Table 8-23 THC speciation profiles by fuel type (NSW EPA, 2012b; Environment Australia, 2003)

Pollutant/metric	% of THC (where THC=VOC)[a]			
	Petrol light duty		Diesel light duty	Diesel heavy duty
	Petrol (E0)	Petrol (E10)		
Benzene	4.95	4.54	1.07	1.07
PAHs (as b(a)p)	0.03	0.03	0.08	0.08
Formaldehyde	1.46	1.82	9.85	9.85
1,3-butadiene	1.27	1.20	0.40	0.40

(a) NSW EPA assume that THC and VOC are equivalent

(b) Based on a combination of PAH fraction of THC from NSW EPA (2012b) and the b(a)p fraction of PAH from Environment Australia (2003)

The EPA speciation profiles were combined with additional information to determine profiles that were applicable to the GRAL THC predictions. Firstly, for petrol vehicles it was assumed that 60 per cent of the fuel used would be E10; this percentage represents the target for petrol sold in New South Wales under the Biofuels Act 2007. Secondly, the percentages in Table 8-23 were weighted according to THC emissions from the different vehicle categories. In practice, THC emissions for each vehicle type vary according to the year, the road type (fleet mix) and the traffic speed. Given the uncertainties associated with the speciation profiles, for this assessment a single combination of road type and speed was used to represent a 'central estimate' of THC emissions (commercial highway road type, with a speed of 50 kilometres per hour), although emissions for three years were estimated (2014, 2021 and 2031). The weighted profiles are given in Table 8-24.

Table 8-24 Weighted THC speciation profiles for 2014, 2021 and 2031

Pollutant/metric	Weighted % of THC for traffic		
	2014	2021	2031
Benzene	4.4	4.3	4.0
PAHs (as b(a)p)	0.03	0.03	0.04
Formaldehyde	2.5	2.5	3.3
1,3-butadiene	1.1	1.1	1.1

Where a refined dispersion modelling technique has been used (as in this case), the criteria in the Approved Methods for individual air toxics relate to incremental impacts (i.e. project only) for an averaging period of one hour and as the 99.9th percentile of model predictions. However, the approach and assessment criteria in the Approved Methods cannot be readily applied to complex road projects in urban areas, as they are based on the assumption that a project represents a new source, and not a modification to an existing source. In the case of the current project the 'impacts' are dependent in part on the emissions from the tunnel ventilation outlets but, more importantly, on how the traffic on the existing road network is affected, and at many receptors the concentrations of air toxics actually decreased as a result of the project. A modified version of the usual approach was therefore used, whereby only the change in the maximum one-hour concentration of each compound as a result of the project was compared with the corresponding impact assessment criterion in the Approved Methods.

Summary

The approaches used for determining the total concentration of each pollutant for the community and RWR receptors are summarised in Table 8-25.

Table 8-25 Methods for combining modelled (GRAL) contribution and background contribution

Pollutant/ metric	Averaging period	Method	
		Community receptors	RWR receptors
CO	1 hour	1-hour GRAL CO added to contemporaneous 1-hour background CO	Maximum 1-hour GRAL CO added to maximum 1-hour background CO
	8 hours (rolling)	Rolling 8-hour GRAL CO added to contemporaneous rolling 8-hour background CO	Maximum 1-hour GRAL CO added to maximum 1-hour background CO, and converted to maximum rolling 8-hour CO
NO_2	1 hour	1-hour GRAL NO_X added to contemporaneous 1-hour background NO_X, and one-hour total NO_X converted to maximum total one-hour NO_2	Maximum 1-hour GRAL NO_X added to 98th percentile 1-hour background NO_X from synthetic profile, then converted to maximum 1-hour NO_2
	1 year	GRAL NO_X added to mapped background NO_X, then converted to NO_2	GRAL NO_X added to mapped background NO_X, then converted to NO_2
PM_{10}	24 hours	24-hour GRAL PM_{10} added to contemporaneous 24-hour background PM_{10}	Maximum 24-hour GRAL PM_{10} added to 98th percentile 24-hour background PM_{10} from synthetic profile
	1 year	GRAL PM_{10} added to mapped background PM_{10}	GRAL PM_{10} added to mapped background PM_{10}
$PM_{2.5}$	24 hours	24-hour GRAL $PM_{2.5}$ added to contemporaneous 24-hour background $PM_{2.5}$	Maximum 24-hour GRAL $PM_{2.5}$ added to 98th percentile 24-hour background $PM_{2.5}$ from synthetic profile
	1 year	GRAL $PM_{2.5}$ added to fixed background $PM_{2.5}$	GRAL $PM_{2.5}$ added to fixed background $PM_{2.5}$ of 8 $\mu g/m^3$

8.3.9 Model evaluation

The main approach for evaluating the performance of the GRAL model for use in the M4 East assessment involved a comparison between predicted and measured concentrations for the full 2014 base year. The method and results of the evaluation are given in Appendix J.

GRAL was configured to provide concentration predictions for CO, NO_X, NO_2 and PM_{10} at each of nine OEH and Roads and Maritime air quality monitoring sites (seven background and two roadside) in the GRAL WestConnex domain. $PM_{2.5}$ was not included as no independent testing of the model performance for $PM_{2.5}$ was possible. The GRAL predictions were for the combined surface road network and the existing M5 East tunnel ventilation outlet. For each monitoring site the GRAL predictions were extracted an hourly time series of concentrations for 2014. These were combined with an estimated background contribution for each monitoring site (as defined in Appendix F). The predicted and measured concentrations were compared using three concentration statistics: annual mean, maximum short-term mean (one hour or 24-hour, depending on the pollutant) and 98th percentile.

The results can be summarised as follows:

- Broadly speaking, there was a good level of agreement between the GRAL predictions and the measurements at both background and roadside sites. An example is shown for annual mean NO_2 in Figure 8-22.
- In almost all cases the model overestimated the concentration. The results suggest that the estimated concentrations ought to be conservative for most of the modelling domain.
- For annual mean and maximum one-hour NO_2 the model with the empirical NO_X-to-NO_2 conversion methods gave more realistic predictions than the model with ozone limiting method.
- The empirical NO_X-to-NO_2 method for determining the maximum one-hour concentration is not well suited to the estimation of other NO_2 statistics such as means and percentiles.

- The temporal variation in concentrations at the roadside sites was, on average, well reproduced

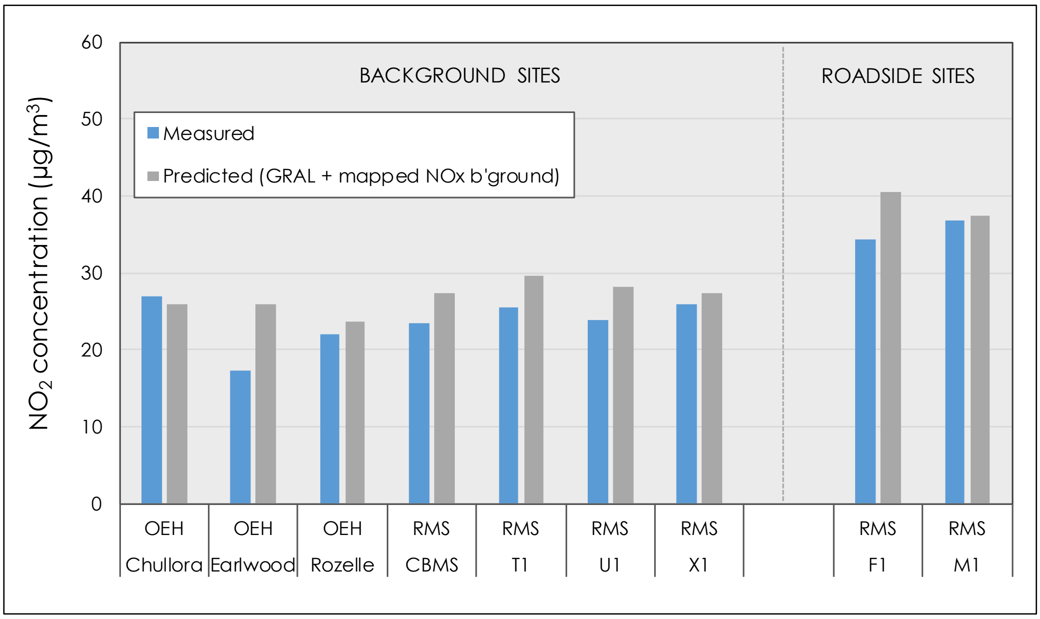

Figure 8-23 **Comparison between measured and predicted annual mean NO_2 concentrations**

The performance of GRAL was also investigated for the project-specific air quality monitoring stations, and the results of this investigation are also given in Appendix J. Given that only partial monitoring data for 2014 were available at each site, the comparisons between the model and the measurements were made for the monitoring period covered at each site.

Although based on monitoring data which only covered between two and five months, the results for the project sites were broadly similar to those for the OEH and RMS sites. In general the predicted concentrations were similar to or higher than the measured concentrations. There were, however, some notable over-predictions, especially for NO_X concentrations.

Overall, these results supported the application of the GRAL model in the assessment, along with the empirical conversion methods for NO_2, noting that the results tend to be quite conservative.

8.4 Results for expected traffic scenarios

The results of the air quality assessment for the expected traffic scenarios are presented in the following sections of the report.

Each pollutant and metric is treated in turn, and in each case the following has been determined:

- The total concentration for comparison against NSW impact assessment criteria and international air quality standards.
- The contributions of the different sources (background, surface roads and ventilation outlets),
- The change in the total concentration. This was calculated as the difference between the 2021-DS and 2021-DM scenario, and between the 2031-DS and 2031-DM scenario.

The results have been presented as:

- Pollutant concentrations at discrete receptors:
    - In bar charts for absolute concentration and changes in concentration for the 31 community receptors.
    - As ranked bar charts for absolute concentration and changes in concentration at the 10,154 RWR receptors.

- Pollutant concentrations across the modelling domain (as contour plots). These have only been provided for the most important pollutants: NO_2, PM_{10} and $PM_{2.5}$.

All results, including tabulated concentrations and contour plots, are provided in Appendix K.

8.4.1 Carbon monoxide (maximum one-hour mean)

Results for community receptors

The maximum one-hour mean CO concentrations at the 31 community receptors with the project in 2021 and 2031 are shown in Figure 8-24. At all these receptor locations the CO concentration was well below the NSW impact assessment criterion of 30 µg/m^3. The concentrations were also well below the lowest international air quality standard identified in the literature (California, 22 µg/m^3).

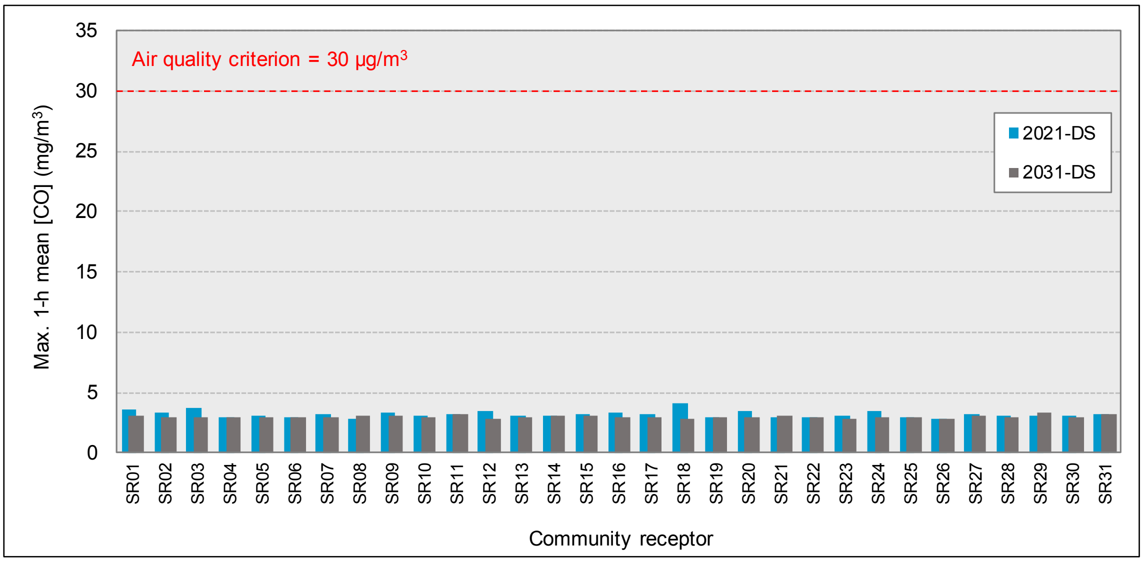

Figure 8-24 Maximum one-hour mean CO at community receptors (2021-DS and 2031-DS)

Figure 8-25 shows the contributions of the background, surface roads and ventilation outlets to the maximum one-hour mean CO concentrations in the 2021-DS scenario. In this Figure the hour of the year is not the same for all receptors; it can be seen from the background concentrations that maximum CO concentration occurred in one of two hours of the year.

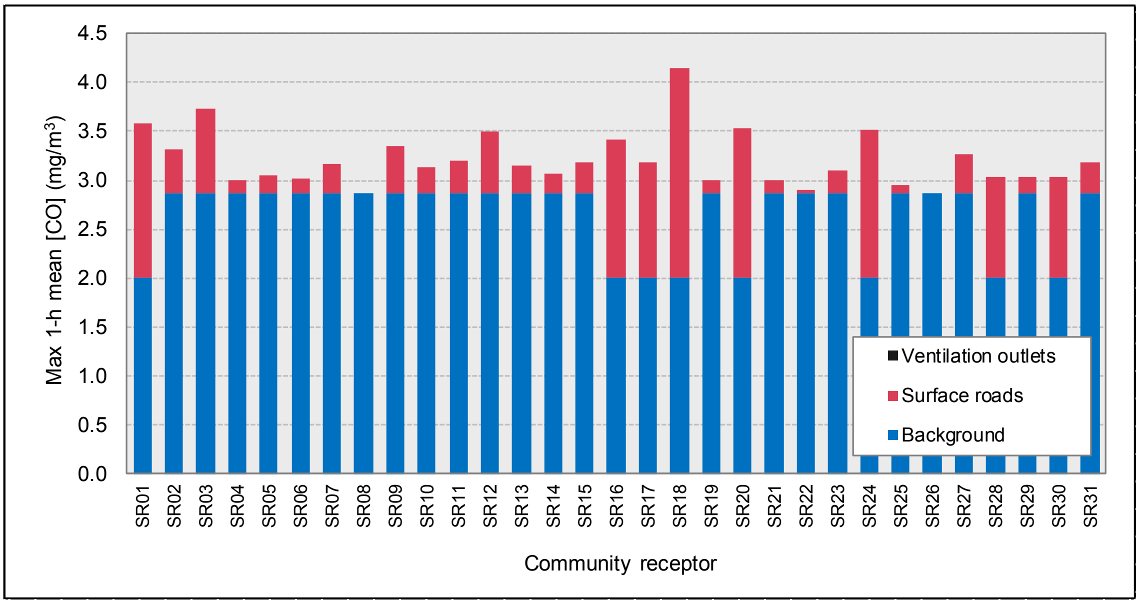

Figure 8-25 Source contributions to maximum one-hour mean CO at community receptors (2021-DS)

At most of the 31 receptor the maximum concentration was dominated by the background, but at some locations there was a notable surface road contribution (up to 73 per cent of the total). The contribution of tunnel ventilation outlets to the maximum CO concentration was zero for all receptors (i.e. the concentration due to outlets was zero during the hour when the maximum total concentration occurred). For each receptor, larger one-hour contributions from roads and tunnel ventilation outlets may well have occurred during other hours of the year, but would have been superimposed on a lower background.

Figure 8-26 shows the changes in concentration in the Do Something scenarios relative to the Do Minimum scenarios for the community receptors. Whilst there was an increase in the maximum CO concentration at some receptors (up to around 0.5 mg/m^3), at most locations there was either little overall change or a reduction.

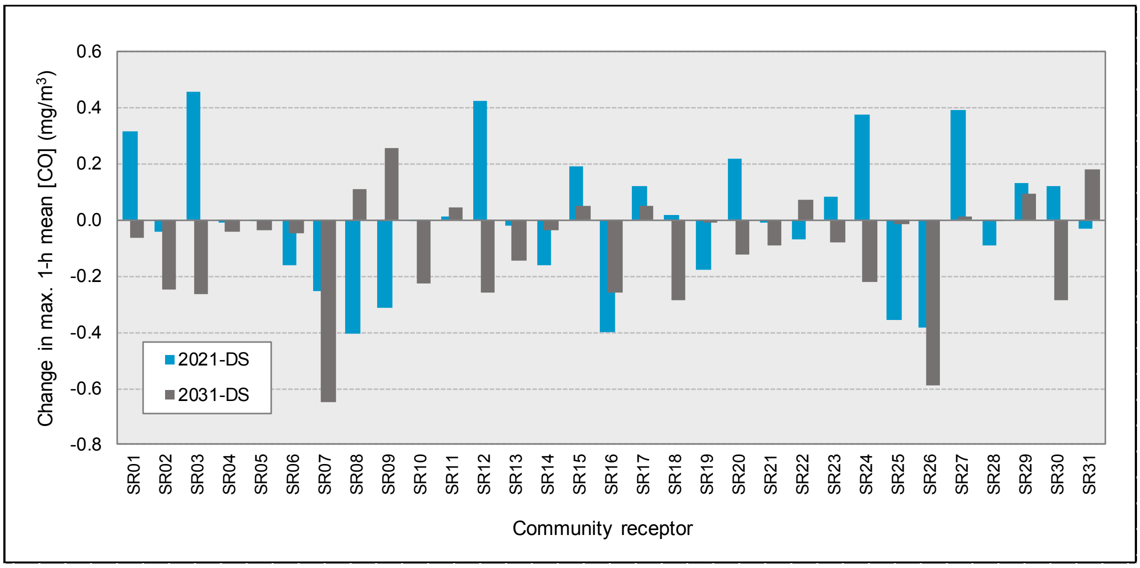

Figure 8-26 **Change in maximum one-hour mean CO at community receptors (2021-DS and 2031-DS)**

Results for RWR receptors

The ranked one-hour CO concentrations at the 10,154 RWR receptors in the 2021-DS scenario are shown in Figure 8-27. The one-hour CO criterion for NSW was not exceeded at any of the RWR receptors in any scenario. In 2021 and 2031 with the project, the highest one-hour concentrations were predicted to be 7.9 mg/m^3 and 6.2 mg/m^3 respectively.

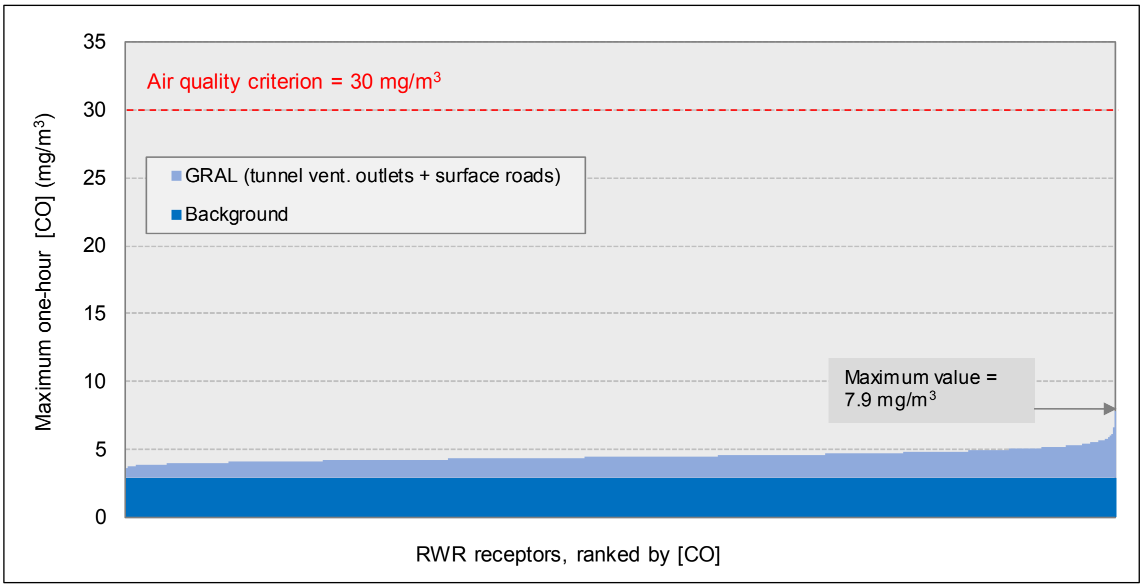

Figure 8-27 **Source contributions to maximum one-hour CO at RWR receptors (2021-DS)**

Given that the maximum one-hour CO concentrations were well below the NSW impact assessment criterion, it was not considered necessary to determine the separate contributions of tunnel ventilation outlets and surface roads.

The changes in the maximum one-hour CO concentration at the RWR receptors in the 2021-DS scenario (relative to the 2021-DM scenario) are shown, again ranked by change in concentration, in Figure 8-28. There was clearly a general reduction in the predicted concentration across the M4 East GRAL domain as a result of the project, with reductions at a large number of locations. There was an increase in CO at 27 per cent of the receptors in 2021, although the increase was greater than 1 mg/m^3 for only 0.3 per cent of receptors.

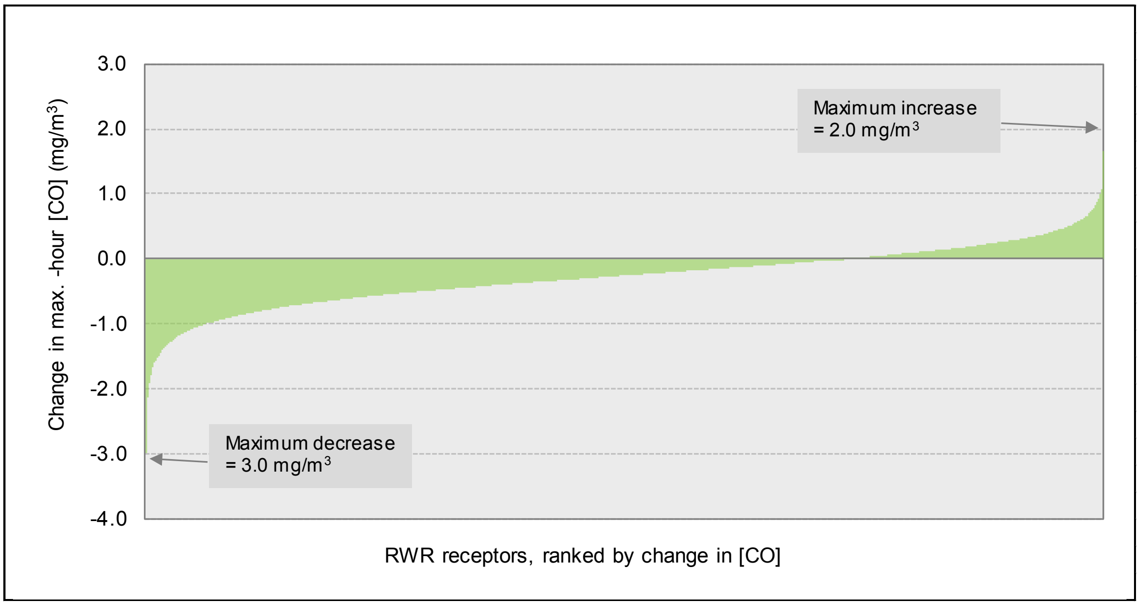

Figure 8-28 **Change in maximum one-hour CO at RWR receptors (2021-DS)**

The results for the 2031-DS scenario are given in Appendix K. These closely resembled the results for 2021.

8.4.2 Carbon monoxide (maximum rolling 8-hour mean)

Results for community receptors

Figure 8-29 shows the maximum rolling eight-hour mean CO concentrations at the community receptors with the project in 2021 and 2031. Because no model predictions were available for the period with the highest background concentration, the maximum background value was combined with the maximum model prediction at each receptor. The background was therefore taken to be the same at all locations. As with the one-hour mean, at all the receptors the concentration was well below the NSW impact assessment criterion, which in this case is 10 µg/m^3. No lower criteria appear to be in force internationally.

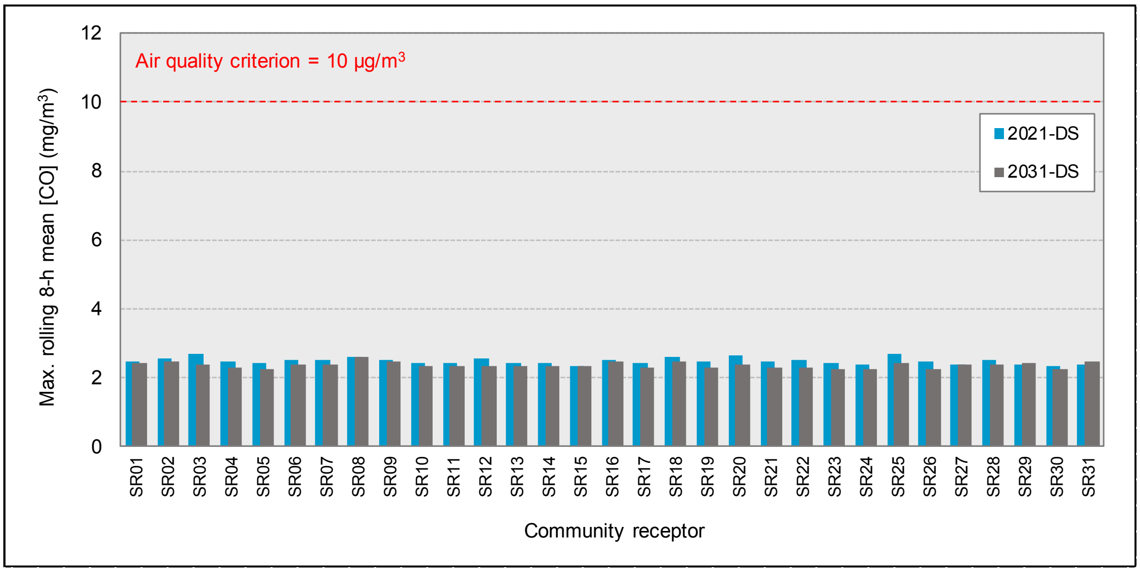

Figure 8-29 **Maximum rolling 8-hour mean CO at community receptors (2021-DS and 2031-DS)**

The main contributor at these receptors in the 2021-DS scenario was the background concentration (Figure 8-30). The surface road contribution ranged from 9 per cent to 22 per cent, whereas the tunnel ventilation outlet contribution was less than 0.3 per cent.

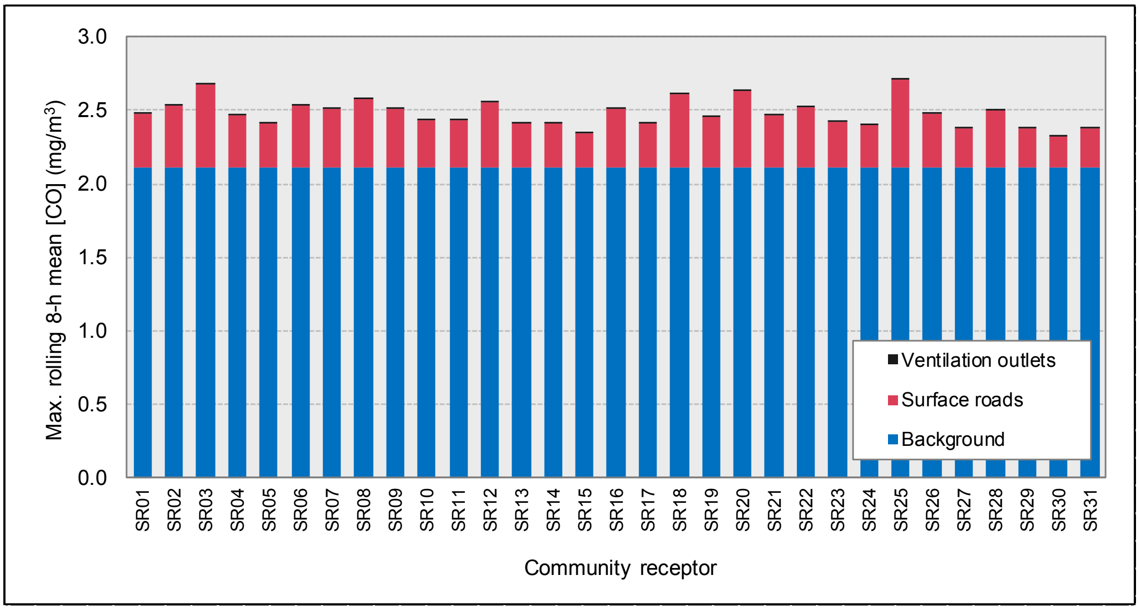

Figure 8-30 **Source contributions to maximum rolling 8-hour mean CO at community receptors (2021-DS)**

Figure 8-31 shows that the change in the maximum rolling 8-hour CO concentration at most of the community receptors was less than 0.3 mg/m^3.

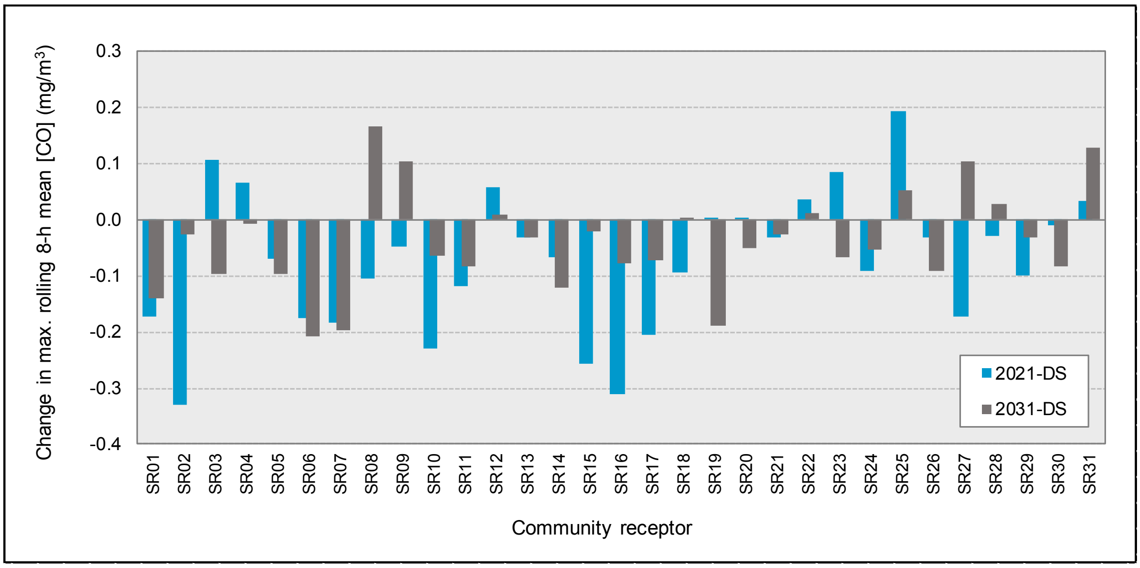

Figure 8-31 Change in maximum rolling 8-hour mean CO at community receptors (2021-DS and 2031-DS)

Results for RWR receptors

Rolling 8-hour mean CO concentrations were not extracted from GRAL. However, these would be broadly similar to those obtained for maximum one-hour concentrations.

8.4.3 Nitrogen dioxide (annual mean)

Results for community receptors

Figure 8-32 shows the annual mean NO_2 concentrations at the 31 community receptors with the project in 2021 and 2031. At all these receptor locations the concentration was below 28 µg/m^3, and therefore less than 45 per cent of the NSW impact assessment criterion of 62 µg/m^3. It should be noted that a lower air quality standard has been adopted elsewhere (e.g. 40 µg/m^3 in the EU). The concentrations at the community receptors were also below this value.

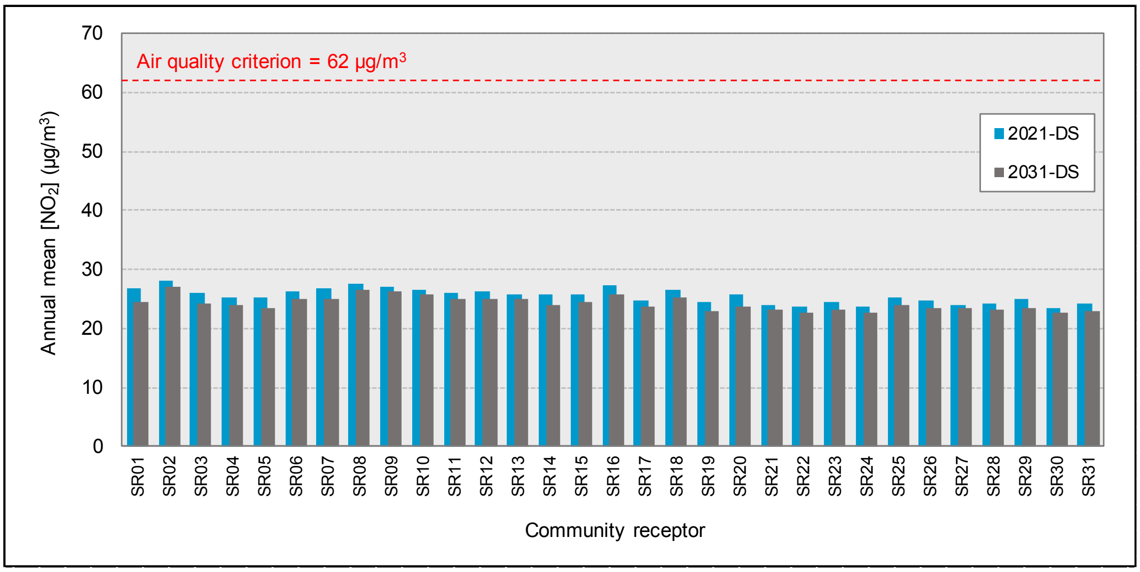

Figure 8-32 **Annual mean NO_2 at community receptors (2021-DS and 2031-DS)**

Figure 8-33 presents the source contributions to total annual mean NO_2 concentrations in the 2021-DS scenario.

The source contributions were estimated using a 'cumulative' approach involving the following steps:

A. The background NO_X concentration alone was converted to NO_2.

B. The sum of the background and road NO_X concentrations was converted to NO_2.

C. The sum of the background, road and outlet NO_X concentrations was converted to NO_2.

The road and outlet contributions were then obtained as the differences in NO_2, where road NO_2 was determined as NO_2 from Step B minus NO_2 from Step A, and outlet NO_2 was determined from Step C minus Step B. This allowed for the reduced oxidising capacity of the near-road atmosphere at higher total NO_X concentrations.

The results indicate that the background at these receptors is likely to responsible for, on average, around 80 per cent of the predicted annual mean NO_2, with most of the remainder being due to surface roads. Surface roads were responsible for between 13 per cent and 25 per cent of the total, depending on the receptor. The contribution of tunnel ventilation outlets was less than 0.4 per cent.

Figure 8-34 shows the changes in concentration in the Do Something scenarios relative to the Do Minimum scenarios for the community receptors. Whilst there was a small increase in the NO_2 concentration at some receptors (<0.5 µg/m^3), at most locations there was a reduction. The largest reduction for these community receptors – around 3.5 µg/m^3 in 2021 – was predicted to occur at receptor SR16 (St Mary's Catholic Primary School), and effectively represented the removal of a large fraction of the surface road contribution at this location.

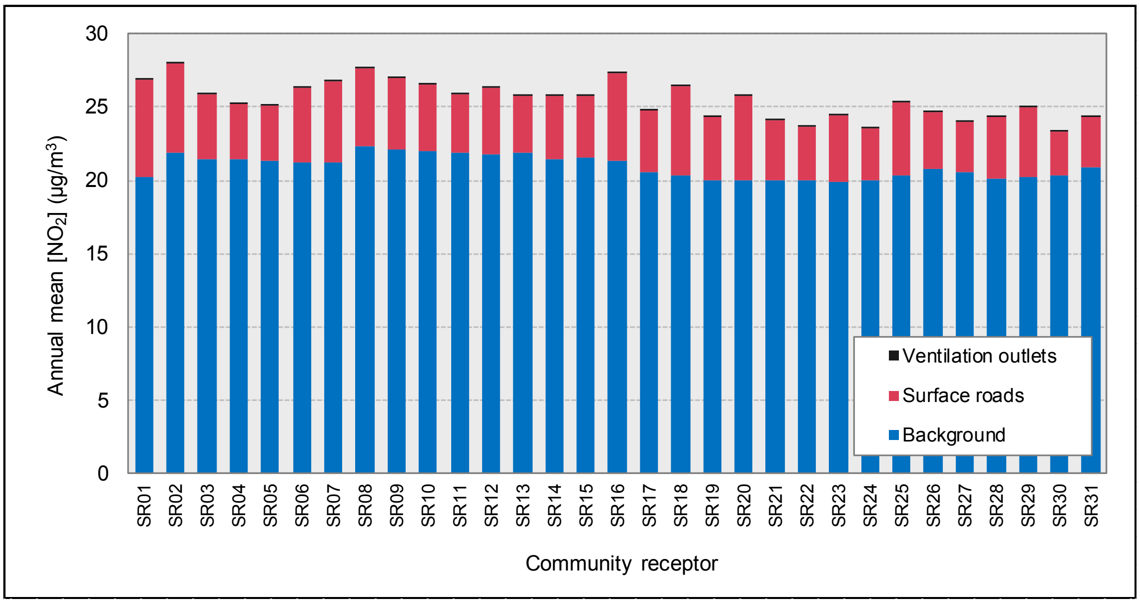

Figure 8-33 Source contributions to annual mean NO_2 at community receptors (2021-DS)

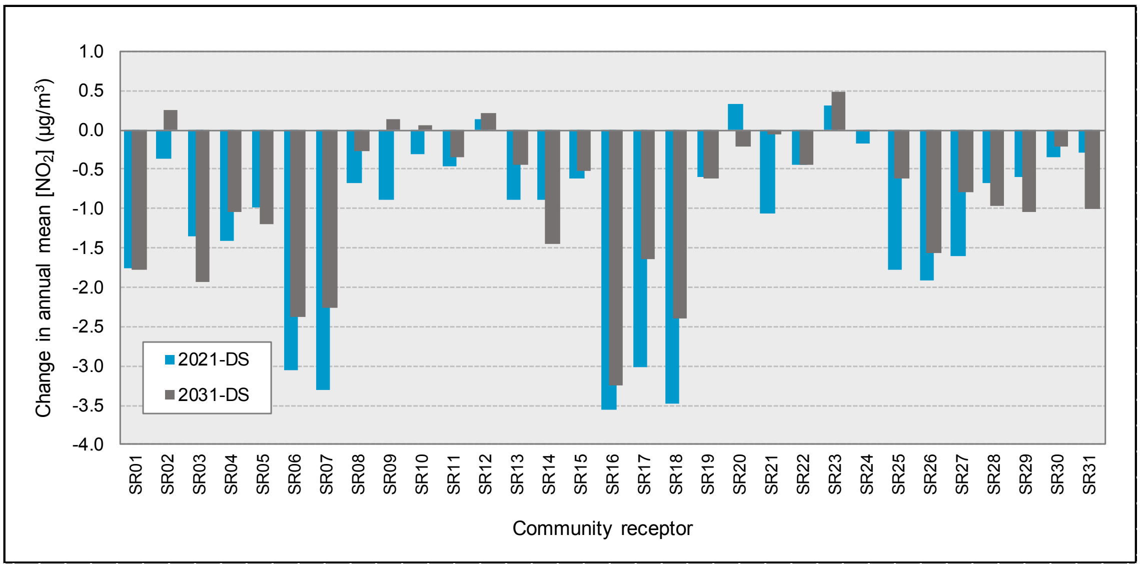

Figure 8-34 Change in annual mean NO_2 at community receptors (2021-DS and 2031-DS)

Results for RWR receptors

The annual mean NO_2 criterion for NSW was not exceeded at any of the 10,154 RWR receptors in any scenario. In 2021 and 2031 the highest concentrations with the project were predicted to be 34.4 µg/m^3 and 31.0 µg/m^3, and in both cases these concentrations represented a decrease relative to the corresponding Do Minimum scenarios. The maximum annual mean NO_2 concentration in the cumulative case (2031-DSC) was 31.6 µg/m^3.

The annual mean NO_2 concentrations at the RWR receptors in the 2021-DS scenario are shown, with a ranking by total concentration, in Figure 8-35. Concentrations at the vast majority of receptors were between around 23 µg/m^3 and 30 µg/m^3. As noted above, all concentrations were well below the assessment criterion of 62 µg/m^3, as well as being below the EU limit value of 40 µg/m^3. The maximum contribution of tunnel ventilation outlets at any location in 2021 was 0.1 µg/m^3, whereas the surface road contribution ranged between 2.4 µg/m^3 and 14.2 µg/m^3. The corresponding values for 2031 were 0.13 µg/m^3, 1.8 µg/m^3 and 10.8 µg/m^3.

