tunnel Ventilation

RTA advise that the tunnel ventilation system was run at full capacity (six exhaust fans) during the period of sampling, in accordance with Change Order No. 113, except for the afternoon of December 4, when bushfires affected the main tunnel power supply. On this afternoon only four fans could be operated from 1600hrs to 1700hrs and only two fans from 1700hrs to 1800hrs.

Cabin Carbon Monoxide

The trip averages for cabin CO ranged from 0-35ppm, with a mean of all trip averages of 10.4ppm. Trip sampling time varied from 3 to 18 minutes.

Trip direction

An analysis of concentrations by trip direction shows that cabin CO levels were significantly lower in the morning compared with travelling in the afternoon ($p=0.05$). There was no significant difference in CO levels when travelling through the west tunnel in the afternoon, compared to travelling east ($p=0.62$).

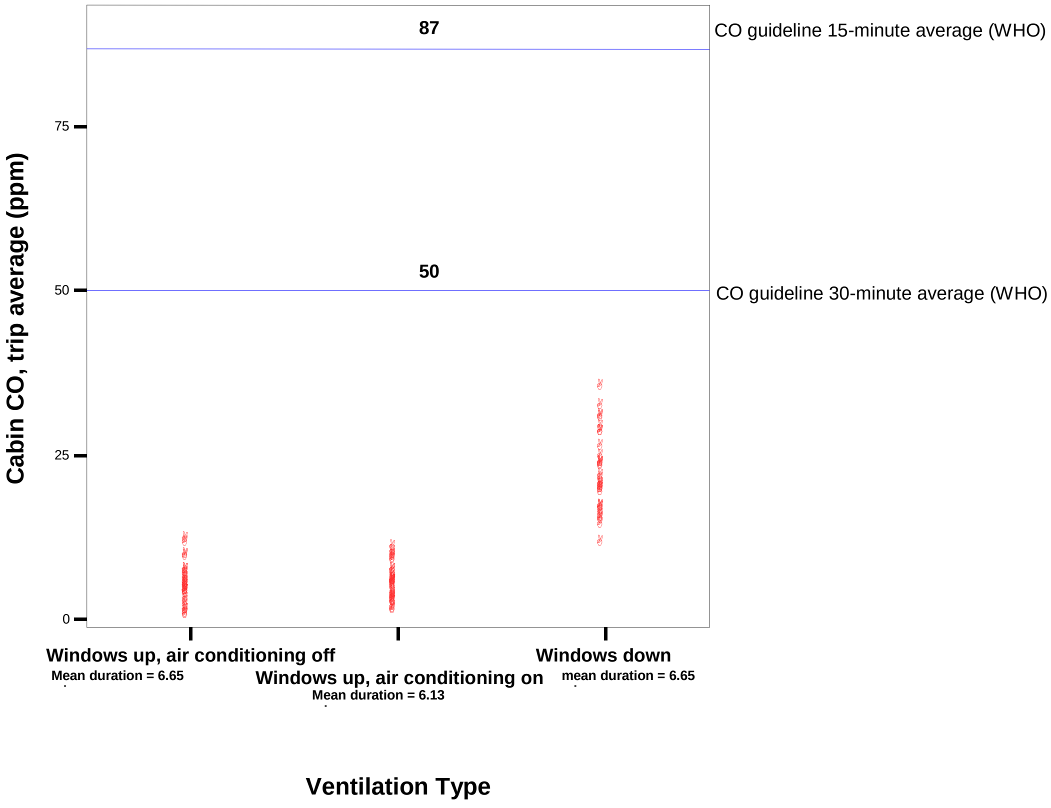
Ventilation

An examination of CO level by vehicle ventilation type (Table 4 and Graph 1) shows that levels of CO inside a cabin are greatly reduced when the windows are closed ($p=0.000$). The use of an air conditioning system does not significantly affect CO concentration ($p=0.72$).

Table 4: Trip averages for cabin CO by ventilation type (ppm)

Ventilation type	N	Minimum	Maximum	Mean	Std. Deviation
Windows up, air conditioning off	30	0	11.9	4.67	3.07
Windows up, air conditioning on	34	0	10.5	4.93	2.71
Windows down	30	11.4	35.0	21.7	5.97

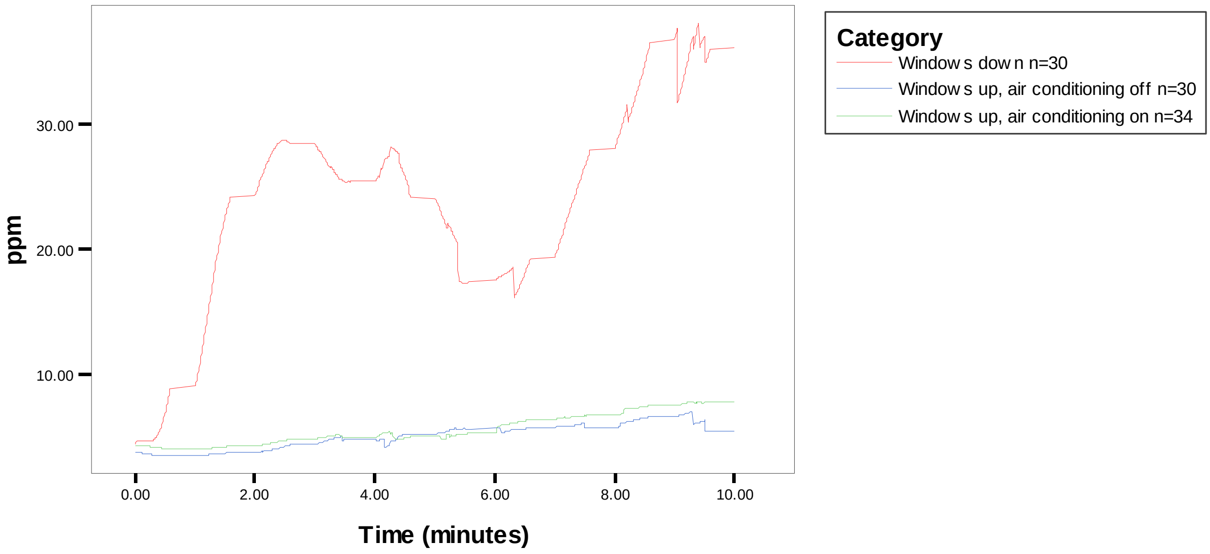
Graph 1: Trip averages for cabin CO by ventilation type



Variation of exposure during journey

The cabin CO concentration for each second of every trip through the tunnels has been averaged and graphed against time for each ventilation type (Graph 2). The graphs indicate that the longer a vehicle is in a tunnel, the more CO the passengers are exposed to. When the windows are open, exposure is immediate. The dip in level mid-trip reflects the ventilation design of the tunnels (fresh air in-take at mid-point). When the windows are up, the exposure to CO is greatly reduced, and increase over time is gradual.

Graph 2: Averaged one-second cabin CO exposure (ppm) by time in tunnel



Maximum CO Concentrations

During the study the trip CO exposure did not exceed the 15-minute WHO guideline of 87 ppm.

External Carbon Monoxide

The trip averages for external CO ranged from 5.3-38.7ppm, with a mean of all trip averages of 20.6ppm.

Trip direction

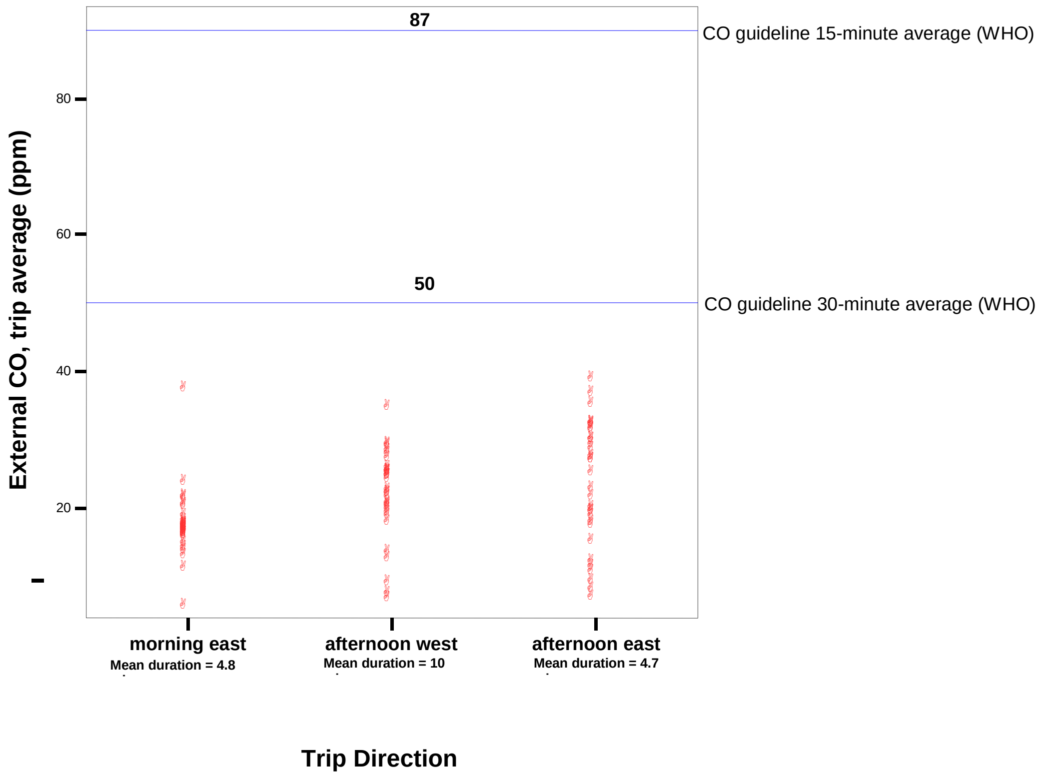
Table 5 shows the trip external carbon monoxide levels for each direction. The external CO concentration was significantly lower in the morning compared with the afternoon trip (p=0.001), however there was no difference between the west and east trip in the afternoon (p=0.42).

Table 5: Trip averages for external CO (ppm) by trip direction

Trip Direction	N	Minimum	Maximum	Mean	Std. Deviation
Morning east	32	5.3	37.2	17.2	4.87
Afternoon west	31	6.5	34.4	21.6	6.52
Afternoon east	31	6.7	38.7	23.2	9.06

Graph 3 compares the average external CO concentration for each trip direction and to the WHO 15- and 30-minute average guidelines.