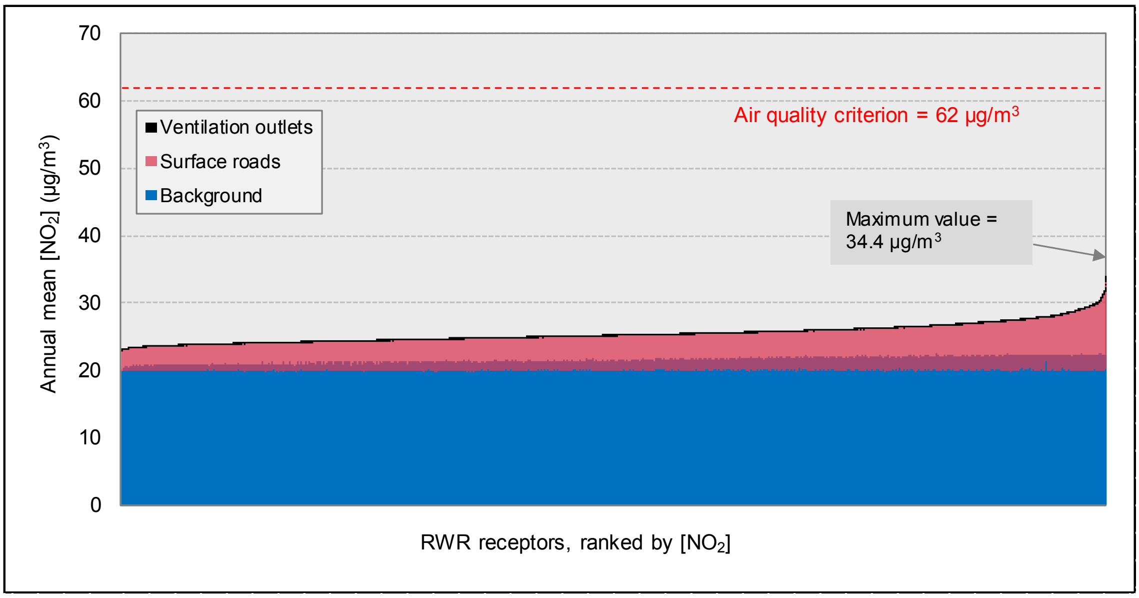

Figure 8-35 **Source contributions to annual mean NO_2 at RWR receptors (2021-DS)**

The change in the annual mean NO_2 concentration at the RWR receptors in the 2021-DS scenario (relative to the 2021-DM scenario) are shown, ranked by change in concentration, in Figure 8-36. There was clearly a general reduction in the predicted annual mean concentration across the M4 East GRAL domain as a result of the project, with substantial reductions at a large number of locations. There was an increase in NO_2 at 15 per cent of the receptors, although the increase was greater than 1 µg/m^3 for only 0.5 per cent of receptors.

The annual mean NO_2 concentrations, and the changes in the annual mean, in the 2031-DS scenario are given in Appendix K. These closely resemble the results for 2021.

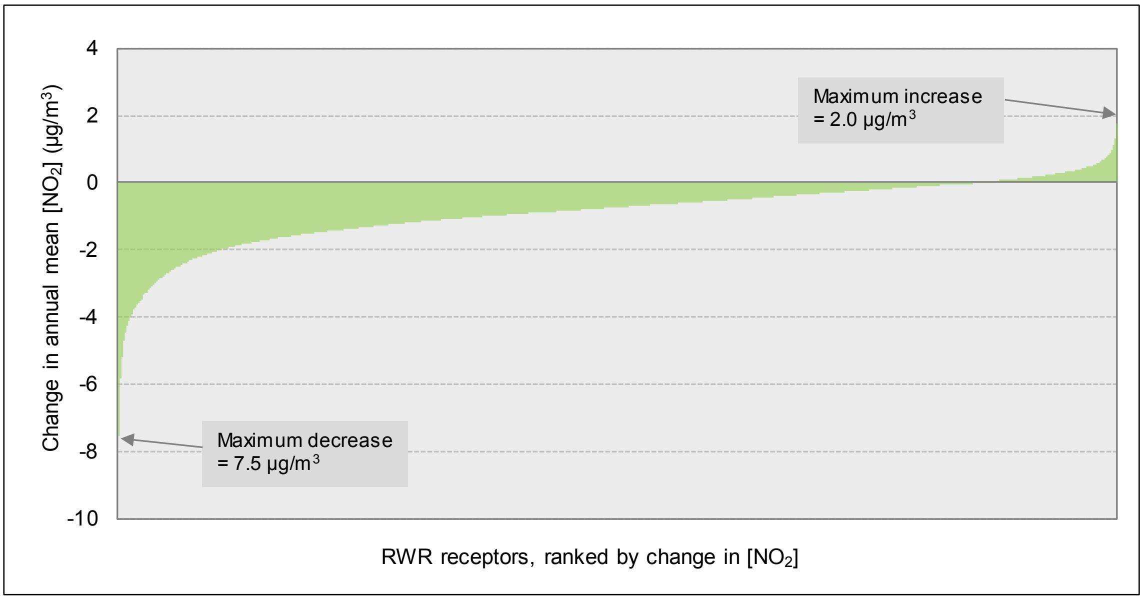

Figure 8-36 **Changes in annual mean NO_2 at RWR receptors (2021-DS)**

Contour plots

Contour plots showing the spatial distribution of annual mean NO_2 concentrations across the M4 East GRAL domain in 2021 are provided for the Do Minimum case (i.e. without the project) in Figure 8-37, and for the Do Something case (i.e. with the project) in Figure 8-38. These plots are based on 527,000 data points, spaced at 10 metre intervals across the domain. Many of the points therefore fall along the axes of roads, and are therefore not necessarily representative of population exposure. The maps also show main surface roads and the locations of the project ventilation facilities.

Annual mean concentrations are clearly the highest along major roads, notably the M4 Motorway and Centenary Drive to the south of Sydney Olympic Park, and to a lesser extent Parramatta Road. The concentrations are also influenced slightly by the background NO_2 concentration gradient, which increases from east to west (see Appendix F, Figure F-38).

An equivalent contour plot for the change in the annual mean NO_2 concentration with the project in 2021 is given in Figure 8-39. This shows the general reductions in NO_2 across the domain, and in particular along Parramatta Road. Some sections of Parramatta Road have larger reductions in concentration than other sections.

The equivalent plots for 2031 are presented in Appendix K.

Figure 8-37 Contour plot showing annual mean NO_2 without the project (2021-DM)

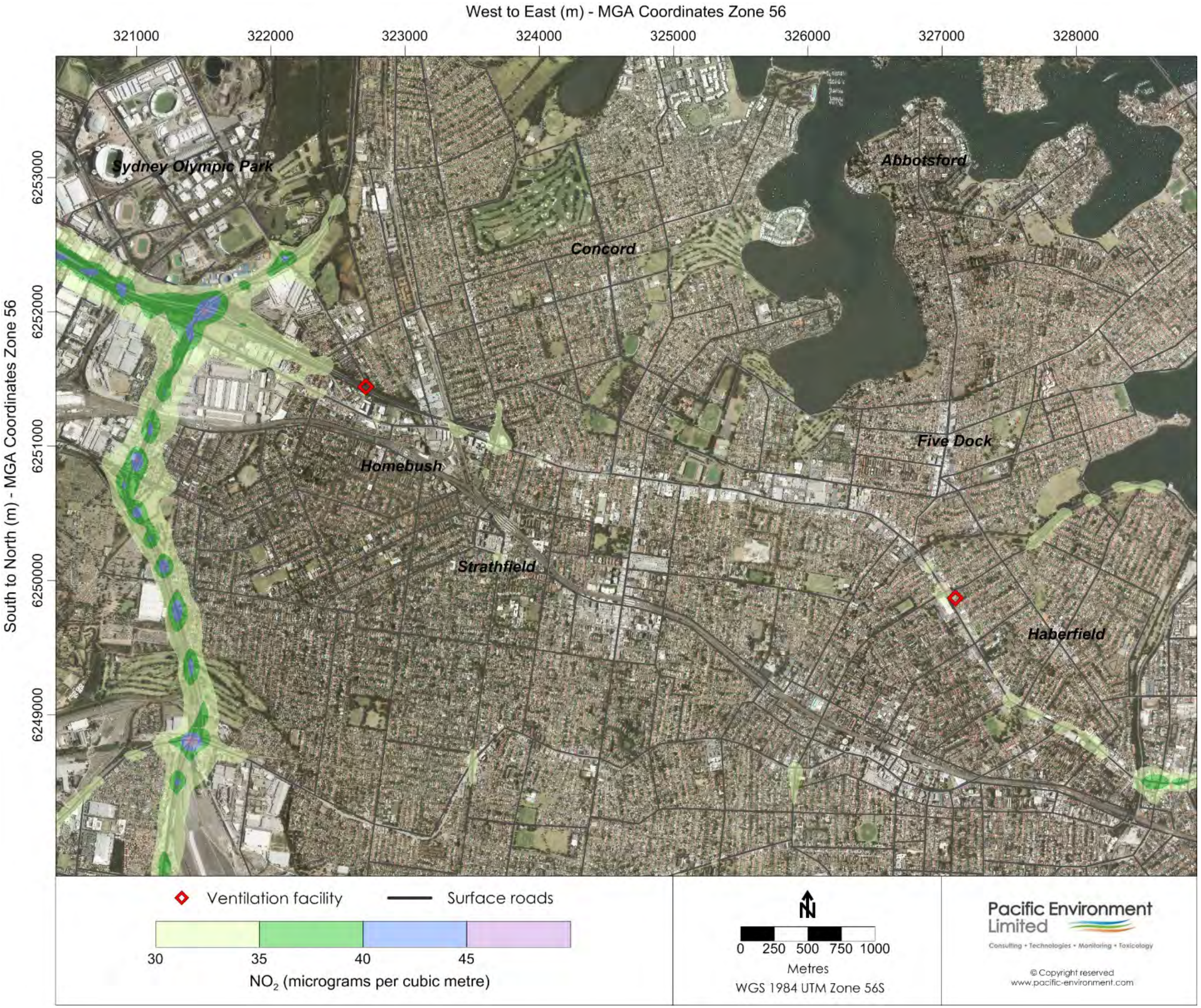

Figure 8-38 **Contour plot showing annual mean NO_2 with the project (2021-DS)**

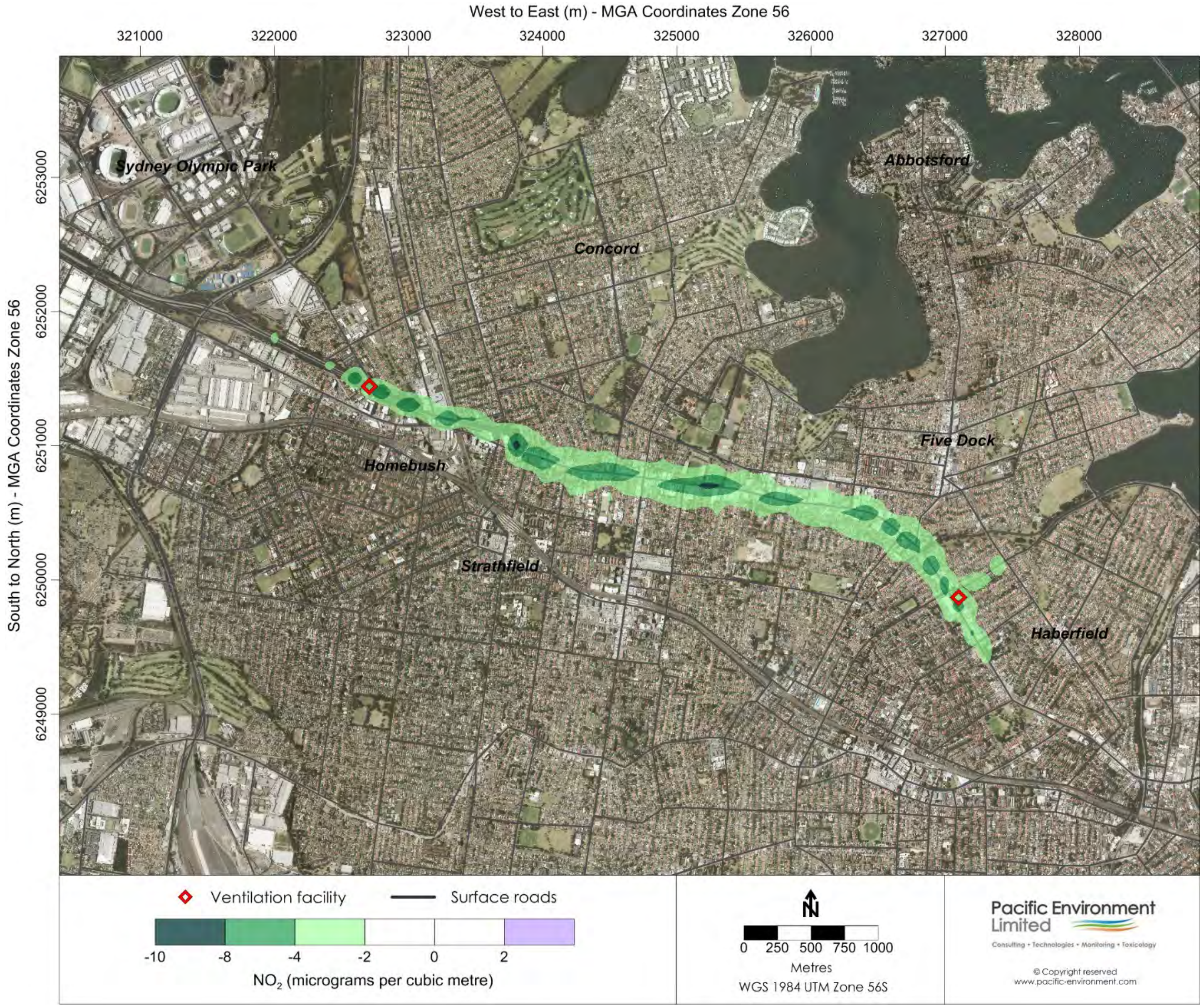

Figure 8-39 Contour plot showing change in annual mean NO_2 with the project (2021-DS)

8.4.4 Nitrogen dioxide (maximum one-hour mean)

Results for community receptors

The maximum one-hour mean NO_2 concentrations at the 31 community receptors with the project in 2021 and 2031 are shown in Figure 8-40. At all receptor locations the maximum concentration was below the NSW impact assessment criterion of 246 µg/m^3. Again, the hour of the year depicted is not the same for all receptors. For example, in the 2021-DS scenario all maximum concentrations occurred in one of ten different hours of the year. Lower, but not necessarily more stringent, air quality standards are in force in other countries. For example New Zealand has a limit value of 200 µg/m^3, but with 9 allowed exceedances per year. There was also compliance with the New Zealand standard at these 31 receptors.

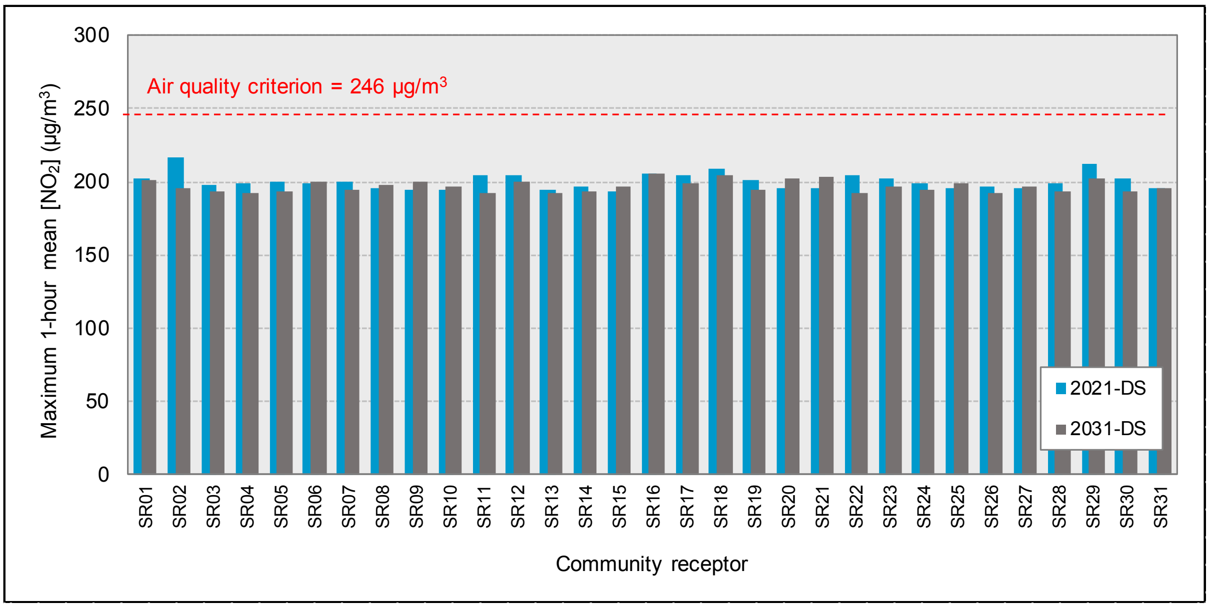

Figure 8-40 Maximum one-hour NO_2 at community receptors (2021-DS and 2031-DS)

To apportion the contributions of different sources to the maximum NO_2 concentration, it was necessary to identify the hour in which the maximum NOx concentration occurred, and then what the modelled surface road and outlet contributions were during that hour. Once the relevant hours had been identified, the source contributions to maximum one-hour NO_2 were estimated using the method described earlier for the annual mean. The results are shown in Figure 8-41.

As with the annual mean, the background was the most important source, with generally a small contribution from surface roads. The outlet contribution to the maximum NO_2 concentration was zero for all receptors. As with one-hour mean CO, larger one-hour contributions from roads and outlets may well have occurred during other hours of the year.

The changes in the maximum concentration in the Do Something scenarios relative to the Do Minimum scenarios (Figure 8-42) were less clear-cut than those for annual mean NO_2, with a mixture of increases and decreases. However, as already noted, none of the increases resulted in an exceedance of the air quality criterion for one-hour NO_2 at the community receptors.

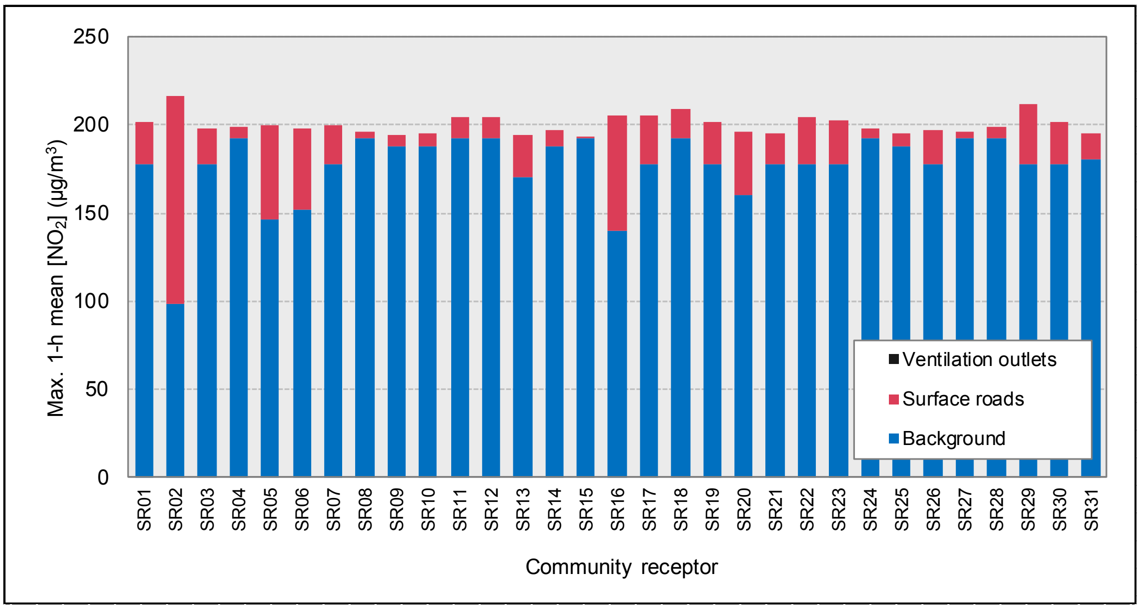

Figure 8-41 Source contributions to maximum one-hour NO_2 at community receptors (2021-DS)

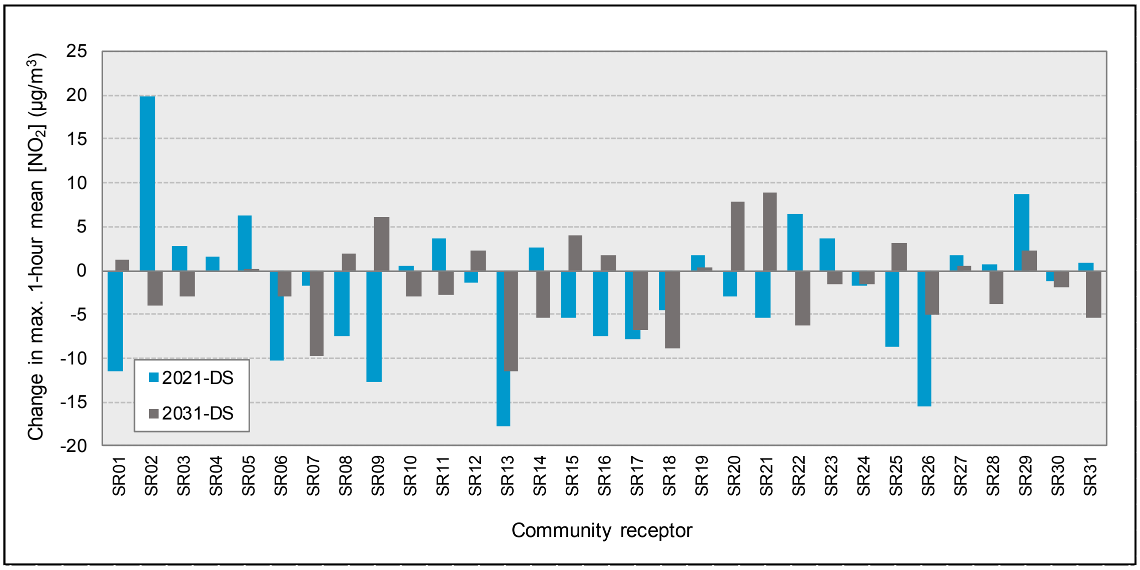

Figure 8-42 Change in maximum one-hour NO_2 at community receptors (2021-DS and 2031-DS)

Results for RWR receptors

The maximum one-hour mean NO_2 concentrations at the RWR receptors in the 2021-DS scenario are shown, with a ranking by total concentration, in Figure 8-43. There were some predicted exceedances of the NSW one-hour NO_2 criterion (246 µg/m^3). In the 2021-DM scenario the maximum concentration exceeded the criterion at 274 receptors (2.7 per cent of all receptors), but with the introduction of the project in the 2021-DS scenario this decreased to 44 receptors (0.4 per cent). In the 2031-DM scenario (plotted in Appendix K) there were exceedances at 21 receptors (0.2 per cent), decreasing to just two receptors (0.02 per cent) in the 2031-DS scenario.

The contributions of surface roads and ventilation outlets are not shown separately in Figure 8-43, as these were not additive. However, the maximum contribution of tunnel outlets to NO_X at any receptor was 13.7 µg/m^3 in 2021-DS (15.6 µg/m^3 in 2031-DS). This would equate to a very small NO_2 contribution relative to the air quality assessment criterion. Compliance with the New Zealand limit value of 200 µg/m^3 with nine allowed exceedances per year could not be determined for the RWR receptors, as time series were not available.

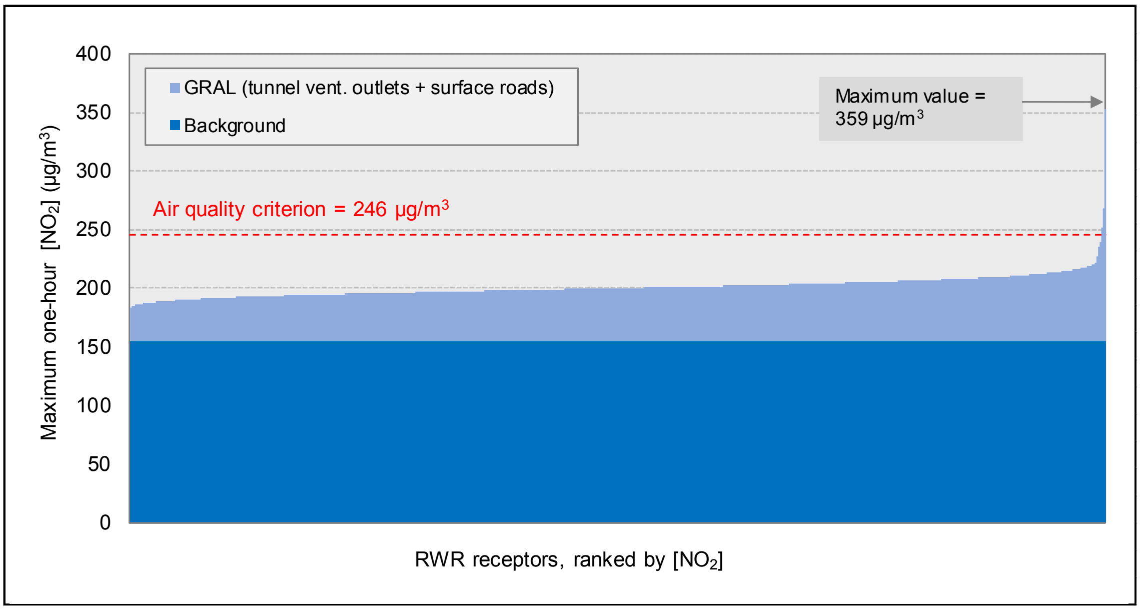

Figure 8-43 Source contributions to maximum one-hour NO_2 at RWR receptors (2021-DS)

No exceedances of the NSW NO_2 criterion have been measured at ambient air quality monitoring stations in Sydney in recent years, and to some extent these predictions may be a result of the conservatism in some of the modelling assumptions, and the tendency of the model to overestimate maximum NO_2 concentrations (see Appendix J, Figure J-6). The extent of the overestimation may also be higher in 2031 and 2031 than in 2014 given the assumption of a higher NO_2/NO_X ratio in future years. However, the predictions are for a wider range of site types than those currently used for monitoring in Sydney, and they suggest that exceedances may be happening at non-monitoring locations.

The change in the maximum one-hour mean NO_2 concentration at the RWR receptors in the 2021-DS scenario (relative to the 2021-DM scenario) are shown, ranked by change in concentration, in Figure 8-44. There was a general reduction in the distribution of predicted maximum one-hour mean concentration as a result of the M4 East project.

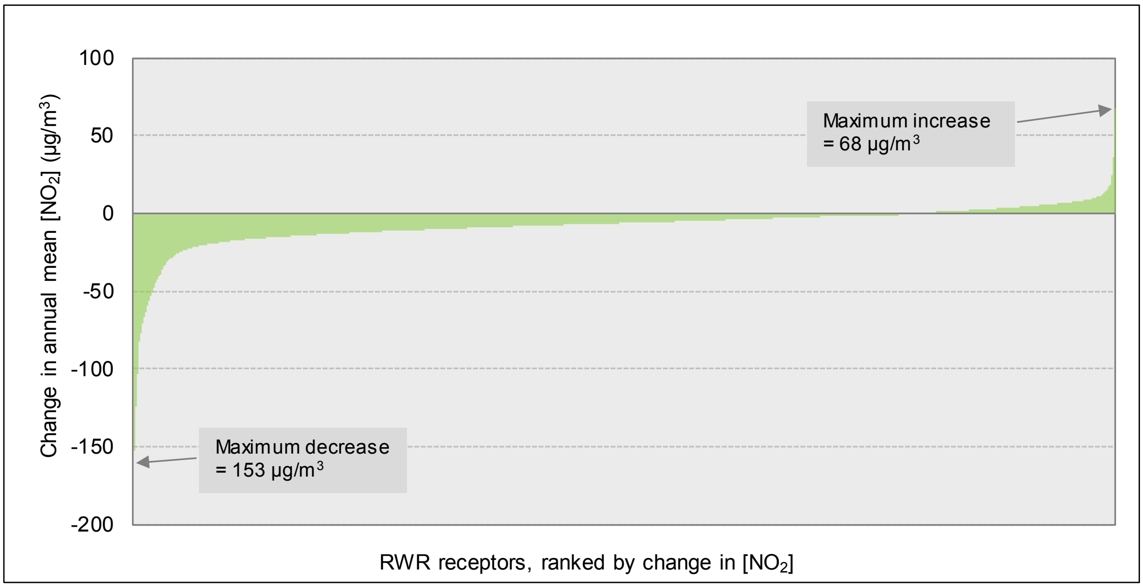

Figure 8-44 Changes in maximum one-hour NO_2 at RWR receptors (2021-DS)

Contour plots

Contour plots of maximum one-hour NO_2 concentrations in 2021 are provided for the Do Minimum scenario in Figure 8-45, and for the Do Something scenario in Figure 8-46. It is important to note that these maps do not represent a particular time period; each point in the map is a maximum value for any hour of the year. As with the annual mean, the maximum one-hour concentrations are clearly the highest along the axes of major roads, and in the west of the domain.

The contour plot for the change in the maximum on-hour NO_2 concentration with the project in 2021 is given in Figure 8-47. This shows substantial reductions in the maximum one-hour NO_2 concentration along Parramatta Road.

The equivalent plots for 2031 are presented in Appendix K.

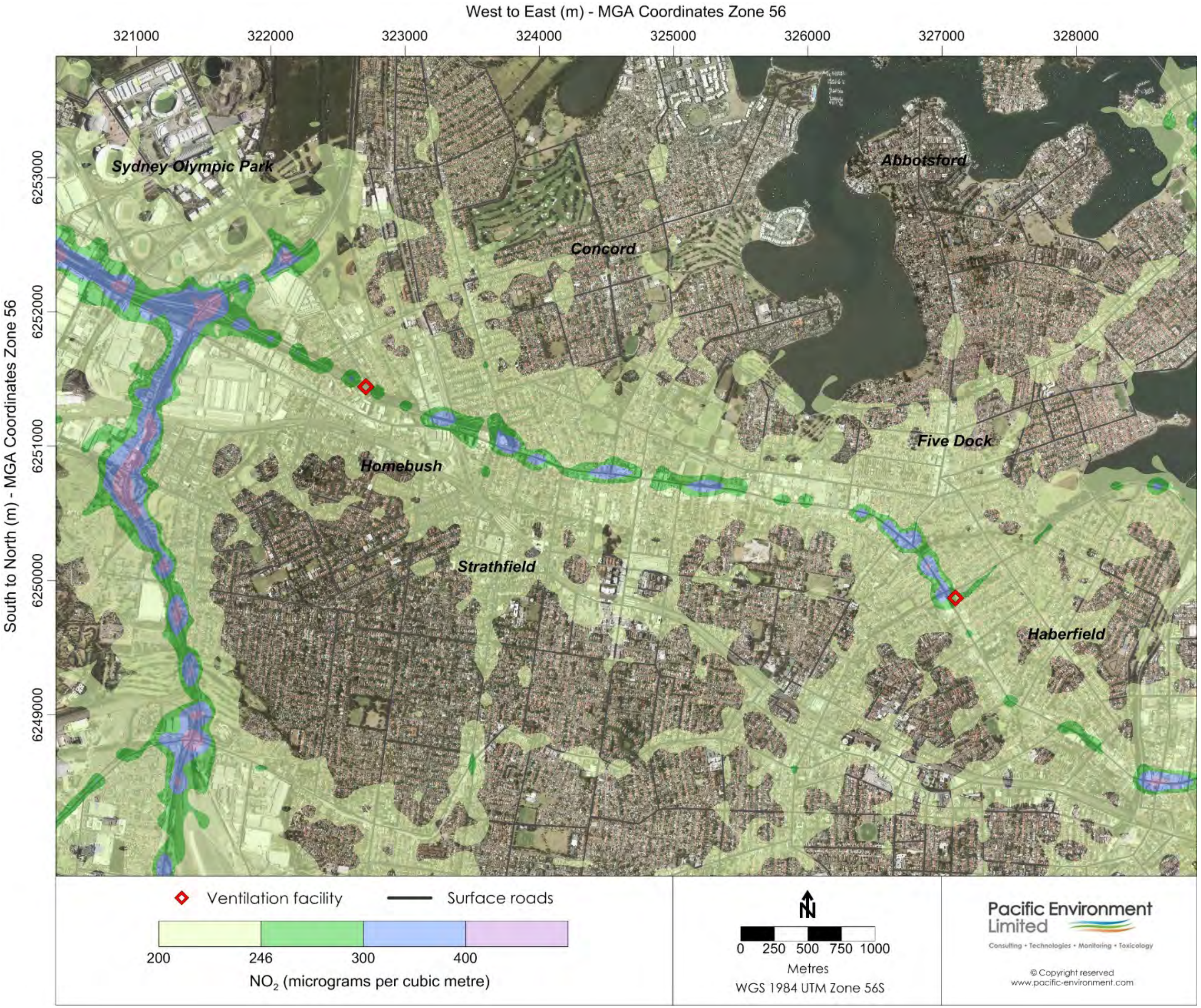

Figure 8-45 Contour plot showing maximum one-hour NO_2 (2021-DM)

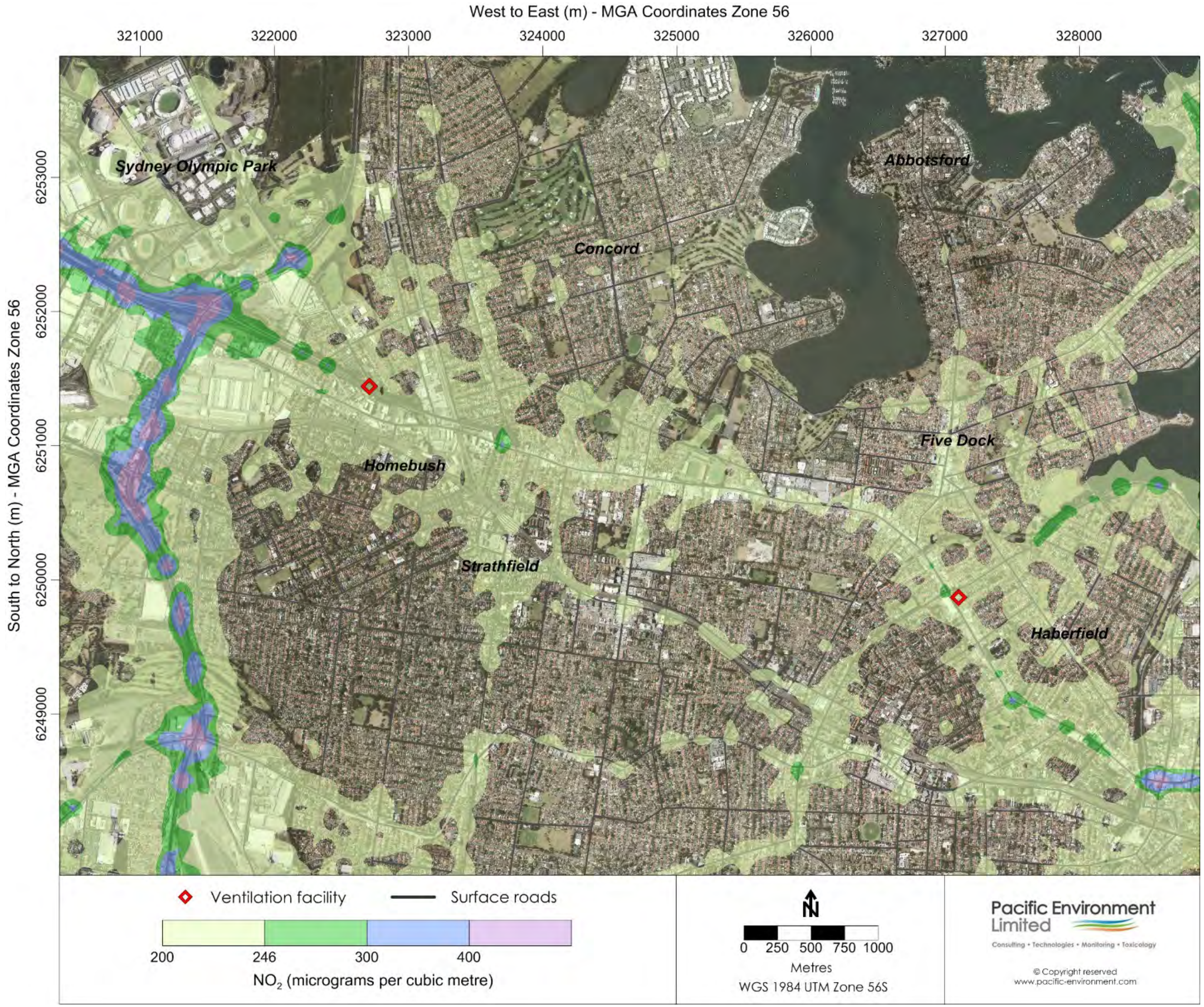

Figure 8-46 **Contour plot showing maximum one-hour NO_2 (2021-DS)**

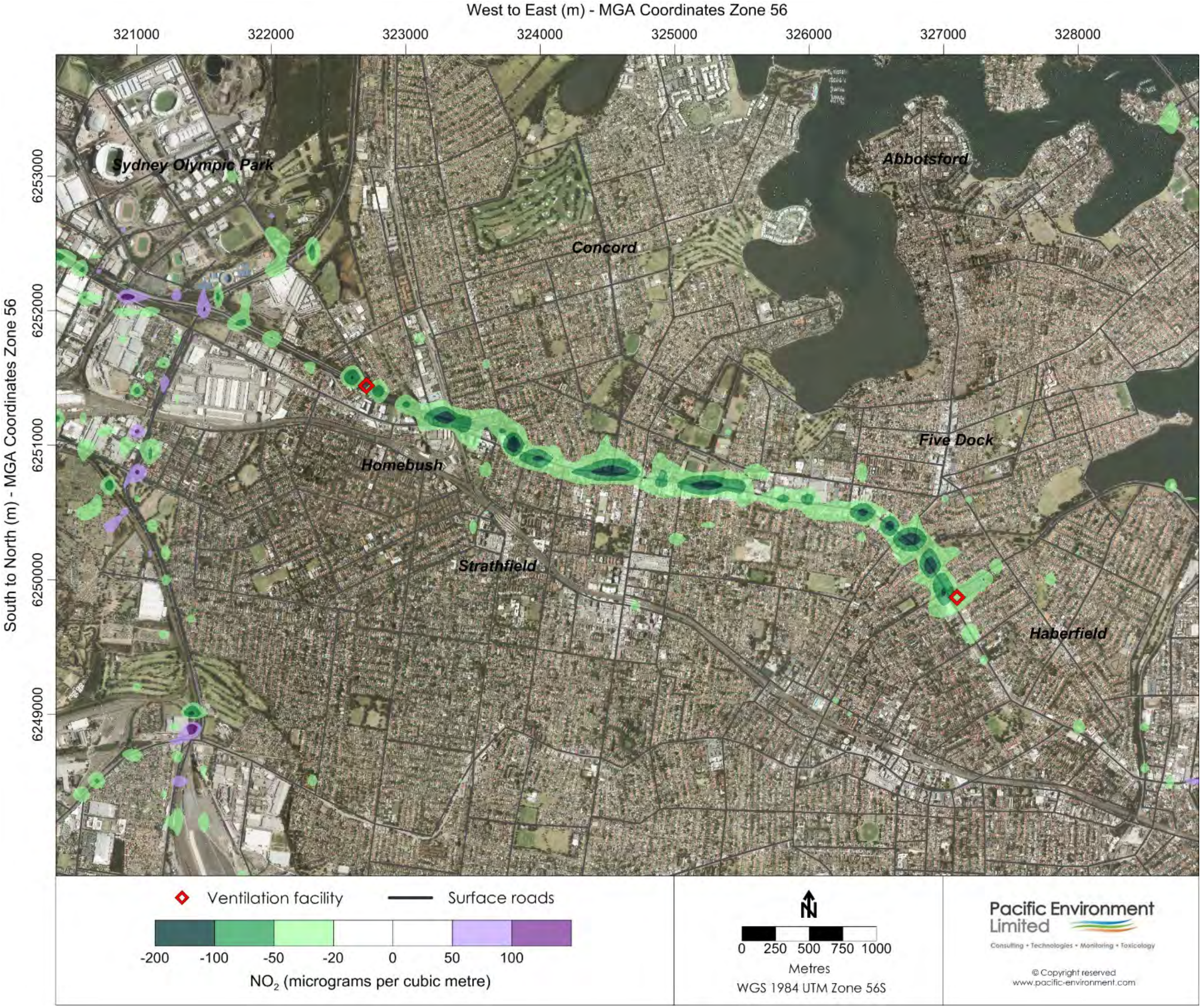

Figure 8-47 **Contour plot showing change in maximum one-hour NO_2 with the project (2021-DS)**

8.4.5 PM_{10} (annual mean)

Results for community receptors

The annual mean PM_{10} concentrations at the 31 community receptors with the project in 2021 and 2031 are shown in Figure 8-48. As with NO_2, there was little variation in concentration between the receptors. At all the community receptors the concentration was below 20 µg/m^3, and therefore well below the NSW impact assessment criterion of 30 µg/m^3. PM_{10} concentrations at these receptors – which are near busy roads in Sydney - were only slightly higher than the lowest PM_{10} standard in the literature (18 µg/m^3 in Scotland), and lower than the proposed target for NSW of 20 µg/m^3.

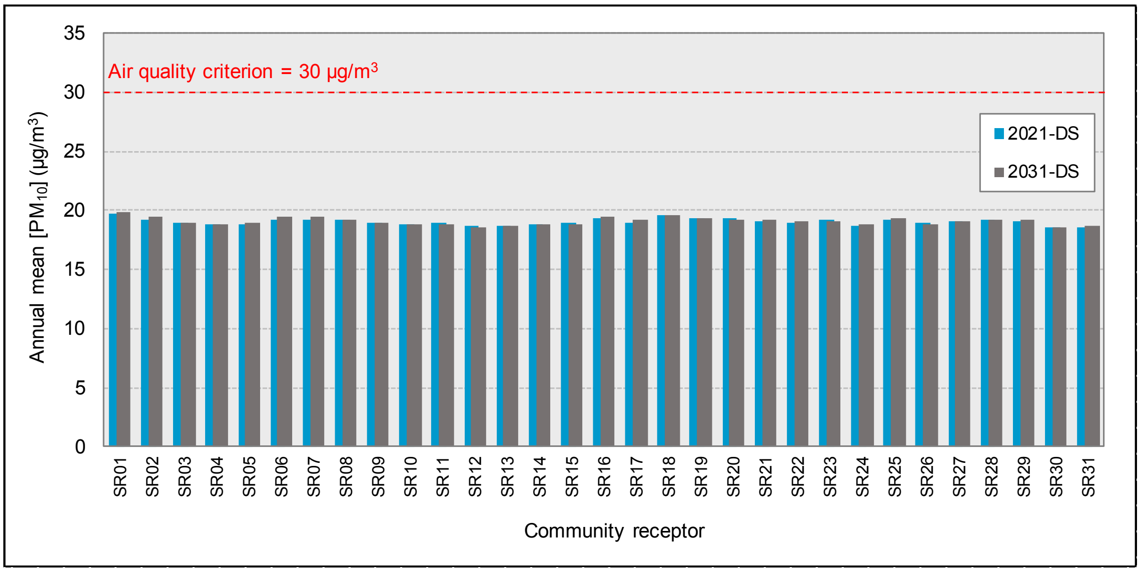

Figure 8-48 Annual mean PM_{10} at community receptors (2021-DS and 2031-DS)

The concentrations in the 2021-DS scenario were again dominated by the background (Figure 8-49), with a small contribution from roads (0.7-1.7 µg/m^3) and a negligible contribution from ventilation outlets.

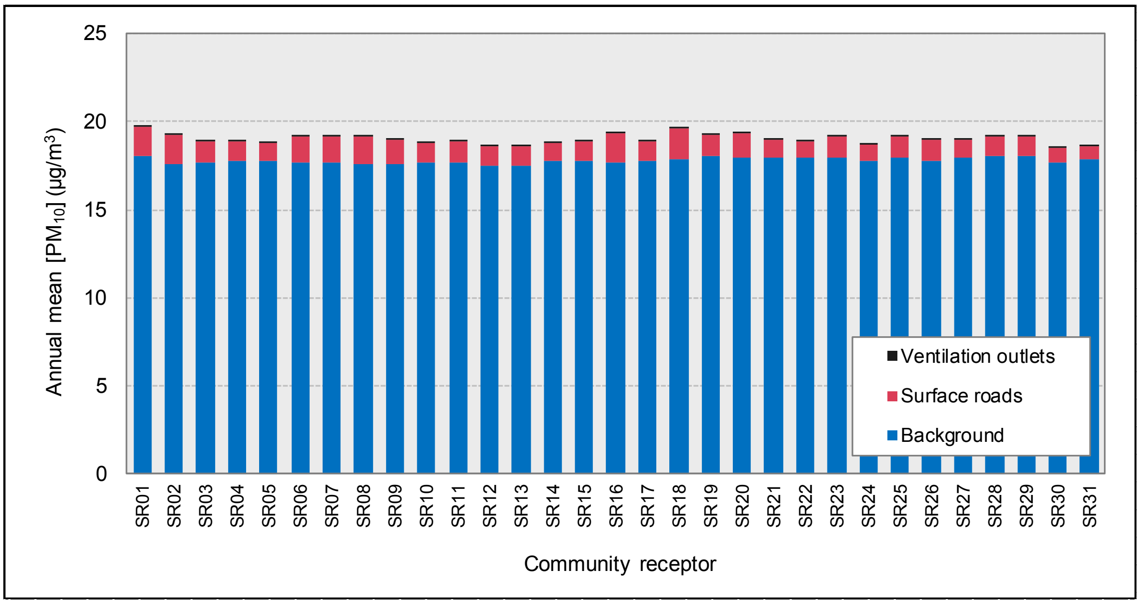

Figure 8-49 Source contributions to annual mean PM_{10} at community receptors (2021-DS)

Figure 8-50 shows the changes in concentration in the Do Something scenarios relative to the Do Minimum scenarios for the community receptors. Small increases in concentration were predicted for some receptors, but decreases were predicted for most.

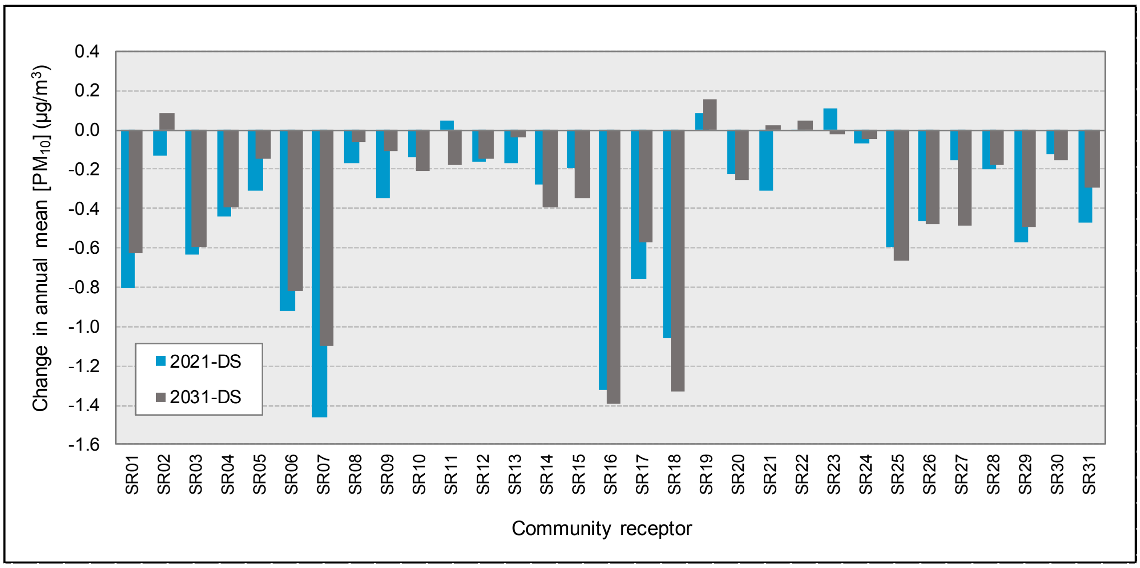

Figure 8-50 Change in annual mean PM_{10} at community receptors (2021-DS and 2031-DS)

Results for RWR receptors

The ranked annual mean PM_{10} concentrations at the RWR receptors in the 2021-DS scenario are shown in Figure 8-51. The concentration at the majority of receptors was below 20 µg/m^3, and concentrations at all receptors were well below the NSW assessment criterion of 30 µg/m^3. The highest predicted concentration at any receptor in this scenario was 22.3 µg/m^3, but as with other pollutants and metrics the highest values were only predicted for a small proportion of receptors. The surface road contribution was between 0.6 µg/m^3 and 4.2 µg/m^3. The largest contribution from tunnel ventilation outlets was just 0.06 µg/m^3 in 2021-DS (0.07 µg/m^3 in 2031-DS).

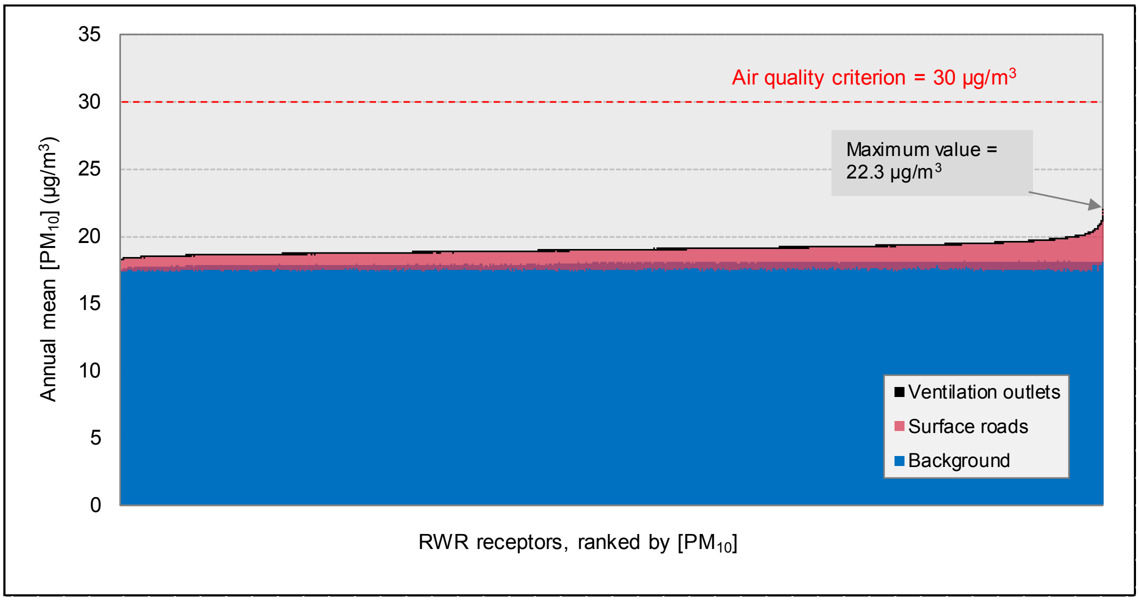

Figure 8-51 Source contributions to annual mean PM_{10} at RWR receptors (2021-DS)

The change in the annual mean PM_{10} concentration at the RWR receptors in the 2021-DS scenario (relative to the 2021-DM scenario) are shown, ranked by change in concentration, in Figure 8-52. Once again, there was a marked reduction in the predicted annual mean concentration along the project corridor as a result of the project, with substantial reductions at a large number of locations. There was an increase in PM_{10} at 16 per cent of the receptors, although the increase was greater than 0.5 $\mu g/m^3$ for only five of the 10,154 receptors. The largest predicted increase in concentration at any receptor as a result of the project in 2021 was 0.7 $\mu g/m^3$, and the largest predicted decrease was 2.8 $\mu g/m^3$.

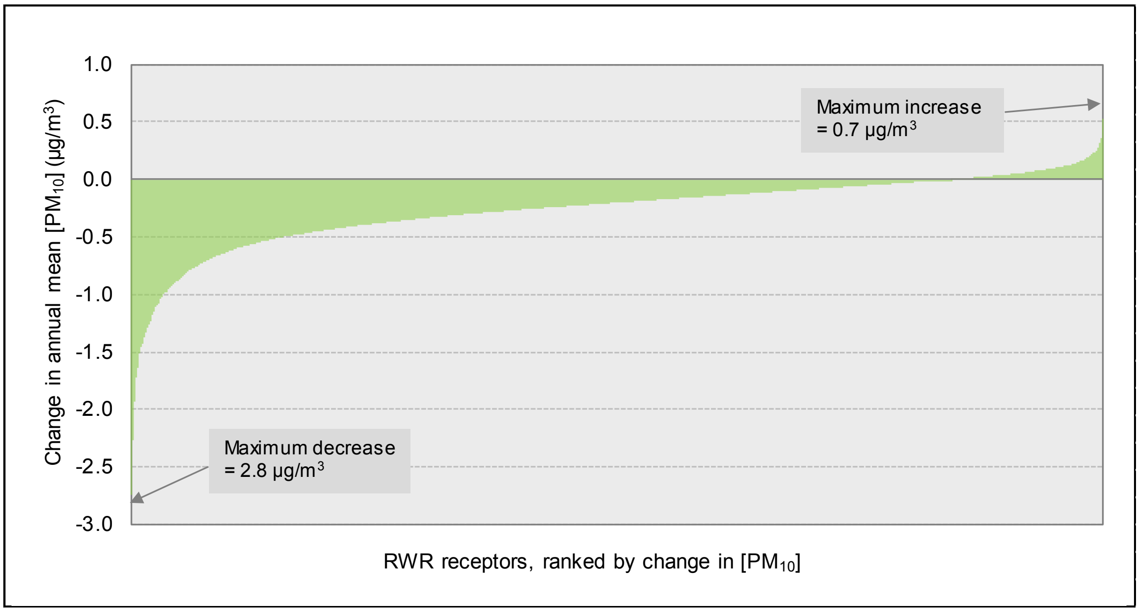

Figure 8-52 Changes in annual mean PM_{10} at RWR receptors (2021-DS)

The corresponding plots for the 2031-DS scenario are given in Appendix K.

Contour plots

The contour plots for annual mean PM_{10} in 2021 are given in Figure 8-53, Figure 8-54 and Figure **8-55**. These show a fairly even distribution across the domain, reflecting the homogenous nature of background concentrations (see Appendix F, Figure F-4) and the relatively small contribution from road traffic. Slightly elevated concentrations are evident along the major road corridors. The contour plot for the change in concentration with the project in 2021 (Figure **8-55**) shows small reductions in annual mean PM_{10} along Parramatta Road.

The equivalent plots for 2031 are presented in Appendix K.

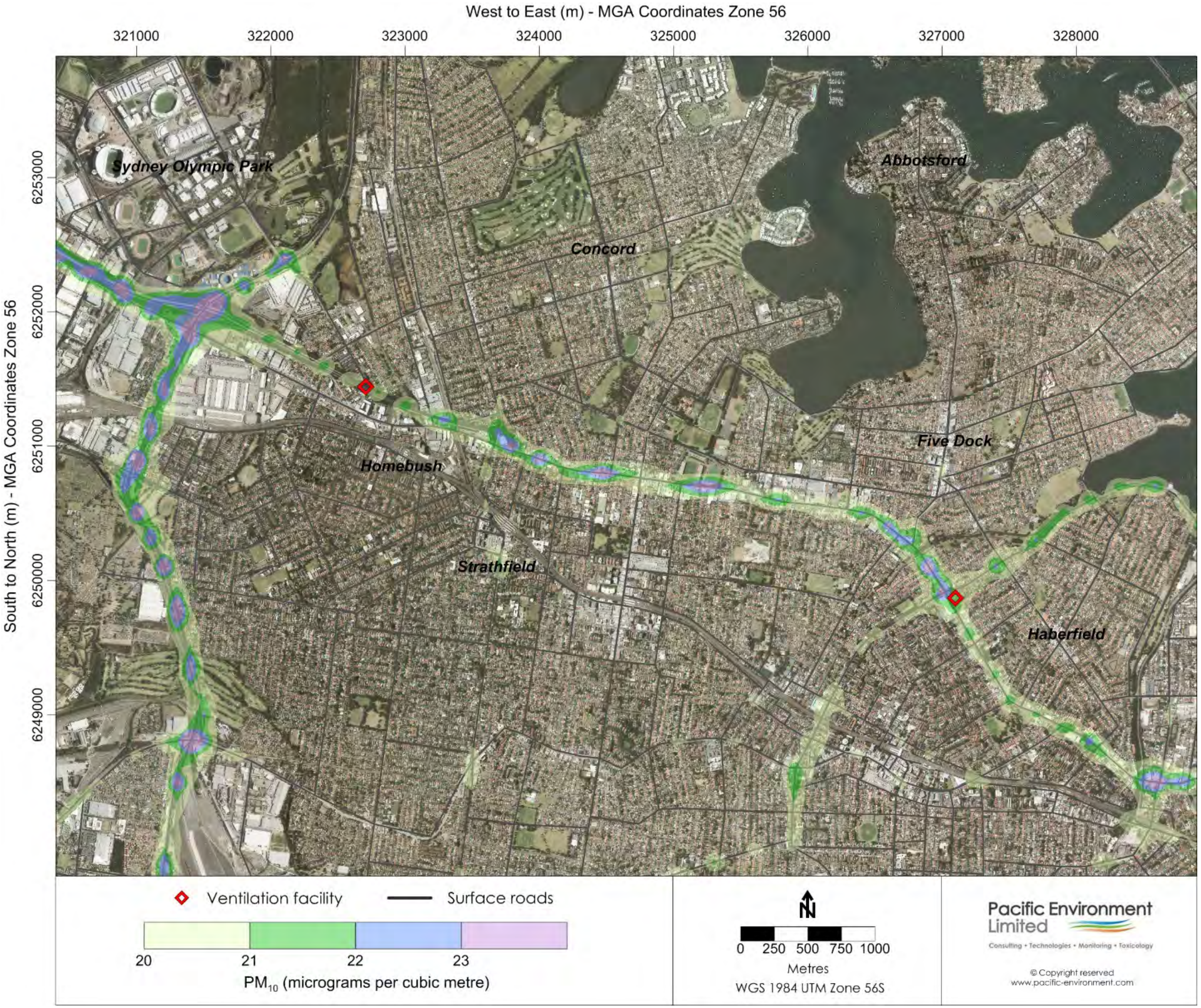

Figure 8-53 Contour plot showing annual mean PM_{10} (2021-DM)

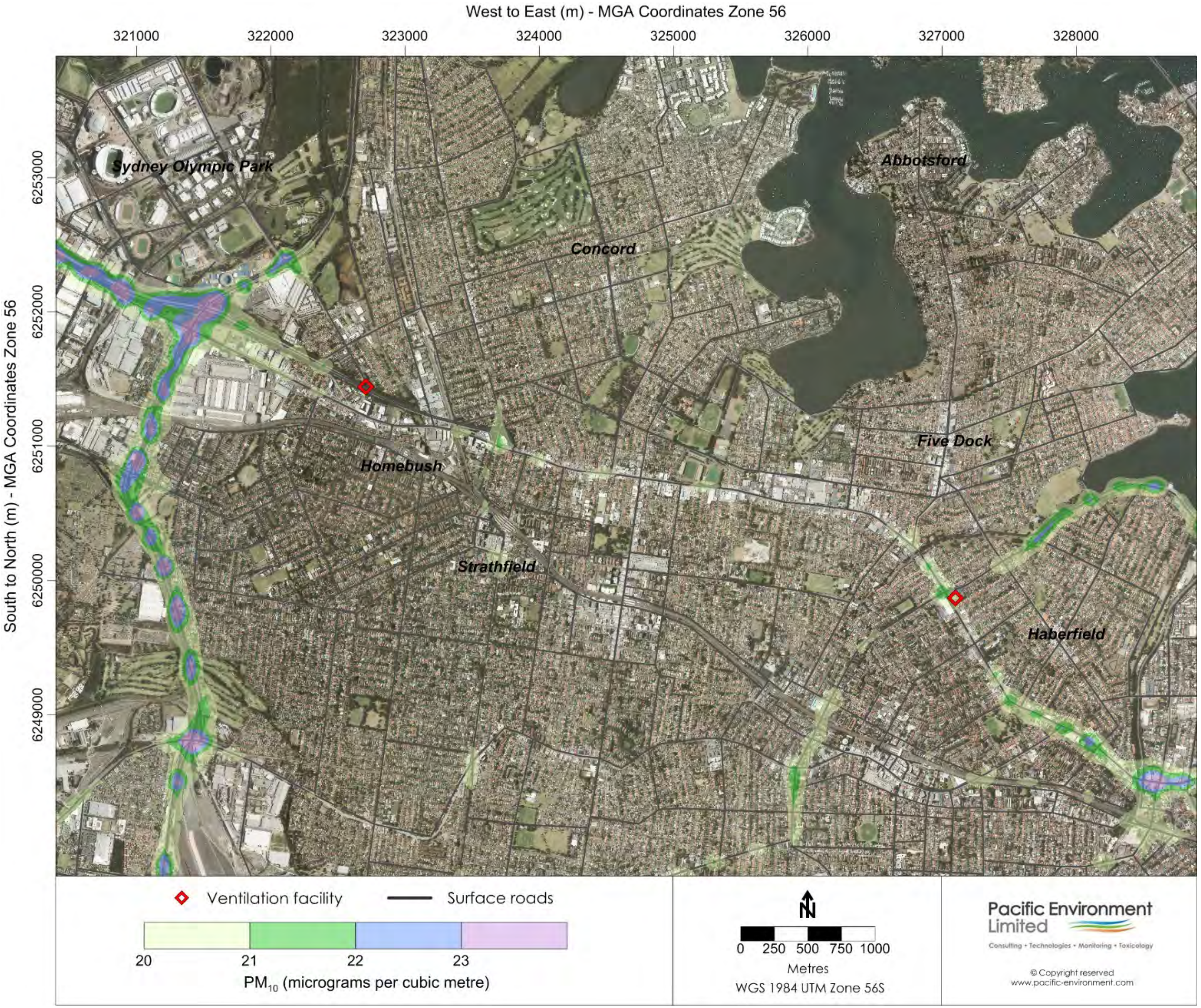

Figure 8-54 Contour plot showing annual mean PM_{10} (2021-DS)

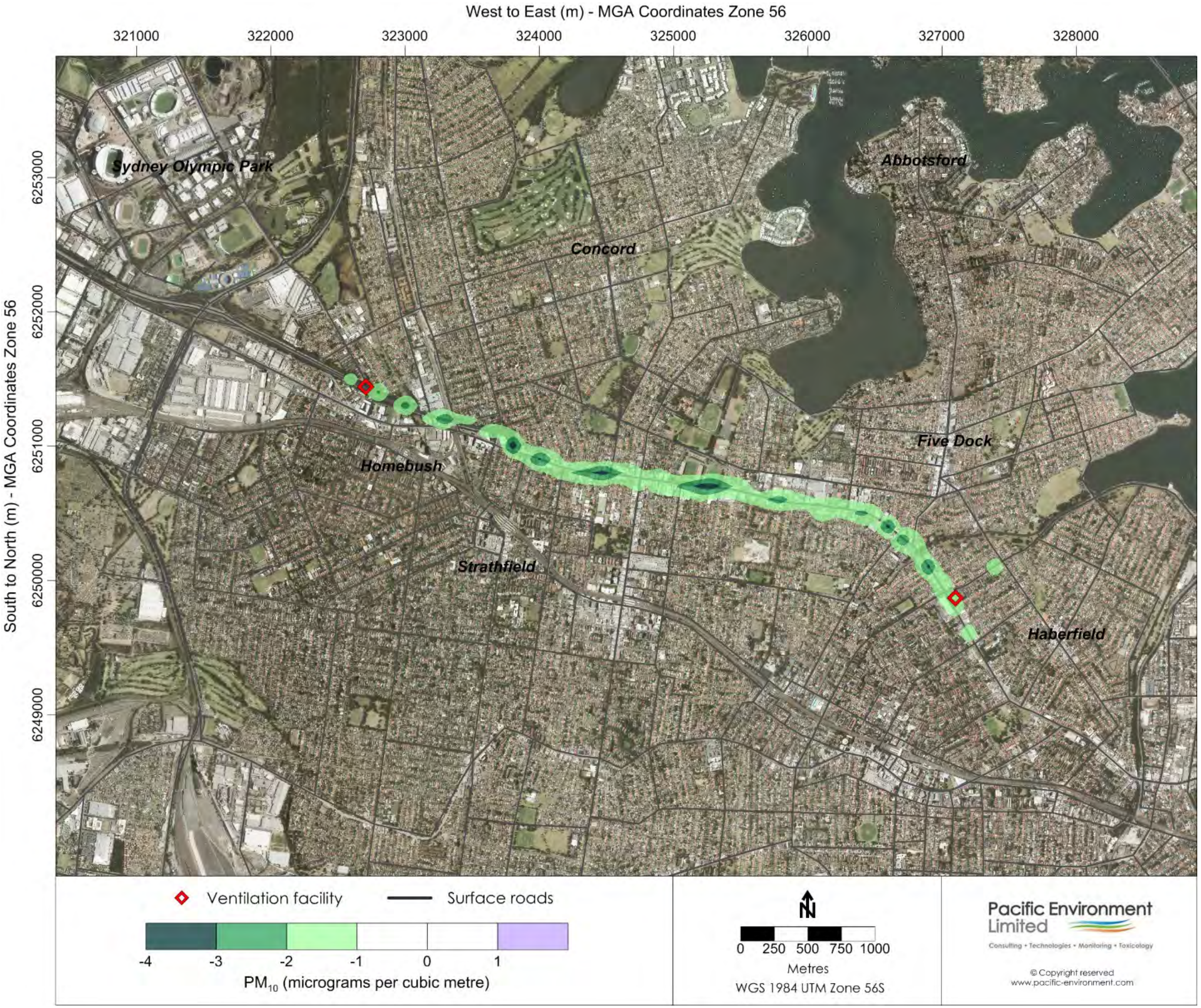

Figure 8-55 **Contour plot showing change in annual mean PM_{10} with the project (2021-DS)**

8.4.6 PM_{10} (maximum 24-hour mean)

Results for community receptors

The maximum 24-hour mean PM_{10} concentrations at the 31 community receptors with the project in 2021 and 2031 are shown in Figure 8-56. At all receptor locations the maximum concentration was below - but close to - the NSW impact assessment criterion of 50 µg/m^3, which is also the most stringent standard in force internationally. At all receptors the maximum total 24-hour concentration occurred on one of only two days of the year (10 February or 31 October), and coincided with the two highest 24-hour background concentrations in the synthetic PM_{10} profile (44.5 and 45.2 µg/m^3). This provided support for the use of a maximum or high percentile value as the background for the RWR receptors across the M4 East GRAL domain (see section 8.4.8).

The surface road contribution to the maximum 24-hour PM_{10} concentration at each receptor was small (generally <2 µg/m^3), as shown in Figure 8-57. The tunnel ventilation outlet contributions were negligible (<0.2 µg/m^3).

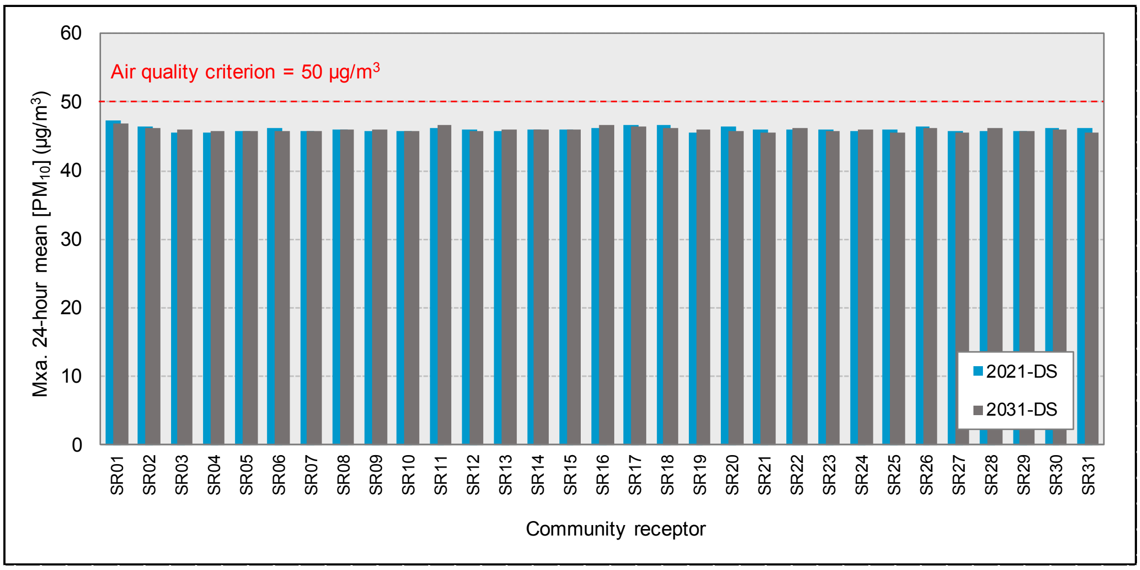

Figure 8-56 Maximum 24-hour PM_{10} at community receptors (2021-DS and 2031-DS)

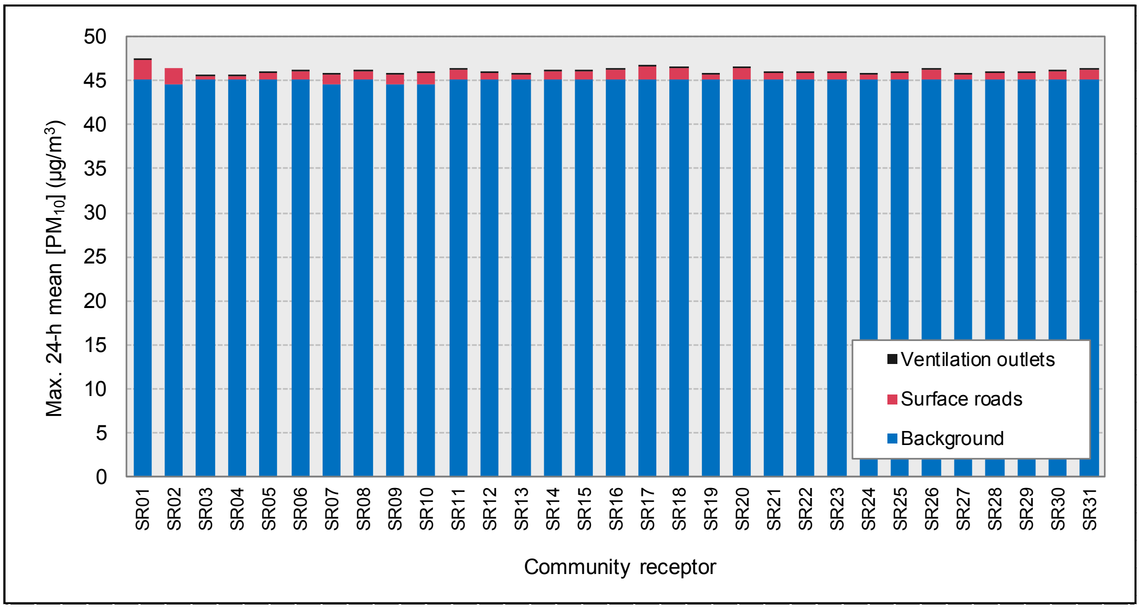

Figure 8-57 Source contributions to maximum 24-hour PM_{10} at community receptors (2021-DS)

Figure 8-58 shows the changes in concentration in the Do Something scenarios relative to the Do Minimum scenarios for the community receptors. The changes were generally small (<2 µg/m^3). Small increases in concentration were predicted with the project for some receptors in 2021 and 2031.

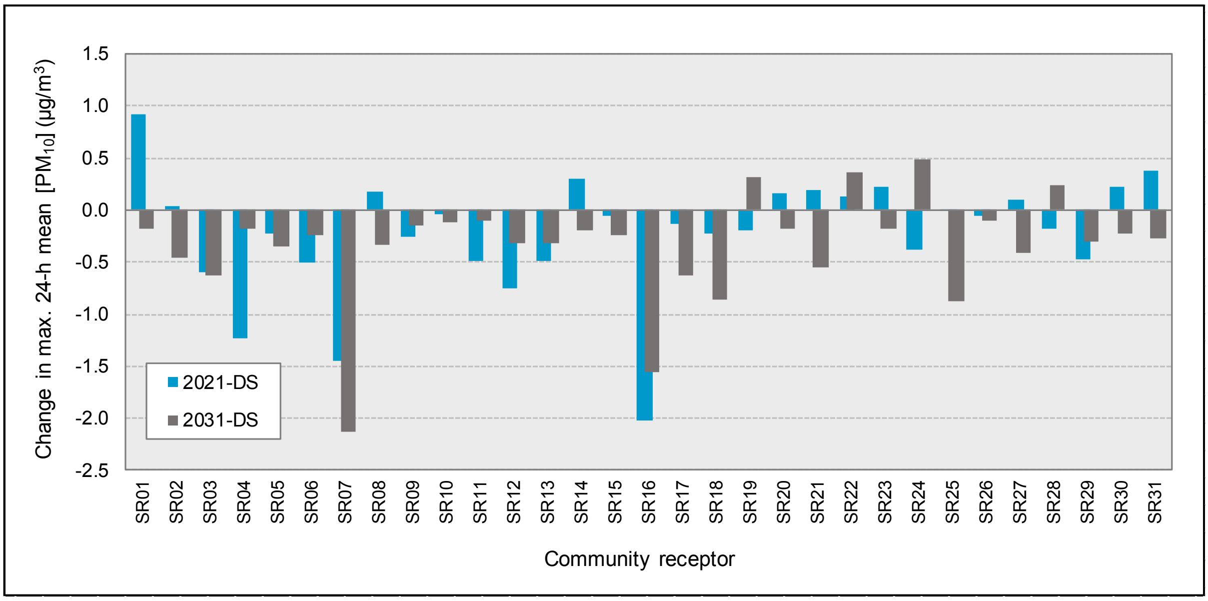

Figure 8-58 Change in maximum 24-hour PM$_{10}$ at community receptors (2021-DS and 2031-DS)

Results for RWR receptors

The ranked maximum 24-hour mean PM$_{10}$ concentrations at the RWR receptors in the 2021-DS scenario are shown in Figure 8-59. Results for RWR receptors were highly dependent on assumption for the background. The concentration at the majority of receptors was below the NSW impact assessment criterion of 50 µg/m^3. The proportion of receptors with a concentration above the criterion decreased from 0.9 per cent in the 2021 Do Minimum scenario to 0.1 per cent with the project. The contributions of surface roads and ventilation outlets were not additive. The maximum contribution of tunnel outlets at any receptor was only 0.37 µg/m^3 in 2021 (0.42 µg/m^3 in 2031).

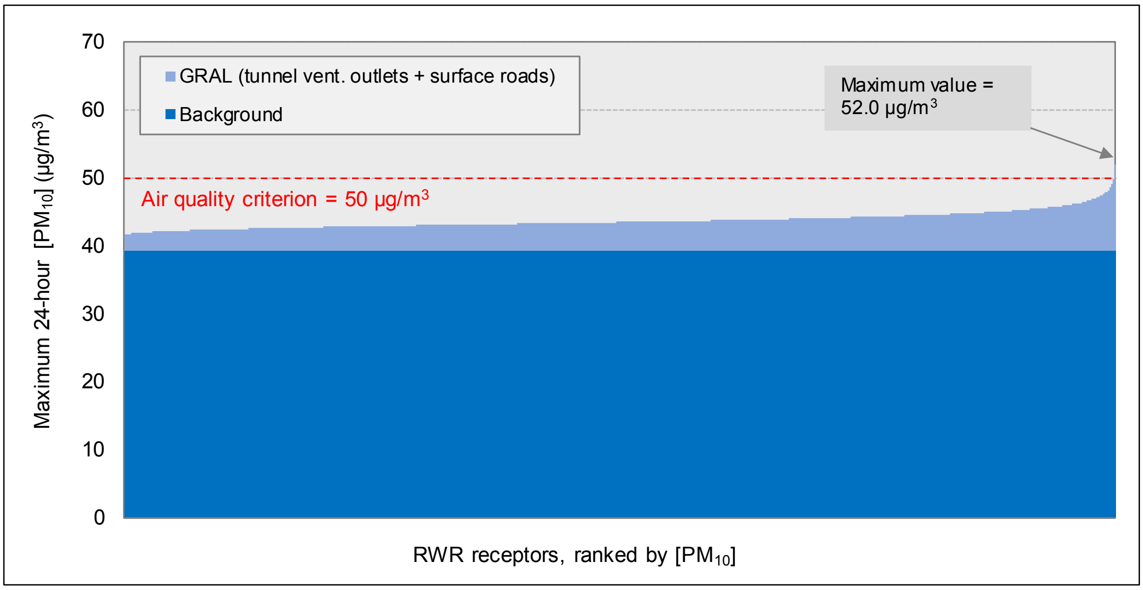

Figure 8-59 Source contributions to maximum 24-hour PM$_{10}$ at RWR receptors (2021-DS)

The changes in the maximum 24-hour mean PM_{10} concentration with the project in 2021 are ranked by change in concentration, in Figure 8-60. The same reduction in predicted concentrations along the project corridor is apparent. There was an increase in the maximum 24-hour PM_{10} at 21 per cent of the receptors, although the increase was greater than 2 µg/m^3 for only 0.3 per cent of receptors. The largest predicted increase in concentration at any receptor as a result of the project was 4.8 µg/m^3, and the largest predicted decrease was 10.6 µg/m^3.

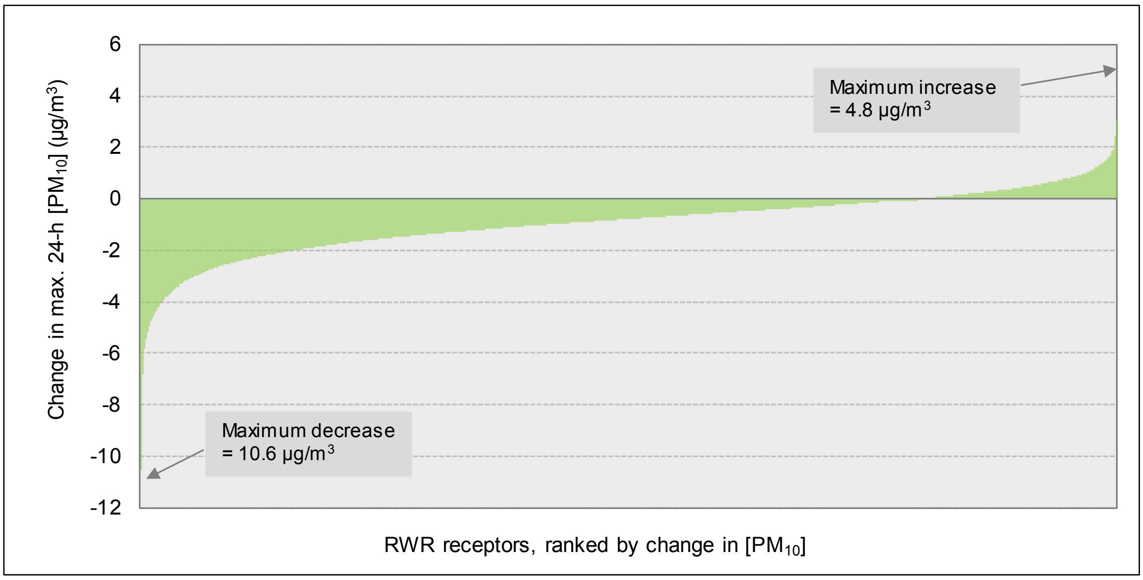

Figure 8-60 Changes in maximum 24-hour PM_{10} at RWR receptors (2021-DS)

Contour plots

The contour plots for maximum 24-hour average PM_{10} in 2021 are given in Figure 8-61, Figure 8-54 and Figure **8-63**. These show a fairly even distribution across the domain, reflecting the homogenous nature of background concentrations (see Appendix F, Figure F-4) and the relatively small contribution from road traffic. Slightly elevated concentrations are evident along the major road corridors.

Figure **8-63** shows the contour plot for the change in maximum 24-hour PM_{10} concentration with the project in 2021. There were reductions of up to 20 per cent of the NSW criterion along some sections of Parramatta Road.

The equivalent plots for 2031 are presented in Appendix K.

Figure 8-61 **Contour plot showing maximum 24-hour average PM$_{10}$ (2021-DM)**

Figure 8-62 Contour plot showing maximum 24-hour average PM_{10} (2021-DS)

Figure 8-63 **Contour plot showing change in maximum 24-hour PM_{10} with the project (2021-DS)**

8.4.7 $PM_{2.5}$ (annual mean)

Results for community receptors

The annual mean $PM_{2.5}$ concentrations at the 31 community receptors with the project in 2021 and 2031 are presented in Figure 8-64. The results are based on an assumed background concentration of 8 µg/m^3 (the AAQ NEPM advisory reporting standard), and therefore the Figure shows exceedances at all receptors. Clearly there would also be exceedances of the proposed NSW target of 7 µg/m^3. Internationally, there are no standards lower than 8 µg/m^3 for annual mean $PM_{2.5}$. The next lowest is 12 µg/m^3 (California, Scotland).