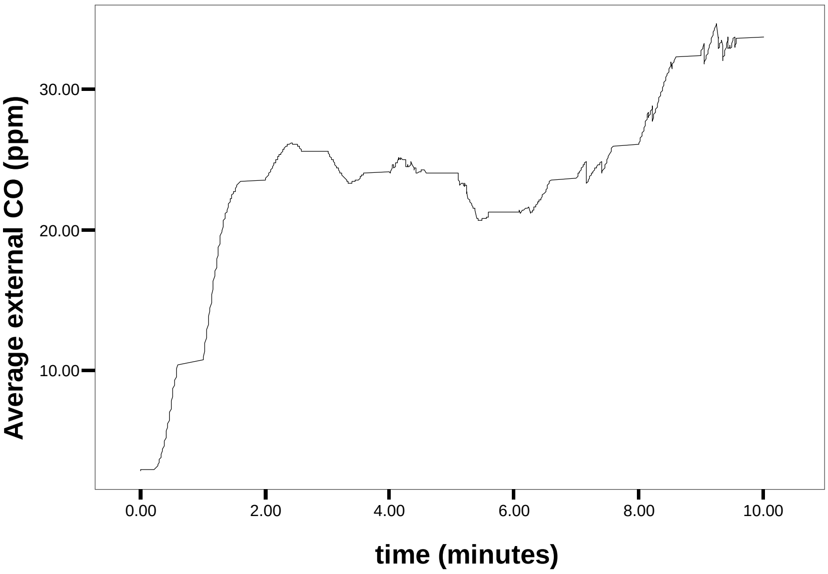
Graph 3: Trip averages for external CO (ppm) by



Variation of exposure during journey

The external CO concentration for every second of each trip through the tunnels has been averaged and graphed against time (n=94 trips), (Graph 4). The external CO concentration displays a similar pattern to that for cabin when the windows are down. A similar drop and then rise again can be seen mid-journey.

Graph 4: Averaged one-second external CO concentration (ppm) by time in tunnel



Comparison with RTA CO monitors

There are eight CO monitors used by the RTA inside the M5 East tunnels, four in each direction. The eastbound monitors are ACO301, ACO302, AQS301 and AQS302. The westbound monitors are ACO403, ACO604, AQS403 and AQS404. We used Pearson's correlation test to see if any fixed tunnel CO monitors correlated with cabin or external CO levels. The CO level used for this comparison, as provided by the RTA, was that taken at the closest 15-minutes to the study vehicle monitoring.

Correlation with cabin CO

There was no correlation between cabin CO and fixed tunnel monitors for the closed cabin scenarios. For the open cabin scenarios, cabin CO levels were correlated with monitor AQS403 (R=0.651, P=0.042) for the westbound afternoon trip. For the eastbound afternoon trip cabin CO levels (windows open) were correlated with monitors AQS301 (R=0.848, P=0.002), ACO302 (R=0.723, P=0.018) and AQS302 (R=0.778, P=0.008). There was no correlation between cabin CO (windows down) and fixed tunnel monitors for the morning eastbound trip.

Correlation with external CO

We found that in the mornings, only monitor ACO301 correlated with external CO levels for the eastbound trip (R =0.432, P=0.014). For the eastbound and westbound afternoon trips, external CO levels were highly correlated with all monitors (Tables 6-7).

Of the monitors that were well correlated with the external trip levels, the most predictive was AQS301 for the eastbound afternoon trip, which was related to external CO by the equation:

$$\mathit{AQS301ppm} = \mathit{external\ COppm} * 1.36 + 20.02$$

Thus, if AQS301 recorded a 15-minute average of 50ppm, one could expect that the external trip level during that time would be approximately 22ppm (ie: (50-20.02)/1.36).

Table 6: Correlation between external CO and fixed monitors westbound afternoon.

RTA westbound CO monitor ACO403	Pearson Correlation	.473
	Sig. (2-tailed)	.007
RTA westbound CO monitor ACO604	Pearson Correlation	.373
	Sig. (2-tailed)	.039
RTA westbound CO monitor AQS403	Pearson Correlation	.568
	Sig. (2-tailed)	.001
RTA westbound CO monitor AQS404	Pearson Correlation	.575
	Sig. (2-tailed)	.001

Table 7: Correlation between external CO and fixed monitors eastbound afternoon.

RTA eastbound CO monitor AQS301	Pearson Correlation	.907
	Sig. (2-tailed)	.000
RTA eastbound CO monitor ACO301	Pearson Correlation	.624
	Sig. (2-tailed)	.000
RTA eastbound CO monitor ACO302	Pearson Correlation	.577
	Sig. (2-tailed)	.001
RTA eastbound CO monitor AQS302	Pearson Correlation	.590
	Sig. (2-tailed)	.000

Cabin Carbon Dioxide

The trip averages for cabin CO_2 ranged from 724-4334ppm, with the mean of all trip averages of 1824ppm. Trip sampling time varied from 3-18 minutes.

Trip direction

There was no significant difference in CO_2 levels when travelling in the morning compared to the afternoon ($p=0.06$), or between the two afternoon trips ($p=0.48$).

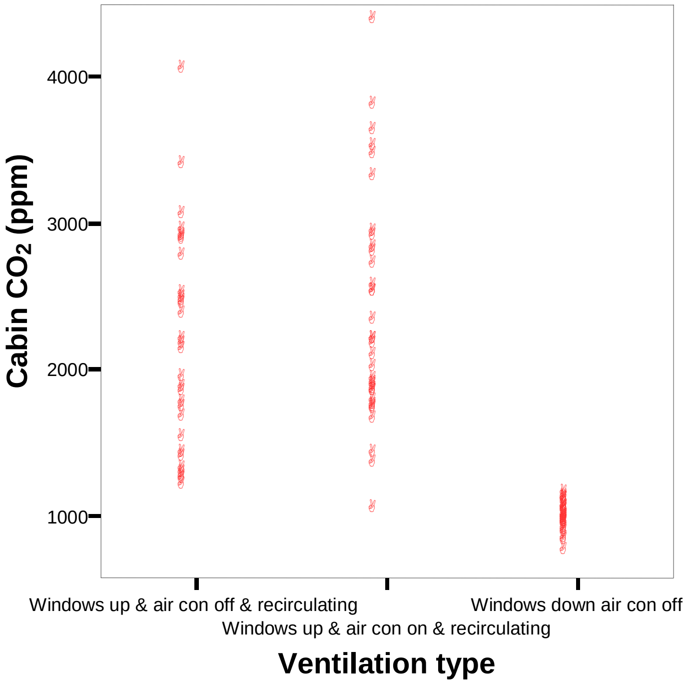
Ventilation

Table 8 shows the trip CO_2 levels for each ventilation type. There was a highly significant increase in cabin CO_2 when the windows were up ($p=0.000$), as shown in graph 5. The use of an air conditioning system did not make a significant difference to the cabin CO_2 concentration ($p=0.29$).

Table 8: Trip averages for cabin CO_2 (ppm) by ventilation type

Ventilation type	N	Minimum	Maximum	Mean	SD
Windows up, air conditioning off	30	1161	3994	2128	725
Windows up, air conditioning on	34	1002	4334	2326	772
Windows down	30	724	1107	951	93

Graph 5: Trip averages for cabin CO_2 (ppm) by ventilation type

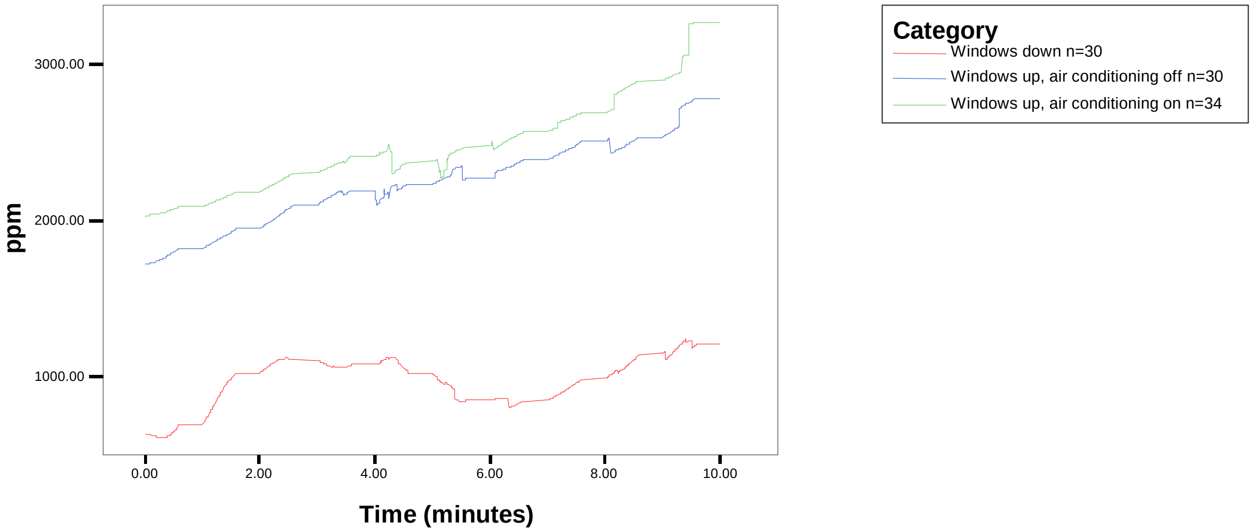


Variation of exposure during journey

The CO_2 concentration for each second of every trip through the tunnels has been averaged and graphed against time for each ventilation type (Graph 6).

The graphs indicate that the longer a vehicle is in a tunnel, the higher the CO_2 concentration. When the windows are up, the exposure to CO_2 is increased.

Graph 6: Averaged one-second cabin CO_2 exposure (ppm) by time in tunnel



External Carbon Dioxide

The trip averages for external CO_2 ranged from 594-1502 ppm, with a mean of all trip averages of 911ppm.

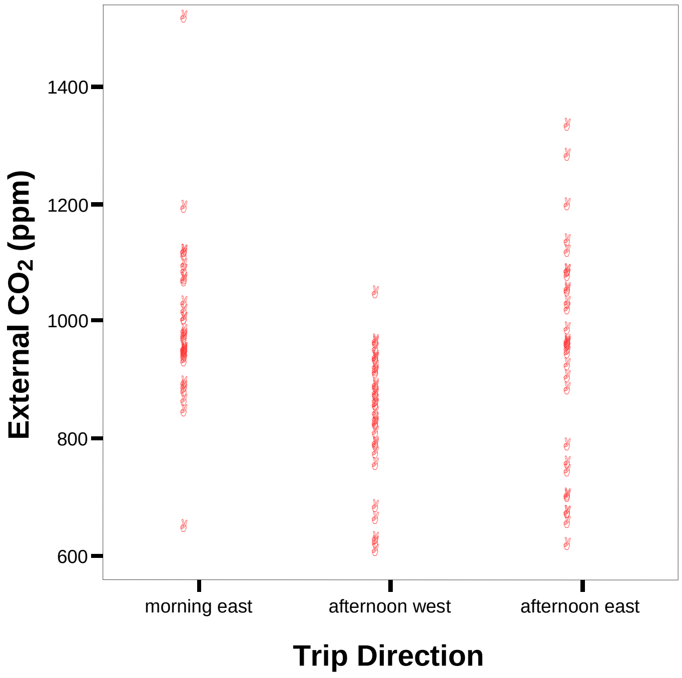
Trip direction

Table 9 shows the trip averages for external CO_2 according to trip direction. External CO_2 results are also represented in Graph 7. Trip averages were significantly higher in morning compared with afternoon trips ($p=0.002$); there were also significantly higher trip average levels of CO_2 in the eastbound afternoon trip compared with the westbound trip ($p=0.01$).