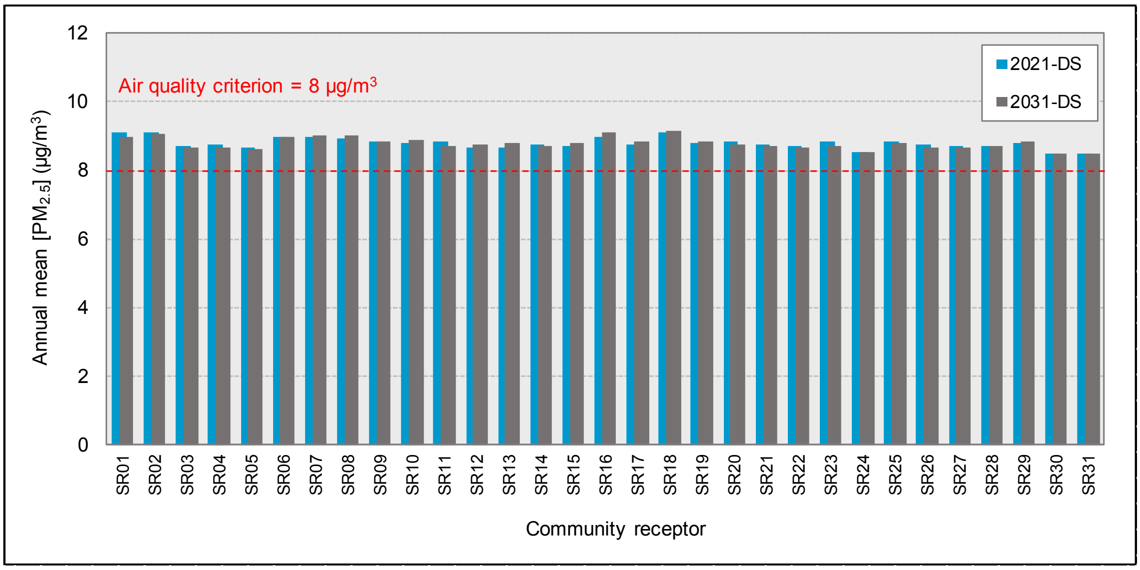

Figure 8-64 **Annual mean $PM_{2.5}$ at community receptors (2021-DS and 2031-DS)**

Figure 8-65 shows that concentrations were again dominated by the background. The surface road contribution was between 0.5 µg/m^3 and 1.1 µg/m^3. The largest contribution from tunnel ventilation outlets was just 0.03 µg/m^3.

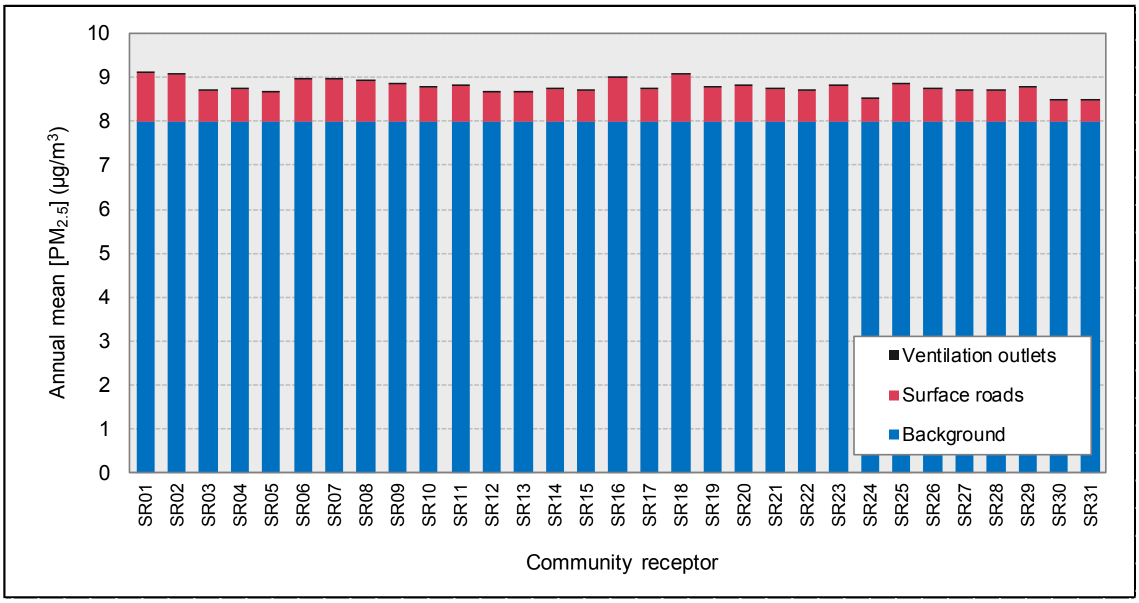

Figure 8-65 **Source contributions to annual mean $PM_{2.5}$ at community receptors (2021-DS)**

Figure 8-66 shows the changes in concentration in the Do Something scenarios relative to the Do Minimum scenarios for the community receptors. Some notable reductions in $PM_{2.5}$ concentrations were predicted at some receptors (up to around 0.9 µg/m^3). Small increases in concentration with the project were predicted for some receptors.

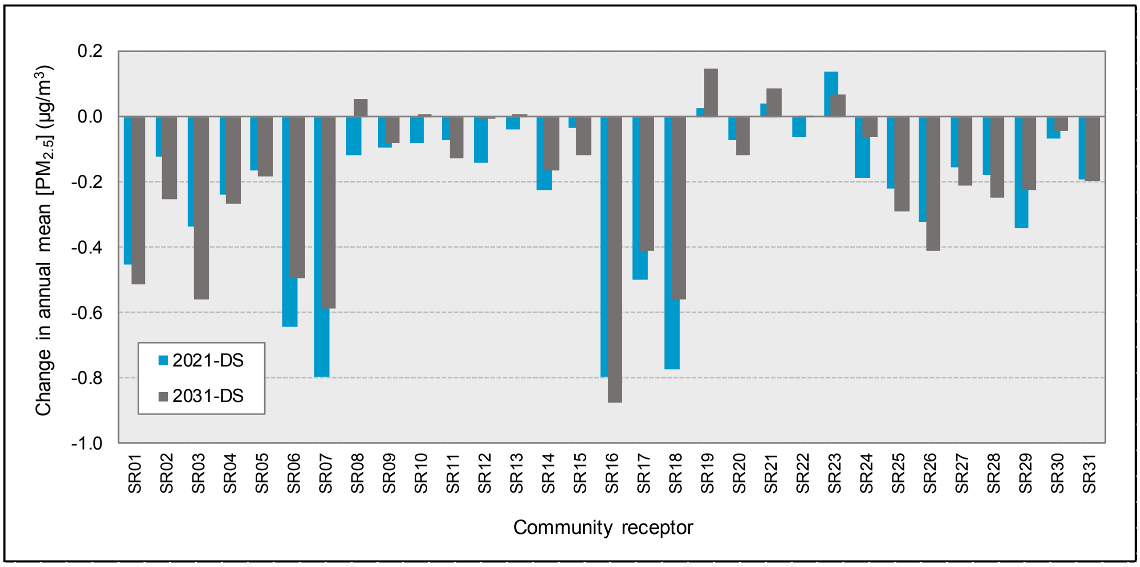

Figure 8-66 **Change in annual mean $PM_{2.5}$ at community receptors (2021-DS and 2031-DS)**

Results for RWR receptors

The ranked annual mean $PM_{2.5}$ concentrations at the RWR receptors in the 2021-DS scenario are shown in Figure 8-67, including the contributions of surface roads and ventilation outlets. As the background concentration was taken to be the same as the NSW criterion of 8 µg/m^3, the concentration at all receptors was above this value. The highest concentration at any receptor in this scenario was 10.8 µg/m^3, but as with other pollutants and metrics the highest values were only predicted for a small proportion of receptors. The surface road contribution was between 0.4 µg/m^3 and 2.8 µg/m^3. The largest contribution from tunnel ventilation outlets in 2021 was 0.04 µg/m^3 (0.05 µg/m^3 in 2031).

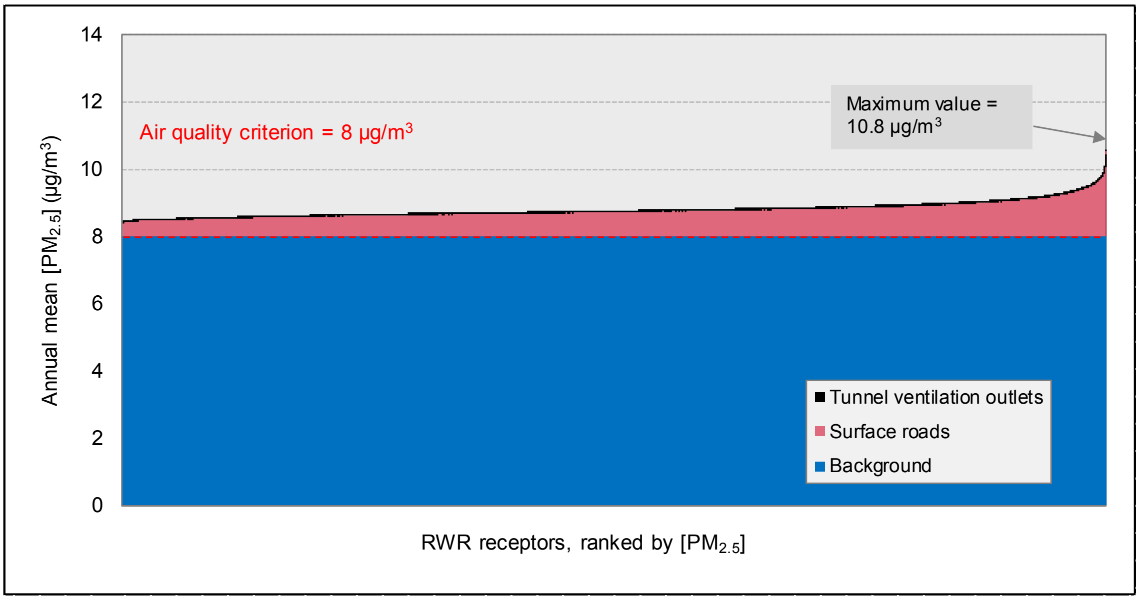

Figure 8-67 **Source contributions to annual mean $PM_{2.5}$ at RWR receptors (2021-DS)**

The change in the annual mean $PM_{2.5}$ concentration at the RWR receptors in the 2021-DS scenario are ranked in Figure 8-68. The pattern here was very similar to that for PM_{10}, with substantial reductions in concentration at a large number of locations. There was an increase in $PM_{2.5}$ at 15 per cent of the receptors, although the increase was greater than 0.2 µg/m^3 for only 0.4 per cent of receptors. The largest predicted increase in concentration at any receptor as a result of the project in 2021 was 0.5 µg/m^3, and the largest predicted decrease was 1.9 µg/m^3.

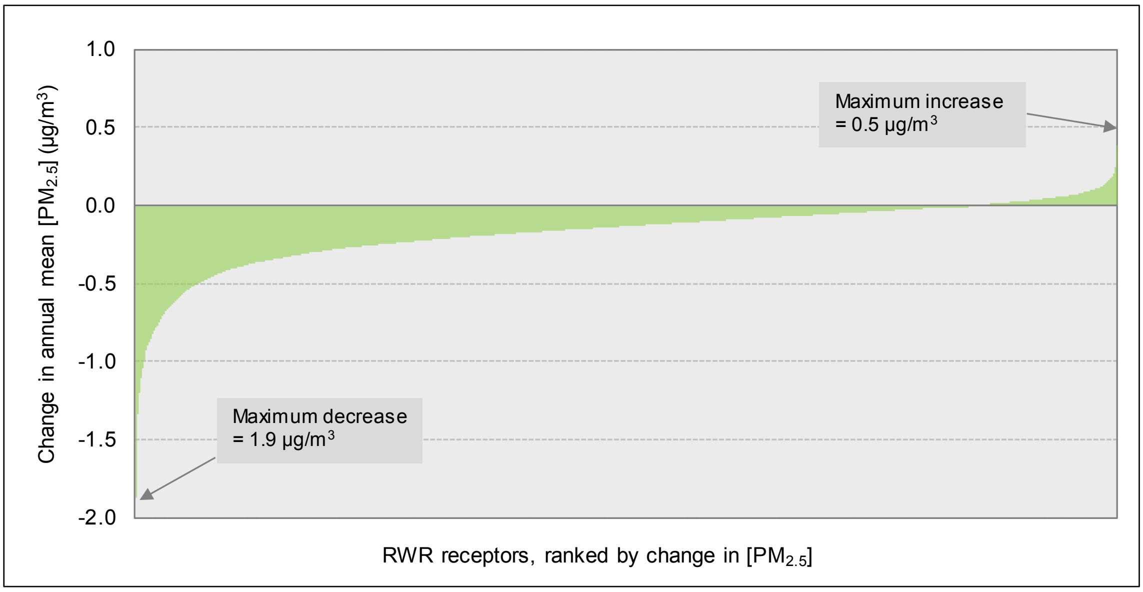

Figure 8-68 **Changes in annual mean $PM_{2.5}$ at RWR receptors (2021-DS)**

The equivalent plots for 2031 are presented in Appendix K.

Contour plots

The contour plots for annual mean $PM_{2.5}$ in 2021 are given in Figure 8-69, Figure 8-70 and Figure **8-71**. These again show a fairly even distribution across the domain, reflecting the homogenous nature of background concentrations and the relatively small contribution from road traffic. The contour plot for the change in concentration with the project in 2021 shows small reductions in annual mean $PM_{2.5}$ along Parramatta Road.

The equivalent plots for 2031 are presented in Appendix K.

Figure 8-69 **Contour plot showing annual mean $PM_{2.5}$ (2021-DM)**

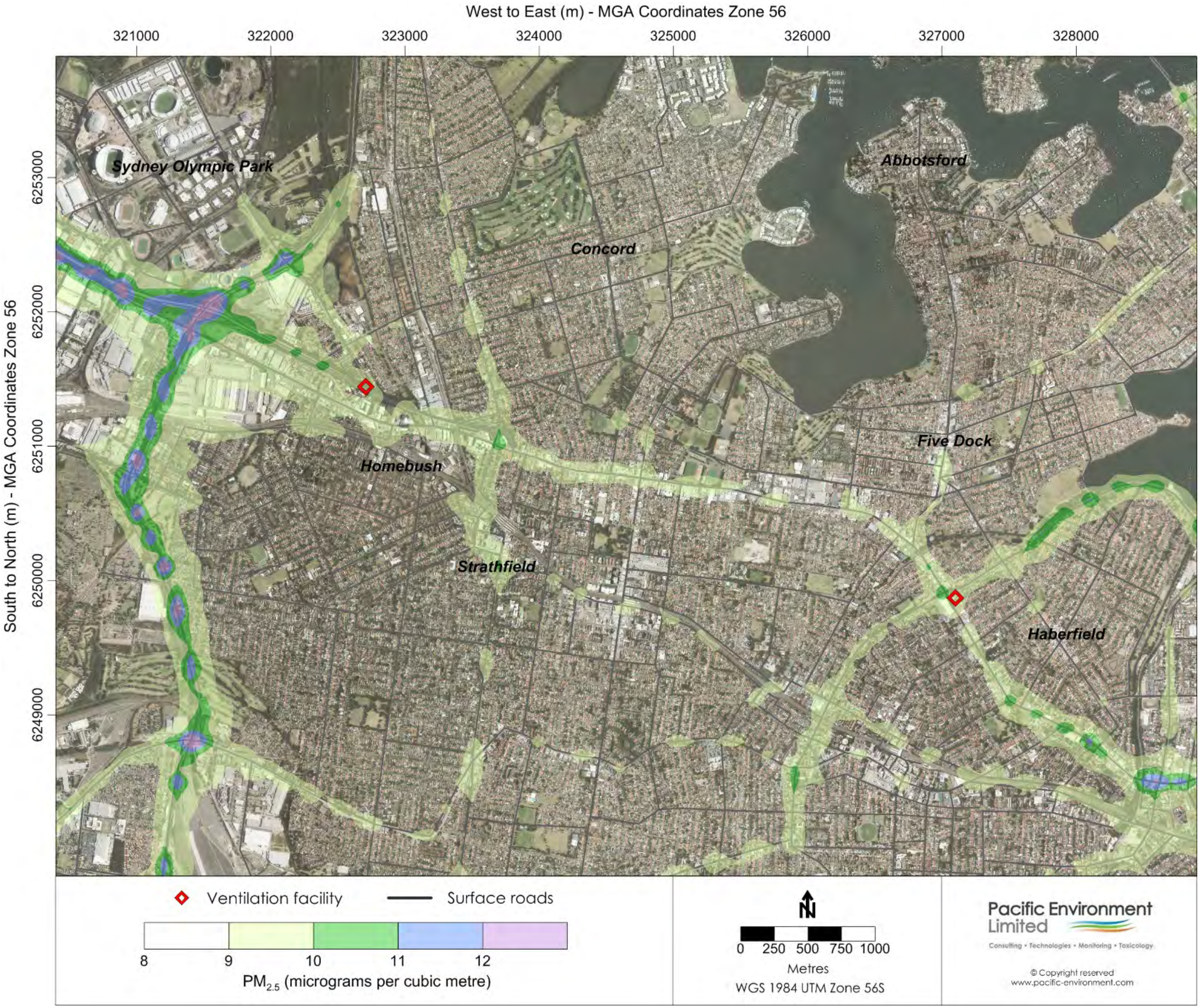

Figure 8-70 Contour plot showing annual mean $PM_{2.5}$ (2021-DS)

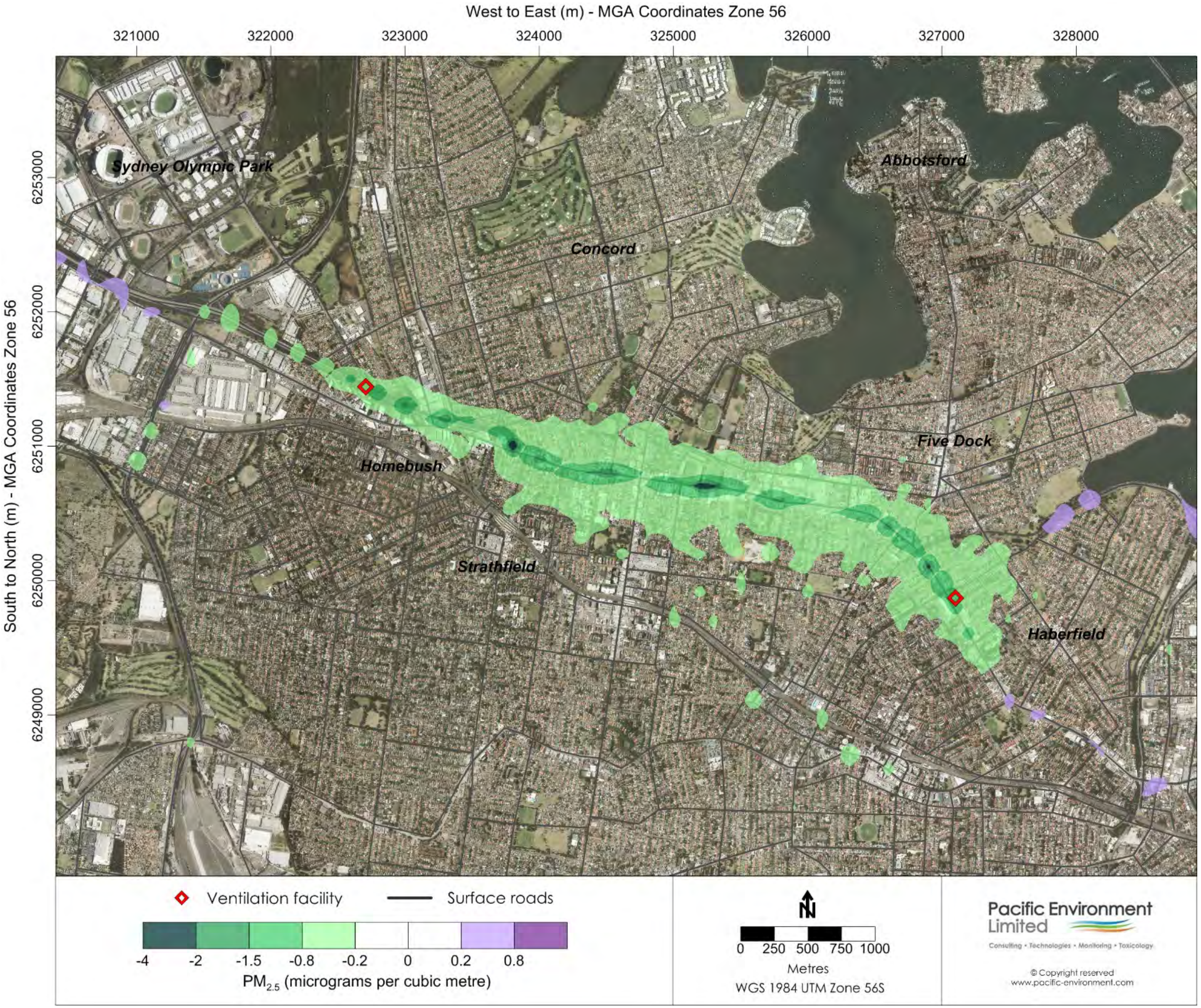

Figure 8-71 **Contour plot showing change in annual mean $PM_{2.5}$ with the project (2021-DS)**

8.4.8 $PM_{2.5}$ (maximum 24-hour mean)

Results for community receptors

The maximum 24-hour mean $PM_{2.5}$ concentrations at the community receptors with the project in 2021 and 2031 are shown in Figure 8-72. At all receptor locations the maximum concentration was below - but close to – the NSW impact assessment criterion of 25 µg/m^3. Internationally, there are no standards lower than 25 µg/m^3 for 24-hour $PM_{2.5}$. However, a target of 20 µg/m^3 is proposed for NSW, and the results suggest that this will be difficult to achieve at present.

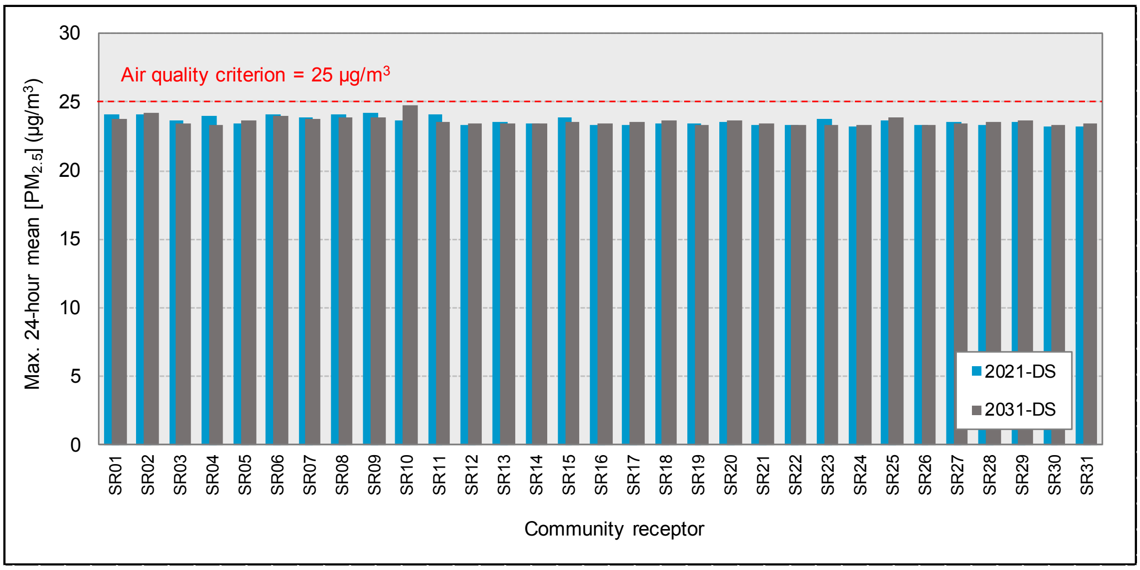

Figure 8-72 Maximum 24-hour mean $PM_{2.5}$ at community receptors (2021-DS and 2031-DS)

At all receptors the maximum total 24-hour concentration occurred on one of two dates (6 August and 12 October), and coincided with the highest 24-hour background concentrations in the synthetic $PM_{2.5}$ profile (21.4 and 23.1 µg/m^3). As with PM_{10}, this provides support for the use of a maximum or high percentile value as the background across the M4 East GRAL domain for the RWR receptors. The road contributions to the maximum 24-hour $PM_{2.5}$ concentration were small (generally <1 µg/m^3), except in a few cases, as shown in Figure 8-73. The outlet contributions were negligible (<0.2 µg/m^3).

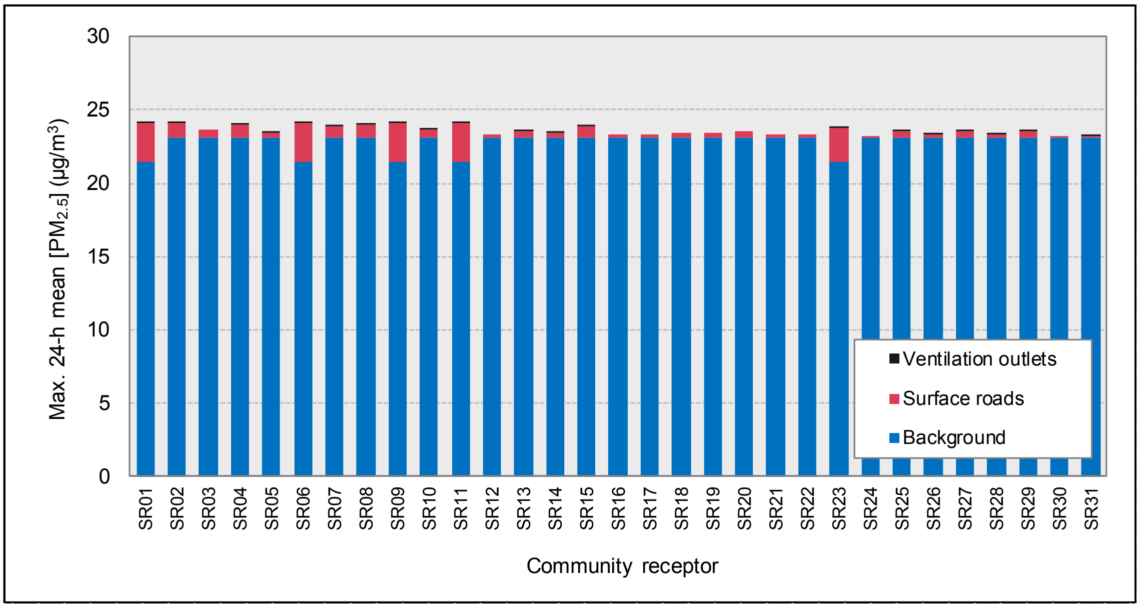

Figure 8-73 Source contributions to maximum 24-hour $PM_{2.5}$ at community receptors (2021-DS)

Figure 8-74 shows the changes in concentration in the Do Something scenarios relative to the Do Minimum scenarios for the community receptors. The changes were generally small (<0.2 µg/m^3), although there were some reductions of up to around 2 µg/m^3 at some receptors. Increases in concentration of up to 0.8 µg/m^3 were predicted with the project for some receptors.

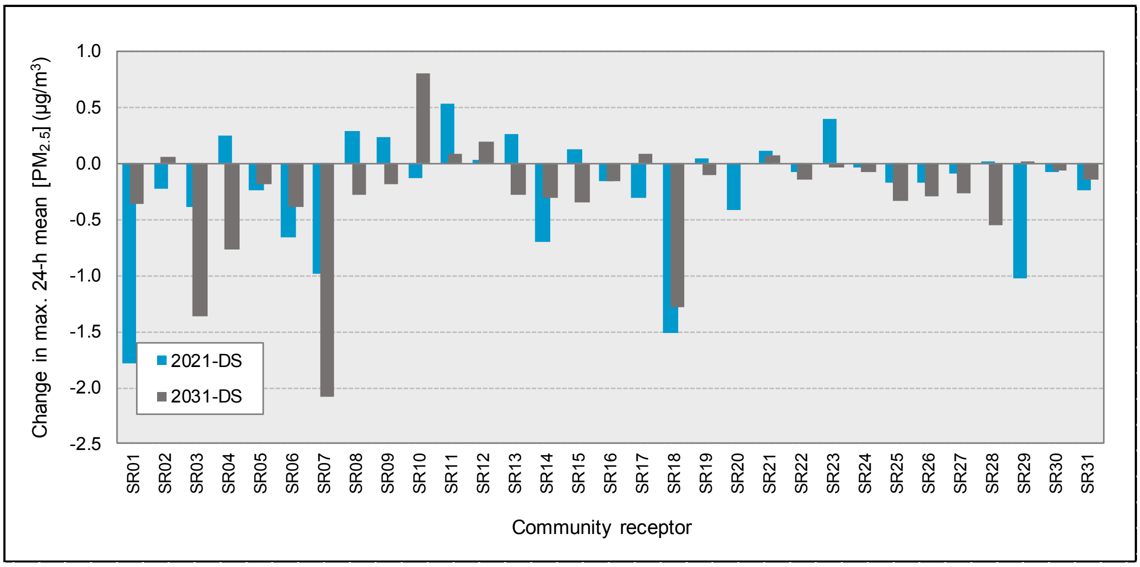

Figure 8-74 Change in maximum 24-hour mean $PM_{2.5}$ at community receptors (2021-DS and 2031-DS)

Results for RWR receptors

The ranked maximum 24-hour mean $PM_{2.5}$ concentrations at the RWR receptors in the 2021-DS scenario are shown in Figure 8-75. The concentration at the majority of receptors was below the NSW impact assessment criterion of 25 µg/m^3. In 2021 the proportion of receptors with a concentration above the criterion decreased from 2.5 per cent in the Do Minimum scenario to 0.5 per cent with the project. As with PM_{10}, the contributions of surface roads and ventilation outlets are not shown separately as these were not additive. The maximum contribution of tunnel outlets at any receptor in 2021 was only 0.25 µg/m^3 in 2021 (0.30 µg/m^3 in 2021).

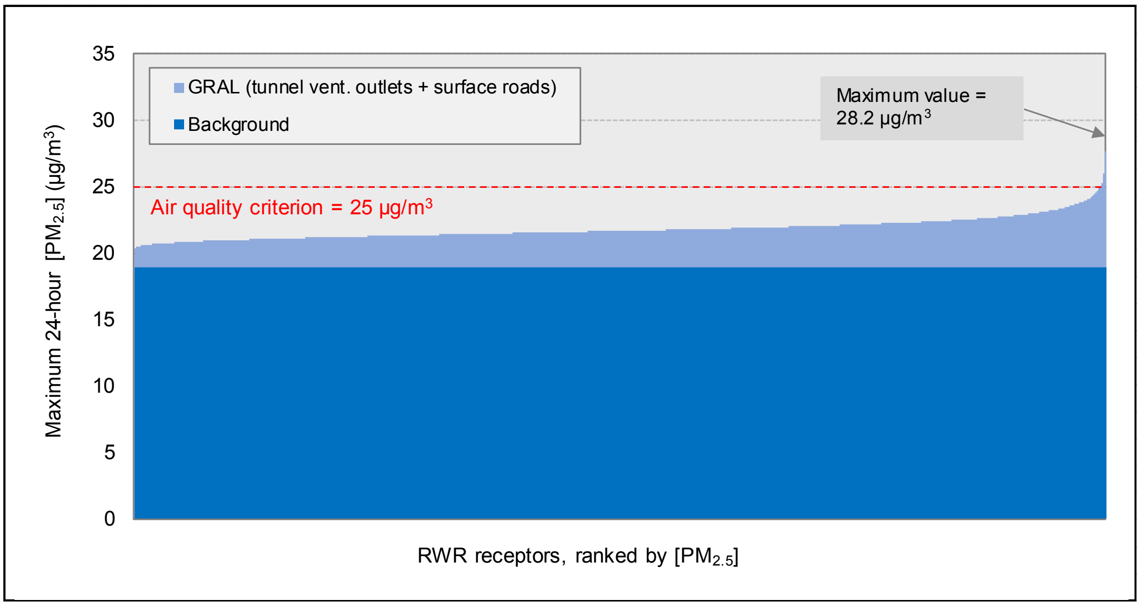

Figure 8-75 Source contributions to maximum 24-hour $PM_{2.5}$ at RWR receptors (2021-DS)

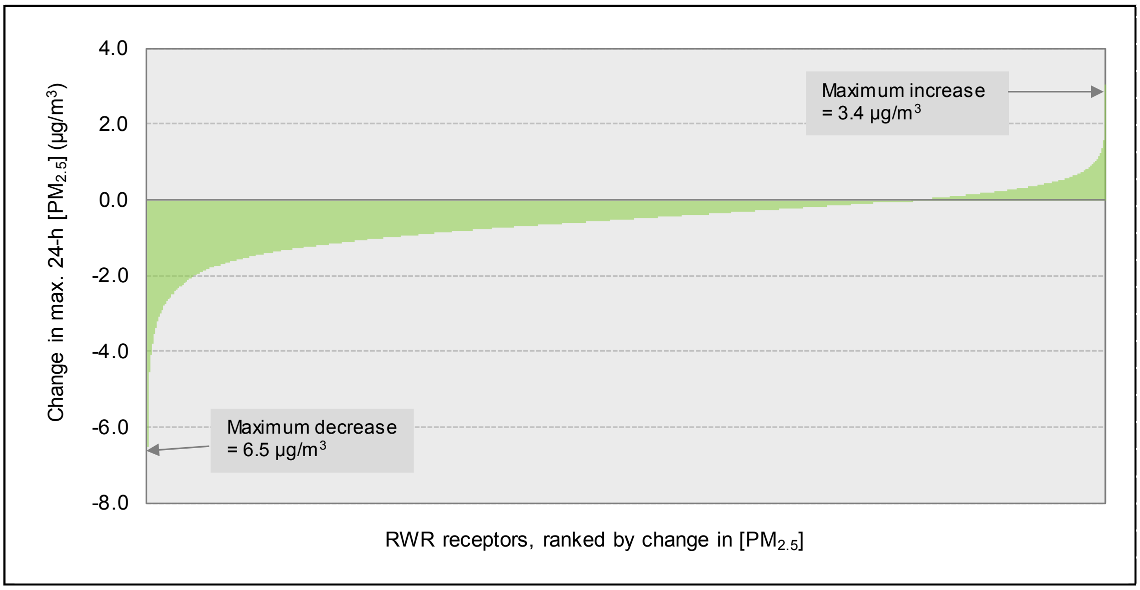

Figure 8-76 Changes in maximum 24-hour $PM_{2.5}$ at RWR receptors (2021-DS)

Contour plots

The contour plots for maximum 24-hour $PM_{2.5}$ in 2021 are given in Figure 8-77, Figure 8-54 and Figure **8-79**. These show a fairly even distribution across the domain, reflecting the homogenous nature of background concentrations (see Appendix F) and the relatively small contribution from road traffic. Slightly elevated concentrations are evident along the major road corridors.

Figure **8-79** shows the contour plot for the change in maximum 24-hour $PM_{2.5}$ concentration with the project in 2021. There were reductions of up to 20 per cent of the NSW criterion in the maximum concentration along some sections of Parramatta Road.

The equivalent plots for 2031 are presented in Appendix K.

Figure 8-77 Contour plot showing maximum 24-hour average $PM_{2.5}$ (2021-DM)

Figure 8-78 **Contour plot showing maximum 24-hour average $PM_{2.5}$ (2021-DS)**

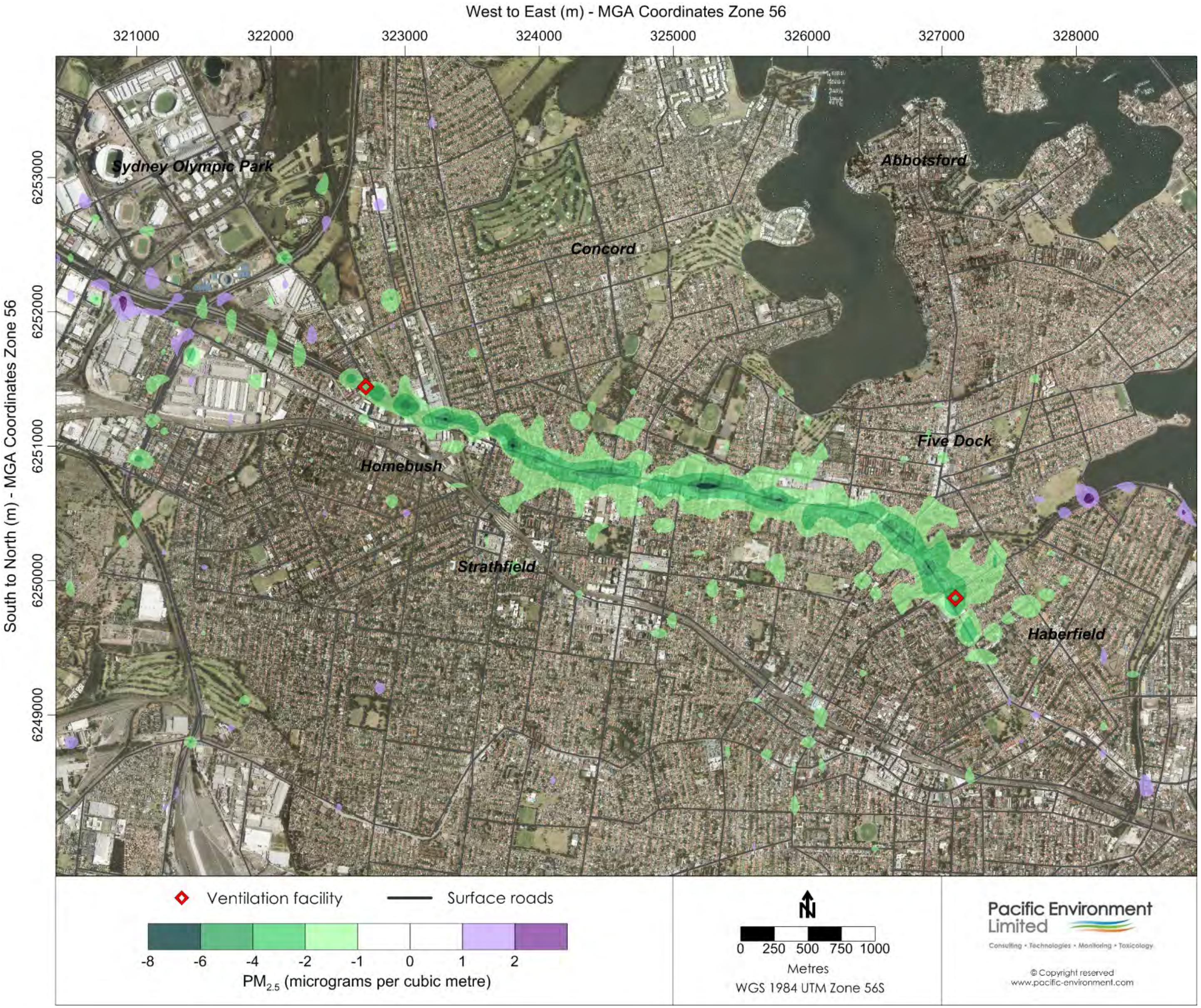

Figure 8-79 **Contour plot showing change in maximum 24-hour $PM_{2.5}$ with the project (2021-DS)**

8.4.9 Air toxics

Four air toxics - benzene, PAHs (as BaP), formaldehyde and 1,3-butadiene - were considered in the assessment. These compounds were taken to be representative of the much wider range of air toxics associated with motor vehicles, and they have commonly been assessed for road projects.

The changes in the maximum one-hour benzene concentration at the community receptors as a result in the project in 2021 and 2031 are show in Figure 8-80, where they are compared with the NSW impact assessment criterion from the Approved Methods. These changes took into account emissions from both surface roads and tunnel ventilation outlets, although the contribution of the latter was, at most, around 25 per cent, and generally less than 10 per cent. It can be seen from the Figure that there was a decrease in the predicted benzene concentration at most these receptors. Where there was an increase in the concentration, this was well below the assessment criterion. The changes in the maximum one-hour BaP, formaldehyde and 1,3-butadiene concentration are presented in Figure 8-81, Figure 8-82, and Figure 8-83 respectively. For each compound, where there was an increase in the concentration, this was well below the NSW impact assessment criterion. The largest increases for the community receptors were also representative of the largest increases for the RWR receptors.