Table 9: Trip averages for external CO_2 (ppm) by trip direction

Trip Direction	N	Minimum	Maximum	Mean	SD
Morning east	32	632	1502	980	140
Afternoon west	31	594	1033	824	109
Afternoon east	31	604	1318	927	187

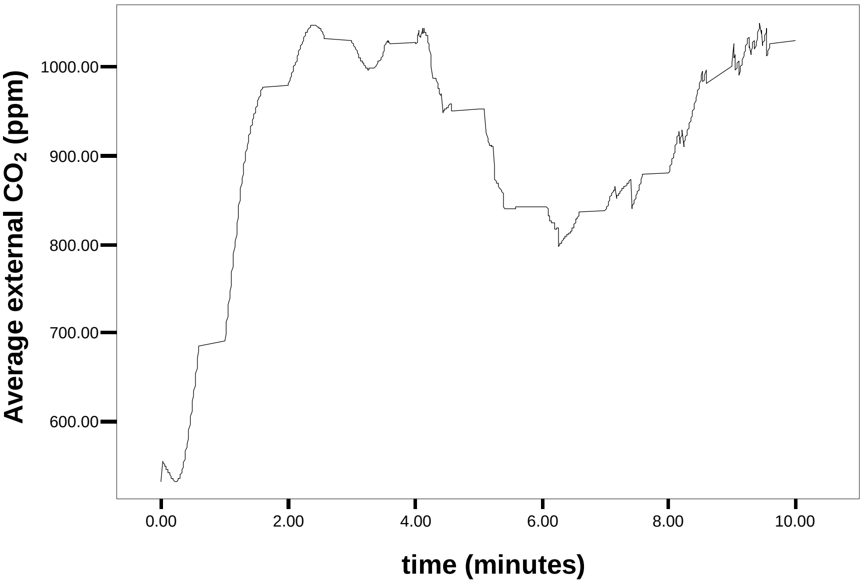
Graph 7: Trip averages for external CO_2 (ppm) by trip direction



Variation of exposure during journey

The external CO_2 concentration for each second of every trip through the tunnels has been averaged and graphed against time (n=94 trips), (Graph 8). The external CO_2 concentration demonstrates a decrease mid-tunnel due to the tunnels' ventilation design.

Graph 8: Averaged one-second external CO2 concentration (ppm) by time in tunnel



$PM_{2.5}$ - Dustrak

Monitoring of $PM_{2.5}$ was performed only in the cabin. The trip averages for cabin $PM_{2.5}$ level was in the range 10-526 µg/m^3, with a mean of all trip averages of 163µg/m^3. Sampling varied from 3-18 minutes.

Trip direction

An analysis by trip direction shows that the mean of trip average $PM_{2.5}$ level when travelling eastbound in the morning was 175 µg/m^3; for westbound trips in the afternoon, 151 µg/m^3; and for eastbound trips in the afternoon, 162 µg/m^3. These differences were not statistically significant ($p=0.63$).

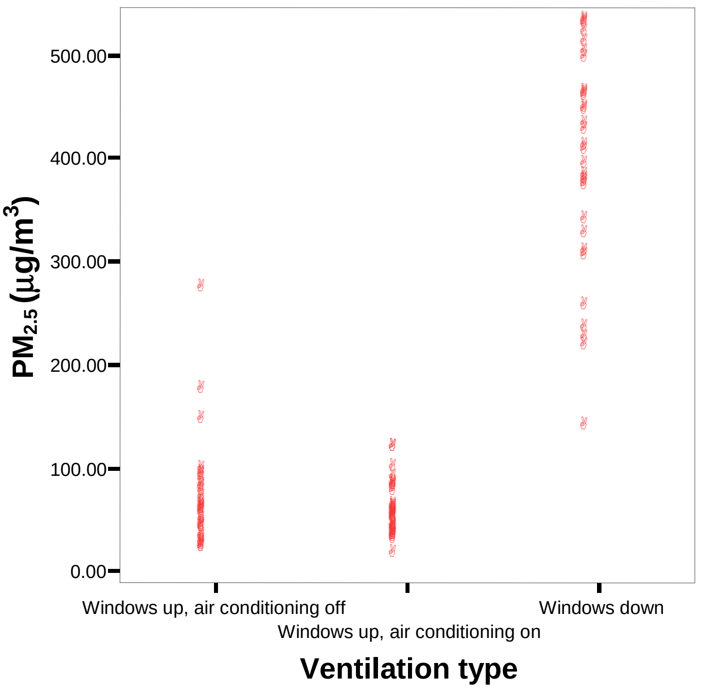
Ventilation

An analysis of $PM_{2.5}$ concentrations by type of cabin ventilation showed that trip averages were significantly reduced when the cabin windows were closed ($p=0.000$). The use of an air conditioning system had no significant effect on $PM_{2.5}$ levels ($p= 0.22$). The trip averages for cabin $PM_{2.5}$ levels by ventilation type are shown in Table 10 and Graph 9.

Table 10: Trip averages for cabin $PM_{2.5}$ (µg/m^3) Dustrak by ventilation type

Ventilation type	N	Minimum	Maximum	Mean	SD
Windows up, air conditioning off	30	15	268	64	52
Windows up, air conditioning on	34	10	113	51	25
Windows down	30	133	526	388	106

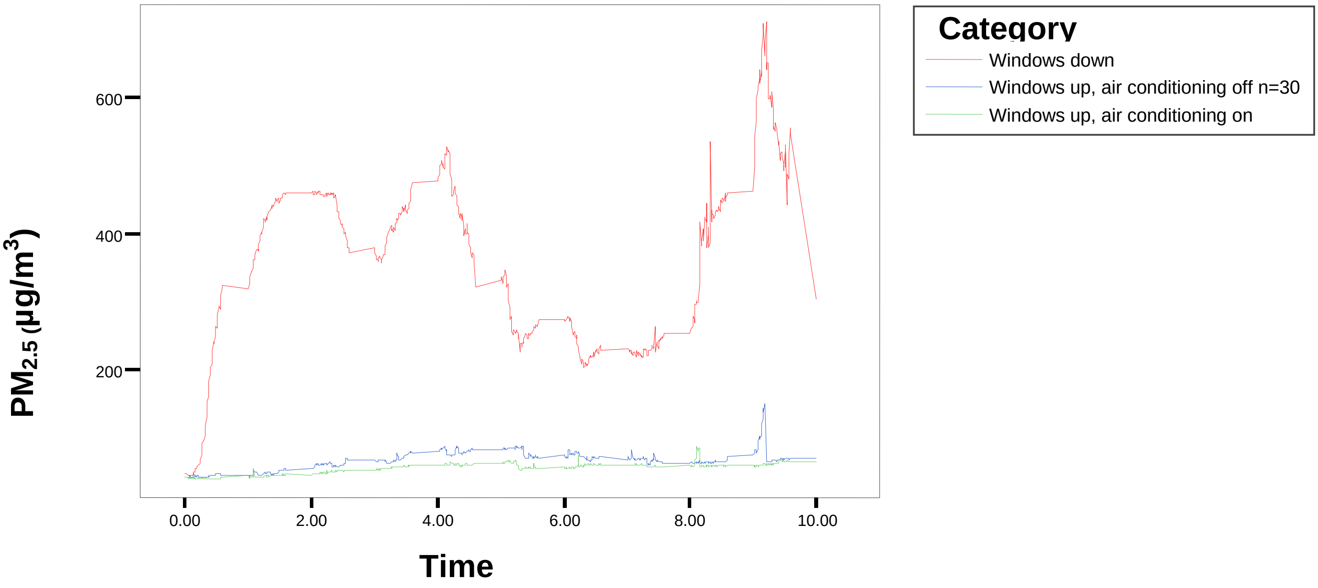
Graph 9: Trip averages for cabin $PM_{2.5}$ (µg/m^3) by ventilation type



Variation of exposure during journey

The $PM_{2.5}$ concentration for each second of every trip through the tunnels has been averaged and graphed against time for each ventilation type (Graph 10). The graphs indicate that the longer a vehicle is in a tunnel, the more $PM_{2.5}$ the passengers are exposed to. When the windows are open, exposure is immediate, and at mid-journey, there is an air exchange, causing a decrease in $PM_{2.5}$ concentration. When the windows are up, the exposure to $PM_{2.5}$ is greatly reduced, and there is a gradual increase over time.

Graph 10: Averaged one-second cabin $PM_{2.5}$ exposure (µg/m^3) by time in tunnel



$PM_{2.5}$ - Gravimetric

One cumulative gravimetric $PM_{2.5}$ measurement was taken per week. These values are given in Table 11. The mean $PM_{2.5}$ level for the study was 89μg/m^3.

Table 11: $PM_{2.5}$ Gravimetric monitoring results

Week	Number of days	Accumulated time	Results (μg/m^3)	Percent of time spent monitoring with windows down (%)
Week 1 30/10-5/11	5	7 hrs 5 mins	51.8	21
Week 2 6/11-12/11	5	7 hrs 55 mins	99.6	38
Week 3 13/11-20/11	6	8 hrs 18 mins	62.2	42
Week 4 21/11-27/11	5	7 hrs 38 mins	90.7	39
Week 5 28/11-4/12	5	7 hrs 1 min	135.4	21
Week 6 5/12-12/12	6	9 hrs	96.3	34

As the concentrations were collected under a variety of ventilation types over weekly trips through the tunnels, an analysis by trip direction or ventilation type is not possible.

The study average level for $PM_{2.5}$ for this method can be compared to the study average using Dustrak of 162μg/m^3. This indicates that the Dustrak significantly overestimated the actual fine particle levels in the vehicles.

Cabin Nitrogen Dioxide

The daily readings for cabin NO_2 were in the range 29.5-250ppbv, with a mean of 101ppbv. Samplers were exposed for an average of 88 minutes (range 71 – 100).

Trip direction

As there was only one NO_2 measurement per day an analysis by trip direction is not possible.

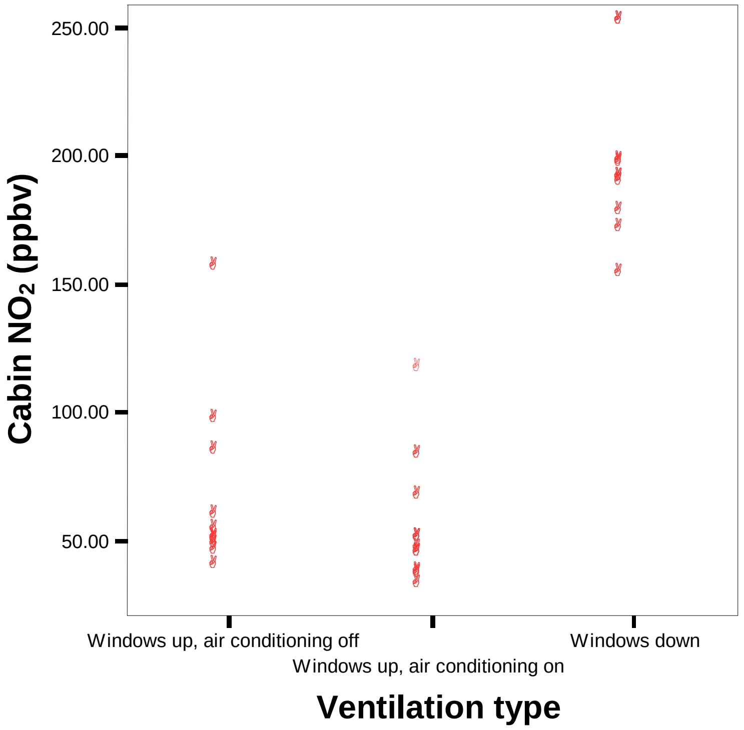
Ventilation

An analysis according to ventilation (Table 12 and Graph 11) shows that NO_2 levels are significantly reduced when the cabin windows are closed (p=0.000). The use of an air conditioning system had no significant effect on NO_2 levels (p= 0.30).

Table 12: Cabin NO_2 levels (ppbv) by ventilation type

Ventilation type	N	Minimum	Maximum	Mean	SD
Windows up, air conditioning off	10	37.7	154	65.9	35.6
Windows up, air conditioning on	12	29.5	114	52.4	23.8
Windows down	10	151.4	250	195	31.8

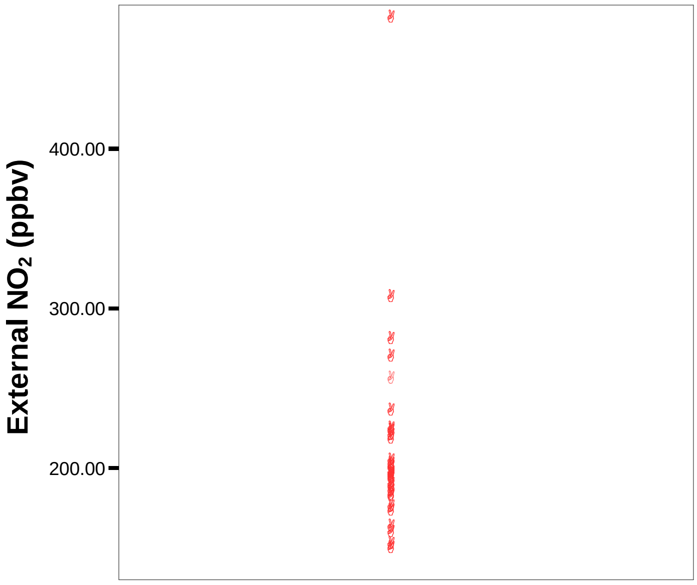
Graph 11: Cabin NO_2 (ppbv) by ventilation type



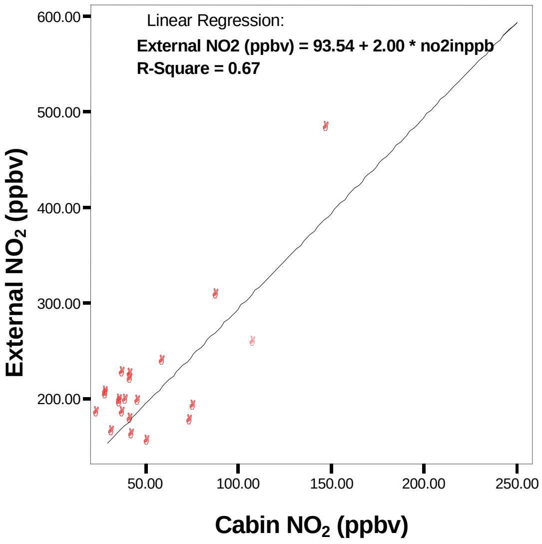
External Nitrogen Dioxide

The daily readings for external NO_2 were in the range 144-477ppbv, with a mean of 207ppbv. As there was only one NO_2 measurement per day, an analysis by trip direction is not possible.

Graph 12: Distribution of external NO_2 (ppbv)



Graph 13: External NO_2 versus cabin NO_2 (when windows are closed)



Graph 13 demonstrates that there is a significant relationship between external and cabin NO_2 levels when the windows are closed.

NO_2 outliers

On 7 November we recorded the maximum external NO_2 level of 477 ppbv and the maximum cabin NO_2 level for ventilation type 1 of 154 ppbv. An examination of data collection, analysis and entry could not account for this outlier. The cabin and external levels for CO, $PM_{2.5}$ and BTEX were unremarkable for this day.

We reviewed the RTA M5 East air monitoring data and EPA ambient air data for this period. All four M5 East stations recorded monthly maxima for 1-hour and 24-hour nitrogen dioxide on 8 November, as well as high levels for carbon monoxide. EPA RPI data suggest bushfire impacts in Sydney East on 8 November. It seems unlikely that external conditions are related to the high in-tunnel nitrogen dioxide levels we recorded on 7 November. Pearson's correlation test showed there was no relationship between ambient NO_2 levels as measured by the EPA and the tunnel NO_2 levels monitored during this study ($p=0.40$).

BTEX

Concentrations of the BTEX gases (benzene, toluene, ethylbenzene and 3 xylene isomers) were measured inside the vehicle. One measurement for each gas was obtained for each day. The mean, maximum and minimum concentrations for each are given in Tables 13-14.

Outliers

Maximum concentrations of benzene and toluene were recorded on 28 November. The concentration of xylene was also high for this day, but was not the highest level measured. Concentrations recorded were up to twice that of the next highest concentration. This occurred when the windows were up and the air conditioning was off. Values recorded were much higher than even the highest value obtained when the windows were down. An examination of sampling procedure, data entry and analysis could not account for this outlier. Review of operator practices (sampler sealing, refuelling, etc) also did not account for this reading. The following analysis is conducted with and without this outlier.

Table 13: Concentrations of BTEX gases (ppbv) including outlier

Gas	N	Minimum	Maximum	Mean	SD
Benzene (ppbv)	32	4.8	59.3	14.3	10.2
Toluene (ppbv)	32	12.9	86.2	26.7	14.4
Ethylbenzene (ppbv)	32	1.8	17.3	4.75	3.00
Xylene (ppbv)	32	8.3	57.5	23.7	12.2

Table 14: Concentrations of BTEX gases (ppbv) excluding outlier

Gas	N	Minimum	Maximum	Mean	SD
Benzene (ppbv)	31	4.8	27.1	12.8	6.14
Toluene (ppbv)	31	12.9	49.0	24.8	9.65
Ethylbenzene (ppbv)	31	1.8	17.3	4.65	2.97
Xylene (ppbv)	31	8.3	57.5	23.0	11.7

Benzene

A maximum benzene concentration of 59.3ppbv was recorded on 28 November with ventilation type 1 (windows up, vents closed, air conditioning off). The next highest benzene level for any ventilation type was 27.1ppbv. The next highest benzene level for ventilation type 1 was 12.5 ppbv on 11/12/02.

When the outlier is included, the average benzene concentration is not significantly reduced when the cabin windows are closed (p=0.08). However, when the outlier is excluded there is a significant reduction in benzene levels when the cabin windows are closed (p=0.00). The use of an airconditioning system does not significantly affect the cabin benzene concentration (p=0.46), even when the outlier is excluded (p=0.28). Refer tables 15 -16 and graph 14.

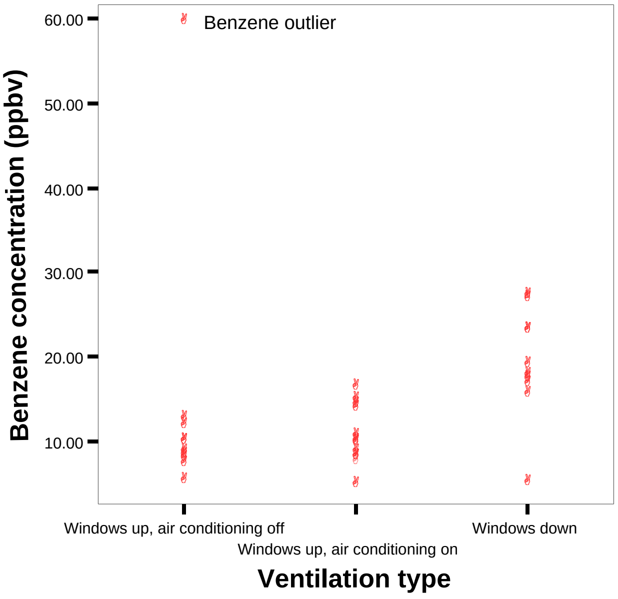
Table 15: Cabin benzene concentrations (ppbv) by ventilation type (including outlier)

Ventilation type	N	Minimum	Maximum	Mean	SD
Windows up & air conditioning off	10	5.1	59.3	14.0	16.1
Windows up & air conditioning on	12	4.8	16.2	10.5	3.48
Windows down	10	4.9	27.1	19.0	6.48

Table 16: Cabin benzene concentrations (ppbv) by ventilation type (excluding outlier)

Ventilation type	N	Minimum	Maximum	Mean	SD
Windows up, air conditioning off	9	5.1	12.5	9.00	2.27
Windows up, air conditioning on	12	4.8	16.2	10.48	3.48
Windows down	10	4.9	27.1	19.01	6.48

Graph 14: Cabin benzene exposure (ppbv) by ventilation type



Toluene

A maximum toluene concentration of 86.2ppbv was recorded on 28 November, at the same time as the benzene outlier discussed in the previous section. The next highest toluene concentration for this ventilation type was 21.9ppbv, and for any ventilation type was 49ppbv (windows down).

Even when this outlier is included there is a significant reduction in toluene concentration inside the cabin when the windows are closed (p=0.025, compared to p=0.000 when the outlier is excluded). The use of air conditioning does not make a significant difference to toluene concentration (p=0.65 compared to p=0.05 when the outlier is excluded). Refer Tables 17-18 and Graph 15.