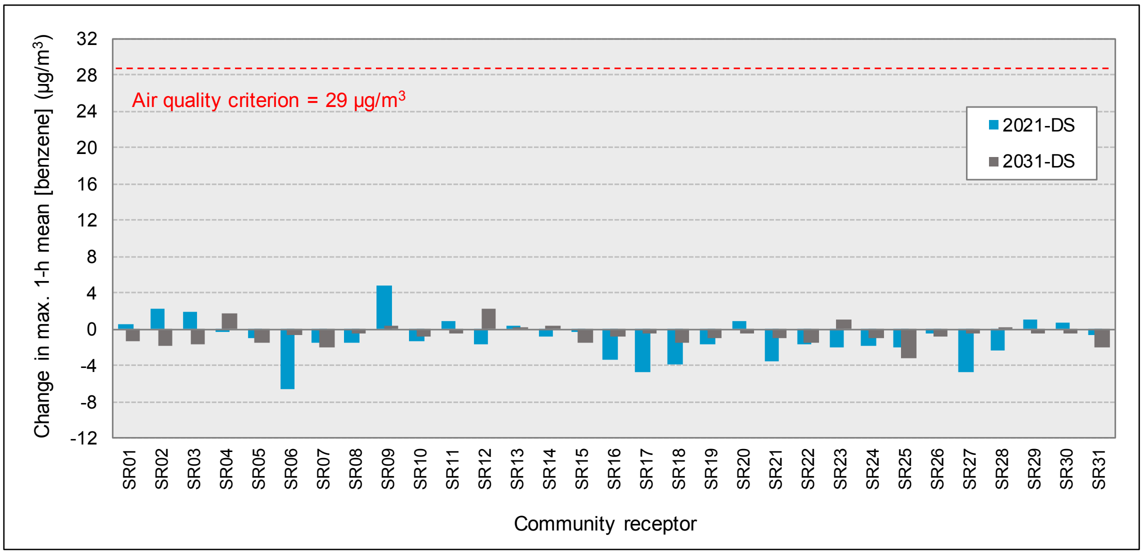

Figure 8-80 Change in maximum one-hour mean benzene at community receptors (2021-DS and 2031-DS)

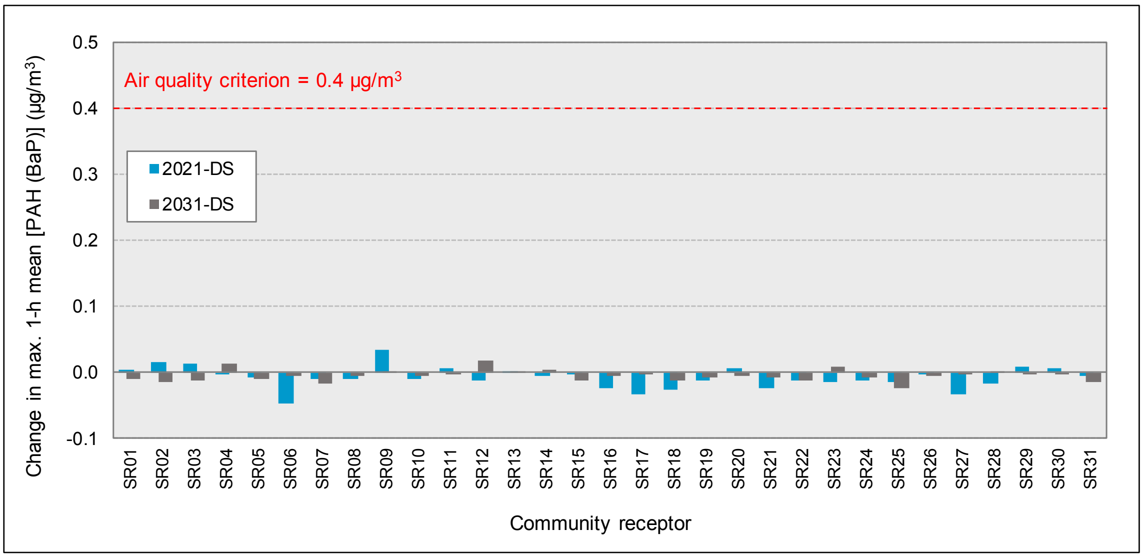

Figure 8-81 Change in maximum one-hour mean b(a)p at community receptors (2021-DS and 2031-DS)

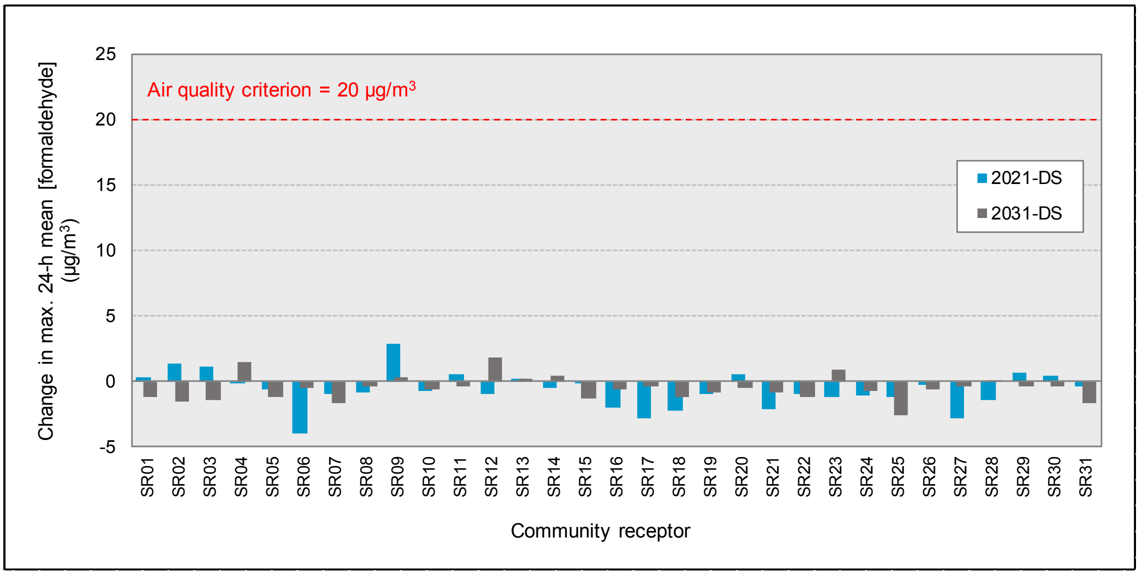

Figure 8-82 Change in maximum one-hour mean formaldehyde at community receptors (2021-DS and 2031-DS)

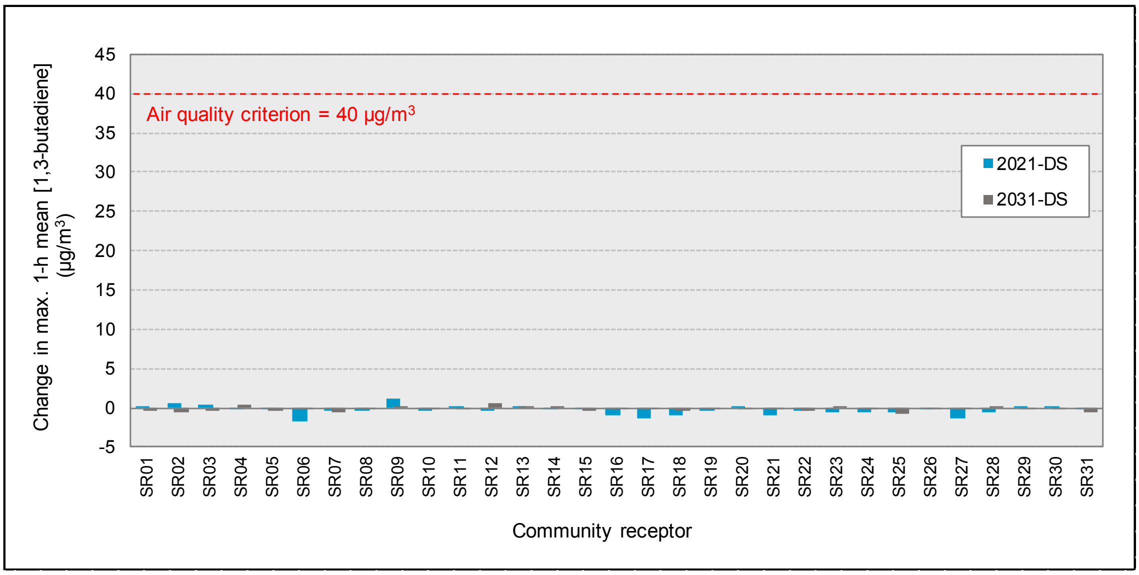

Figure 8-83 Change in maximum one-hour mean 1,3-butadiene at community receptors (2021-DS and 2031-DS)

8.4.10 Odour

The issue of odour is mentioned in the SEARs. Odours associated with motor vehicle emissions tend to be very localised and short-lived, and there are not expected to be any significant, predictable or detectable changes in odour as a result of the project.

For each of the 10,154 RWR receptors the change in the maximum one hour THC concentration as a result of the project was calculated. The largest change in the maximum one-hour THC concentration across all receptors was then determined, and this was converted to an equivalent change for three of the odorous pollutants identified in the Approved Methods (toluene, xlyenes, and acetaldehyde). These pollutants were taken to be representative of other odorous pollutants from motor vehicles.

The changes in the levels of three odorous pollutants as a result of the project, and the corresponding odour assessment criteria from the Approved Methods, are given in Table 8-26. It can be seen that the change in the maximum one-hour concentration of each pollutant was an order of magnitude below the corresponding odour assessment criterion in the Approved Methods.

Table 8-26 Comparison of changes in odorous pollutant concentrations with criteria in Approved Methods (RWR receptors)

Scenario	Largest increase in maximum one-hour THC concentration relative to Do Minimum scenario (µg/m^3)	Largest increase in maximum one-hour concentration for specific compounds		
		Toluene (µg/m^3)	Xylenes (µg/m^3)	Acetaldehyde (µg/m^3)
2021-DS	172.1	14.0	11.5	2.2
2031-DS	109.3	8.9	7.3	1.7
2031-DSC	112.9	9.2	7.6	1.7
Odour criterion (µg/m^3)		360	190	42

8.5 Results for regulatory worst case scenarios

The results for the regulatory worst case scenarios are given in Table 8-28. The Table shows the maximum contribution of tunnel ventilation outlets at any of the 10,154 RWR receptors in the relevant scenarios. The equivalent maximum values for the expected traffic scenarios are also shown.

Table 8-27 Results of regulatory worst case assessment (RWR receptors)

Pollutant and period	Units	Maximum ventilation outlet contribution at any receptor				
		Regulatory worst case scenario		Expected traffic scenario		
		RWC-A	RWC-B	2021-DS	2031-DS	2031-DSC
CO (one hour)	(mg/m^3)	0.12	0.23	N/A[(a)]	N/A[(a)]	N/A[(a)]
NO_X (annual)	(µg/m^3)	3.49	6.98	0.47	0.56	1.11
NO_X (1 hour)	(µg/m^3)	59.36	114.82	13.67	15.55	28.06
NO_2 (annual)	(µg/m^3)	0.56[(b)]	1.12[(b)]	0.10	0.13	0.28
NO_2 (1 hour)	(µg/m^3)	N/A	N/A	N/A	N/A	N/A
PM_{10} (annual)	(µg/m^3)	0.19	0.38	0.03	0.04	0.09
PM_{10} (24 hour)	(µg/m^3)	1.40	2.79	0.21	0.27	0.53
$PM_{2.5}$ (annual)[(c)]	(µg/m^3)	0.19	0.38	0.02	0.03	0.06
$PM_{2.5}$ (24 hour) [(c)]	(µg/m^3)	1.40	2.79	0.15	0.18	0.36
THC (one hour)	(µg/m^3)	11.88	22.96	N/A[(a)]	N/A[(a)]	N/A[(a)]

(a) Not determined.
(b) Estimated as 16% of NO_X.
(c) The same emission rates were used for PM_{10} and $PM_{2.5}$.

The contribution to the annual mean NO_2 concentration was estimated on the assumption of a NO_2/NO_X ratio of 0.16, and the assumption that the contributions of the background and surface roads would also be high (hence any additional NO_2 from the ventilation outlets would be primary in origin). It could also be assumed with some validity that the NO_2/NO_X ratio is much higher (even unity), but in this case the absolute NO_2 concentration would be considerably lower.

The contribution to the maximum one-hour NO_2 concentration cannot be determined, as it depends upon the contributions from the background and the surface roads, and these contributions are not known for the one-hour period when the maximum NO_X concentration occurs.

The concentrations for the regulatory worst case scenarios were, of course, higher than those for the expected traffic scenarios in all cases, and the following points are noted for the former:

- The maximum contribution to the one-hour CO concentration was negligible, especially taking into account the fact that predicted CO concentrations for the expected traffic scenarios were well below the NSW impact assessment criterion.
- The maximum contribution to the annual mean NO_2 concentration was not insignificant. For example, the 6.98 µg/m^3 for the RWC-B scenario was around 11 per cent of the NSW criterion (62 µg/m^3). However, the predicted total annual NO_2 concentrations at the RWR receptors in the expected traffic scenarios were all at least 25 µg/m^3 below the criterion.
- The maximum contribution to the one-hour mean NO_2 concentration could have been significant, but could not be quantified accurately. However, the relative contributions from the background, surface roads and ventilation outlets presented earlier in the report suggest that any exceedances of the one-hour NO_2 criterion are much more likely to be due to a high background and emissions from existing surface roads rather than as a result of emissions from the project ventilation outlets.
- The maximum contribution from the ventilation outlets in the regulatory worst case scenarios would not have had a significant impact on annual mean PM_{10} and $PM_{2.5}$ concentrations.
- The most significant result was that for the 24-hour $PM_{2.5}$ contribution (and similarly the 24-hour PM_{10} contribution).

Whilst the contributions to maximum one-hour concentrations of NO_2 and 24-hour concentrations of $PM_{2.5}$ could have been significant, the contributions would be theoretical worst cases and there are several reasons why they would not represent a cause for concern in reality. For example:

- The probability of a ‘worst case event’ occurring that would lead to these concentrations in the ventilation outlets is very low
- Were a worst-case event to occur, the probability of it lasting up to one hour would be very low. It is extremely unlikely that such an event would last for 24 hours
- The probability of a worst-case event coinciding with the worst 24-hour period for dispersion would be very unlikely.
- The probability of a worst-case event coinciding with a high background concentration would also be very low. In the case of NO_2, even if this were to occur the NO_2/NO_X ratio would be low.

In Section 8.3 it was shown that the peak in-tunnel concentrations for all traffic scenarios, including the capacity traffic at different speeds, were well within the in-tunnel concentrations associated with the regulatory worst case scenarios. It therefore follows that the predicted ventilation outlet contributions to ambient concentrations for any in-tunnel traffic scenario would be lower than those shown in Table 8-27.

It can be concluded that emissions from the project ventilation outlets, even in the regulatory worst case scenarios, would be extremely unlikely to result in an adverse impacts on local air quality. WDA will conduct ambient air quality monitoring to demonstrate that emissions from the ventilation outlets will have no detectable impact on local air quality.

8.6 Summary of key assumptions

The assumptions in the air quality impact assessment for the project that were likely to have had the most influence on the outcomes of the assessment are discussed in this Section. This discussion is provided to clarify the level of uncertainty and conservatism in the assessment, and consequently the total conservatism in the predicted air quality impacts of the project.

Table 8-28 Summary of key assumptions and implications for conservatism

Topic and sub-topic		Method and assumptions	Implications for conservatism
1	Background (ambient) air quality		
1.1	General	Background concentrations of air pollutants were derived using the data from OEH air quality monitoring stations in the study area.	The data from the OEH monitoring stations was found to be broadly representative of the data from a project-specific monitoring site on the project corridor.
		It was assumed that there would be no contribution from the road network to the concentrations at these sites.	There is likely to be a small contribution from the road network at the monitoring sites. The contribution will vary by pollutant.
		The GRAL model gave non-zero (but generally small) values at the locations of the background monitoring sites.	Total predicted concentrations (GRAL + background) will be generally overestimated across the GRAL domain. The maximum annual mean GRAL predictions at background sites were: - CO 0.03 mg/m^3 - NO_X 29.1 µg/m^3 - PM_{10} 1.6 µg/m^3
		Pollutant concentrations at background monitoring stations in 2014 were assumed to be representative of background concentrations in 2021 and 2031.	The implications of this cannot be quantified. It could be argued that concentrations in the future will decrease as emission controls improve (across all sectors of activity). However, any improvements could also be offset by increases in population and activity.
1.2	CO, rolling 8-hour mean	Hourly monitoring data from three OEH monitoring stations in 2014 were combined, and the highest monitored concentration in each hour was selected as the background value for that hour.	This resulted in an average concentration that was higher than the average for any individual station, and a distribution of concentrations that was shifted towards higher values than for any individual station.
1.3	NO_X, annual mean	Background annual mean NO_X concentrations were mapped across the GRAL domain.	Notwithstanding the comments under item 1, this approach can be viewed as accurate rather than conservative.
1.4	NO_X, one-hour mean	Hourly monitoring data from three OEH monitoring stations in 2014 were combined, and the highest monitored concentration in each hour was selected as the background value for that hour.	This resulted in an average concentration that was higher than the average for any individual station, and a distribution of concentrations that was shifted towards higher values than for any individual station.
1.5	PM_{10}, annual mean	Background annual mean PM_{10} concentrations were mapped across the GRAL domain.	Notwithstanding the comments under item 1, this approach can be viewed as accurate rather than conservative.

Topic and sub-topic		Method and assumptions	Implications for conservatism
1.6	PM_{10}, 24-hour mean	24-hour monitoring data from three OEH monitoring stations in 2014 were combined, and the highest monitored concentration in each hour was selected as the background value for that hour.	This resulted in an average concentration that was higher than the average for any individual station, and a distribution of concentrations that was shifted towards higher values than for any individual station.
1.7	$PM_{2.5}$, annual mean	A single value of 8 µg/m^3 was assumed for the whole GRAL domain.	The measurement of $PM_{2.5}$ is rather uncertain, and therefore it cannot be stated with confidence that this approach is either accurate or conservative.
1.8	$PM_{2.5}$, 24-hour mean	24-hour monitoring data from three OEH monitoring stations in 2014 were combined, and the highest monitored concentration in each hour was selected as the background value for that hour.	This resulted in an average concentration that was higher than the average for any individual station, and a distribution of concentrations that was shifted towards higher values than for any individual station.
2	Traffic forecasts		
2.1	Traffic volumes for M4 East tunnel and surface roads	Traffic volumes were taken from WRTM. The traffic data for a typical weekday were applied to every day of the year in the dispersion model.	This resulted in overestimates of concentrations at weekends.
3	Emission model (surface roads)		
3.1	Model selection	Emissions from vehicles on surface roads were calculated using a model that was adapted from the NSW EPA's inventory model.	The EPA model is not designed to be conservative for surface roads, but the analysis presented in Appendix E indicates that for the conditions in the Lane Cove Tunnel (and probably more widely for tunnels in Sydney during normal operation), the EPA emission factors overestimate real-world emissions (see below).
3.2	CO emission factors	NSW EPA model	LCT analysis indicated an overestimation of real-world emissions in 2013 by a factor of 2.0 to 2.8.
3.3	NOX emission factors	NSW EPA model	LCT analysis indicated an overestimation of real-world emissions in 2013 by a factor of 2.2 to 3.3.
3.4	PM_{10} emission factors	NSW EPA model, includes both exhaust and non-exhaust sources	LCT analysis indicated an overestimation of real-world emissions in 2013 by a factor of 1.8-3.2.
3.5	$PM_{2.5}$ emission factors	NSW EPA model, includes both exhaust and non-exhaust sources	LCT analysis indicated an overestimation of real-world emissions in 2013 by a factor of 1.7-2.9.
3.6	THC emission factors	NSW EPA model. Exhaust emissions only (no evaporation).	Not included in LCT analysis.

Topic and sub-topic		Method and assumptions	Implications for conservatism
4	Emission model (M4 East tunnel)		
4.1	Model selection	Emissions from vehicles in the M4 East tunnel were calculated using emission factors published by PIARC.	The PIARC emission factors were developed for the purpose of tunnel ventilation design, and as such have been developed to include a design safety margin. The analysis presented in Appendix E indicates that for the conditions in the Lane Cove Tunnel (and probably more widely for tunnels in Sydney during normal operation), the PIARC emission factors overestimate real-world emissions (see below).
4.2	CO emission factors	PIARC model (emission factors provided by PIARC for Australia)	LCT analysis indicated an overestimation of real-world emissions in 2013 by a factor of 1.6 to 1.7.
4.3	NO_X emission factors	PIARC model (emission factors provided by PIARC for Australia)	LCT analysis indicated an overestimation of real-world emissions in 2013 by a factor of 1.4 to 2.0.
4.4	$PM_{2.5}$ emission factors (total)	PIARC model (emission factors provided by PIARC for Australia)	LCT analysis indicated an overestimation of real-world emissions in 2013 by a factor of 2.6 to 4.3.
4.5	$PM_{2.5}$ emission factors (exhaust only)	PIARC model (emission factors provided by PIARC for Australia)	LCT analysis indicated an overestimation of real-world emissions in 2013 by a factor of 1.5.
4.6	$PM_{2.5}$ (non-exhaust)	Non-exhaust $PM_{2.5}$ was excluded from the calculations in Appendix L on the grounds that the PIARC emission factors are highly conservative. Moreover, PIARC states that non-exhaust particles are mainly larger than 1 µm in diameter, and do not strongly affect light extinction. Whilst this is therefore likely to be a valid exclusion for tunnel ventilation design, non-exhaust particles could not be excluded from the ambient air quality assessment (as they represent a real source). Non-exhaust PM was therefore factored into the ventilation outlet emissions based on ratios established using the EPA model.	The analysis of the data from the Lane Cove Tunnel showed that the PIARC method yields very conservative estimates of PM emissions for tunnel operation. The PIARC emission estimates based on exhaust PM alone (i.e. with non-exhaust PM excluded) remain conservative (by a factor of around 1.5).
4.7	Other pollutants	Emission factors are only presented by PIARC for CO, NO_X and $PM_{2.5}$. Emissions of other pollutants and metrics (PM_{10}, THC) were determined using ratio methods. The ratios were derived using the EPA model for the same traffic conditions and tunnel configurations as those used in Appendix L.	The conversion method used was not inherently conservative.

Topic and sub-topic		Method and assumptions	Implications for conservatism
4.8	Future year scaling factors	PIARC provides adjustment factors up to the year 2020 to account for expected continuous improvement in engine technologies and emissions. This assessment considered traffic in the years 2021 and 2031. No reduction in emissions was assumed beyond 2020.	The use of 2020 factors for 2031 is expected to result in the overestimation of 2031 emissions and resultant ground level pollutant concentrations due to expected improvements in vehicle emissions over time.
4.9	Portal intake air	Pollutant loads in portal intake air were not considered in the dispersion modelling.	A screening assessment was undertaken for the NorthConnex project. This demonstrated that pollutant loads in portal intake air did not significantly alter the outcomes of the air quality impact assessment (AECOM, 2014b).
5	Dispersion modelling (general)		
5.1	Terrain	Terrain data were taken from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) website. A 30-metre resolution was used for the modelling of meteorology.	The terrain data were assumed to accurately reflect the study area.
5.2	Meteorology	Data from the BoM Canterbury Racecourse AWS meteorological station were chosen as the input to GRAMM for modelling.	The site was considered to be representative of the meteorology in the domain.
6	Dispersion modelling (ventilation outlets)		
6.1	Portal emissions	The assessment has been conducted assuming zero emissions from the tunnel portals; that is, all vehicle emissions have been assumed to be vented via the tunnel ventilation outlets near the end of each tunnel.	-
6.	Ventilation outlet heights	The ventilation emission points had been assumed to be either 30.5 or 25 metres above ground, depending on the location.	A basic sensitivity analysis has shown that the total predicted concentrations are not likely to be sensitive to ventilation outlet height, based on a sensitivity range of 25 to 35 metres.
	Ventilation outlet exit diameter	The dispersion modelling involved wither time-varying or fixed ventilation outlet diameters, depending on the outlet.	-
	Volumetric flow rates	Volumetric flow rates were initially calculated for each hour of the day based on predicted traffic volumes.	-
	Road gradient	The total tunnel emissions have been calculated based on the sum of each tunnel section's emissions, factoring in the length of each section, the time taken for vehicles in the tunnel to pass through each section, the density of vehicles in the tunnel and the respective gradients.	-

Topic and sub-topic		Method and assumptions	Implications for conservatism
	Outlet temperature	An annual average outlet temperature was used for each ventilation outlet modelled in GRAL.	A basic sensitivity analysis has shown that the total predicted concentrations are not likely to be sensitive to ventilation outlet temperature, based on a sensitivity range of 15 to 35^{0}C.
8	Post-processing (NO_2) – community receptors		
	NO_X-to-NO_2 conversion, annual mean	A 'best estimate' approach was used, which gave the most likely annual mean NO_2 concentration for a given annual mean NO_X concentration.	The approach used was not inherently conservative.
	NO_X-to-NO_2 conversion, maximum one-hour mean	A 'detailed' contemporaneous approach was used. This involved the use of a conservative upper bound function which gave the maximum likely one-hour mean NO_2 concentration for a given one-hour mean NO_X concentration.	Given the wide range of possible NO_2 concentrations for a given NO_X concentration, this approach was used to conservatively estimate the maximum one-hour mean NO_2 concentrations. The dispersion modelling evaluation showed, however, that this method was less conservative than the OLM.
9	Post-processing (NO_2) – RWR receptors		
	NO_X-to-NO_2 conversion, annual mean	A 'best estimate' approach was used, which gave the most likely annual mean NO_2 concentration for a given annual mean NO_X concentration.	The approach used was not inherently conservative.
	NO_X-to-NO_2 conversion, maximum one-hour mean	A 'simple' statistical (non-contemporaneous) approach was applied to determine the maximum one-hour NO_X concentrations for the much larger number of residential, workplace and recreational' (RWR) receptors. The maximum one-hour mean NOx value predicted by GRAL was added to the 98th percentile NOx value for the background in the synthetic profile for 2014. The conversion of NO_X to NO_2 was then based on the functions used in the detailed approach.	In general the simple method performed in a similar manner to the detailed method, giving slightly lower maximum NO_2 values.

8.7 Sensitivity tests

Several sensitivity tests were conducted for various model inputs. These included:

- The influence of ventilation outlet temperature.
- The influence of ventilation outlet height.
- The inclusion of buildings near tunnel ventilation outlets.

These tests were based upon a sub-area of the M4 East GRAL domain of approximately 2 km x 2 km around the project’s eastern ventilation outlet. Only the ventilation outlet contribution, and only annual mean $PM_{2.5}$ and maximum 24-hour $PM_{2.5}$, were included in the tests. A sub-set of 13 sensitive receptors was evaluated. The predicted concentrations were indicative, as the aim of the sensitivity tests was to compare to assess the proportional sensitivity of the model to specific input parameters.

The following sections present the results of the tests.

8.7.1 Ventilation outlet temperature

The ventilation outlet temperatures for the project assessment were around 25°C. For the temperature sensitivity tests the effects of using outlet temperatures 10˚C below and above this value were modelled. In temperature test 1 (TT01) the outlet temperature was set to 15˚C, and in temperature test 2 (TT02) the outlet temperature was set to 35˚C.

Table 8-29 below presents the results of the temperature sensitivity test. The results show that the predicted concentrations for the ventilation outlet were higher for the lower temperature (by a factor of, on average, around 1.5). However, the predicted concentrations remained well below the advisory reporting standards for $PM_{2.5}$, and made up a very small proportion of the total combined results (for surface roads and ventilation outlets). Even with a significant change in ventilation outlet temperature, the total predicted concentration (roads and ventilation outlets) is unlikely to be impacted significantly. The assumption of a single annual average temperature in GRAL was therefore considered unlikely to represent a large source of uncertainty in the overall predictions.

Table 8-29 Sensitivity test results for temperature (tunnel ventilation outlet only)

ID	Name	TT01 (15°C)		TT02 (35°C)	
		$PM_{2.5}$ (µg/m^3)			
		Max 24h	Annual	Max 24h	Annual
		Advisory Reporting Standard			
		25	*8*	*25*	*8*
SR01	Peek-A-Boo Early Learning	0.098	0.008	0.064	0.004
SR17	Rosebank College	0.074	0.010	0.062	0.008
SR18	Little VIPs	0.123	0.019	0.082	0.011
SR19	Ella Community Child Care Centre	0.092	0.009	0.075	0.006
SR20	Ramsay Street Medical Centre	0.091	0.010	0.066	0.006
SR21	St. John of Arc Catholic School	0.081	0.009	0.058	0.006
SR22	Saint Joan of Arc's Catholic Church Haberfield	0.083	0.009	0.063	0.006
SR23	Dobroyd Point Public School	0.073	0.006	0.060	0.004
SR24	Domremy College	0.081	0.007	0.065	0.005
SR25	The Infants Home	0.057	0.008	0.039	0.004
SR27	Educare Playschool	0.077	0.009	0.048	0.006
SR28	Goodstart Early Learning	0.101	0.009	0.082	0.005
SR29	Haberfield Public School	0.095	0.009	0.066	0.004

8.7.2 Ventilation outlet height

The heights of the ventilation outlets for the project assessment were 30.5 metres (western ventilation facility) and 25 metres (eastern ventilation facility). In height test 1 (HT01) the height was set to 25 metres and in height Test 2 (HT02) the height was set to 35 metres. These values were approximately five metres below and above the height of the western ventilation facility outlet modelled for the project.

Table 8-30 presents the results of the height sensitivity test. The results were similar to those for the temperature sensitivity tests, with the lower outlet resulting in concentrations that were around 1.5 times greater, on average, than the higher outlet. Again, ventilation outlet height is unlikely to represent a large source of uncertainty in the overall predictions.

Table 8-30 Sensitivity test results for height (tunnel ventilation outlet only)

ID	Name	HT01 (25 metres)		HT02 (35 metres)	
		PM$_{2.5}$ (µg/m^3)			
		Max 24h	Annual Ave	Max 24h	Annual Ave
		Advisory Reporting Standard			
		25	*8*	*25*	*8*
SR01	Peek-A-Boo Early Learning	0.098	0.007	0.066	0.005
SR17	Rosebank College	0.079	0.010	0.065	0.008
SR18	Little VIPs	0.132	0.018	0.080	0.012
SR19	Ella Community Child Care Centre	0.107	0.008	0.076	0.007
SR20	Ramsay Street Medical Centre	0.092	0.009	0.067	0.007
SR21	St. John of Arc Catholic School	0.080	0.008	0.064	0.007
SR22	Saint Joan of Arc's Catholic Church Haberfield	0.086	0.008	0.064	0.007
SR23	Dobroyd Point Public School	0.070	0.005	0.056	0.005
SR24	Domremy College	0.084	0.007	0.063	0.005
SR25	The Infants Home	0.061	0.008	0.037	0.005
SR27	Educare Playschool	0.070	0.008	0.053	0.007
SR28	Goodstart Early Learning	0.104	0.007	0.074	0.006
SR29	Haberfield Public School	0.105	0.007	0.070	0.005

8.7.3 Buildings

Buildings may be included in dispersion modelling to account for building wake in the vicinity of a ventilation outlet. However, for the project assessment buildings were excluded (the rationale for this was provided earlier in the report). The sensitivity of the inclusion of buildings to predicted concentrations was therefore assessed.

The same model domain, resolution and receptor list as for the temperature and height tests were used. The closest commercial buildings to the Project's eastern ventilation outlet were included in test BT01, and in test BT02 they were excluded. The locations and heights of these buildings were estimated from Google Earth.

Table 8-31 presents the results of the buildings sensitivity test. The results show that, when buildings were included, there was an average increase in concentrations associated with the ventilation outlet by a factor of approximately 1.5. Whilst this test was not comprehensive, it indicates that the inclusion or exclusion of buildings is unlikely to represent a large source of uncertainty in the overall predictions. The total predicted concentrations, and the conclusions of the assessment, would not change significantly with the inclusion of buildings.

Table 8-31 Sensitivity test results for buildings (tunnel ventilation outlet only)

ID	Name	BT01 PM$_{2.5}$ (µg/m^3) Max 24h	BT01 Annual Ave	BT02 Max 24h	BT02 Annual Ave
	Advisory Reporting Standard	*25*	*8*	*25*	*8*
SR01	Peek-A-Boo Early Learning	0.100	0.009	0.081	0.005
SR17	Rosebank College	0.083	0.010	0.070	0.009
SR18	Little VIPs	0.129	0.021	0.095	0.014
SR19	Ella Community Child Care Centre	0.103	0.009	0.089	0.007
SR20	Ramsay Street Medical Centre	0.094	0.011	0.076	0.008
SR21	St. John of Arc Catholic School	0.085	0.009	0.070	0.007
SR22	Saint Joan of Arc's Catholic Church Haberfield	0.086	0.009	0.065	0.007
SR23	Dobroyd Point Public School	0.073	0.006	0.062	0.005
SR24	Domremy College	0.089	0.007	0.067	0.006
SR25	The Infants Home	0.080	0.010	0.037	0.005
SR27	Educare Playschool	0.088	0.009	0.059	0.007
SR28	Goodstart Early Learning	0.109	0.009	0.086	0.006
SR29	Haberfield Public School	0.120	0.010	0.079	0.006

9 Assessment of cumulative impacts

9.1 Overview

This Chapter of the report addresses the cumulative impacts of the project and the M4-M5 Link. These impacts have already been considered at several points earlier in this report.

The Chapter focuses on cumulative operational impacts. For cumulative construction impacts, the project has already been identified as high risk, and therefore the same conclusions and mitigation measures as those described in Chapter 7 and Chapter 10 would apply.

9.2 In-tunnel air quality

The peak in-tunnel concentrations for the expected traffic cumulative scenario (2031-DSC), were assessed in Appendix L and section 8.3. The results showed that the peak concentrations for all traffic scenarios, including worst-case conditions, were well within the concentrations associated with the regulatory worst case.

9.3 Ambient air quality

9.3.1 Results for expected traffic scenarios

The results for the expected traffic scenarios and all pollutants are presented in Appendix K.

In the majority of cases the results for the community receptors in the 2031-DSC scenario were very similar to those in the 2031-DS scenario, and an example of this is provided (for annual mean NO_2) in Figure 9-1. The results are therefore not discussed further here..

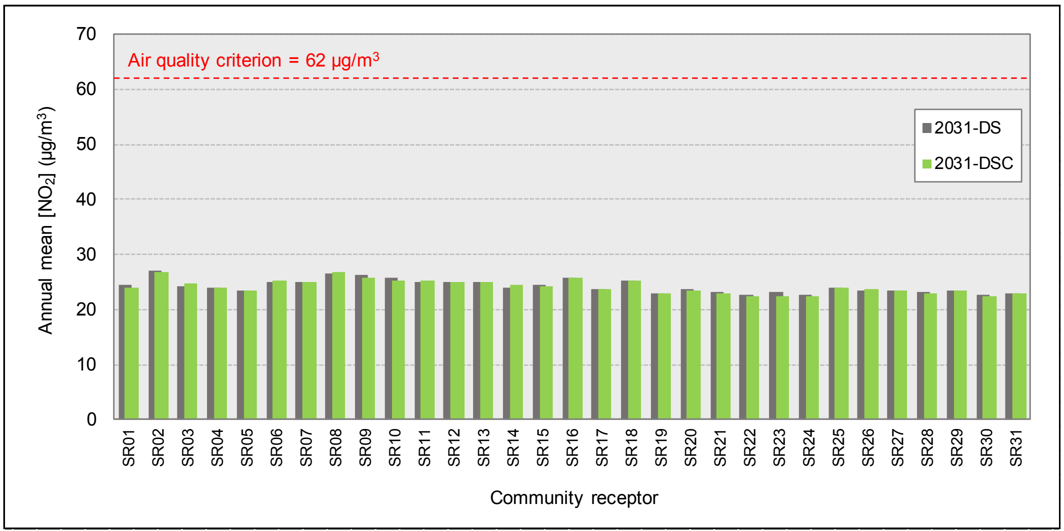

Figure 9-1 **Annual mean NO_2 at community receptors (2031-DS and 2031-DSC)**

The results for the 2031-DSC scenario at the RWR receptors were also broadly similar to those for the 2031-DS scenario.

9.3.2 Results for regulatory worst case scenarios

The results for the regulatory worst case assessment presented in section 8.6.

10 Management of impacts

10.1 Construction impacts

Step 3 of the construction assessment involved determining mitigation measures for each of the four potential activities in Step 2. This was based on the risk of dust impacts identified in Step 2C. For each activity, the highest risk category was used. The results are shown in Table 10-1 to Table 10-6, and are all highly recommended. Most of the recommended measures are routinely employed as 'good practice' on construction sites.

A Construction Air Quality Management Plan will be produced to cover all construction phases of the M4 East project. This should contain details of the site-specific mitigation measures to be applied. Additional guidance on the control of dust at construction sites in NSW is provided as part of the NSW EPA Local Government Air Quality Toolkit[28]. Detailed guidance is also available from the UK (GLA, 2006) and the United States (Countess Environmental, 2006). For precise requirements, reference should be made to the Baseline Conditions of Approval for the project.

Table 10-1 Mitigation for all sites: Communication

	Mitigation measure
1	Develop and implement a stakeholder communications plan that includes community engagement before work commences on site.
2	Display the name and contact details of person(s) accountable for air quality and dust issues at the boundaries of each construction area. This may be the environment manager/engineer or the site manager.
3	Display the head or regional office contact information

Table 10-2 Mitigation for all sites: Dust management

	Mitigation measure
4	Develop and implement a Construction Air Quality Management Plan which requires consultation with NSW EPA. Any measures that are required will differ depending on the activities occurring, and so will need to be tailored for each individual site.
Site management	
5	Record all dust and air quality complaints, identify cause(s), take appropriate measures to reduce emissions in a timely manner, and record the measures taken.
6	Make complaints available to the Secretary upon request.
7	Record any exceptional incidents that cause dust and/or air emissions, either on- or offsite, and the action taken to resolve the situation in the log book.
8	Regular communication with other high risk construction sites within 500 metres of the site boundary to ensure plans are co-ordinated and dust and particulate matter emissions are minimised. It is important to understand the interactions of the off-site transport/deliveries which might be using the same strategic road network routes.
Monitoring	
9	Undertake regular on-site and off-site inspection, where receptors are nearby, to monitor dust, record inspection results.
10	Carry out regular site inspections to monitor compliance with the DMP, record inspection results, and make an inspection log available to the local authority when asked.

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[28] http://www.epa.nsw.gov.au/air/lgaqt.htm

	Mitigation measure
Preparing and maintaining the site	
11	Plan site layout so that machinery and dust causing activities are located away from receptors, as far as is possible.
12	Ensure where reasonable and feasible appropriate control methods are implemented to minimise dust emissions from the project site.
13	Ensure where reasonable and feasible appropriate control methods are implemented to minimise dust emissions from the project site.
14	Manage the quality of site runoff water.
15	Remove materials that have a potential to produce dust from site as soon as possible, unless being re-used on site. If they are being re-used on-site cover as described below.
16	Stockpiles would be located outside overland flowpaths, and where left exposed and undisturbed for longer than 28 days, would be finished and contoured to minimise loss of material in flood or rainfall events. Materials which require stockpiling for longer than 28 days would be stabilised by compaction, covering with anchored fabrics, or seeded with sterile grass where appropriate.
Operating vehicle/machinery and sustainable travel	
17	Ensure all construction vehicles comply with their relevant emission standards.
18	Ensure that, where practicable, engine idling is minimised when vehicles are stationary.
19	Avoid the use of diesel or petrol powered generators and use mains electricity or battery powered equipment where practicable.
20	Impose and signpost a maximum-speed-limit of 20 km/h on surfaced and unsurfaced haul roads and in work areas. Haul roads should be treated with water carts and monitored during earthworks operations, ceasing works if necessary during excessive winds where dust controls are not effective.
21	Produce a Sustainability Plan to manage the sustainable delivery of goods and materials.
22	Promote and encourages sustainable travel (public transport, cycling, walking, and car-sharing).
Construction	
23	Where practicable, only use cutting, grinding or sawing equipment fitted or in conjunction with suitable dust suppression techniques such as water sprays or local extraction (e.g. suitable local exhaust ventilation systems).
24	Ensure an adequate water supply on the site for effective dust/particulate matter suppression/mitigation, using non-potable water where possible and appropriate.
25	Where possible, use enclosed chutes and conveyors and covered skips.
26	Minimise drop heights from conveyors, loading shovels, hoppers and other loading or handling equipment and use fine water sprays on such equipment wherever appropriate.
27	Ensure equipment is readily available on site to clean any dry spillages, and clean up spillages as soon as reasonably practicable after the event using appropriate cleaning methods.
Waste management	
28	No bonfires and burning of waste materials.

Table 10-3 Mitigation specific to demolition

	Mitigation measure
29	Soft strip inside buildings before demolition (retaining walls and windows in the rest of the building where possible, to provide a screen against dust).
30	Ensure effective water suppression is used during demolition operations. Hand held sprays are more effective than hoses attached to equipment as the water can be directed to where it is needed. In addition high volume water suppression systems, manually controlled, can produce fine water droplets that effectively bring the dust particles to the ground and may be more useful for covering larger areas.

31	Minimise explosive blasting where possible, using appropriate manual or mechanical alternatives.
32	Bag and remove any biological debris or other hazardous materials such as asbestos, or damp down such material before demolition.

Table 10-4 Mitigation specific to earthworks

	Mitigation measure
33	Re-vegetate earthworks and exposed areas/soil stockpiles to stabilise surfaces as soon as practicable.
34	Use Hessian, mulches or tackifiers where it is not possible to re-vegetate or cover with topsoil, as soon as practicable.
35	Where possible, only remove any covers for exposed areas in small areas during work, and not all at once.

Table 10-5 Mitigation specific to construction

	Mitigation measure
36	Avoid scabbling (roughening of concrete surfaces) if possible.
37	Ensure sand and other aggregates are stored in bunded areas and are not allowed to dry out, unless this is required for a particular process, in which case ensure that appropriate additional control measures are in place.
38	Ensure bulk cement and other fine powder materials are delivered in enclosed tankers and stored in silos with suitable emission control systems to prevent escape of material and overfilling during delivery.
39	For smaller supplies of fine powder materials ensure bags are sealed after use and stored appropriately to prevent dust.

Table 10-6 Mitigation specific to track-out

	Mitigation measure
40	Use water-assisted dust sweeper(s) on the access and local roads, to remove, as necessary, any material tracked out of the site.
41	Avoid dry sweeping of large areas.
42	Ensure vehicles entering and leaving sites are covered to prevent escape of materials during transport.
43	Inspect on-site haul routes for integrity and instigate necessary repairs to the surface as soon as reasonably practicable.
44	Record all inspections of haul routes and any subsequent action in a site log book.
45	Where reasonable and feasible, haul roads will be maintained with water carts and graders, and the condition of the roads will be monitored.
46	Implement site exit controls (e.g. wheel washing system and rumble grids) to dislodge accumulated dust and mud prior to leaving the site where reasonably practicable.
47	Ensure there is an adequate area of hard surfaced road between the wheel wash facility and the site exit, wherever site size and layout permits.
48	Access gates to be located at least 10 m from receptors where possible.

10.2 Operational impacts

10.2.1 Overview

The SEARs for the M4 East project require details of, and justification for, the air quality management measures that have been considered. This Section of the report firstly reviews the measures that are available for improving tunnel-related air quality, and then describes their potential application in the context of the project. The measures have been categorised as follows:

- Tunnel design
- Ventilation design and control
- Air treatment systems
- Emission controls and other measures

10.2.2 Review of approaches

Tunnel design

It is important that the tunnel infrastructure is designed in such a way that the generation of pollutant emissions by the traffic using the tunnel is minimised. The main considerations include avoiding large gradients and congested traffic conditions, including the management of traffic on the roads leading in and out of the tunnel. In addition, the risk of incidents leading to congestion needs to be addressed, including accidents involving oversized vehicles.

Ventilation design and control

There are several reasons why a tunnel needs to be ventilated. The main reasons are:

- Control of the internal environment. It must be safe and comfortable to drive through the tunnel. Vehicle emissions must be sufficiently diluted so as not to be hazardous during normal operation, or when traffic is moving slowly.
- Protection of the external environment. It is unacceptable for polluted air from tunnel portals, or ventilation outlets to present a health or nuisance hazard to the community. Ventilation, and the dispersion of pollutants, is overwhelmingly the most popular method for minimising the impacts of tunnels on ambient air quality. Collecting emissions and venting them via ventilation outlets is a very efficient way of dispersing pollutants. Studies show that the process of removing surface traffic from heavily trafficked roads and disposing of the same amount of pollution from an elevated location results in substantially lower concentrations at sensitive receptors (PIARC, 2008).
- Ventilation outlets need to be designed and sited accordingly, and high vertical discharge velocities from outlets may be required to assist dispersion.
- Emergency situations. When a fire occurs in a tunnel it is desirable to be able to control the heat and other combustion products in the tunnel so as to permit safe evacuation of occupants, and to provide the emergency services with a safe route to deal with the fire and to rescue any trapped or injured persons.

A two-fold approach to ventilation design is generally adopted:

- The amount of fresh air required to dilute pollutants to acceptable levels is calculated based on the likely emissions from vehicles in the tunnel, and the ventilation system is designed accordingly. The choice and design of a suitable ventilation system depends upon the following factors:
    - Tunnel length and geometry.
    - Traffic flow and composition.
    - Fresh air requirement under normal and specific traffic conditions.
    - Admissible air pollution levels around tunnel portals.

    - Fire safety considerations.
- Sensors are installed in the tunnel to initiate the operation of the ventilation system in order to maintain the level of pollutants below limit values, or to force the closure of the tunnel should certain limit values be exceeded.

Short tunnels can be adequately and safely ventilated by the piston effect. The external wind may also generate a flow of air within a tunnel due to the static air pressure difference between the portals.

There are three basic concepts for mechanical tunnel ventilation:

- Longitudinal ventilation, whereby air is introduced to, or removed from, the tunnel at a limited number of points. The main movement of air is along the tunnel from the entrance to the exit.
- Transverse ventilation, whereby air may be introduced into a tunnel at various points along its length, and may also be extracted at other points along its length. The main movement of air inside the tunnel is perpendicular to the longitudinal axis of the tunnel.
- Semi-transverse ventilation. Semi-transverse ventilation involves a combination of longitudinal and transverse ventilation. For example, fresh air can be delivered longitudinally through the tunnel portals, and exhaust air is removed uniformly (and transversely) over the length of the tunnel.

Jet fans may also be mounted within the tunnel space, usually at fixed intervals along the tunnel and near to the tunnel ceiling. They function by producing a relatively narrow jet of air moving at a high speed (typically 30 m/s), and rely upon turbulent friction and jet entrainment effects to transfer momentum from the jet into the main body of air in the tunnel.

Ventilation control is achieved by adjusting the number of fans in operation at any one time, with the individual units being operated at full power or not running. A further refinement is available in installations where fan speed is controllable. The required level of ventilation at any particular time tends to be determined in response to visibility levels and the concentrations of airborne pollutants. Normally, the CO concentration or the visibility inside the tunnel in are the only parameters measured for this purpose.

Air treatment systems

There are several air treatment options for mitigating the effects of tunnel operation on both in-tunnel and ambient air quality. Where in-tunnel treatment technologies have been applied to road tunnels, these technologies have focused on the management and treatment of PM. The most common of these is the electrostatic precipitator (ESP), and this is discussed in detail below. Information is provided on the method of operation, the international experience with ESPs in tunnels, and the effectiveness of systems. Other techniques include filtering, denitrification and biofiltration, agglomeration and scrubbing. These are described in less detail.

In Australia, the issue of air treatment frequently arises during the development of new tunnel projects. This issue is generally pursued by local residents or environmental protection associations. All tunnel projects have, however, gravitated towards a decision not to install an air treatment system, and to rely instead on the primary approach of dilution of air pollution (through ventilation systems) (PIARC, 2008; CETU, 2010).

Electrostatic precipitators

Description of method

For a number of years work has progressed on the application of electrostatic precipitators (ESPs) to road tunnel air. In a typical ESP the air flow is initially passed through an ionising chamber containing wires or plates maintained at several thousand volts. These produces a corona that releases electrons into the air-stream. The electrons attach to particles in the air flow, and give them a net negative charge. The particles then pass through a collector chamber or passageway which contains multiple parallel collecting plates. The collecting plates are grounded and attract the charged dust particles.

The cleaning of an ESP is vital to ensure that it remains in proper working order (CETU, 2010). In a conventional ‘dry’ electrostatic precipitator the collecting plates are periodically shaken to dislodge the collected dust, which then falls into hoppers for collection and disposal. Most electrostatic precipitation systems also involve a regular manual washing and cleaning of the collecting plates to remove collected particles, and to maintain operational efficiency.

Dry ESPs are effective in removing particles between 1 and 10 microns in diameter. Varying efficiency results have been claimed and reported in relation the removal of sub-micron particles. Some ESPs can be retro-fitted to tunnels. Child and Associates (2004) described a relatively low-cost Norwegian system which can be bolted directly to the tunnel roof and fixed to the jet fans. Removal efficiencies of between 66 per cent (PM_1) and 98 per cent (PM_{10}) are claimed.

The ionisation phase prior to the filtration of dust particles produces nitrogen dioxide (NO_2). Specifically, the ionisation produces ozone which reacts with nitrogen monoxide (NO) to form NO_2 (CETU, 2010).

ESPs are generally configured in one of two ways:

- Bypass-type installations. These are typically used to improve visibility in long tunnels, with the air being extracted, filtered and re-injected into the tunnel.
- Extraction-type installation. Where major environmental requirements are involved, ESPs can be installed at the level of the polluted air outlets.

Installations by country

Around the world, there are relatively few road tunnels with installed filtration systems. The international experience with ESPs and filtration systems has been reviewed in a number of documents (e.g. Child & Associates, 2004; Willoughby et al., 2004; NHMRC, 2008; PIARC, 2008; CETU, 2010; AECOM, 2014b). A review of the use of the international electrostatic precipitators by country is provided below. Norway and Japan are two of the world leaders in the construction of road tunnels, and both countries are also involved in the development of ESPs.

Japan

The application of ESPs to remove particles from tunnel air began in Japan, which has about 8,000 road tunnels comprising a total length of 2,500 kilometres. More ESPs have been installed in road tunnels in Japan than in any other country. CETU (2010) listed 46 road tunnels in which ESPs are installed, or was being installed at the time of its report. Most of the Japanese tunnels with particulate matter filtration are less than five kilometres long. ESPs were installed for the first time anywhere in the world in the Tsuruga tunnel (2.1km) in 1979. The development of ESPs has extended the range of longitudinal ventilation. The first long tunnel combining longitudinal ventilation and ESPs was the Kan'etsu tunnel (11km) in 1985.

According to Willoughby et al. (2004), there is no fixed policy in Japan on the installation and use of ESPs, but that tunnels are considered on a case by case basis. CETU state that the ESPs have been installed either to improve in-tunnel visibility, to manage the discharge air pollution from tunnel ventilation outlets or portals, or both. No Japanese road authority gave health concerns as a reason for installation of ESPs. Willoughby et al., (2004) also note that the policy in Japan is to consider ESPs for tunnels longer than 2 km, although ESPs have been installed in shorter tunnels on an experimental basis. Where particulate matter filtration technology is installed to manage in-tunnel visibility (the main reason in Japan), this is typically as a result of a high percentage of diesel powered vehicles and a very high percentage of heavy goods vehicles using the road tunnel (AECOM, 2014b).

For most Japanese road tunnels with ESPs, the ESPs are located in bypass passages (to improve visibility). However, potential environmental impacts have led to the installation of electrostatic precipitators in around ten tunnels. For example, ESPs have been installed at the base of the extraction outlets in the Tennozan (2 km), Kanmon (3.5 km), Asukayama (0.6 km), Midoribashi (3.4 km) and Hanazonobashi tunnels (2.6 km). The Tokyo Bay tunnel (9.6 km) is mainly equipped with ceiling-based ESPs (CETU, 2010). The location the tunnel under Tokyo Bay makes the use of an intermediate ventilation outlet to manage in-tunnel air quality impractical, and a particulate matter filtration system has been installed as an alternative means to manage in-tunnel visibility.

In each case where ESPs have been installed in ventilation outlets, the reason given was that they were installed to limit particulate emissions in response to community concerns, but without support by technical assessment, dispersion modelling or any air quality monitoring at nearby receptors (Willoughby et al., 2004).

Norway

Norway has around 1,000 road tunnels. Norwegian tunnels have specific challenges in terms of visibility. In-tunnel visibility deteriorates significantly in winter when studded tyres are used. These increase abrasion of the road surface and, consequently, the suspension of PM (CETU, 2010). In warmer climates, where studded tyres are not required (such as in Sydney), road abrasion is much less of an issue (AECOM, 2014b).

Only eight of the tunnels in Norway have a PM filtration system installed. Two of these tunnels, the Festning Tunnel and the Bragernes Tunnel, have filtration systems that are designed principally to improve emissions to the environment (CETU, 2010). The Festning Tunnel passes beneath central Oslo. It is 1.8 kilometres long and carries 60,000 vehicles per day. The Laerdal Tunnel, which is the longest road tunnel in the world at 24.5 kilometres, also features a PM treatment system. The tunnel only carries 1,000 vehicles per day, and the principal purpose of the filtration system is to improve visibility within the tunnel, as the tunnel is deep underground with no opportunity to introduce additional fresh air along its length.

According to CETU (2010), the precipitators located upstream of extraction systems in Norwegian tunnels are no longer used for a variety of reasons, in particular the need to replace electrical cables. There are also doubts concerning the benefits of putting the systems back into service given that they have proved less effective than predicted.

Spain

The M-30 Orbital Motorway circles the central districts of Madrid. It is the innermost ring road, with a length is 32.5 kilometres. It has at least three lanes in each direction, supplemented in some parts by two or three lane auxiliary roads. It connects to the main Spanish radial national roads that start in Madrid. From 2005 to 2008, major upgrading works took place, and now a significant portion of the southern part runs underground. The M-30 Orbital Motorway is essentially a number of independent tunnels and surface roads. They are the longest urban motorway tunnels in Europe, with sections of more than six kilometres in length and three to six lanes in each direction (AECOM, 2014b). Overall there are 22 particulate matter filtration systems and four denitrification systems installed by four different manufacturers (CETU, 2010).

France

The Mont Blanc Tunnel was retrofitted with an ESP system around 2010. The tunnel is a two lane bi-directional tunnel 11.6 kilometres long and originally constructed in 1965. It has a relatively small cross sectional area. The objective of the particulate matter filtration system is to contribute to various local initiatives aimed at improving air quality in the Chamonix Valley (CETU, 2010).

Italy

Only one tunnel in Italy - the Le Vigne tunnel in Cesene - has a particulate matter filter system installed. This tunnel is 1.6 kilometres in length and is located in a heavily populated area which is particularly sensitive to air emission from the tunnel portals. The objective of the particulate matter filtration system for this tunnel is to reduce the emission levels from the tunnel portals.

Germany

One tunnel in Germany (under the Elbe in Hamburg) has a small-scale particulate matter filtration systems installed. This has been installed by filtration system manufacturers for trial and development purposes (CETU, 2010).

South Korea and Vietnam

Five tunnels in South Korea and one tunnel in Vietnam (Hai Van Pass tunnel) are equipped with ESPs. The 2010 CETU study identifies that in these two countries, the systems are mainly used to provide adequate in-tunnel visibility where there are constraints on the intake of fresh air into the tunnels (as an alternative means of managing in-tunnel visibility).

Hong Kong

Design and construct contracts have been awarded for the Central Wan Chai Bypass in Hong Kong. It is understood that both denitrification and particulate matter filtration systems are to be installed in this tunnel. This is a 3.7 kilometre twin tunnel with three lanes of traffic in each direction. It is due to open in 2017.

Australia

An in-tunnel air treatment system - including ESP and denitrification technologies – was trialled in the Sydney M5 East tunnel. In its former configuration, prior to the installation of the system, 90 per cent of the exhaust air from the tunnel was discharged via a ventilation outlet, with the remaining 10 per cent being discharged at the portals. Although measurement campaigns have indicated that these discharges do not present any significant impact on external air quality, the filtration system was installed at the tunnel's western portal. The trial was used to manage in-tunnel air being recycled between the westbound and eastbound tunnels, rather than in relation to in-tunnel air being emitted from the ventilation outlet for the tunnels. A structure was built to host air the ESP and NO_2 treatment systems, ventilators, offices and an information centre. A 300 m ventilation duct was also built. Rather than being discharged by the structure, air is re-injected into the tunnel and then eventually discharged by the existing outlet or the portals. The end-to-end cost of this treatment project has been estimated to be 50 million Australian dollars. The high cost reflects the fact that the tunnel was not originally designed to accommodate such systems (CETU, 2010).

Effectiveness

Japan

The two major manufacturers of ESPs in Japan are Matsushita Electric Co Ltd and Mitsubishi Heavy Industries. Both companies claim efficiency of at least 80 per cent removal of particles for their ESPs (Willoughby et al., 2004). While this is guaranteed by the companies, it is based on laboratory data and the performance has not been measured in an operating tunnel. Research by both companies has targeted improvement of particle collection efficiency and an increase in air speed through the ESPs. The companies report that testing has shown that for air speeds of up to 9 m/s an efficiency of 90 per cent can be achieved. ESPs have been developed and installed (Asukayama tunnel) that can operate at speeds of up to 13 m/s. At this speed, however, the efficiency drops to just over 80 per cent (Willoughby et al., 2004).

As confirmed in the CETU report (2010), ESPs have been installed at the Central Circular Route (Chuo-Kanjo-Shinjuku) in Tokyo since 2007. Data published on the website of the Tokyo Metropolitan Expressway Company claims a minimum 80 per cent PM reduction.

Austria

Child and Associates (2004) report the findings of a study by the Technical University of Graz of an Austrian ESP system in the Plabutsch tunnel. The removal efficiency ranged from more than 99 per cent for particles larger than 10 µm to 67 per cent for particles smaller than 1 µm.

South Korea

For an ESP installed in the Chinbu tunnel in South Korea, Drangsholt (2000) reports an average removal efficiency for particles between 0.3 µm and 10 µm of 83 per cent to 97 per cent.

Australia

The ESP trial in the Sydney M5 East westbound tunnel commenced in March 2010 and lasted 18 months. NSW Roads and Maritime Services (formerly the Roads and Traffic Authority) engaged CSIRO to undertake a six-month monitoring and analysis program of the ESP to review the system's performance.

In a review of the trail, AMOG (2012) concluded the following:

- The PM removal efficiency (for the air passing through the ESP) was around 65 per cent, compared with a target efficiency of 80 per cent. There was a corresponding improvement in in-tunnel visibility. After mixing the filtered air with the tunnel air, the net improvement was reduced to 29 per cent. This was reduced to a much lower overall improvement in visibility at the western end of the tunnel of 6 per cent, which may not have been perceptible to tunnel users.

- The ESP was unable to effectively or, given the cost of the system, cost-effectively, remove PM.
- Around 200 m^3/s of air was drawn through the ESP. It is possible that the ESP was operating at or beyond its air flow velocity limit. The efficiency of the ESP could be improved by significantly reducing the throughput of air or increasing the path length of the system. Both of these options would add to the capital cost of the system, and the space required.
- A major concern was the unreliability of the ESP system, when meant that it could only be used for 84 per cent of the duration of the study.
- The operation of the ESP should cease.

Operational periods

The operating periods of ESPs in tunnels are highly variable. ESPs are not automatically operated continuously, and a number of systems appear to have been rarely (or never) used. Child and Associates (2004) cited the reasons given including low traffic flows, variable efficiency, complexity of operation, and particle levels being well within limit values. In both Norway and Japan the operation of air cleaning technologies is on a needs basis, as the net effect of the technology (coupled with its effectiveness) dictates that the technology is best used when air quality is at its worst and hence the benefit is greatest (Dix, 2006).

The ESPs in Japanese tunnels operate based on actual pollution measurements. In the case of the Kan’etsu tunnel this results in an average operating time of 143 hours per month (20 per cent of the time) at the north portal and 40 hours per month (3 per cent of the time) at the south portal. The Tokyo Bay tunnel only records 12 to 13 hours of operation per year (i.e. approx. 0.15 per cent of the time) (Dix, 2006)

In Norway the need for ESP operation it is usually on a time clock which corresponds with peak hour traffic (Dix, 2006).

According to CETU (2010), the ESPs on the Madrid M-30 network were initially operated for 20 hours per day, but now only operate for a few hours each week.

Material filters

Some dust filtration systems remove airborne particulate matter using physical filters. For example, Matsushita manufacture a system in which sheet filters are attached to filter units, which are incorporated into the dust collector. The dust collector is equipped with an automatic carrying mechanism to transfer the filter units to the regeneration part. When a filter is polluted and clogged with dust and soot, the filter is automatically regenerated by air blow to exfoliate dust and soot. Physical filters may be used in conjunction with ESPs.

According to Willoughby et al. (2004), fabric (‘bag’) filters are in use in 14 tunnels in Japan, including installation as recently as the Tokyo Bay tunnel. However, as this equipment has been found to only filter about 20 per cent of total PM it is understood that its use is being discontinued. A significant issue is the inability of filter materials to remove the very fine particles that are present in vehicle exhaust.

Denitrification systems

Description of method

Denitrification refers to systems or processes that are designed to remove NO_2, and other oxides of nitrogen, from tunnel air. A number of alternative systems are available. NO_X removal by catalytic and biological processes has been tested in Austria, Germany and Japan in the early 1990s. Due to their weak performance in NO removal efficiency these tests were stopped. Subsequent developments have concentrated on pilot systems for NO_2 removal. No significant progress in robust NO treatment has been reported.

Installations and effectiveness by country

Norway

As of 2004, the operational use of denitrification technology in road tunnels had been limited to the installation of a system supplied by Alstom in the Laerdal tunnel in Norway (Child & Associates, 2004).

However, the performance and efficiency of this installation is difficult to assess, because traffic volumes in the Laerdal tunnel are relatively low. The resulting pollution levels within the tunnel are lower than those required to trigger the use of the electrostatic precipitation and denitrification systems that have been installed. Based on tests in the Festnings tunnel, the Alstom system removes 85-90 per cent of NO_2 and 60-75 per cent of hydrocarbons (Child & Associates, 2004).

Japan

In Japan two types of NO_X-reduction system were developed in 2004. In one of the systems - called 'adsorption' system - NO_2 molecules are removed by the physical adsorption effects of removing agents. In the other system - called 'absorption' - NO_2 molecules are chemically changed to neutral salts by removing agents soaked in alkaline water solutions, and are removed by the absorption of the neutral salts. Both systems have shown NO_2 removal efficiency of 90 per cent. Both technologies are being trialled in the ventilation outlets of the Central Circular Shinjyuka Tunnel. The tunnel is located in crowded city area where it is difficult to comply with the local environmental standards for NO_2 (PIARC, 2008; CETU, 2010).

Germany

FILTRONtec in Germany has also developed a denitrification system. This system has been successfully demonstrated in German road tunnels, although no commercial applications of this technology have taken place (Child & Associates, 2004).

Spain

The M30 project in Madrid has major denitrification systems which are in occasionally in operation (PIARC, 2008).

Australia

The ESP trial in the Sydney M5 East westbound tunnel also included an assessment of a denitrification system consisting of an array of modules containing activated carbon as the filter medium. Around 50 m^3/s of air was drawn through the system.

In a review of the trail, AMOG (2012) concluded the following:

- The system removed 55 per cent of the NO_2 in the processed air, which was much less than expected.
- The system only processed 14 per cent of the air in the westbound tunnel, so could not have a large impact on in-tunnel NO_2 levels. Enlargement of the system to process all tunnel air was considered to be impractical.
- The system is not cost-effective at reducing NO_2, but there may be potential to develop an effective system.

Other technologies

Consideration also needs to be given to the potential use of other novel techniques for reducing in-tunnel pollutant concentrations which are distinctly different from those discussed earlier. A number of these techniques are reviewed below.

Wet electrostatic precipitation

'Wet' ESP differs from dry ESP primarily in the mechanism by which the collecting electrodes are cleaned, and the collected particles removed. In a typical wet ESP, a continuous washing process is used to clean the collecting electrodes, rather than the mechanical shaking process employed in dry ESPs. The wet environment also creates a potential for the removal, or part removal, of soluble pollutant gases, and assists in retaining and removing ultrafine particles. Some conventional electrostatic precipitation systems already involve an automatic wash process to periodically clean the collection plates, and remove the particles that have been collected. The distinction between this approach and the wet system is that the latter involves a continuously wet environment. One of the advantages argued for wet electrostatic precipitation, compared with the conventional process, is that the presence of a continuously wet environment increases the level of efficiency in removing particles smaller than 1 μm and soluble gaseous contaminants. Wet electrostatic precipitation has been used in a number of industrial applications, but does not appear to have been used in road tunnel applications (Child & Associates, 2004).

Bio-filtration

Bio-filtration is general term used to describe processes in which contaminated air is passed over or through some medium containing micro-organisms capable of consuming, converting or otherwise removing some or all of the harmful pollutants present. Child and Associates (2004) describe bio-filtration systems manufactured by Fijita. Polluted air is passed through an aeration layer into one or two soil beds, each 50 centimetres thick. Removal efficiencies are stated as 95 per cent for TSP 91 per cent for NO_2, 88 per cent for NO, 95 per cent for CO and 94 per cent for SO_2. The authors note, however, that the application of bio-filtration processes to emission treatment in road tunnels involves a conflict between the need to move large volumes of air relatively quickly and the need for air to have relatively long exposures or residence times for the biological processes to be effective. Bio-filtration remains an emission treatment option of potential interest, but still an emerging or developing option in respect of road tunnel applications.

Agglomeration

Agglomeration is an electrostatic process whereby opposite electrical charges are applied to very fine airborne particles, causing them to combine or agglomerate into larger particles, which can then be more easily and effectively removed by other processes, or by gravity. Some electrostatic precipitation technologies include the principle of agglomeration in their basic designs. From a road tunnel viewpoint, agglomeration remains an emerging or developing technology, but would appear to have the potential to enhance the effectiveness of other PM removal systems (Child and Associates, 2004).

Scrubbing

Scrubbing describes a range of processes in which contaminated air is passed through a wash liquid, and pollutants are either entrained or dissolved in the liquid. Scrubbing is a well-established treatment technology in a number of industrial process applications, but generally in applications involving more heavily contaminated or polluted air streams than are experienced in road tunnels. Scrubbing has a potential application in the treatment of road tunnel emissions, but at this stage remains an emerging or developing technology in such applications (Child and Associates, 2004).

Photo-catalytic coatings

Considerable efforts have been made by researchers to develop and refine construction materials and coatings which have the potential for reducing levels of air pollution. The de-polluting properties of these materials are normally reliant upon photo-catalysis, whereby a photo-catalytic substance is used to increase the rate of chemical reactions. One of the most commonly used photo-catalysts is the compound titanium dioxide (TiO_2).

The potential of photo-catalytic coatings to reduce air pollution in tunnels is limited on account of the absence of sunlight, although application to portal walls and street furniture may be beneficial (though not necessarily cost-effective). Italy has experimented with photocatalytic denitrification at the relatively short (350 metres) bidirectional Umberto Tunnel in Rome. However, health concerns relating to TiO_2 appear to have limited its use (CETU, 2010).

Emission controls and other measures

Various operational measures are available to manage in-tunnel emissions and ambient air quality. These include the following:

- Traffic management. Traffic management may be employed by tunnel operators to control exposure to vehicle-derived air pollution. Measures might include (PIARC, 2008):
    - Allowing only certain types of vehicle.
    - Regulating time of use.
    - Tolling (including differential tolling by vehicle type, emission standard, time of day, occupancy)
    - Reducing capacity.
    - Lowering the allowed traffic speed.
- Incident detection. Early detection of incidents and queues is essential to enable tunnel operators and the highway authority to put effective traffic management in place. Monitoring via CCTV cameras is normally a vital part of the procedure for minimising congestion within tunnels.
- Preventing abnormal loads.
- Public information and advice. Traffic lights, barriers, variable message signs, radio broadcasts, loudspeakers and other measures can help to provide driver information and hence influence driver behaviour in tunnels.
- Cleaning the tunnel regularly avoiding high concentrations of small particles (PIARC, 2008).

10.2.3 Summary and implications for the M4 East project

Tunnel design

The project design provisions to reduce pollutant emissions and concentrations within the tunnel will include:

- Minimal gradients. The main alignment tunnels would have a maximum gradient of four per cent. By comparison, the M5 East tunnel has a grade of up to eight per cent on the western exit, which causes trucks to slow down and increase emissions.
- Large main line tunnel cross-sectional area (90 square metres). The tunnel will have a large cross-sectional area to reduce the pollutant concentration for a given emission into the tunnel volume, and to permit greater volumetric air throughput.
- Increased height. The height of the M4 East tunnel (5.3 metres) will be significantly greater than that of the M5 East tunnel (4.6 metres). This will reduce the risk of incidents involving high vehicles blocking the tunnel and leading to disruption of traffic.

Ventilation design and control

The project ventilation system has been designed and would be operated so that it will achieve some of the most stringent standards in the world for in-tunnel air quality, and will be effective at maintaining local air quality. The design of the ventilation system will ensure zero portal emissions.

The ventilation system would be automatically controlled using real-time traffic data covering both traffic mix and speed, and feedback from air quality sensors in the tunnel, to ensure in-tunnel conditions are managed effectively in accordance with the agreed criteria. Furthermore, specific ventilation modes will be developed to manage breakdown, congested and emergency situations.

Air treatment

The effectiveness of the treatment of tunnel emissions has been evaluated as part of the environmental assessment phase of a number of existing Sydney road tunnels, including the M5 East, Cross City Tunnel and Lane Cove Tunnel. It has also been subject of numerous NSW Legislative Council (Upper House) inquiries and independent scientific reviews including by the CSIRO. In general these evaluations have indicated that it is more cost-effective to reduce pollutants at the source, using improved fuel standards and engine technology, which will result in greater benefits to air quality, both in-tunnel and in the ambient air, at the local and regional scales (WDA, 2013).

Electrostatic precipitators

The EIS for NorthConnex included an analysis of the potential costs and benefits of tunnel filtration systems, and argues why such systems are not warranted (AECOM, 2014a,b). These same arguments are also relevant to the M4 East project, and are summarised below.

- M4 East in-tunnel air pollutant levels, which are comparable to best practice and accepted elsewhere in Australia and throughout the world, would be achieved without filtration. As the conventional ventilation system is effective, there would be little benefit in providing an in-tunnel filtration system.
- This Air Quality Assessment Report has demonstrated that the emissions from the ventilation outlets of the M4 East tunnel have a negligible impact on existing ambient pollutant concentrations. These would meet ambient air quality criteria and would pose a very low risk to human health. In this context, there is no basis to justify installation of filtration systems.
- Of the systems that have been installed, the majority have subsequently been switched off or are currently being operated infrequently (in some cases only a few hours per year in response to unusual or infrequent conditions, and/ or ongoing maintenance requirements). Where the operation of in-tunnel air treatment systems have been discontinued or reduced, the reasons have been that
    - The technology has proved to be less effective than predicted.
    - The forecast traffic volumes have not eventuated.
    - Reductions in vehicle emissions.

  As a result of these reasons, the high ongoing operational costs of the technology have not been justified.
- Most tunnels achieve acceptable air quality criteria without filtration. Less than one per cent of tunnels in the world use filtration to reduce particulate matter or nitrogen dioxide levels to maintain acceptable in-tunnel or external air quality. No tunnels in Australia use filtration to meet

If in-tunnel air quality levels could not be achieved with the proposed ventilation system, the most effective solution would be the introduction of additional ventilation outlets and additional air supply locations. This is a proven solution and more sustainable and reliable than tunnel filtration systems.

Incorporating filtration to the ventilation outlets would have negligible benefit and require a significant increase in the size of the tunnel facilities to accommodate the equipment. It would result in increased project size, community footprint, and capital cost. The energy usage would be substantial and does not represent a sustainable approach. Further, the air leaving the outlet is not highly concentrated with pollutants (as demonstrated by the air quality assessment) since it must be of a quality to be acceptable for tunnel users. Any predicted impact on local air quality is very small even without a filtration system.

In summary, the provision of a tunnel filtration system does not represent a feasible and reasonable mitigation measure and is not being proposed.

Denitrification

The technology around tunnel air filtering systems for nitrogen dioxide is relatively new and any benefit has yet to be sufficiently measured.

Emission controls

Smoky vehicle cameras would be installed to automatically detect vehicles with excessive exhaust smoke, with penalties applying to offenders. A similar initiative is in place for the M5 East tunnel and has resulted in a reduction of smoky vehicles using the tunnel.

11 Summary and conclusions

This report presents an assessment of the construction and operational activities that have potential to impact on in-tunnel, local and regional air quality.

The main conclusions of the air quality assessment for the project are summarised below.

11.1 Construction impacts

In the absence of specific direction for projects in NSW, the potential impacts of the construction phase of this project were assessed using guidance published by the UK Institute of Air Quality Management. Professional judgement was required at some stages, and where justification for assumptions could not be fully informed by data a precautionary approach was adopted.

The UK guidance was adapted for use in NSW, taking into account factors such as the assessment criteria for ambient PM_{10} concentrations. The assessment was qualitative in the sense that it assessed the risk that construction works may have on local air quality.

The risk assessment determined that standard management measures would be sufficient to mitigate the effects of construction works on local air quality at the nearest receptors.

11.2 Operational impacts

11.2.1 In-tunnel air quality

In-tunnel air quality for the project was modelled using the IDA Tunnel software and Australia-specific emission factors from PIARC. Consideration was given to peak in-tunnel concentrations of CO and NO_2, as well as the peak extinction coefficient (for visibility). The work covered expected traffic scenarios, capacity traffic scenarios (at a range of speeds, including congestion) and a vehicle breakdown scenario. The information presented in the report has confirmed that the tunnel ventilation system will be designed to maintain in-tunnel air quality well within operational limits for all scenarios.

11.2.2 Ambient air quality (expected traffic)

General conclusions

The following general conclusions have been drawn from this assessment:

- The predicted concentrations of all criteria pollutants at receptors were usually dominated by the existing background contribution. This applied to short-term criteria as well as annual means. The background concentrations were especially dominant for PM_{10} and $PM_{2.5}$.
- For some pollutants and metrics (such as annual mean NO_2) there was also a significant contribution from the modelled surface road traffic.
- Under expected traffic conditions the contribution of tunnel ventilation outlets to pollutant concentrations was negligible for all receptors.
- Any predicted changes in concentration were driven by changes in the traffic volumes on the modelled surface road network, not by the tunnel ventilation outlets.
- Exceedances of some air quality criteria (one-hour NO_2, 24-hour PM_{10}, annual $PM_{2.5}$ and 24-hour $PM_{2.5}$) were predicted to occur at a small proportion of receptors both with and without the project. However, because there was a general reduction in the distribution of predicted concentrations across all receptors, the numbers of receptors with exceedances decreased with the project.
- There would be a general improvements in air quality along Parramatta Road as a result of the project. This is due to a reduction in traffic volumes along Parramatta Road and the improved dispersion of emissions from diverted traffic through tunnel ventilation outlets.

Pollutant-specific conclusions (2021-DS and 2031-DS scenarios)

Carbon monoxide (maximum one-hour mean)

- In all scenarios the predicted maximum one-hour CO concentration was well below the NSW impact assessment criterion of 30 µg/m^3, as well as the lowest international air quality standard identified in the literature.
- There were reductions in maximum CO concentrations at most receptors as a result of the project. There was an increase in CO at 27 per cent of the receptors in 2021, although the increase was greater than 1 mg/m^3 for only 0.3 per cent of receptors.

Carbon monoxide (maximum rolling 8-hour mean)

- As with the one-hour mean, at all the receptors the concentration was well below the NSW impact assessment criterion, which in this case is 10 µg/m^3. No lower criteria appear to be in force internationally.
- The tunnel ventilation outlet contribution at the community receptors was less than 0.3 per cent in 2021.

Nitrogen dioxide (annual mean)

- The annual mean NO_2 criterion for NSW was not exceeded at any receptor in any scenario. The annual mean NO_2 concentrations at the vast majority of receptors were between around 23 µg/m^3 and 30 µg/m^3. In 2021 and 2031 the highest concentrations with the project were predicted to be 34.4 µg/m^3 and 31.4 µg/m^3, compared with the NSW impact assessment criterion of 62 µg/m^3. The concentrations in 2021 and 2031 were also below international standards.
- The maximum contribution of tunnel ventilation outlets at any location in 2021 was 0.1 µg/m^3, whereas the surface road contribution ranged between 2.4 µg/m^3 and 14.2 µg/m^3. The corresponding values for 2031 were 0.13 µg/m^3, 1.8 µg/m^3 and 10.8 µg/m^3.
- There were substantial reductions in annual mean NO_2 at a large number of locations in 2021. There was an increase in NO_2 at 15 per cent of the receptors, although the increase was greater than 1 µg/m^3 for only 0.5 per cent of receptors.
- Annual mean concentrations are highest along major roads, notably the M4 Motorway and Centenary Drive to the south of Sydney Olympic Park, and to a lesser extent Parramatta Road. The project resulted in a general reduction in annual mean NO_2 concentrations along the Parramatta Road corridor.

Nitrogen dioxide (maximum one-hour mean)

- At all community receptor locations investigated in detail, the maximum on-hour NO_2 concentration was below the NSW impact assessment criterion of 246 µg/m^3. There was also compliance with the most stringent international standards at these receptors.
- As with the annual mean, the background was the most important source, with generally a small contribution from surface roads. The ventilation outlet contribution to the maximum NO_2 concentration was zero for all these community receptors.
- There was a general reduction in the distribution of predicted maximum one-hour mean concentrations along the project corridor as a result of the M4 East project.
- There were some predicted exceedances of the one-hour NO_2 criterion at other receptors in the M4 East domain, but not as a consequence of the project. Indeed, the project resulted in a decrease in the number of exceedances. For example, in the 2021-DM scenario the maximum concentration exceeded the criterion at 274 receptors (2.7 per cent of all receptors), but with the introduction of the project in the 2021-DS scenario this decreased to 44 receptors (0.4 per cent).
- The maximum contribution of tunnel outlets to NO_X at any receptor was 13.7 µg/m^3 in 2021-DS (15.6 µg/m^3 in 2031-DS). This would equate to a very small NO_2 contribution relative to the air quality assessment criterion.
- As with the annual mean, the maximum one-hour NO_2 concentrations were highest along the axes of major roads. Substantial reductions in the maximum one-hour NO_2 concentration were predicted along Parramatta Road.

PM_{10} (annual mean)

- The annual mean PM_{10} concentration at the majority of receptors in 2021 was below 20 µg/m^3, and therefore well below the NSW impact assessment criterion of 30 µg/m^3. PM_{10} concentrations were only slightly higher than the lowest PM_{10} standard in the literature (18 µg/m^3 in Scotland), and generally lower than the proposed target for NSW of 20 µg/m^3. The highest predicted concentration at any receptor with the project in 2021 was 22.3 µg/m^3, but as with other pollutants and metrics the highest values were only predicted for a small proportion of receptors.
- The surface road contribution was between 0.6 µg/m^3 and 4.2 µg/m^3. The largest contribution from tunnel ventilation outlets was just 0.06 µg/m^3 in 2021-DS (0.07 µg/m^3 in 2031-DS).
- Again, there was a marked reduction in the distribution of predicted concentrations along the project corridor as a result of the project, with substantial reductions at a large number of locations. In 2021 there was an increase in PM_{10} at 16 per cent of the receptors, although the increase was greater than 0.5 µg/m^3 for only five of the 10,154 receptors. The largest predicted increase in concentration at any receptor as a result of the project in 2021 was 0.7 µg/m^3, and the largest predicted decrease was 2.8 µg/m^3.
- For annual mean PM_{10} there was a fairly even spatial distribution across the domain, reflecting the homogenous nature of background concentrations and the relatively small contribution from road traffic. Slightly elevated concentrations were evident along the major road corridors.

PM_{10} (maximum 24-hour mean)

- At all community receptor locations the maximum concentration was below - but close to - the NSW impact assessment criterion of 50 µg/m^3, which is also the most stringent standard in force internationally.
- The surface road contribution to the maximum 24-hour PM_{10} concentration at each community receptor was small (generally <2 µg/m^3). The ventilation outlet contributions were negligible (<0.2 µg/m^3).
- Some exceedances were predicted at a small proportion of other receptors. In 2021 the proportion of receptors with a concentration above the criterion decreased from 0.9 per cent in the Do Minimum scenario to 0.1 per cent with the project. The maximum contribution of tunnel outlets at any receptor was only 0.37 µg/m^3 in 2021 (0.42 µg/m^3 in 2031).
- With the project in 2021, there was an increase in the maximum 24-hour PM_{10} concentration at 21 per cent of all receptors, although the increase was greater than 2 µg/m^3 for only 0.3 per cent of receptors. The largest predicted increase in concentration at any receptor as a result of the project was 4.8 µg/m^3, and the largest predicted decrease was 10.6 µg/m^3.
- There were predicted to be reductions of up to 20 per cent of the NSW criterion along some sections of Parramatta Road.