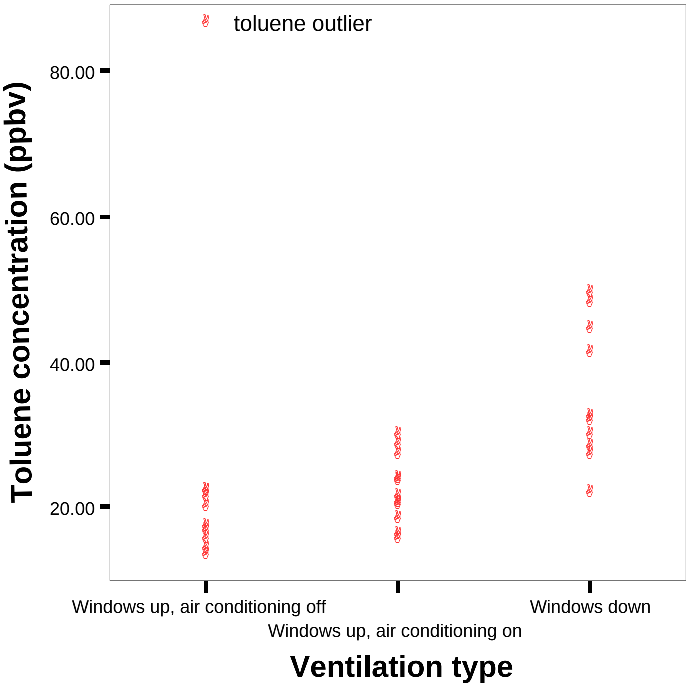
Table 17: Cabin toluene concentrations (ppbv) by ventilation type (including outlier)

Ventilation type	N	Minimum	Maximum	Mean	SD
Windows up, air conditioning off	10	12.9	86.2	24.5	21.9
Windows up, air conditioning on	12	15.3	29.6	21.6	4.70
Windows down	10	21.4	49.0	35.1	9.54

Table 18: Cabin toluene concentrations (ppbv) by ventilation type (excluding outlier)

Ventilation type	N	Minimum	Maximum	Mean	SD
Windows up, air conditioning off	9	12.9	21.9	17.7	3.46
Windows up, air conditioning on	12	15.3	29.6	21.6	4.70
Windows down	10	21.4	49.0	35.1	9.54

Graph 15: Cabin toluene exposure (ppbv) by ventilation type



Ethylbenzene

The average ethylbenzene concentration measured inside the study vehicle was 4.75 ppbv (range 1.8-17.3ppbv). The maximum ethylbenzene concentration (17.3ppbv) was recorded on 10 December, when the windows were down. The next highest value recorded was 8.90ppbv, and was also when the windows were down. There is a significant reduction in ethylbenzene concentration when the car windows are up (p=0.01). Excluding the outlier does not change this reduction. Turning on the air conditioning system did not make a significant difference to the ethylbenzene concentration (p=0.86).

The minimum, maximum and mean concentrations for each ventilation type, with and without the outlier are given in Tables 19-20.

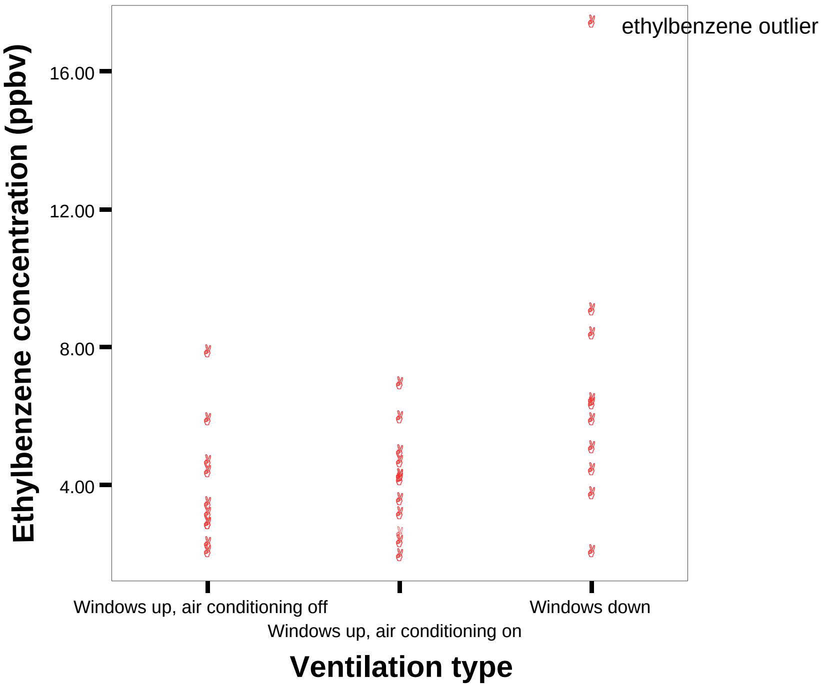
Table 19: Cabin ethylbenzene concentration (ppbv) by ventilation type (including outlier)

Ventilation type	N	Minimum	Maximum	Mean	SD
Windows up, air conditioning off	10	1.90	7.70	3.78	1.80
Windows up, air conditioning on	12	1.80	6.80	3.91	1.47
Windows down	10	1.90	17.3	6.73	4.25

Table 20: Cabin ethylbenzene concentration (ppbv) by ventilation type (excluding outlier)

Ventilation type	N	Minimum	Maximum	Mean	SD
Windows up, air conditioning off	10	1.90	7.70	3.78	1.80
Windows up, air conditioning on	12	1.80	6.80	3.91	1.47
Windows down	9	1.90	8.90	5.56	2.19

Graph 16: Cabin ethylbenzene exposure (ppbv) by ventilation type



Xylene

Three xylene isomers (p-, m- and o-xylene) were measured inside the study vehicle as it traversed the tunnel. A xylene outlier for ventilation type 1 occurred on 6 November, which was a different occasion to the other outliers. Cabin xylene concentration was significantly reduced when the windows were closed (p=0.002). Excluding the outlier did not change this reduction. Turning on the air conditioning system did not make a significant difference to the xylene concentration (p=0.96). Minimum, maximum and mean concentrations for each ventilation state, with and without the outlier, are given in Tables 21-22.

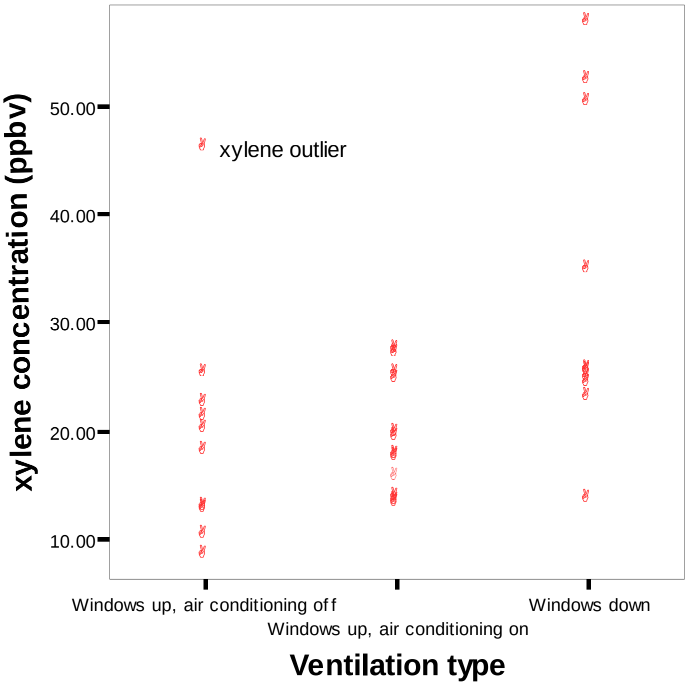
Table 21: Cabin xylene concentrations (ppbv) by ventilation type (including outlier)

Ventilation Type	N	Minimum	Maximum	Mean	SD
Windows up, air conditioning off	10	8.3	45.9	19.6	10.8
Windows up, air conditioning on	12	13.0	27.2	19.4	5.34
Windows down	10	13.4	57.5	33.0	15.0

Table 22: Cabin xylene concentrations (ppbv) by ventilation type (excluding outlier)

Ventilation Type	N	Minimum	Maximum	Mean	SD
Windows up, air conditioning off	9	8.3	25.1	16.67	5.90
Windows up, air conditioning on	12	13.0	27.2	19.39	5.34
Windows down	10	13.4	57.5	33.03	15.0

Graph 17: Cabin xylene exposure (ppbv) by ventilation type



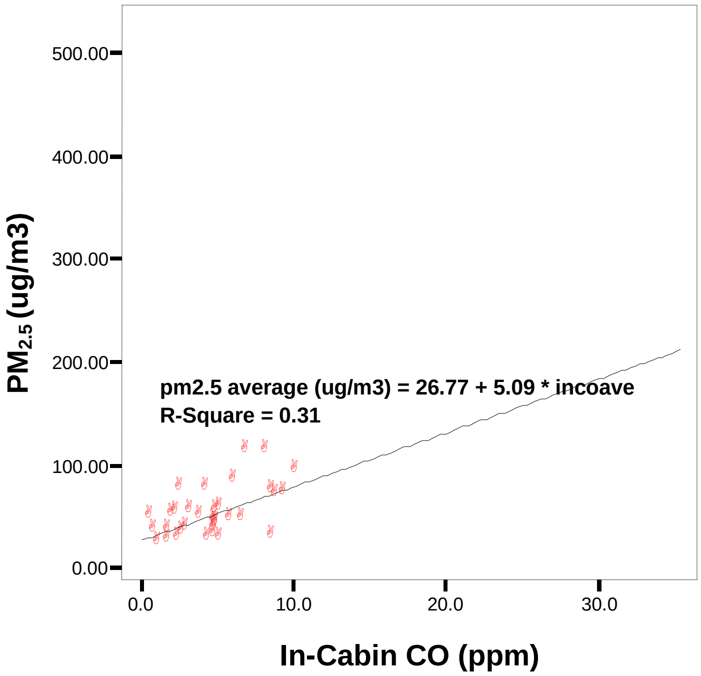
Trends in pollutants

How did the different pollutants correlate?

There was no association between cabin NO_2 and cabin $PM_{2.5}$, or between cabin NO_2 and cabin CO, however the different collection methodologies employed do make an association unlikely. The trip CO and $PM_{2.5}$ for ventilation type 2 did demonstrate an association (graph 18).