$PM_{2.5}$ (annual mean)

- Annual mean $PM_{2.5}$ concentrations were dominated by the background. The surface road contribution was between 0.5 µg/m^3 and 1.1 µg/m^3. The largest contribution from tunnel ventilation outlets was just 0.03 µg/m^3.
- The predictions for annual mean $PM_{2.5}$ were based on an assumed background concentration of 8 µg/m^3 (the AAQ NEPM advisory reporting standard), and therefore exceedances were predicted for all receptors. Internationally, there are no standards lower than 8 µg/m^3 for annual mean $PM_{2.5}$. Clearly the predicted exceedances were not a consequence of the project.
- The highest concentration at any receptor in the 2021-DS scenario was 10.8 µg/m^3, but as with other pollutants and metrics the highest values were only predicted for a small proportion of receptors. The surface road contribution was between 0.4 µg/m^3 and 2.8 µg/m^3. The largest contribution from tunnel ventilation outlets in 2021 was 0.04 µg/m^3 (0.05 µg/m^3 in 2031).
- There were substantial reductions in concentration at a large number of locations. There was an increase in $PM_{2.5}$ at 15 per cent of the receptors, although the increase was greater than 0.2 µg/m^3 for only 0.4 per cent of receptors. The largest predicted increase in concentration at any receptor as a result of the project was 0.5 µg/m^3, and the largest predicted decrease was 1.9 µg/m^3.

$PM_{2.5}$ (maximum 24-hour mean)

- At all community receptor locations the maximum concentration was below - but close to – the NSW impact assessment criterion of 25 µg/m^3. Internationally, there are no standards lower than 25 µg/m^3 for 24-hour $PM_{2.5}$.
- The road contributions to the maximum 24-hour $PM_{2.5}$ concentration were small (generally <1 µg/m^3), except in a few cases. The outlet contributions were negligible (<0.2 µg/m^3).
- The maximum 24-hour mean $PM_{2.5}$ concentrations at the majority of receptors was below the NSW impact assessment criterion of 25 µg/m^3. The proportion of receptors with a concentration above the criterion decreased from 2.5 per cent in the Do Minimum scenario to 0.5 per cent with the project. The maximum contribution of tunnel outlets at any receptor was only 0.25 µg/m^3 in 2021 (0.30 µg/m^3 in 2021).

Air toxics

- Four air toxics - benzene, PAHs (as BaP), formaldehyde and 1,3-butadiene - were considered in the assessment. These compounds were taken to be representative of the much wider range of air toxics associated with motor vehicles, and they have commonly been assessed for road projects.
- The changes in the maximum one-hour concentrations were compared with the relevant NSW impact assessment criteria. For each compound, where there was an increase in the concentration, this was well below the NSW impact assessment criterion.

Pollutant-specific conclusions (2031-DSC scenario)

In the majority of cases the results for the community and RWR receptors in the 2031-DSC scenario were very similar to those in the 2031-DS scenario..

11.2.3 Ambient air quality (regulatory worst case)

The regulatory worst case scenario was assessed for the tunnel ventilation outlets only. The findings were as follows:

- The maximum contribution to the maximum one-hour CO concentration was negligible.
- The maximum contribution to the annual mean NO_2 concentration was not insignificant. However, total concentrations would have remained well below the criterion.
- The maximum contribution to the maximum one-hour mean NO_2 concentration could be significant, but could not be quantified definitively.
- The maximum contribution from the ventilation outlets would not have had a significant impact on annual mean PM_{10} and $PM_{2.5}$ concentrations.
- The most significant result was that for the 24-hour $PM_{2.5}$ contribution (and similarly the 24-hour PM_{10} contribution).

Whilst the contributions to maximum one-hour concentrations of NO_2 and 24-hour concentrations of $PM_{2.5}$ could be significant they would not represent a cause for concern in reality.

The peak in-tunnel concentrations for all traffic scenarios, including the capacity traffic at different speeds, were well within the in-tunnel concentrations associated with the regulatory worst case scenarios. It therefore follows that the predicted ventilation outlet contributions to ambient concentrations for any in-tunnel traffic scenario would be lower than those for the regulatory worst case.

It can be concluded that emissions from the project ventilation outlets, even in the regulatory worst case scenarios, would be extremely unlikely to result in an adverse impacts on local air quality. WDA will conduct ambient air quality monitoring to demonstrate that emissions from the ventilation outlets will have no detectable impact on local air quality.

11.3 Management of impacts

11.3.1 Construction impacts

A range of measures for the management of construction impacts has been provided in the report. Most of the recommended measures are routinely employed as ‘good practice’ on construction sites. A Construction Air Quality Management Plan will be produced to cover all construction phases of the M4 East project. This should contain details of the site-specific mitigation measures to be applied.

11.3.2 Operational impacts

The report has provided a review of the measures that are available for improving tunnel-related air quality, and then describes their potential application in the context of the project. The measures that will be adopted for the project are summarised below.

Tunnel design

The project design provisions to reduce pollutant emissions and concentrations within the tunnel will include:

- Minimal gradients. The main alignment tunnels would have a maximum gradient of 4 per cent.
- Large main line tunnel cross-sectional area (90 m^2).
- Increased height to reduce the risk of incidents involving high vehicles blocking the tunnel.

Ventilation design and control

The project ventilation system has been designed and would be operated so that it will achieve some of the most stringent standards in the world for in-tunnel air quality, and will be effective at maintaining local air quality. The design of the ventilation system will ensure zero portal emissions.

The ventilation system would be automatically controlled using real-time traffic data covering both traffic mix and speed, and feedback from air quality sensors in the tunnel, to ensure in-tunnel conditions are managed effectively in accordance with the agreed criteria. Furthermore, specific ventilation modes will be developed to manage breakdown, congested and emergency situations.

Air treatment

The provision of a tunnel filtration system does not represent a feasible and reasonable mitigation measure and is not being proposed. The reasons for this are as follows:

- M4 East in-tunnel air pollutant levels, which are comparable to best practice and accepted elsewhere in Australia and throughout the world, would be achieved without filtration.
- Emissions from the ventilation outlets of the M4 East tunnel will have a negligible impact on existing ambient pollutant concentrations.
- Of the systems that have been installed, the majority have subsequently been switched off or are currently being operated infrequently.
- Incorporating filtration to the ventilation outlets would require a significant increase in the size of the tunnel facilities to accommodate the equipment. It would result in increased project size, community footprint, and capital cost. The energy usage would be substantial and does not represent a sustainable approach.

If in-tunnel air quality levels could not be achieved with the proposed ventilation system, the most effective solution would be the introduction of additional ventilation outlets and additional air supply locations. This is a proven solution and more sustainable and reliable than tunnel filtration systems.

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Appendix A - Traffic pollutants and their effects

A.1 Overview

This Appendix summarises the health and non-health effects of the traffic-related pollutants that were included in the assessment.

Road vehicles emit a complex mixture of pollutants. These are generated though combustion processes (CO, NO_X, PM and many different hydrocarbon compounds), evaporation processes (VOCs) and abrasion processes (PM from tyre wear, brake wear, *etc.*). The resuspension of material on the road surface also contributes to ambient PM concentrations, but this is not always considered in models because of its site-specific nature and a lack of suitable emission factors.

Various studies have linked road traffic emissions to health outcomes, and this Appendix has considered reviews of these studies by the following organisations:

- The World Health Organization (WHO).
- The United States Environmental Protection Agency (USEPA).
- The Committee on the Medical Effects of Air Pollutants (COMEAP) in the UK.
- The Health Effects Institute (HEI).

In the following sections a traditional approach is used to explain the health effects of traffic pollutants, whereby each pollutant is treated separately. The traffic pollutants causing most concern at present are NO_2 and PM. For example, $PM_{2.5}$ from vehicle exhaust is increasingly cited as a key health-related metric. It has been noted by WHO that there is an elevated health risk associated with living close to roads, but also that this is unlikely to be explained by $PM_{2.5}$ alone (WHO Regional Office for Europe, 2013).

A.2 Carbon monoxide

A.2.1 Health effects

Carbon monoxide (CO) is a colourless, odourless gas. It can be harmful to humans because, when inhaled, it is taken up by haemoglobin in the blood (forming carboxyhaemoglobin) in preference to oxygen, thus reducing the capacity of the blood to transport oxygen. The affinity of CO for haemoglobin is more than 200 times greater than that of oxygen.

At low concentrations the symptoms of CO intoxication include lethargy in healthy adults, and chest pain in people with heart disease. At higher concentrations CO leads to impaired vision and coordination, headaches, dizziness, confusion and nausea. CO is fatal at very high concentrations[1]. Symptoms are not generally reported until the carboxyhaemoglobin level in the blood exceeds 10%. This is approximately the equilibrium value achieved with an ambient concentration of 70 mg/m^3 for a person engaged in light activity. There is evidence that there is a risk for individuals with cardiovascular disease at lower carboxyhaemoglobin levels. A carboxyhaemoglobin level in the blood of 40-50% usually leads to death. However, in most Australian towns and cities the levels of CO in ambient air are well below those that are hazardous to human health. Only in larger cities do CO levels have the potential to have harmful effects[2].

A.2.2 Other effects

CO plays a role in the formation of ground-level ozone. It also has an indirect radiative forcing effect on climate by elevating concentrations of methane and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g. the hydroxyl radical, OH) that would otherwise destroy them.

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[1] http://www.epa.gov/iaq/co.html#Health_Effects

[2] http://www.environment.gov.au/protection/publications/factsheet-carbon-monoxide-co

A.3 Nitrogen dioxide

A.3.1 Health effects

NO_2 is one of the most important road traffic pollutants. It is an irritant and oxidant which has been linked to a range of adverse health effects including deterioration in lung function, respiratory symptoms, asthma prevalence and incidence, cancer incidence, and birth outcomes (e.g. birth weight). The most consistent associations, however, have been found with respiratory outcomes (COMEAP, 2009).

For short-term exposure the extensive review by the WHO Regional Office Europe (2013) noted that many studies have documented associations between variations in NO_2 concentration and respiratory symptoms, hospital admissions and mortality, even after adjustment for PM and other pollutants for some health outcomes.

For long-term exposure there is likely to be a causal relationship between NO_2 and respiratory effects, although NO_2 may act as a marker for other traffic pollutants. The evidence for cardiovascular effects and total mortality is suggestive, but not sufficient to infer a causal relationship (WHO Regional Office for Europe, 2013; USEPA, 2015).

A recent review by NSW Health (2015) concluded that there are some limited data to support the setting of a health-based NO_2 limit for road tunnels. At concentrations below 0.2 ppm no health effects have been observed in chamber studies. At concentrations between 0.2 ppm and 0.5 ppm for 20-30 minutes, some health effects have been observed in susceptible groups. For example, Svartengren et al. (2000) found that exposure to air pollution in road tunnels may significantly enhance asthmatic reactions to subsequently inhaled allergens. NSW Health noted that, for exposures at concentrations above 0.5 ppm for 20-30 minutes, health effects were observed in healthy people. It was concluded that the evidence suggests that sensitive populations may experience adverse health effects if exposed for 20-30 minutes to tunnel air with an NO_2 concentration of 0.5 ppm.

A.3.2 Other effects

Emissions of nitrogen oxides NO_x are implicated in regional phenomena such as acidification, eutrophication and loss of biodiversity, as well as the formation of secondary PM in the atmosphere. NO_2 also absorbs visible solar radiation and contributes to impaired atmospheric visibility. It is an important regulator of the oxidising capacity of the troposphere (the lowest layer of the atmosphere), in that it controls the build-up and fate of radicals[3]. It also plays a critical role in determining ozone concentrations in the troposphere.

A.4 Particulate matter

A.4.1 Health effects

The pollutant generally accepted as having the greatest public health impact is particulate matter (Harrison, 2010). The biological effects of inhaled particles are determined by their physical and chemical properties, by their sites of deposition, and by their mechanisms of action. The extent to which particles can penetrate the respiratory tract, and their potential for causing health effects, is directly related to their size (Harrison et al., 2010). Notably, particles with a diameter of less than 2.5 µm can penetrate deep into the human respiratory system, and it is these which are of most concern.

In recent years evidence has accumulated indicating that airborne particles have a range of adverse effects on health. These effects – which are diverse in scope, severity and duration - include:

- Premature mortality.
- Aggravation of cardiovascular disease such as atherosclerosis.
- Aggravation of existing respiratory disease such as asthma.

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[3] Radicals (or 'free radicals') are atomic or molecular species with unpaired electrons. These unpaired electrons are usually highly reactive, so radicals are likely to take part in chemical reactions.

- Changes to lung tissue, structure and function.
- Cancer[4]. Importantly, the International Agency for Research on Cancer has recently classified outdoor air pollution as carcinogenic to humans, with a specific emphasis on PM and diesel engine exhaust (IARC, 2012; 2013).
- Reproductive and developmental effects.
- Changes in the function of the nervous system.

There is evidence that short-term and long-term exposure to $PM_{2.5}$ causes illness and death from cardiovascular conditions, and is likely to cause respiratory conditions (USEPA 2009; WHO Regional Office for Europe, 2013). The effects observed in relation to $PM_{2.5}$ from a large study conducted in Australia and New Zealand (EPHC, 2010) are consistent with the effects reported in the international literature.

There is extensive evidence that short-term exposure to PM_{10} is associated with health effects, and that these effects are independent of the effects of $PM_{2.5}$ (USEPA, 2009; WHO Regional Office for Europe, 2013). There is substantially less evidence that long-term exposure to PM_{10} has health effects that are independent of those caused by long-term exposure to $PM_{2.5}$. As with $PM_{2.5}$, the effects observed in the Australian and New Zealand NEPC multi-city study (EPHC, 2010) in relation to PM_{10} exposure are consistent with those observed internationally.

Studies have also investigated the relationship between specific PM components (for example, black carbon, secondary organic aerosol (SOA) and secondary inorganic aerosol (SIA)) and health effects (WHO Regional Office for Europe, 2013). In the future, the use of these metrics may provide a better indication of exposure to PM from particular sources, such as vehicle exhaust, and may improve the understanding of the associated health risks.

No safe threshold has been identified for the human health effects of particles (NSW DECCW, 2010); for $PM_{2.5}$ there is substantial evidence of health associations down to very low levels. In Canada, Crouse et al. (2012) investigated the long-term exposure to ambient $PM_{2.5}$ and observed associations with cardiovascular mortality at concentrations as low as only a few micrograms per cubic meter. This last study is particularly relevant, because it investigated the effects of $PM_{2.5}$ at the levels commonly experienced in Australia.

A.4.2 Other effects

Particulate matter has the capacity to influence climate locally, regionally and globally. Black carbon from combustion sources has much the same effect as a greenhouse gas, although the mechanisms are different. White particles such as ammonium sulfate are reflective and have a net cooling effect by reflecting incoming solar radiation back to space. Water-soluble particles can act as cloud condensation nuclei, thus affecting the reflectivity of clouds and leading to a reduction in land surface warming (Harrison, 2010).

Airborne particles also reduce atmospheric visibility by the scattering and absorption of visible light. Visibility is an important safety concern for tunnel design. The amount of scattering or absorption is dependent upon particle size, composition and density. Vehicle exhaust contains a large number of very small particles (0.01 to 0.20 µm diameter) (see Appendix B), and particles in this size range are very effective at light extinction (PIARC, 2012).

A.5 Air toxics

Road vehicles produce a wide range of organic compounds through combustion and evaporation. These compounds are involved in the formation of photochemical smog, which is associated with irritation of the eyes and respiratory tract, amongst other things. Many of the organic compounds emitted by road vehicles also have impacts on health and the environment in their own right.

It is uncommon for air quality assessments to address a large number of organic pollutants. It is more usual for a small number of the most important components to be assessed, with inferences being

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[4] Particles may contain carcinogenic substances such as polycyclic aromatic hydrocarbons (PAHs) or heavy metals.

made in relation to others. The compounds included in the assessment were benzene, benzo(a)pyrene (as a marker for polycyclic aromatic hydrocarbons), formaldehyde, and 1,3-butadiene. With respect to road traffic these pollutants are generally less of a concern than in the past, as improvements in fuel quality, through higher fuel standards, in recent years have reduced the amounts being emitted from vehicles.

A.5.1 Benzene

Benzene is a constituent of road transport fuel, but since 2006 the benzene content of petrol in Australia has been limited to 1% by volume (compared with 5% previously). This reduction had an immediate and sustained impact on ambient benzene levels.

Short-term inhalation exposure to benzene can cause drowsiness, dizziness, headaches, as well as eye, skin, and respiratory tract irritation, and, at high levels, unconsciousness. Long-term inhalation exposure has caused blood disorders including reduced numbers of red blood cells and anaemia. Reproductive effects have been reported for women. Increased incidence of leukaemia has been observed in humans occupationally exposed to benzene. The USEPA has classified benzene as known human carcinogen[5].

A.5.2 Polycyclic aromatic hydrocarbons (PAHs)

The term PAH covers a large group of organic compounds with two or more fused aromatic rings. Around 500 PAHs and related compounds have been detected in the air (WHO, 2000). PAHs are formed by incomplete combustion of fuels, including transport fuels, and can be present in both the gas and (more commonly) particle phases. The USEPA has designated 32 PAH compounds as priority pollutants. A short list of compounds is often targeted for measurement in environmental samples. Of these, the most measurements have been made for benzo(a)pyrene, and this compound is used as a marker for PAHs in the Air Toxics NEPM.

PAHs are a concern because they are persistent in the environment for long periods of time. There is little information on the health effects of exposure to individual PAHs at specific concentrations. Short-term exposure to mixtures of PAHs is known to cause skin irritation and inflammation. Anthracene, benzo(a)pyrene and naphthalene are direct skin irritants, while anthracene and benzo(a)pyrene are reported to cause an allergic skin response. The health effects of long-term exposure to PAHs may include cataracts, kidney and liver damage and jaundice. Naphthalene, a specific PAH, can cause the breakdown of red blood cells if inhaled or ingested in large amounts. Long-term studies of workers exposed to mixtures of PAHs and other workplace chemicals have shown an increased risk of skin, lung, bladder and gastrointestinal cancers (USEPA, 2008; SA Health, 2009).

A.5.3 Formaldehyde

Formaldehyde is a colourless gas with a pungent odour. Major sources include power plants, manufacturing facilities, incinerators, and automobile exhaust. Short-term and long-term inhalation of formaldehyde can result in respiratory symptoms, and eye, nose, and throat irritation. Limited human studies have reported an association between formaldehyde exposure and lung and nasopharyngeal cancer. The USEPA considers formaldehyde to be a probable human carcinogen[6].

A.5.4 1,3-butadiene

Motor vehicle exhaust is a source of 1,3-butadiene. Although it breaks down quickly in the atmosphere, it is usually found in ambient air at low levels in urban and suburban areas. Short-term exposure to 1,3-butadiene by inhalation results in irritation of the eyes, nasal passages, throat, and lungs. Epidemiological studies have reported a possible association between 1,3-butadiene exposure and cardiovascular diseases. The USEPA has classified 1,3-butadiene as carcinogenic to humans by inhalation[7].

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[5] http://www.epa.gov/ttn/atw/hlthef/benzene.html

[6] http://www.epa.gov/ttn/atw/hlthef/formalde.html

[7] http://www.epa.gov/ttnatw01/hlthef/butadien.html

Appendix B - Pollutant formation, dispersion and transformation

B.1 Overview

This Appendix summarises the processes that are involved in the formation of traffic pollutants, and their subsequent dispersion and transformation in the atmosphere. It is not designed to be comprehensive, but to provide additional contextual information for the pollutants included in the assessment.

B.2 Formation of primary pollutants

B.2.1 Combustion

Most road vehicles are powered by internal combustion engines in which energy is derived from the burning of fuel in air. The main products of combustion are CO_2 and water vapour. However, several different processes lead to other compounds being present in vehicle exhaust in lower concentrations. The formation these compounds during combustion is summarised in the following sections.

B.2.1.1 Carbon monoxide

Not all of the fuel is completely consumed during combustion. Incomplete combustion usually results from insufficient oxygen in the combustion mixture, and this leads to the production of carbon monoxide (CO). Historically, the main source of CO in urban areas has been petrol vehicles. However, emissions of CO from petrol vehicles have reduced substantially in recent years as a result of the emission legislation effectively mandating the fitting of a three-way catalyst (TWC)[1]. Diesel engines produce relatively little CO as they burn the fuel with excess air in the combustion chamber, even at high engine loads.

B.2.1.2 Hydrocarbons

During combustion the flame is ‘quenched’ by the cylinder walls, leaving behind unburnt and partially burnt fuel that is expelled with the exhaust. The unburnt and partially burnt fuel contains many different organic compounds, referred to collectively as total hydrocarbons (THC). As with CO, hydrocarbon emissions from petrol vehicles have greatly decreased as a result of TWCs, and hydrocarbon emissions from diesel engines are low for the reason mentioned above for CO.

B.2.1.3 Oxides of nitrogen

At the high temperatures and pressures in the combustion chamber some of the nitrogen in the air is oxidised, forming mainly nitric oxide (NO) with some nitrogen dioxide (NO_2). NO formation is also enhanced by oxygen-rich fuelling conditions, and proceeds via two main mechanisms. The main NO mechanism is known as the ‘thermal’ (or Zel’dovich) cycle, and this is responsible for more than 90 per cent of emissions (Heywood, 1988; Vestreng *et al.*, 2009). NO_2 is predominantly a secondary pollutant, being produced by the oxidation of NO in atmospheric photochemical reactions (see Section B.4). Any NO_2 that is emitted directly from vehicles is referred to as ‘primary NO_2’.

NO_X emissions from petrol vehicles have also decreased as a consequence of TWCs. However, analyses in Europe have shown that, despite the reductions in vehicle emissions that are calculated in inventories, NO_2 concentrations at many roadside monitoring sites are not decreasing. Further analyses have indicated that a significant proportion of ambient NO_2 must be emitted directly from vehicle exhaust, and that the direct road traffic contribution to ambient NO_2 has increased in recent

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[1] Concentrations of pollutants in the exhaust gas depend on the air/fuel mixture. For lean mixtures (*i.e.* where there is an excess of air in the combustion chamber) the exhaust gases contain little CO or HC, but high concentrations of NO_X. Rich mixtures (*i.e.* where there is an excess of fuel) produce high concentrations of CO and HC, with little NO_X. A TWC results in the simultaneous conversion of CO to CO_2, HC to water, and NO_X to nitrogen. The emission rates of these pollutants are typically an order of magnitude lower than those for non-catalyst petrol cars. A closed-loop air-fuel ratio controller is required to maintain stoichiometric conditions for the TWC to work effectively. Precise control is especially important for efficient NO_X reduction, as the NO_X conversion drops dramatically for lean mixtures.

years (Jenkin, 2004; Carslaw and Beevers, 2004; Carslaw, 2005; Hueglin *et al*., 2006; Grice *et al*., 2009). Two contributing factors have been cited:

- Diesel vehicles emit more NO_x than petrol vehicles, and with a larger proportion of NO_2 in NO_x (termed *f*-NO_2). The market share of diesel vehicles has increased in many European countries in recent years.
- The average value of *f*-NO_2 in diesel exhaust is increasing. This appears to be linked to the growth in the use of specific after-treatment technologies in modern diesel vehicles which involve *in situ* generation of NO_2, such as catalytically regenerative particle filters (Carslaw, 2005).

Furthermore, it seems likely that real-world NO_x emissions from road vehicles are not decreasing as rapidly as models are predicting (Rexeis and Hausberger, 2009). Whilst this does not, in itself, affect actual NO_2 concentrations, it does suggest that NO_x controls have not been sufficiently stringent, or that vehicles are not performing as expected. The consequence of this is that there is now a great deal of interest in the tighter regulation of NO_x and NO_2 emissions from diesel vehicles and the effects of different after-treatment devices.

Historically a fairly low value for *f*-NO_2 (5-10 per cent) has been used in air quality and in-tunnel assessments in NSW. However, primary NO_2 emissions from vehicles in Sydney are not well documented. A recent update of the evidence was provided by Boulter and Bennett (2015). Several different data sets and analytical techniques were presented, including emission modelling, the analysis of ambient air quality measurements, and the analysis of emissions from tunnel ventilation outlets. The work focussed on highway traffic conditions, as these were considered to be the most relevant to tunnels in Sydney. The findings suggested that there has been a gradual increase in *f*-NO_2 in recent years, from less than 10 per cent before 2008 to around 15 per cent in 2014.

Time series (2003-2041) of NO_X and NO_2 emission factors for highway traffic in the NSW EPA inventory model, weighted for the default traffic mix in each year, and the associated values of *f*-NO_2, are shown in Figure B-1. The *f*-NO_2 values for different vehicle types and emission legislation were taken from Pastramas *et al.* (2014). Emission factors are also presented for situations with and without the adoption of the Euro VI regulation. Whilst the NO_X emission factors are predicted to decrease with time, there is a sharp increase in *f*-NO_2 after 2008, with a levelling off at around 12-15 per cent (no Euro VI case) between 2020 and 2030. The main reason for the increase in *f*-NO_2 is the increased market penetration of diesel cars into the Sydney vehicle fleet. There is insufficient information on the types and distributions of exhaust after-treatment devices fitted to vehicles in Sydney, and so it is not possible to determine the extent to which this is a contributing factor.

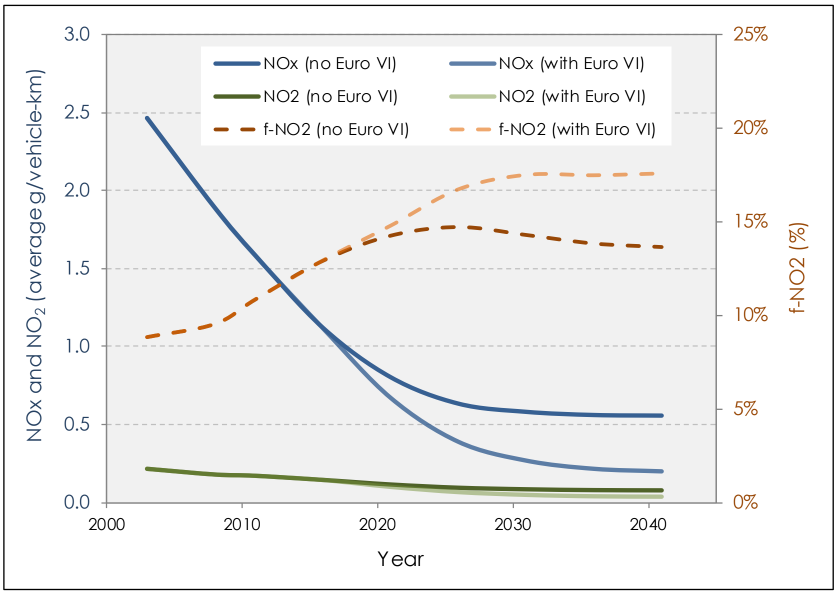

Figure B-1 **Emission factors for NO_x, NO_2 and f-NO_2 from the GMR emissions inventory model for highways/freeways (80 km/h), weighted for default traffic mix.**

B.2.1.4 Particulate matter

Incomplete combustion also results in the production of particulate matter (PM). Diesel vehicles therefore represent the main (exhaust) source of PM from road transport, although recent studies indicate that gasoline-powered vehicles with direct fuel injection also contribute to PM emissions (PIARC, 2012).

Particles in diesel exhaust cover a range of sizes, and the shape of the size distribution depends on whether the weighting is by number or mass, as shown in Figure B-2. There are three distinct size modes: the nucleation mode (sometimes referred to as ‘nuclei’ or ‘nanoparticles’), the accumulation mode, and the coarse mode. The nucleation mode has traditionally been defined as particles with a diameter of less than 50 nanometres (nm), but other size-cut offs have been used. Accumulation mode particles range in size from around 50 nm to around 1 µm, with particles smaller than 0.1 µm being referred to as ultrafine particles. The coarse mode consists of particles larger than around 1 µm.

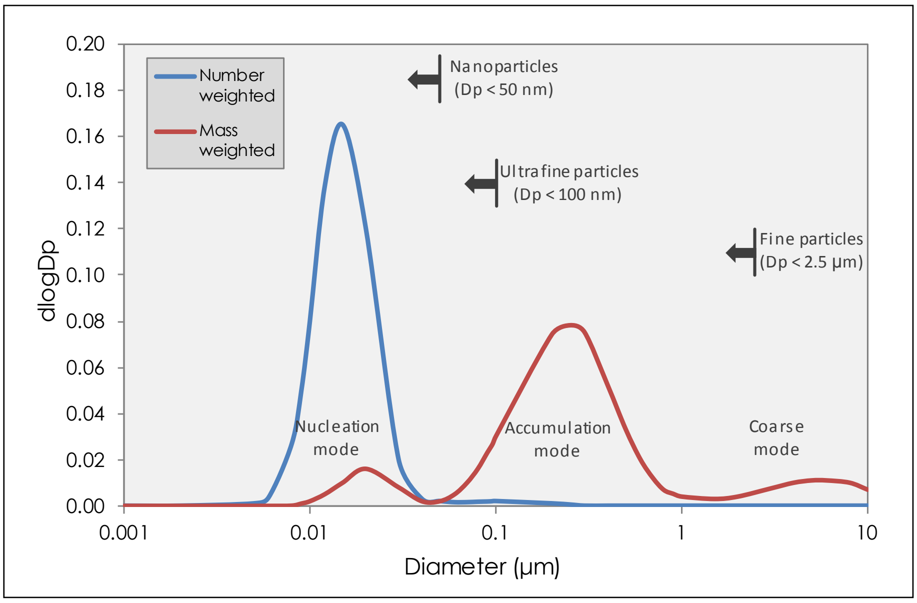

Figure B-2 **Typical particle size distributions in vehicle exhaust; the y-axis is a normalised log scale (adapted from Kittelson, 1998)**

The processes of particle formation during diesel combustion have been described in detail (*e.g.* Heywood, 1988). Carbonaceous spherules (soot) are initially created in the cylinder. A phase of particle growth then follows, involving the adsorption of gas-phase components, as well as coagulation and agglomeration. Almost all the particle mass found in the exhaust prior to dilution is present as these carbonaceous agglomerates. Most nucleation mode particles are thought to originate from the condensation of volatile material (hydrocarbons, hydrated sulphuric acid and salts) in the exhaust gas during dilution, rather than during combustion itself, and their formation is a function of measurement parameters such as temperature, dilution ratio, residence time, and humidity (Kittelson, 1998; Abdul-Khalek *et al*., 1999; Mathis, 2002), as well as fuel sulphur content (Maricq *et al*., 1999; Ntziachristos *et al*., 2000). Particles in the coarse mode are formed by re-entrainment of material previously deposited on engine cylinder and exhaust system surfaces.

The usual means of complying with the stringent PM mass emission limits for modern diesel vehicles is through the use of a diesel particulate filter (DPF) which physically captures particles in the exhaust stream. However, DPFs can have limited effectiveness in controlling non-solid PM components, and some increases in particle number have also been reported due to hydrocarbon and sulphate nucleation occurring downstream of after-treatment devices.

B.2.2 Evaporation

Volatile organic compounds (VOCs) are emitted from the fuel systems of petrol vehicles as a result of evaporation. The compounds which are emitted are mainly of light hydrocarbons (C_4-C_6) (CONCAWE, 1987). Evaporative emissions from diesel-fuelled vehicles are considered to be negligible due to the low volatility of diesel fuel.

There are several different mechanisms of evaporation. ‘Diurnal losses’ result from the thermal expansion and emission of vapour, mainly in the fuel tank, in response to changes in ambient temperature during the day. ‘Hot-soak losses’ occur when a warm engine is turned off and heat is dissipated into the fuel system. Whilst a vehicle is being driven the engine provides a continuous input of heat into the fuel system, resulting in ‘running losses’.

Evaporative emissions are dependent upon four major factors: the vehicle design, the ambient temperature, the volatility of the petrol and the driving conditions. Emissions are decreasing as a result of new cars being equipped with sealed fuel injection systems and activated carbon canisters in fuel tank vents (Krasenbrink et al., 2005).

B.2.3 Abrasion and resuspension

As well as being present in vehicle exhaust, PM is generated by various abrasion processes including tyre wear and brake wear.

Tyre wear is a complex process. The amount, size, and chemical composition of the emitted PM is influenced by various factors including tyre characteristics, the type of road surface, vehicle characteristics and vehicle operation. Tyres contain a vast array of organic compounds and several important inorganic constituents. Although some research has been carried out to characterise wear particles, the understanding remains incomplete (Thorpe and Harrison, 2008).

Brake wear particles are composed of metals (iron, copper, lead, etc.), organic material, and silicon compounds which are used as binders in brake pads, but again composition varies greatly (Thorpe and Harrison, 2008). Test track and wind tunnel measurements have revealed that typically 50 per cent of the brake wear debris escapes the vehicle and enters the atmosphere, although the actual proportion depends on the severity of the braking and the design of the vehicle (Sanders et al., 2003). It appears that most airborne brake wear particles are quite coarse, although a substantial proportion has a diameter of less than 2.5 μm (Garg et al., 2000; Abu-Allaban et al., 2003; Iijimia et al., 2007).

Another source - the resuspension of material previously deposited on the road surface - occurs as a result of tyre shear, vehicle-generated turbulence, and the action of the wind. Studies in the United States have indicated that resuspension is responsible for between 30 per cent and 70 per cent of total PM_{10} in urban areas (Zimmer et al., 1992; Gaffney et al., 1995; Kleeman and Cass, 1999). Large contributions of resuspension have also been observed in some European studies (notably in Scandinavia), although the conditions in these studies (e.g. climate, use of studied tyres in winter) are not necessarily representative of those in Sydney.

It is possible that non-exhaust PM is less important for tunnels than for surface roads, as under normal operating conditions in many road tunnels there is probably less braking than on surface roads (e.g. fewer intersections), and less cornering (i.e. tyre wear). This is likely to result in less material being deposited on roads in tunnels than on roads in the external environment, resulting in a smaller contribution from resuspension. However, these effects are not well quantified at present.

B.3 Pollutant dispersion and transformation

B.3.1 Spatial distribution of pollution in an urban area

Once pollutants have been released into the atmosphere they are subject to various physical dispersion processes. These processes, in combination with a varying density of emission sources and chemical transformations (see Section B.4), result in a very uneven distribution of pollution across an urban area.

Figure B-3 shows a simplified representation of pollutant concentrations in and around an urban area with a high density of population and activity in the centre and a lower density in the surrounding districts. The regional background pollution originates from a range of sources, extends over a wide area, and is relatively constant outside the urban area. Within the urban area there is an additional ‘urban background’ component which is influenced by area-wide emission sources such as domestic and commercial heating, as well as general contributions from transport and industry. Alongside heavily-trafficked roads there is likely to be a significant local contribution to the concentration. This local traffic contribution is more pronounced for some pollutants (notably NO_X) than others (such as PM).

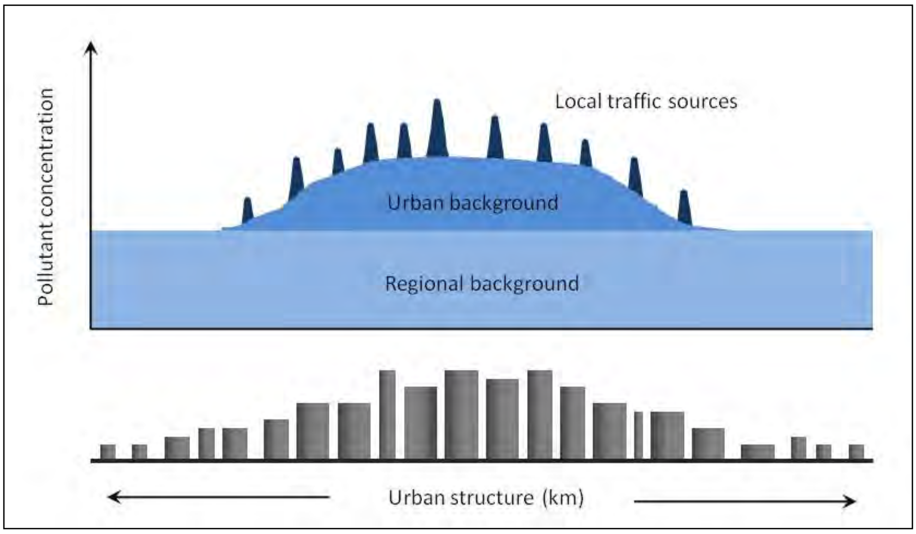

Figure B-3 **Simplified representation of urban structure and pollution levels (adapted from Keuken et al., 2005)**

The general dispersion and transformation of pollutants is influenced to a large extent by the local meteorology. For example, the temperature inversions and low wind speeds associated with stable high-pressure systems can restrict dispersion and lead to high concentrations. High temperatures in summer promote the formation of ozone and other photochemical pollutants, and extreme weather events are often associated with peak levels of pollution. The frequency and severity of pollution events in Sydney are strongly influenced by the regional terrain and the presence of the sea, which affect the circulation of air (DSEWPC, 2011).

Dispersion is also influenced by the local topography and by the presence of local obstacles such as buildings. Buildings generate turbulence and can create complicated air flow patterns including areas of accelerated flow and wakes. The influence of buildings on the plume from a tunnel ventilation outlet is known as building downwash. This can occur when the aerodynamic turbulence induced by nearby buildings causes a pollutant emitted from the elevated outlet to be rapidly mixed to the ground. This will depend on a number of factors such as the height and speed at which the plume is released, as well as the height of the nearest buildings and their distance from the stack. Whether or not a plume is directly influenced by building downwash will also depend on the speed of the ambient air at the time the plume is released. In other words, if wind speeds are low, the effect the building has on the plume may be negligible.

In the vicinity of roads, vehicle-induced turbulence needs to be taken into account. Alongside roads the turbulence caused by the moving vehicles is likely to be more significant than that caused by buildings.

B.3.2 Concentration gradients near roads

Traffic pollutants undergo rapid changes in the near-road environment, and concentration gradients in the vicinity of roads have been examined in various studies. Some examples of the results for different pollutants and periods of the day are shown in Figure B-4. The Figure is based on the findings of Gordon et al. (2012), who used a mobile laboratory to measure the concentration gradients of ultrafine particles (UFP), black carbon (BC), CO_2, NO, and NO_2 at varying distances from a major highway in Toronto, Canada.

For primary pollutants such as NO and BC, concentrations decay exponentially with increasing distance from the road. Reviews have shown that these typically decrease to background levels between around 100 and 500 metres from roads (e.g. Karner et al., 2010; Zhou and Levy, 2007).

Many primary pollutants react together, and with pollutants from other sources, to form secondary pollutants. For these the situation is more complex; because of the time required for their formation, the concentrations of secondary pollutants are not always highest near the emission source.