Graph 18: Cabin $PM_{2.5}$ Dustrak and CO

Windows up, air conditioning on and recirculating



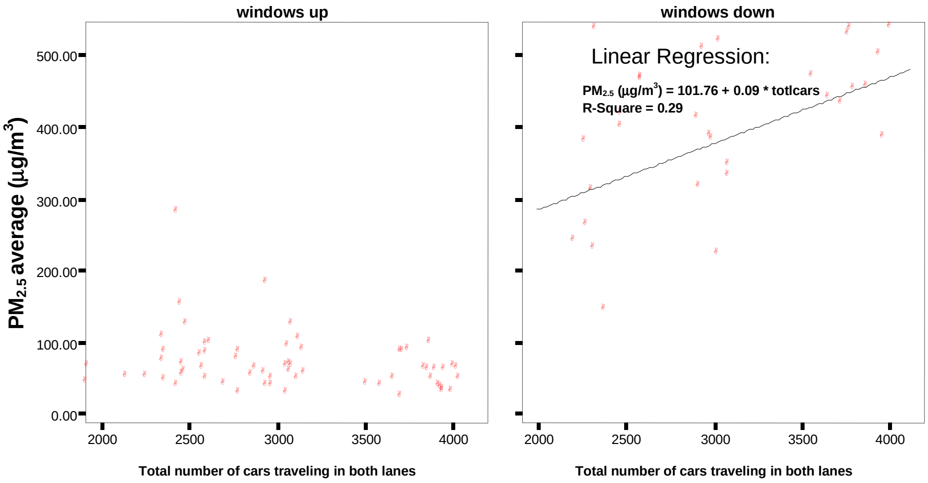
Number of cars

An analysis of pollutants by number of cars in the tunnel did not show any relationship. This analysis was limited due to the way data on number of cars was collected. The pollutants analysed were measured over a short time period, ie trip durations ranged from 3-18 minutes. Data on number of cars provided by the RTA are for one-hour periods corresponding to the times when the study was being conducted.

When concentrations of pollutants were split according to two ventilation types (windows up or windows down), a relationship with number of cars could be seen for $PM_{2.5}$ when the windows were down, but not for any other pollutant measured (Graphs 19 & 20).

Graphs 19-20: Cabin $PM_{2.5}$ exposure versus number of cars

Split by windows up or down



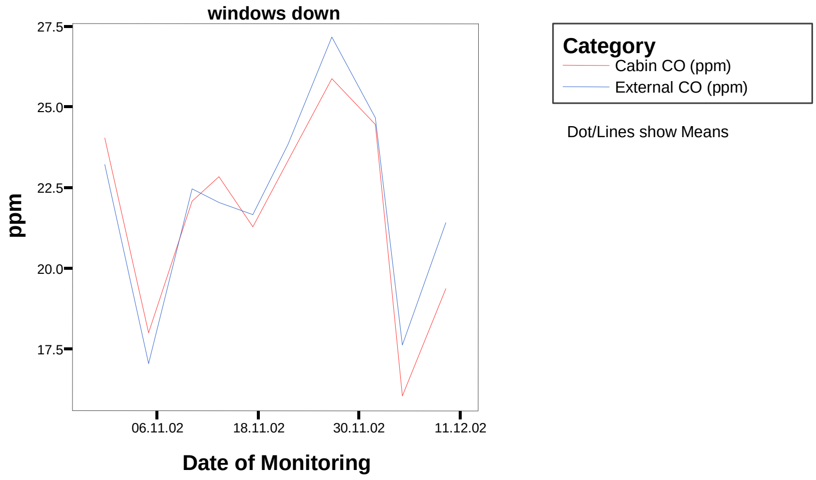
Cabin and external comparisons

External and cabin measurements were taken for carbon monoxide, carbon dioxide and nitrogen dioxide. It is clear that when the windows are down, the cabin concentrations closely match the external measurements i.e. what is outside is the same as what is inside. Table 23 and Graphs 21-23 illustrate this.

Table 23: Ratio of external pollutant levels to cabin pollutant levels by ventilation type

Ventilation type	**CO**	**NO_2**	**CO_2**
Windows up, air conditioning off	0.23	0.30	2.30
Windows up, air conditioning on	0.25	0.25	2.51
Windows down	0.98	0.96	1.07

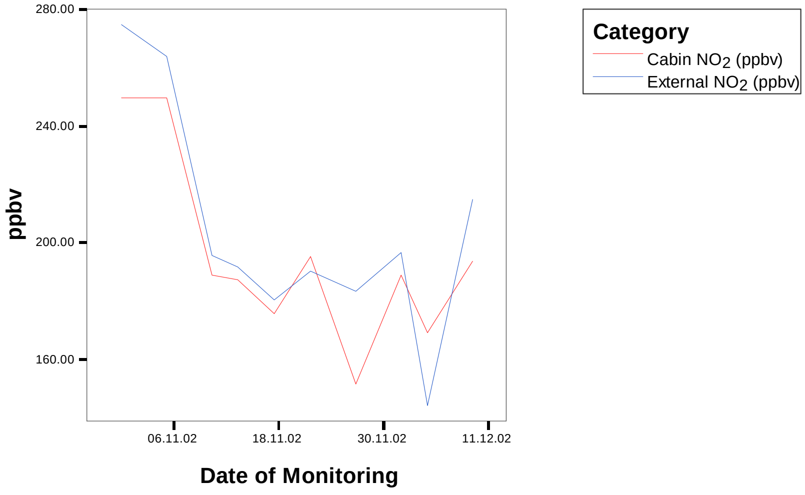
Graph 21: Cabin (windows down) and external CO concentrations (ppm)



Dot/Lines show Means

Graph 22: Cabin (windows down) and external CO_2 concentrations (ppm)

Graph 23: Cabin (windows down) and external NO_2 concentrations (ppbv)



The Sydney Bushfires December 2002

Major bushfires occurred in the Sydney area over 4-8 December 2002. EPA pollution indices were high, and PM_{10} readings, as recorded at M5 East freeway air quality monitoring stations, were above the 24-hour air quality standard.
The study was monitoring air quality inside the M5 tunnel during this period. Mean $PM_{2.5}$, CO and NO_2 levels for the 4-6 December (excluding the weekend of 7-8 December) are given in Table 24. These values were not significantly different to those measured during the whole study period.

Table 24: $PM_{2.5}$, CO and NO_2 concentrations during the Sydney bushfires compared to the whole study period

	Mean/Range during bushfires	**Mean/range for whole period**
$PM_{2.5}$ (Dustrak) (ug/m3)	141 (19-524)	163 (10-526)
NO_2 external (ppbv)	160 (144-188)	207 (144-476)
NO_2 cabin (ppbv)	89.4 (42-169)	101 (29.5-250)
CO external (ppm)	17.4 (7-28)	20.6 (5-39)
CO cabin (ppm)	8.4 (0.1-16.7)	10.4 (0.1-35)

5. DISCUSSION AND FINDINGS

General

This is the first publication in Australia of concentrations of a range of pollutants from the cabin and exterior of a vehicle traversing a road tunnel. For all pollutants measured there were highly significant differences in exposure levels between an open cabin and a closed cabin.

The use of a single vehicle for many journeys means that the variability found should derive mainly from variations in tunnel pollutant levels rather than vehicle factors, apart from that tested – ventilation. However the generalisability of these findings to other vehicles is unknown. It is likely that the closed cabin scenario approximates a best-case scenario, as the vehicle was relatively new and well maintained. The windows down scenario may approximate a worst-case, such as may be experienced by motorcyclists or in older vehicles.

The long exposure period required for passive sampling (nitrogen dioxide and air toxics) means that the monitoring period does not reflect the typical commuter exposure in the tunnel. The lower sensitivity of passive sampling devices meant that each was exposed for 8 –16 trips per day, an unlikely number of trips for any individual. The need to expose the passive samplers in the non-peak tunnel (morning, westbound) will tend to underestimate the exposure in the peak directions, however this impact is lessened by the ventilation characteristics of the tunnel – air in the first half of the westbound tunnel is derived mainly from the eastbound tunnel, and fresh air exchange occurs at the mid-point.

While the sampling methodologies we employed are not specified by current Australian standards, most of these measures have been extensively validated against standard methodologies [15-17]. The Dustrak is acknowledged as having less external validity, depending on the source of particles it is sampling [18], however, we were able to correct this error by using a recognised collection method simultaneously.

The carbon monoxide measurements are also validated by strong correlations between levels recorded by the RTA at fixed monitors inside the tunnels and our external levels during afternoon trips. Further validation of these instruments is demonstrated by identical or similar concentrations measured internally and externally when the windows were open. The different methodology for nitrogen dioxide – a passive diffusion sampler – yielded a similar correlation for this ventilation scenario.

While it was not a primary focus of this investigation, there appears to be little relationship between tunnel pollutant levels and ambient air. This is not unexpected, due to the concentration of pollutant sources in the tunnel, but would require further investigation to completely explore any relationship.

In the two ventilation scenarios with closed windows and vents there was no effect of the use of the air-conditioning system on pollutant levels. Thus these two scenarios can be considered together.

Carbon Monoxide

We showed that when the vehicle windows are open, carbon monoxide levels increase rapidly from a low background level and parallel the tunnel carbon monoxide levels. As the main tunnel air intake is around the mid-point, CO levels drop here, then rise rapidly again. When the vehicle cabin is closed, carbon monoxide accumulates gradually during the transit, and the impact of the mid-trip fresh air cannot be discerned. This confirms observations from previous studies that air exchange into a closed cabin is relatively slow. At 10 minutes closed cabin levels were on average 6.5ppm, compared to average tunnel levels around 20ppm. This equates to around 2 air changes per hour for this moving vehicle. Work done by the California Air Resources Board in 1997, found that air changes were around 2 per hour for a stationary Ford Explorer with windows closed and vents on recirculate, and rose to around 13 per hour when the vehicle was moving at freeway speeds [19].

Closed cabin CO levels were on average 25% of open cabin levels. The maximum trip exposure for the open cabin of 35ppm did not exceed the 15-minute WHO guideline of 87ppm. The WHO guidelines are set to be protective of the most susceptible individuals – those with ischaemic heart disease and foetuses - from the effects of carbon monoxide. The guidelines are also protective against the acute neurological effects of carbon monoxide such as impaired driving ability. As the longest trip was 18-minutes, comparison to the 30-minute WHO guideline is not warranted; however, trip values were also all below this level. Instantaneous peak values (78ppm) did not approach established limits, such as the Worksafe Australia Short-Term Exposure Limit of 400ppm. Given these findings, tunnel carbon monoxide levels do not pose a risk to public health.

Significant differences were observed between morning and afternoon for the cabin and external CO measures. While not reflected in the correlation tests performed, this is probably related to vehicle numbers in the tunnel, which are high in both directions in the afternoon.

The lack of correlation between closed cabin CO levels and fixed tunnel monitors demonstrates that individual fixed monitors provide a poor estimate of a motorist's exposure to CO while in a tunnel if the car cabin is closed.

Carbon Dioxide

We measured carbon dioxide simultaneously with carbon monoxide to determine if the closed cabin scenario was likely to result in levels that are uncomfortable for occupants. Occupant perceptions of air quality suggest that carbon dioxide concentrations above 1000ppm indicate an inadequate supply of fresh air in mechanically ventilated buildings[20]. Outdoor levels generally range between 400 – 500ppm. We found that the mean trip CO_2 with the windows down was 950ppm, however the levels were substantially increased when the windows were wound up. Occupants may thus perceive the cabin conditions as "stuffy" with the windows up and air intake off. The mean levels of CO_2 measured external to the vehicle in the tunnel were similar to the levels measured in the cabin with windows down. No carbon dioxide levels reached the level thought to be associated with health effects, around 5000ppm. Observational studies have shown an effect on blood acid balance after several weeks' exposure at this level, but no effects were observed after 6 hours [21].

It is important to note that CO_2 levels are dependent on the number of occupants in the vehicle when window are closed. For vehicles with only one occupant, closed cabin trip levels should be halved, approximately 1100ppm. Of course, if the number of occupants is greater than two, levels will be correspondingly higher.

Fine Particles

$PM_{2.5}$ was measured with similar methods to CO and CO_2 as well as with gravimetric collection by MicroVol. The pattern of findings with active sampling was similar to CO, however trip averages for fine particles in the closed cabin scenario were only about 15% of the open cabin level. While the Dustrak is a useful methodology, and enables the demonstration of changes in fine particle levels over time as well as relative concentrations, problems with its calibration relative to standard particle methodologies are well recognised [18]. The fine particle levels recorded with the MicroVol are more appropriately compared to health-based dose-response effects.

Our MicroVol measurement of $PM_{2.5}$ used gravimetric collection over all trips during a week. It thus reflects an average level of exposure for all ventilation scenarios. Comparing the two particle collection methods it would appear that the Dustrak overestimated $PM_{2.5}$ by around 80%. By comparison, a recent Sydney commuter study where exposures were measured for 5 hours in a car found a cabin $PM_{2.5}$ of 25$\mu g/m^3$ using a Microvol [23]. We found levels nearly four times this averaged across all ventilation scenarios. Ambient $PM_{2.5}$ levels during the study period were 17$\mu g/m^3$ or about 20% of the measured levels in the vehicle.

While some investigators have suggested that adverse health effects of fine particles may occur in response to short-term (less than an hour) exposures [24], fine particle standards are based on well-established 24-hour exposure dose-response effects. Individuals with pre-existing heart or lung disease are most susceptible to the effects of fine particles, and effects of increased levels have also been demonstrated on asthmatic children [10], [25], [26]. As there are no health guidelines for fine particle exposure for less than 24-hours, it cannot be predicted whether exposures to these high levels over a usual trip length of 6-minutes, or even during a traffic stoppage, would have an adverse effect on motorists' health. We provide calculations as to the impact commuting may have on fine particle exposures in Appendix D, which demonstrate that the impact of using the tunnels is small on daily particle exposure.

Svartengren exposed asthmatic volunteers to tunnel air in Stockholm for 30-minutes and subsequently assessed lung function for 18 hours. $PM_{2.5}$ levels averaged 95$\mu g/m^3$ (range 60-262) in a car with windows closed and fan on measured with a Tapered Element Oscillating Microbalance (TEOM). The measures from a TEOM are comparable to gravimetric collection, and this level is similar to our MicroVol levels, which were collected across the range of ventilation scenarios. Adverse respiratory effects to $PM_{2.5}$ exposure appeared mild compared to nitrogen dioxide. Subjects with exposure in excess of 100 $\mu g/m^3$ had a slightly greater early reaction to allergen challenge [27].

Nitrogen dioxide

Nitrogen dioxide concentrations were measured simultaneously in cabin and externally with passive samplers. The two measures were very similar on days when the windows in the car were down. While cabin levels were much lower than external levels when the cabin was closed, there was still a strong relationship between external and cabin levels.

Air NEPM standards have been developed for application to ambient air, thus the situation we are measuring is not an appropriate application of these standards. The nitrogen dioxide standard is however derived from observations that adverse effects are observed in asthmatics exposed to concentrations above 200 – 300ppbv over 30 to 60minutes [4]. Our collection period is comparable to this trial exposure. It is unlikely that our measures represent any individual's exposure, as at least four consecutive typical transits of the tunnel are required to accumulate this exposure. However, as tunnel transits can take up to 30minutes, equivalent to the minimum exposure period where the effect on asthmatics is established, there is some justification for comparing worst-case tunnel nitrogen dioxide exposures with this adverse effect level. However, we are also aware that longer transits are associated with incidents such as accidents and breakdowns, in which case the tunnel ventilation is switched to incident mode, emitting air via the portals to rapidly reduce pollutant levels. Our measures do not allow us to identify whether or not incident mode ventilation effectively reduced NO_2 exposure.

The mean nitrogen dioxide exposure for the open cabin scenario was 195ppbv, and on two occasions the exposure was at or above 200ppbv. Most results from the external measurements also exceeded this level. By contrast, the maximum level experienced with the cabin closed was 154ppbv.

Typically ambient NO_2 levels in Sydney are well below the standard, and it is uncommon for the Air NEPM standard to be exceeded [5]. In the recent Sydney commuter study, average cabin NO_2 levels were below even the minimum cabin level in the tunnels (in type 2 ventilation category) of 29.5ppbv[23]. Thus NO_2 exposures in the tunnels represent a significant increase above usual cabin levels, particularly if the windows are open. The usual exposure period for tunnel users is however relatively short.

NO_2 has rarely been reported from vehicles or tunnels. In Svartengren's study of asthmatics in a Stockholm tunnel, NO_2 levels averaged 141ppbv, compared to the average in this study of 101ppbv. Svartengren determined that subjects exposed to tunnel NO_2 levels above 146ppbv for 30 minutes had a significantly greater early reaction following allergen exposure as well as reduced lung function and more asthmatic symptoms compared to those with lower exposure [27]. In our study the concentrations measured with open windows all exceeded 146ppbv. Only on one day in the closed cabin scenario was this level exceeded.

There is little information available to determine the minimum length of exposure to NO_2 that may precipitate an effect in asthmatics. A Swedish investigator, Barck [described in 28], exposed asthmatics to 240ppbv NO_2 for 15minutes and found an increased inflammatory response after allergen challenge. Thus it appears high levels of NO_2 can impact on asthmatics following exposures shorter than the 30 minutes previously established. This has obvious implications for situations such as road tunnels.

Based on these recent findings of the effect of NO_2 on asthmatics, road authorities in Europe are considering setting guidelines for NO_2 in road tunnels [28]. We recommend that agencies in NSW should develop a better understanding of NO_2 levels in our road tunnels, and work towards developing guidelines to control NO_2 exposure, as has occurred for CO.

Pending these investigations, motorists can minimise NO_2 exposure by closing windows and switching ventilation to recirculate. At present, we also advise road users in open vehicles, such as motorcyclists, who suffer from asthma, to avoid using the tunnels when transit times are likely to be prolonged.

BTEX Gases

Our study also showed a similar pattern for BTEX gases – levels were in general twice as high with the open cabin scenario compared to the closed cabin. Compared to other studies that have measured these gases in vehicles, levels were not particularly high. It is already established that levels in vehicles are significantly higher than ambient levels (in Sydney these are 1-2ppbv), and that factors such as road congestion and car maintenance and age play an important role in determining in-vehicle levels [19, 29]. No previous studies have focussed on levels in vehicles using tunnels, except for Weisel who found that levels increased 1.5–4 times in a tunnel compared to other New York City commutes [29]. Internationally, in-vehicle benzene levels have varied from around 3ppbv to around 20ppbv, the exception being Chan's study in Taipei, where the average level in cars was 78ppbv [30]. Benzene levels were previously documented in Sydney cars by Duffy in 1996. Samples were collected during 8 commutes along two congested surface routes, and averaged 22ppbv in post-1986 vehicles. Duffy used three ventilation scenarios – all had windows closed, and varied the use of air conditioner and vents. There was no consistent effect of the scenarios on in-cabin levels, but the study was limited in its ability to detect a difference due to the limited number of samples. The significantly lower levels found in our vehicle for the closed car scenario compared to Duffy may reflect improved vehicle body or exhaust system manufacture.

An important factor highlighted by Duffy and other previous researchers is that exposure to BTEX gases is significantly higher in older vehicles. However it is unlikely that any vehicle would experience a higher exposure in the tunnels than our open cabin scenario unless that vehicle were a strong source of BTEX gases due to a malfunctioning exhaust system. In this case, however, occupant exposure would be higher whether or not the vehicle was using a tunnel.

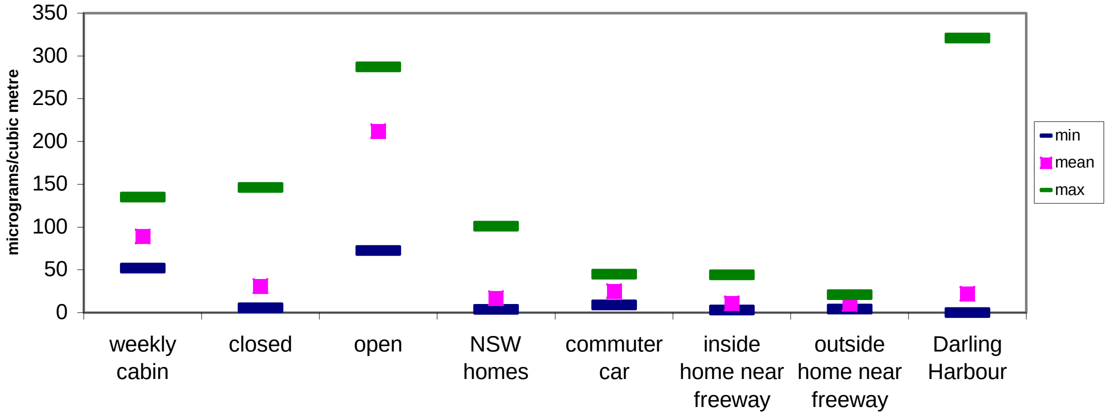
Overall, while we have confirmed previous commuter studies demonstrating that BTEX gas levels in vehicles are significantly higher than ambient levels, even the peak levels are several orders of magnitude below those associated with acute health effects. Published acute health lowest effect levels for air toxics include 7.6parts per million for benzene (lowest observed affect level for bone marrow toxicity) [31], 88 parts per million for toluene (neurological effects on workers) [3], around 200parts per million ethylbenzene (eye irritation) [32] and 70 parts per million for xylene (neurological effects) [3]. It is important to note that all these units are parts per million, thus around 1000 times higher than the levels we found in the vehicle cabin.

As benzene is a genotoxic carcinogen, it is recommended that exposures should be as low as possible. However, for normal commuters, use of the tunnels even with windows down, does not make a substantial difference to long-term benzene exposure (App D). Unless individuals traversed the tunnels many times per day it is unlikely that exposures from the tunnels would contribute significantly to life-time exposure; however, it is important to note that closing the cabin to tunnel air reduces exposures by approximately half.

Comparison to other exposures

We present a compilation of pollutant levels measured in other microenvironments in Sydney to provide a context for the levels found in the tunnel. These represent varying collection periods, but as far as possible we have tried to present comparable collection periods to those in this study. An important feature to remember is that the exposure duration in the tunnel is usually short compared to the time spent in most of these other microenvironments, which reduces the likelihood of adverse health impacts.

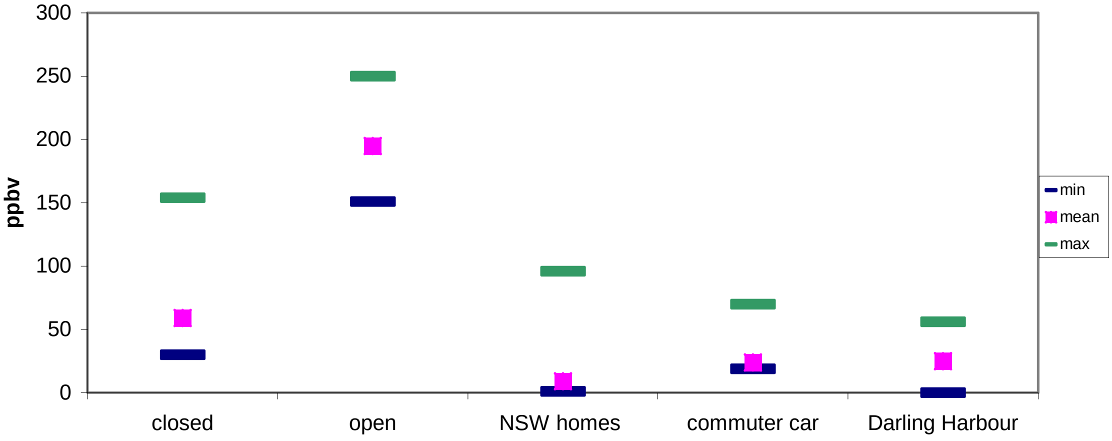
Graph 24: Comparison of $PM_{2.5}$ levels



For this comparison, we have adjusted the Dustrak readings obtained in open and closed cabin modes by 80% to allow comparison with fine particles collected by more standard methods. The results provided for NSW homes were collected over one week as PM_{10} and the levels demonstrated here have been adjusted assuming a PM_{10} to $PM_{2.5}$ ratio of 0.7 [33]. These indoor levels were collected during winter, with a focus on areas with high prevalence of wood heaters, and included homes where smoking occurred. Those from inside and outside homes near a freeway were collected over 24hours in non-smoking residences in the autumn [34]. Results for commuter cars were collected over 5 hours in spring [23]. The Darling Harbour levels are derived from 10-minute data undertaken outdoors for the Cross City Tunnel project to reflect a peak urban site [35].

This comparison demonstrates that while similar peak levels are found in other microenvironments for $PM_{2.5}$, the mean level in the tunnels with the windows down is significantly higher than all other microenvironments that have been assessed in Sydney.

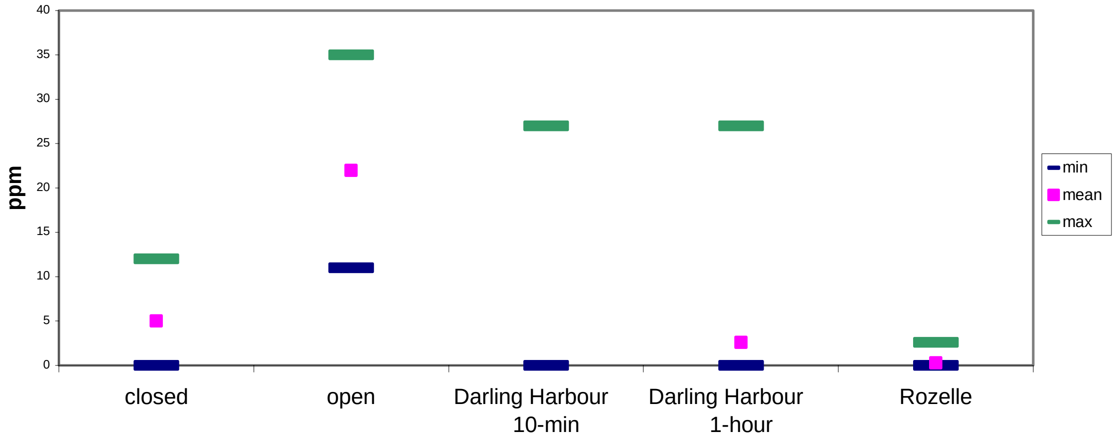
Graph 25: Comparison of nitrogen dioxide levels



This comparison of exposure to nitrogen dioxide in microenvironments is sourced from the studies detailed above. The NSW homes levels were averaged over a week, in a range of homes including those using unflued gas appliances, which are strong sources of nitrogen dioxide. Calculated 1-hour levels during unflued appliance use were much higher (20 – 291ppb, median 112ppb) [36].

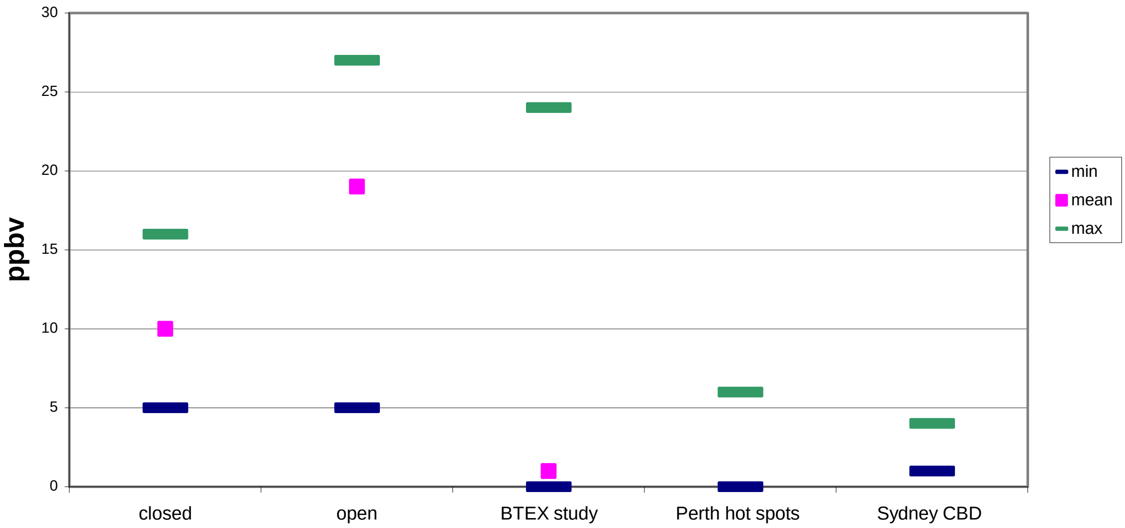
Similarly to the $PM_{2.5}$ comparison, while peak levels in other settings may be similar in some cases to those found in the tunnels, the tunnel range with open windows demonstrates a significantly elevated mean. The length of exposure in the tunnel is conversely typically much shorter than the other microenvironments, so that the increased level may not translate to an increased risk of health effects.

Graph 26: Comparison of carbon monoxide levels



We are aware of less local monitoring in microenvironments for CO than for fine particles and nitrogen dioxide. The comparisons provided here are from the Cross City Tunnel Representations Report, representing a peak urban site in Darling Harbour, and the ambient EPA monitor at Rozelle. A mean value for the 10-minute Darling Harbour data was not published, which limits our ability to make a comparison between the tunnel and peak urban exposure. Again, while the peak values in Darling Harbour are similar to those found in the tunnels, the mean tunnel level appears to be considerably higher.

Graph 27: Comparison of benzene levels



Additional data sources used in the comparison of benzene include the data in the Environment Australia Technical Report No. 6 – BTEX Personal Exposure Monitoring in Four Australian Cities [32]. The BTEX study results are those from 24-hour sampling of non-smoking volunteers in Sydney, Melbourne, Perth and

Adelaide. Part of this report focussed on 12-hour sampling of probable hot spots in Perth. The peak 12-hour level for benzene was in a basement car park. Due to the low concentration of benzene in petrol in Western Australia, it could be expected that levels in a Sydney car park are higher, by a factor of up to three. The Sydney CBD values are the reported 24-hour range from the EA publication.

Similarly to most of the other pollutant comparisons made here, the tunnel values only differ substantially from other microenvironments in the mean of the open cabin scenario. While this does seem to represent a significant increase in exposure, the impact of this on health is likely to be small, as all exposures are well below known acute effect levels, and the impact from the short time spent in the tunnel on life-time exposure is very small (App D).

Conclusions

During the six weeks of peak hour commutes when we sampled in the tunnels we did not find pollutant exposures that exceeded established guidelines. Pollutant levels when the windows were open were significantly higher than when the cabin was closed. Even closed cabin pollutant levels were higher than those found in most other settings. Due to the short transit time this increased level of pollutants known to be associated with chronic effects is unlikely to have a significant impact on health, however closing the vehicle cabin is a simple precautionary measure, and consistent with WHO advice on reduction of life-time exposure to carcinogens.

We have identified that road tunnel ventilation systems may need to manage NO_2 in a similar way as is currently done for CO, and recommend that NSW agencies collaborate on improving our understanding of tunnel NO_2 levels and determining whether short-term exposure guidelines need to be developed.

As at times tunnel transits can be prolonged, and pollutant levels may be higher than during our sampling, we believe that a precautionary approach is for commuters to close the vehicle cabin while in road tunnels so that any potential acute impact of elevated pollutant exposure can be minimised. Pending a better understanding of NO_2 levels in tunnels we would advise that motorists in open vehicles and motor cyclists avoid using the tunnels when transits are likely to be prolonged, particularly if they suffer from asthma.

6. ACKNOWLEDGMENTS

The authors gratefully acknowledge many people who made this study possible.

We wish to offer huge thanks to all persons in the South Eastern Sydney Public Health Unit who greatly assisted with the project and those persons include Steven Hatzi, Diane Smith, Lauren Booth, Angela Wong and Professor Bernard Stewart.

We also seek to gratefully acknowledge the dedication of Rob Gillett, Principal Project Scientist and Jennifer Powell, (Experimental Scientist), of the CSIRO Division of Atmospheric Research who provided air monitoring advice, analysis of samples and ongoing support. Steve Faulkner (M5 East Freeway Development Manager, RTA Motorway Services Branch) who regularly provided traffic statistics. Michael Chertok (Acting Senior Policy Analyst, Air Quality & Physical Hazards, Environmental Health Branch, NSW Health) who provided details of current and past research into this area.