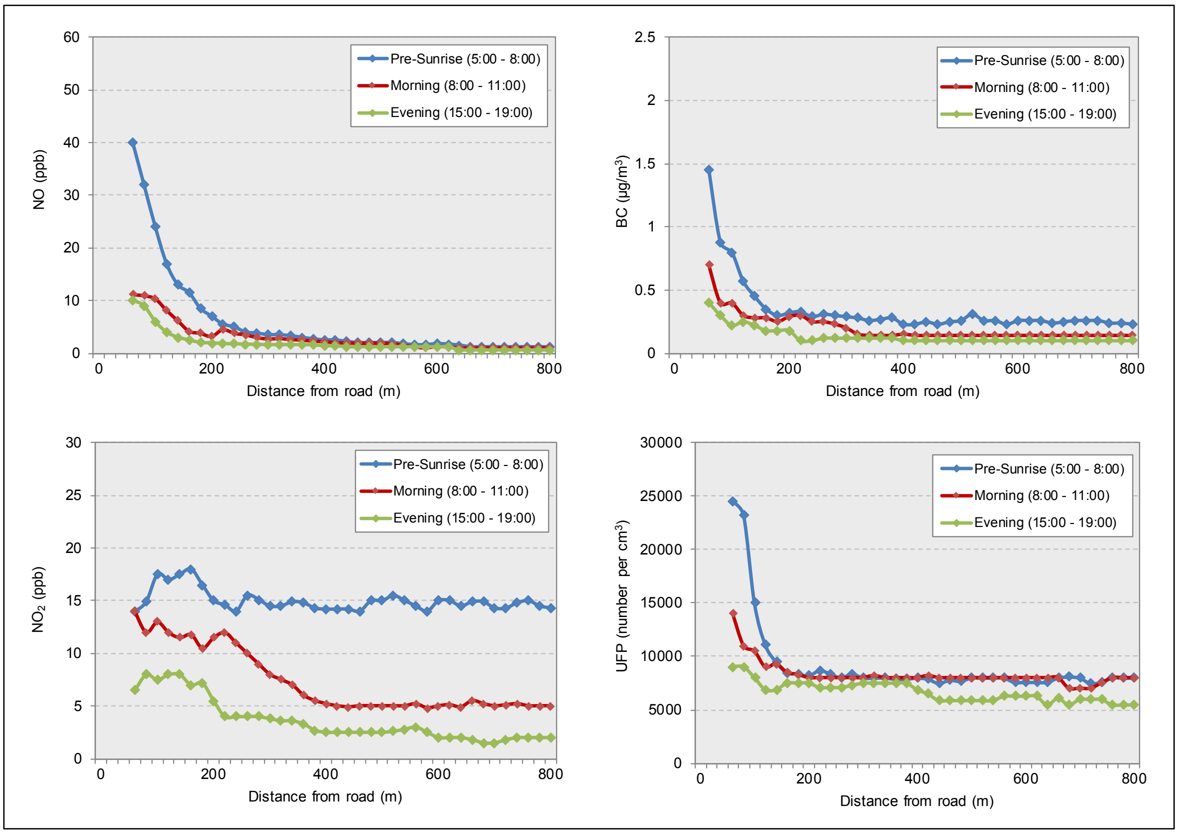

Figure B-4 **Median concentrations of pollutants in the vicinity of a major highway (adapted from Gordon et al., 2012)**

B.3.3 Pollutant transformation

B.3.3.1 Nitrogen dioxide

Some of the most important reactions for near-road air quality are those that lead to the formation and destruction of NO_2. Under the majority of atmospheric conditions, the main mechanism for NO_2 formation in the atmosphere is through rapid reaction of NO with ozone (O_3):

Equation B1

$$\mathbf{NO + O_3 \rightarrow NO_2 + O_2}$$

Where this is the only important reaction (e.g. at night-time), NO is transformed into NO_2 until either all the NO has been converted to NO_2 or until all the ozone has been used up. At polluted locations comparatively close to sources of NO_x (such as roads) NO is in large excess and it is the availability of O_3 which limits the quantity of NO_2 that can be produced by this reaction. The timescale for consumption of O_3 depends on the concentration of NO. Under normal ambient daytime conditions the reverse process also occurs – the destruction of NO_2 by photolysis to form NO and ozone, as shown in Equation B2 and Equation B3:

Equation B2

$$\mathbf{NO_2 + sunlight \rightarrow NO + O}$$

Equation B3

$$\mathbf{O + O_2 (+M) \rightarrow O_3 (+M)}$$

where **M** is a third body, most commonly nitrogen.

Dilution process decreases the NO_2 concentration with distance from the road, whereas chemical reactions tend to favour NO_2 production. As a result, the decay rate of NO_2 is lower than that of NO in near-road environments (see Figure B-4). However, the NO_2/NO_X ratio increases with increasing distance from the roadway until it reaches the background level.

It is worth noting that inside a road tunnel there is usually a high concentration of NO from vehicle exhaust, and any available oxidant - principally ozone - is removed relatively quickly. Once the ozone is removed, NO_2 formation via Equation B1 will stop (Barrefors, 1996). As there is little natural sunlight inside a road tunnel, the destruction of NO_2 via Equation B2 is also limited. Consequently, much of the NO_2 in tunnel air is likely to be primary in origin.

B.3.3.2 Particulate matter

The fate of freshly emitted particles in the atmosphere depends upon their size. Nucleation mode particles have a short lifetime in the atmosphere since they readily transform into larger particles and deposit efficiently to surfaces. Accumulation mode particles are too large to be subject to rapid diffusion and too small to settle from the air rapidly under gravity. Their further growth is inhibited because they do not coagulate quickly and there are diffusion barriers to their growth by condensation. Particles in the accumulation mode can therefore have a long atmospheric lifetime (typically 7–30 days). For coarse particles range gravitational settling velocities become appreciable and therefore atmospheric lifetimes are shorter than for accumulation mode particles.

A substantial fraction of the fine PM mass, especially at background locations, is secondary in nature. Secondary particles are formed by atmospheric reactions involving both inorganic and organic gaseous precursors, several of which are emitted by road vehicles.

The formation of secondary inorganic aerosol is comparatively well understood, although some mechanistic details still remain to be determined (USEPA, 2009). This aerosol is composed mainly of ammonium sulfate ($(NH_4)_2SO_4$) and ammonium nitrate (NH_4NO_3), with some sodium nitrate. These compounds originate from the conversion of sulfur oxides (SO_X) and nitrogen oxides (NO_X) in the atmosphere to sulfuric and nitric acids, which are then neutralised by atmospheric ammonium (NH_4^+). The precursor to atmospheric ammonium is ammonia (NH_3). SO_X and NO_X typically arise from combustion sources. NH_3 emissions are dominated by agricultural sources, such as the decomposition of urea and uric acid in livestock waste (AQEG, 2005).

Secondary organic aerosol is linked to the formation and transformation of low-volatility organic compounds in the atmosphere. The formation of these compounds is governed by a complex series of reactions involving a large number of organic species (Kroll and Seinfeld, 2008). As a result of this complexity a great deal of uncertainty exists around the process of formation (USEPA, 2009).

The formation of secondary particles happens slowly; the overall oxidation rates of SO_2 and NO_2 are around 1 per cent per hour and 5 per cent per hour respectively. The slowness of these processes - and the fact that the resulting particles are small and therefore have a relatively long atmospheric lifetime - means that secondary particles are usually observed many kilometres downwind of the source of the precursors.

Particles are removed from the atmosphere by both dry deposition and wet deposition processes. Dry deposition is caused by gravitational sedimentation, interception/impaction, diffusion or turbulence, although other processes can occur. In wet deposition, atmospheric water (raindrops, snow, *etc.*) scavenges airborne particles, with subsequent deposition on the earth’s surface.

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Appendix C - Review of legislation and criteria relating to emissions and air quality

C.1 National emission standards for new vehicles

C.1.1 Exhaust emissions

For emission testing purposes, the legislation distinguishes between the following:

- Light-duty vehicles. These have a gross vehicle mass (GVM) of less than 3,500 kilograms, and are subdivided into:
    - Light-duty passenger vehicles, including cars, sports utility vehicles (SUVs), four-wheel drive (4WD) vehicles and 'people movers'.
    - Light-duty commercial vehicles, including vans and utility vehicles used for commercial purposes.

  The legislation also distinguishes between petrol and diesel vehicles.
- Heavy-duty vehicles, with a GVM of more than 3,500 kilograms.

Exhaust emissions are inherently variable, and so the best way to ensure that an emission test is reproducible is to perform it under standardised laboratory conditions. Light-duty vehicles are tested using a power-absorbing chassis dynamometer. The emissions from heavy-duty vehicles are regulated by engine dynamometer testing, reflecting that the same engine model could be used in many different vehicles.

The Australian Design Rules (ADRs) set limits on the exhaust emissions of CO, HC, NO_X and PM. Some of the pollutants in vehicle exhaust are not regulated, including specific 'air toxics' and the greenhouse gases CO_2, CH_4 and N_2O. The specific emission limits which apply to light-duty and heavy-duty vehicles, and their timetable for adoption in the ADRs, are listed on the Australian Government website[1]. Although the test procedures have changed with time, the exhaust emission limits have tightened significantly in recent years. There has been a greater alignment with the international vehicle emissions standards set by the UNECE[2], although the Australian standards have delayed introduction dates (DIT, 2010).

Australia is currently implementing the Euro 5[3] emission standards for new light-duty vehicle models (cars and light commercial vehicles). New vehicle models have been required to comply with these standards since November 2013. The Euro 6 standards will commence for new models from July 2017 (Australian Government, 2010). Existing model vehicles must meet the Euro 6 standards from 1 July 2018. With full implementation of Euro 6, the World Harmonized Light-duty Vehicle Test Cycle (WLTC) will replace the current test cycle (Mock et al., 2014).

In the case of heavy-duty vehicles the Euro V standards are currently being implemented in Australia, and the Euro VI standards are currently under discussion. Whilst the Euro VI standards will reduce the limit on NO_X emissions by 77 per cent relative to Euro V, and by 89 per cent relative to Euro IV, advanced test protocols that improve real-world conformity to NO_X limits should result in reductions that are closer to 95 per cent (Muncrief, 2015).

The ADRs do not mandate the use of particular technology. However, it was necessary for vehicle manufacturers to fit catalytic converters to light-duty petrol vehicles in order to meet the emission limits introduced by ADR37/00. For light-duty diesel vehicles, particulate traps will generally be required for compliance with the very low PM emission limits at the Euro 5 stage. For Euro 6/VI the required NO_X reductions will be achieved with combustion improvements (high-pressure fuel injection

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[1] http://www.infrastructure.gov.au/roads/environment/emission/

[2] United Nations Economic Commission for Europe.

[3] In accordance with the European legislation, a slightly different notation is used in this Report to refer to the emission standards for LDVs, HDVs and two-wheel vehicles. For LDVs and two-wheel vehicles, Arabic numerals are used (e.g. Euro 1, Euro 2…etc.), whereas for HDVs Roman numerals are used (e.g. Euro I, Euro II…etc.).

and advanced air/fuel management), exhaust gas recirculation, closed-loop SCR systems and lean NO_x trap (LNT) technology.

The European Commission is introducing a mandatory test procedure for ‘real driving emissions’ (RDE), to be applied during the type approval of light-duty vehicles. These are measured on the road by a portable emission measurement system (PEMS), rather than in the laboratory. The RDE initiative complements the introduction of the WLTC and procedures. The new RDE procedure will require exhaust emission control systems to perform under a broad range of different operating conditions.

Several shortcomings of the regulations have been identified in the EU. For heavy-duty vehicles the Euro V standards have not achieved the anticipated reductions in NO_X emissions (Ligterink et al., 2009). Whilst the Euro 5 standards have resulted in dramatic reductions in PM emissions from light-duty diesels, real-world NO_X emissions from Euro V trucks and buses have continued to far exceed certification limits (Carslaw et al., 2011).

C.1.2 Evaporative emissions

The test procedure for evaporative emissions involves placing a vehicle inside a gas-tight measuring chamber equipped with sensors to monitor the temperature and VOC concentrations, and following a prescribed operational procedure. The chamber is known as a SHED (Sealed Housing for Evaporative Determination). The limits for evaporative emissions are specified in the ADRs.

C.2 In-tunnel limits

Guidelines for the calculation of the fresh air requirements of tunnel ventilation systems are presented by PIARC (2012). Three types of value are defined:

- Design values: These determine the required capacity of the tunnel ventilation system. The ventilation capacity for normal tunnel operation is defined by the air demand required to dilute vehicle emissions to maintain allowable in-tunnel air quality.
- Set points: These are used for the incremental operation of the tunnel ventilation system. For example, tunnel sensors trigger mechanical ventilation in stages before the measured concentration of a gas reaches its sensor limit level (Highways Agency et al., 1999). Set points are generally lower than design values, and are selected so that the design conditions are not exceeded, taking into account the time lag between the traffic conditions and the ventilation system.
- Threshold values: These ensure safe operation of the tunnel, and must not be exceeded. If a threshold value is attained, immediate action is required, such as tunnel closure.

It is prudent for design modelling to include predictions for a range of traffic speeds, and to establish worst-case conditions. However, PIARC notes that the application of overly stringent design values can result in over-sizing of the ventilation system, and thresholds or set points that are too low can cause excessive operational energy use and cost. Nevertheless, the PIARC document states that the emission factors it provides for designing tunnel ventilation tend to be conservative, including a safety margin.

Table C-2 provides a summary of the PIARC in-tunnel CO and visibility limits for ventilation design, tunnel operation, and tunnel closure. The 100 ppm value for CO corresponds to a WHO recommendation for short-term (15-minute) exposure, and is widely used for ventilation design. Exposure at this concentration should not persist for more than 15 minutes, although the length of most tunnels is such that the exposure duration is much less than 15 minutes. In such cases, a higher level of CO may be allowed in the tunnel. The limits for visibility are designed for the purpose of safe driving rather than the protection of health.

The limit values for in-tunnel CO and visibility in a number of countries are shown in Table C-3. The national limits for CO in each country are broadly similar to the values recommended by PIARC.

Table C-1 CO and visibility limit values (PIARC, 2012)

Traffic situation	CO conc. (ppm)	Visibility	
		Extinction coefficient (/m)	Transmission *s* (beam length: 100 m)
Free-flowing peak traffic 50-100 km/h	70	0.005	60
Daily congested traffic, stopped on all lanes	70	0.007	50
Exceptional congested traffic, stopped on all lanes	100	0.009	40
Planned maintenance work in a tunnel under traffic(a)	20	0.003	75
Threshold for closing the tunnel(b)	200	0.012	30

(a) National workplace guidelines should be considered.

(b) To be used for tunnel operation only, and not for ventilation design.

Table C-2 In-tunnel CO and visibility limits for ventilation design and tunnel closure

Country	Condition for ventilation design	Limit values for ventilation design		Limit values for tunnel closure	
		CO (ppm)	Visibility (/m)	CO (ppm)	Visibility (/m)
Austria	Regular congestion	100	0.007	150(a)	0.012(a)
				100(b)	-
France	Free-flow and congested	50	0.005	-	-
Germany	Regular congestion	70	0.005	200	0.012
	Occasional congestion	100	0.007	-	-
Hong Kong	5-min average	100	-	-	-
Japan	60 km/h	50-100	<0.009	150	0.012
	80 km/h	50-100	<0.007		
Norway(c)	Mid-tunnel	75	-	100(d)	-
Switzerland	Any	70	0.005	200(e)	0.012(e)
UK(f)	Tunnel <500 m	10	PIARC	-	-
	Tunnel 500 m to 1,000 m	50	PIARC	-	-
	Tunnel 1,000 m to 2,500 m	35	PIARC	-	-
USA	Fluid peak traffic, 60 km/h	100	<0.009	150	0.012
	Fluid peak traffic, 80-100 km/h	100	<0.007		
	Congested traffic	100	<0.009		

(a) If exceeded for more than 1 minute.

(b) If exceeded for more than 10 minutes.

(c) In Norway, NO/NO_2 and particulate matter are also used for design and control purposes.

(d) If exceeded at tunnel mid-point for more than 15 minutes.

(e) If exceeded for more than 3 minutes.

(f) Limit values for tunnels longer than 2,500 m are derived from first principles.

Sources: Norwegian Public Roads Administration (2004), ASTRA (2003), CETU (2010), MEPC (1993), RABT (2003), RVS (2004)

PIARC has not released definitive recommendations for NO_2 in tunnels, and there are scientific and technical challenges in managing compliance with NO_2 limits. Based on the findings of health studies PIARC has proposed an in-tunnel limit for NO_2 of 1 ppm as the design value, defined as an average value along the length of the tunnel (PIARC, 2012).

It is noted by PIARC that many countries do not apply a NO_2 limit specifically for tunnels, but occupational short-term exposure limits apply. These are typically higher than the 1 ppm proposed by

PIARC. Some countries have introduced NO_2 as the target pollutant for in-tunnel air quality monitoring, with the threshold value normally following national and/or WHO recommendations. Depending on the situation, either NO_2 or NO_x inside the tunnel, or NO_2 outside the tunnel, can be taken as the design parameter for ventilation sizing.

Examples of in-tunnel NO_2 values for ventilation control from several countries are summarised in Table C-4. It is noted in PIARC (2012) that the WHO limits aim at improving air quality in general, and are not intended to be applied to peak exposures. Nevertheless, different values have been adopted for different time frames, and it appears that some of these are quite stringent. In the UK, consideration was given to lowering the NO_2 limit to 1 ppm, but tunnel operators stated that it would not be feasible to comply with this limit (Tarada, 2007). PIARC adds that passage through a tunnel typically only lasts for a few minutes, and therefore stringent NO_2 thresholds should only be considered where it might be warranted by traffic conditions and/or ambient conditions.

The CO, NO_2 and PM concentrations in the ambient fresh air used for dilution are normally relatively low, but should be checked for tunnels in urban areas, where ambient CO concentrations are typically between 1 ppm and 5 ppm. A typical ambient peak NO_2 concentration would be 200 µg/m^3. The situation can be modified, however, when air from the portal of one bore enters the portal of the adjacent bore as ‘fresh air’, although simple structural design features (*e.g.* anti-recirculation walls) can minimise or even eliminate such effects (PIARC, 2012).

For longitudinally ventilated tunnels in which traffic demands are high, or may change suddenly, PIARC recommends a minimum air flow speed of 1.0-1.5 m/s.

Table C-3 International in-tunnel NO_2 limits

Country	NO_2 (ppm)	Notes	Source
PIARC	1.0	Averaged over tunnel length	PIARC (2012)
Belgium	0.2	1 hour	WHO (2006)
	0.5	<20 minutes	PIARC (2012)
France	0.4	15 minutes, average for length of tunnel	CETU (2010)
Hong Kong	1.0	5 minutes, ventilation control	Hong Kong EPD (1995)
Norway(a)	0.75	15 minutes, tunnel mid-point	Norwegian Public Roads Administration (2004)
Sweden(b)	0.2	1 hour	WHO (2006)
UK(c)	4	Tunnel <500 m	Highways Agency *et al.* (1999)
	3	Tunnel 500 m to 1,000 m	
	1.5	Tunnel 1,000 m to 2,500 m	

(a) Resulting in tunnel closure.

(b) PIARC states that Sweden is in the process of abandoning the WHO threshold.

(c) Design and control. Limit values for tunnels longer than 2,500 m are derived from first principles.

C.3 Ambient air quality standards and goals

For the criteria pollutants included in the assessment, the impact assessment criteria in the NSW Approved Methods are compared with the WHO guidelines and the standards in other countries/organisations in Table C-5. For CO the NSW standards are numerically lower than, or equivalent to, those in most other countries and organisations. The NSW standards for NO_2 are higher than in the other countries and organisations except for the United States. In the case of PM_{10}, the NSW standard for the 24-hour mean is lower than or equivalent to the standards in force elsewhere, whereas the annual mean standard is in the middle of the range of values for other locations. The $PM_{2.5}$ standards are lower than, or equivalent to, those used elsewhere. However, such comparisons do not necessarily mean that the Australian standards are more or less stringent than those elsewhere. For example, to a large degree the lower standards in Australia for PM are made possible by relatively low natural background concentrations and the absence of significant anthropogenic transboundary pollution (which is a major issue in Europe, for example). Moreover, there are differences in implementation; there is no legal requirement for compliance with the standards and goals in Australia, whereas there is in some other countries and regions.

Table C-4 Comparison of international health-related ambient air quality standards(a)

Country/Region/ Organisation	CO			NO_2			PM_{10}		$PM_{2.5}$	
	15 min. (mg/m^3)	1 hour (mg/m^3)	8 hours (mg/m^3)	1 hour (µg/m^3)	1 day (µg/m^3)	1 year (µg/m^3)	24-hours (µg/m^3)	1 year (µg/m^3)	24-hours (µg/m^3)	1 year (µg/m^3)
NSW Approved Methods	100(0)	30(0)	10(0)	246(0)	-	62	50(0)	30	25(0)(b)	8(b)
WHO	100(0)	30(0)	10(0)	200	-	40	50(c)	20	25(c)	10
Canada	-	-	-	-	-	-	120(d,e)	-(d)	28/27(f)	10/8.8(f)
European Union	-	-	10(0)	200(18)	-	40	50(35)	40	-	25(g)
Japan	-	-	22(0)	-	75-115	-	-	-	-	-
New Zealand	-	30(h)	10(1)	200(9)	100(h)	-	50(1)	20(h)	25(h)	-
UK	-	-	10(0)(i)	200(18)	-	40	50(35)	40	-	25
UK (Scotland)	-	-	10(0)(j)	200(18)	-	40	50(7)	18	-	12
United States (USEPA)	-	39(1)	10(1)	190(k)	-	100	150(1)	-	35(l,m)	12(l)
United States (California)	-	22(0)	10(0)	344(0)	-	57	50	20	-	12

(a) Numbers in brackets shows allowed exceedances per year for short-term standards. Non-health standards (e.g. for vegetation) have been excluded.
(b) Advisory reporting standard.
(c) Stated as 99th percentile.
(d) Although there is no national standard, some provinces have standards.
(e) As a goal.
(f) By 2015/2020.
(g) The 25 µg/m^3 value is initially a target, but will become a limit in 2015. There is also an indicative 'Stage 2' limit of 20 µg/m^3 for 2020.
(h) By 2020.
(i) Maximum daily running 8-hour mean.
(j) Running 8-hour mean.
(k) 98th percentile, averaged over 3 years.
(l) Averaged over three years.
(m) Stated as 98th percentile.

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Appendix D - Examples of previous ambient air quality assessments

D.1 Road tunnel assessments

Table D-1 NorthConnex, Sydney

Project (type of assessment)	NorthConnex (EIS)
Project description	A proposed nine-kilometre toll tunnel linking the M1 Pacific Motorway at Wahroonga to the Hills M2 Motorway at West Pennant Hills. During operation, the ventilation system would draw fresh air into the tunnels and emit air from within the tunnels via two ventilation facilities. One of the ventilation facilities would be located near the northern tunnel portal and one would be located near the southern tunnel portal.
Pollutants/metrics modelled	PM_{10}, $PM_{2.5}$, TSP, NO_x, CO, PAHs and VOCs
Approach	- Assessment scenarios. - The dispersion models. - Meteorological data. - Terrain and land use data. - Sensitive receivers. - Model input parameters. - Emissions assumptions (estimation and rates). - Ventilation outlet parameters. - Cumulative assessment.
Scenarios	Three principal air quality scenarios were evaluated: - Comparison of air quality with and without the project. - Assessment of air quality at the expected opening of the project (2019), and after ten years of operation (2029). - Assessment of air quality in the event of a breakdown in one of the tunnels.
Traffic data	Strategic Sydney traffic model
Background air quality	For PM_{10}, $PM_{2.5}$ and NO_2, the ambient concentrations were determined by taking the maximum of the concentrations predicted by CAL3QHCR (with the project) and those measured by the OEH at its Lindfield and Prospect monitoring stations. For CO the maximum concentration recorded at the OEH monitoring station at Prospect was used.
Emission factors	PIARC.
Met/dispersion model(s)	MM5/CALMET/CALPUFF (ventilation stacks) and CAL3QHCR (surface roads). Meteorological grid domain: 60 kilometres x 62.5 kilometres Meteorological grid resolution: 250 metre resolution. Five surface met stations.
Receptors	A total of 6,919 discrete receptors were assessed. Of these, 3,332 were located along the project corridor.
Model validation	Not specified.
Construction assessment	Potential construction air quality impacts associated with the project were assessed qualitatively by describing the nature of proposed works, plant and equipment, potential emissions sources and levels.
Reference	AECOM (2014a,b)

Table D-2 East-West Link, Eastern Section, Melbourne

Project (type of assessment)	East West Link: Eastern Section, Melbourne. (project cancelled)
Project description	Six-lane tunnel from the Eastern Freeway in Clifton Hill to CityLink in Parkville.
Pollutants/metrics modelled	Peak and mean CO Peak and mean NO_2 Peak and mean PM_{10} Peak and mean $PM_{2.5}$ AQ criteria from Victoria's State Environment Protection Policy (Air Quality Management 2001) (SEPP (Air Quality Management)).
Approach	Regional impacts were downscaled to the local level to identify potential hot-spots within a few hundred metres (major intersection level) and to quantify the changes from ‘no-build’ to ‘build’ scenarios. Compared model predictions to design criteria for the predicted ground-level concentration at portal locations and elevated/depressed road sections. Consideration was given to the possibility of turning down/off the forced ventilation during low-usage overnight conditions to achieve minimal portal emission impact (this was subsequently adopted as an operational practice). For tunnel vent emissions, a point source assessment was undertaken to establish performance requirements. Risk assessment matrix included.
Scenarios	2021 without project 2021 with project 2031 with project
Traffic data	Traffic model AM peak, PM peak, mid-day, off-peak
Background air quality	Hourly varying values for NO_2 and PM_{10} (TEOM) were taken from two EPA Victoria monitoring sites. The data for 2008 were used to match the concentrations with the meteorological data. Background values for other pollutants were taken from other recent road projects in Victoria.
Emission factors	PIARC
Met/dispersion model(s)	AUSPLUME 6.0 and AUSROADS 1.0
Receptors	Hoddle Street Overpass: roadside receptors. A series of discrete receptors was placed across transects from the Eastern Freeway for the location of maximum ground-level concentrations for NO_2 to a distance of 250 metres away. The dominating line source was CityLink, at a height of around 10 metres above ground level, and as such receptors were placed at this height to obtain worst-case results. Gridded receptors were modelled with ±1.0 km domain and 20 m resolution Total number of receptors was not given.
Model validation	Not specified.
Construction assessment	Environmental management plan created for construction, but only qualitatively assessed.
Notes	Strategic transport modelling (VLC 2013) was undertaken for the purpose of estimating the amounts and types of vehicles that could potentially use East West Link – Eastern Section roads. Assessed future scenarios with and without the Project.
Reference	GHD (2013)

Table D-3 Waterview Connection, Auckland

Project (type of assessment)	Western Ring Route: Waterview Connection, Auckland, New Zealand
Project description	Two tunnels between Great North Road Interchange and the Alan Wood Reserve. Separate tunnels for northbound and southbound traffic. Longitudinal ventilation.
Pollutants/metrics modelled	Max 8-hour mean CO Max 1-hour mean CO Max 1-hour mean NO_x Max 1-hour mean NO_2 Max 24-hour mean PM_{10} Annual mean PM_{10} Max 24-hour mean $PM_{2.5}$ Annual mean benzene Criteria from National Environmental Standards (AQNES), New Zealand Air Quality Guidelines (NZAAQG) and Auckland Regional Air Quality Targets (ARAQT).
Approach	Only portal emissions modelled.
Scenarios	Base year of 2006 2016 With Project 2016 Do Nothing 2026 With Project 2026 Do Nothing
Traffic data	EMME/3 traffic model
Background air quality	The baseline scenario was the cumulative air quality for the 2006 base year. PM_{10}: hourly 2007 data from the mean of 1-hour average concentrations from 5 sites. $PM_{2.5}$ hourly 2007 data from the mean of 1-hr average concentrations from 3 sites. CO: hourly 2007 data from the mean of 1-hr average concentrations from 6 sites. Benzene: Baseline derived from passive monitoring conducted for the Project.
Emission factors	Detailed emissions factors have been derived from VEPM. Portal emission rates varied with respect to traffic volume and ambient wind speed.
Met/dispersion model(s)	GRAL (tunnel portals), VEPM, CALMET, CALPUFF, AUSROADS (surface roads)
Model validation	The 2006 base year scenario was used for validation of the dispersion model. Data on meteorology and measured background concentrations were taken from 2007, although the traffic volumes used in the model were based on 2006 census data.
Receptors	Sensitive receptors within 2km of either tunnel ventilation stack or within 300 m of a major surface road. 25 schools 38 early-learning centres 11 healthcare centres 10 residential 6 sports fields 8 receptors with “Existing SH20 Designation”
Construction assessment	Compliant with the raft NZTA Standard Producing Air Quality Assessments for State Highway Projects and the NZ Ministry for Environment’s Good Practice Guide for Assessing and Managing the Environmental Effects of Dust Emissions”
Reference	BECA (2010)

Table D-4 Lane Cove Tunnel, Sydney

Project (type of assessment)	Lane Cove Tunnel, Sydney
Project description	Tunnel consists of twin tubes ventilated by two ventilation outlets.
Pollutants/metrics modelled	Max 8-hour mean CO Max 1-hour mean CO Max 1-hour mean NO_2 Annual men NO_2 Max 24-hour mean PM_{10} Annual mean PM_{10} 1-hour mean HC Annual mean HC Criteria: EPA/AAQ NEPM.
Approach	Validation of the ambient air quality assessment undertaken for the tunnel ventilation system as assessed in the Environmental Assessment for the Revised Ventilation Design for the Lane Cove Tunnel Project, utilising actual monitoring data. Two modelling scenarios: using estimated emissions from the EIS and using measured stack emissions data.
Scenarios	Emissions data from in-stack monitoring. Modelling included normal and congested conditions.
Traffic data	Traffic volume data for the period of October 2007 to September 2008.
Background air quality	Background air quality monitoring was undertaken at Epping Road, Mowbray Road and Military Road for the Proposal. In addition, the OEH air quality monitoring site at Lindfield was used.
Emission factors	PIARC (2006 taken to be worst case scenario)
Met/dispersion model(s)	TAPM/CALMET/CALPUFF
Receptors	Concentrations at receptors at both ground and elevated levels.
Model validation	Predicted results using stack monitoring data were compared with the predicted results using emission estimations from the EIS.
Construction assessment	Emissions from construction were estimated using SPCC and USEPA emission factors. No dispersion modelling was undertaken.
Reference	PAEHolmes (2010)

Table D-5 Northern Link, Brisbane

Project (type of assessment)	Northern Link (Legacy Way), Brisbane (EIS)
Project description	The Project involved the construction and operation of an underground toll road (tunnel) between the Western Freeway, in Toowong, and the Inner City Bypass (ICB), at Kelvin Grove. Longitudinal tunnel, two ventilation outlets.
Pollutants/metrics modelled	Max 8-hour mean CO Max 1-hour mean NO_2 Annual mean NO_2 Max 24-hour mean PM_{10} Annual mean PM_{10}
Scenarios	See below.
Traffic data	- Annualised Average Daily Traffic (AADT) for years 2007 (existing), 2014, 2016, 2021 and 2026. - Scenarios with and without project. - Modelled 2007 (existing), 2014, 2016, 2021 and 2026 AADT for selected surface roads and in tunnel sections. - Indicative flow profiles for light and heavy vehicles by hour of day for each section of tunnel and for surface roads.
Background air quality	The background data were constructed from air quality monitoring data, specifically, those collected from the Bowen Hills and Rocklea sites.
Emission factors	National Pollutant Inventory (2000)
Met/dispersion model(s)	CALMET/ CALPUFF, CAL3QHCR
Receptors	Exact receptor locations not specified.
Model validation	Not specified
Construction assessment	Qualitative assessment of potential impacts of specific activities and mitigation measures.
Reference	Holmes Air Sciences (2008)

Table D-6 Airport Link, Brisbane

Project (type of assessment)	Airport Link, Brisbane (EIS)
Project description	Twin-bore, 6 km road tunnel from Bowen Hills to Wooloowin in Brisbane. Longitudinal ventilation, three elevated outlets near each end as well as an intermediate outlet at Kedron.
Pollutants/metrics modelled	Max 8-hour mean CO Max 1-hour mean NO_2 Annual mean NO_2 Max 24-hour mean PM_{10} Annual mean PM_{10} Criteria: EPA/AAQNEPM
Approach	Emissions estimated for each ventilation outlet and all surface roads.
Emission factors	PIARC, modified to account for age, vehicle mix, speed etc. No potential future improvements in vehicle technology or fuel standards included. SEQ inventory EFs compared with PIARC EFs.
Background air quality	2004 was chosen for both the background meteorological and ambient air quality monitoring records. The monitoring sites are summarised as follows: - Eagle Farm, operated by the EPA but now decommissioned, included measurements of NOx, O_3, SO_2 and PM_{10}. - Bowen Hills, operated by Simtars but now decommissioned, included measurements of CO, NOx, PM_{10} and $PM_{2.5}$. - Kedron, currently monitoring and operated by Simtars. Measurements include CO, NOx, PM_{10} and $PM_{2.5}$.
Met/dispersion model(s)	CALMET/ CALPUFF; CAL3QHCR for near-road impacts.
Receptors	Not specified.
Model validation	Not specified.
Construction assessment	Not considered, as modelled for the feasibility assessment.
Reference	Holmes Air Sciences (2006)

Table D-7 Vic Park Tunnel, Auckland

Project (type of assessment)	Vic Park Tunnel, Auckland
Project description	Realignment of State Highway 1 between Harbour Bridge and Wellington St, including tunnel and widening of existing carriageway.
Pollutants/metrics modelled	Max 8-hour mean CO Max 1-hour mean CO Max 1-hour mean NO_2 Max 24-hour mean NO_2 Max 24-hour mean PM_{10} Annual mean PM_{10} Annual mean benzene Criteria from NZ National Environmental Standards (NES) for Air Quality.
Approach	Modelled both the surface roads and the proposed tunnel portal.
Scenarios	In total four scenarios were modelled: - 2010 without the VPT project - 2010 with the VPT project - 2021 without the VPT project - 2021 with the VPT project
Traffic data	Traffic models developed by BECA.
Background air quality	Takapuna. The monitoring station is located approximately 8-kilometres from the site and about 25 m from a major intersection. It is important to note that the concentrations measured at both these sites are already influenced by traffic emissions.
Emission factors	New Zealand Transport Emission Rate model (NZTER). Assumed that tunnel was a motorway, with EFs being derived for free, interrupted and congested flow conditions.
Met/dispersion model(s)	CALINE 4/CAL3QHCR applied to both surface roads and tunnel portals
Receptors	10 ground-level receptors, 15 elevated receptors at heights up to 14 m.
Model validation	In the modelling validation study, the total NOx concentrations were modelled and the NO_2 concentrations were calculated based on the NSW accepted practice which assumes that NO_2 concentrations are 10% of NOx by weight at the kerbside, 15% by weight at 10 m and 20% by weight at 30 m and beyond.
Construction assessment	Construction impacts were not assessed in the study.
Notes	Breakdown of vehicles by fuel type based on NZ Motor Vehicle Registration Statistics, Land Transport Safety Authority (LTSA), 2004. Fleet composition assumed to be constant for future scenarios.
Reference	Holmes Air Sciences (2006)

Table D-8 M5 East Tunnel, Sydney

Project (type of assessment)	M5 East Tunnel, Sydney (partial portal emissions and trial of tunnel filtration technology). The filtration trial proceeded without partial portal emissions.
Project description	Potential impacts of regular partial portal emissions from the tunnel to manage in-tunnel haze. Four-kilometre long twin tunnels from Bexley to Arncliffe, with a recirculating ventilation system with a single ventilation outlet located at Turrella (approximately 800 m from the tunnel).
Pollutants/metrics modelled	Max 8-hour mean CO Max 1-hour mean CO Max 15-min mean CO Max 30-min mean CO Max 1-hour mean NO_2 Annual mean NO_2 Max 24-hour mean PM_{10} Annual mean PM_{10} 24-hour mean PM2.5 Annual mean $PM_{2.5}$ VOCs/PAH
Approach	Model the dispersion of emissions from the M5 East tunnel portals by computational fluid dynamics (CFD), and a health risk assessment.
Scenarios	Varying air volumes emitted from the portals.
Traffic data	Modelled emissions based on fleet average emission data (NPI 2000).
Background air quality	Background concentration for the criteria pollutants, PM_{10}, CO and NO_2, were derived from the ambient monitoring stations located adjacent to the Bexley Road (F1) and Marsh Street (M1) portals for each 5-minute period throughout the whole of the calendar year 2005.
Emission factors	Pollutant concentrations in the air discharged during portal emissions determined using measurements from sensors within the tunnel and other reported emission factors.
Met/dispersion model(s)	CFD (FLUENT) Varying portal outflow rates were modelled, with the maximum outflow rate being continuous from 5 am and 7 pm for conservatism.
Receptors	At Bexley Rd, a closely-spaced (30m spacing) rectangular shaped modelling receptor grid was employed covering all relevant residences within the range of 0 to 150 m of the portal. At the Marsh St portal, to ensure that the whole of the residential area was modelled a selection of individual residences covering all residences within 200 m of the portal were modelled.
Model validation	State-of-the-art CFD modelling software, FLUENT Version 6.2d, with current ISO 9001 certification and guaranteed model validity was used.
Construction assessment	Construction impacts not quantitatively assessed, although an environmental management plan was created to include construction activities (only relevant to the construction of the filtration plant).
Reference	Synergetics (2006)

Table D-9 Cross City Tunnel, Sydney

Project (type of assessment)	Cross City Tunnel, Sydney
Project description	Twin two-lane road tunnels for traffic travelling east–west across Central Sydney between Darling Harbour and Kings Cross.
Pollutants/metrics modelled	Max 8-hour mean CO Max 1-hour mean CO Max 1-hour mean NO_2 Max 24-hour mean PM_{10} Annual mean benzene Criteria: EPA/AAQ NEPM.
Approach	Modelled 3 ventilation options: - 2 ventilation outlets (one near the exit portal of each tunnel) - 2 ventilation outlets (one near the exit portal of each tunnel with a cross-over vent stack near the eastern portals). - 1 stack (at western end with recirculation at the eastern end). Adopted option was a single outlet at the western end with an additional ventilation tunnel from the eastern end of the project.
Scenarios	With construction Without tunnel construction and minor road improvements
Traffic data	Traffic volume data collected in 1998, and 2006, and projected for 2016. Details of traffic model given in “Technical Paper No. 8”
Background air quality	Details given in "Technical Paper No. 16 Air Quality"
Emission factors	Details not given in report, but in "Technical Paper No. 16 Air Quality"
Met/dispersion model(s)	AUSPLUME
Receptors	Elevated receptors: Darling Walk (15 metres), IMAX Theatre (30 metres), Park Royal Hotel (40 metres) Millennium Towers (60 metres), Darling Park Stage 3 (70 metres), Darling Park Stage 2 (145 metres) 37 Street receptors around Sydney CBD.
Model validation	Details not given.
Construction assessment	Described on an area by area basis in precincts: Darling Harbour, Central, Hyde Park.
Notes	All emissions assumed to vent through a ventilation outlet. A single outlet option was adopted.
Reference	PPK (2000)

D.2 Surface road assessments

Table D-10 WestConnex M4 Widening

Project (type of assessment)	WestConnex M4 Widening
Project description	- M4 Widening including: - Construction of a new two lane viaduct for westbound traffic, on the southern side of the existing viaduct structure between Church Street, Parramatta and Wentworth Street, Granville. - Reconfiguration of the traffic lanes on the existing viaduct structure to four lanes eastbound and two lanes westbound. - Construction of a new bridge/viaduct over Duck River at Auburn.
Pollutants/metrics modelled	Max 8-hour mean CO Max 1-hour mean CO Max 1-hour mean NO_2 Annual mean NO_2 Max 24-hour mean PM_{10} Annual mean PM_{10} 24-hour mean $PM_{2.5}$ Annual mean $PM_{2.5}$ VOCs/PAH
Approach	To determine whether there is any significant change in the existing levels of emissions from the road, and where the change occurs and the relative scale of the change.
Scenarios	Four scenarios were assessed: - Base 'do minimum' (2017) - without the M4 Widening project. - M4 Widening (2017) - project opening year. - Future 'do minimum' (2027) - 10 years after the Base 'do minimum', but not including the M4 Widening or the WestConnex schemes. - Full WestConnex (2027) – development of the full WestConnex Scheme represented by adding all stages of the scheme to the Future 'do minimum' case.
Traffic data	Source of traffic volumes not specified.
Background air quality	The background monitoring data includes data for NO_2, CO (Rozelle and Chullora) and PM_{10}.
Emission factors	TRAQ (derived from method in NSW GMR emissions inventory).
Met/dispersion model(s)	TRAQ (CALINE 4)
Receptors	7 Receptors along a transect of the proposed widening. At these receptors, air quality was assessed at 20m, 50m and 100m from the nearest lane of the motorway
Model validation	Not specified
Construction assessment	Assessed quantitatively using USEPA AP42 Emissions Factors
Notes	None.
Reference	Todoroski Air Sciences (2014)

Table D-11 Pacific Highway, Ballina Bypass

Project (type of assessment)	Pacific Highway Ballina Bypass (EIS).
Project description	Upgrade between Hexham and the QLD border by constructing a four lane duel carriageway bypass of Ballina.
Pollutants/metrics modelled	Max 1-hour mean CO Max 1-hour mean NO_x Max 1-hour mean HC Max 1-hour mean PM_{10} Max 1-hour mean lead Criteria: NEPM, NHMRC
Approach	Model the impacts of the potential bypass construction and compare this to existing air quality.
Scenarios	Bypass construction in 2016. No bypass construction (existing air quality)
Traffic data	EMME/2 transport model using 1994 as a base year and the future scenario in 2016
Background air quality	CO was monitored over a two week period from 21/7/1997 at a location 50 m away from the Pacific Highway and 200m east of Teven Road.
Emission factors	Not stated in main report.
Met/dispersion model(s)	CALINE 4
Receptors	8 receptors along the proposed bypass and three receptors in Ballina.
Model validation	Not specified.
Construction assessment	Construction emissions estimated using SPCC and USEPA EFs.
Notes	Emission rates for morning and afternoon peak hours for 2 scenarios.
Reference	Connell Wagner (1998)

Table D-12 Pacific Highway Upgrade, Banora Point

Project (type of assessment)	Pacific Highway Upgrade, Banora Point
Project description	Freeway-standard link between the Chinderah bypass and the Tweed Heads bypass, bypassing an existing section of the Pacific Highway.
Pollutants/metrics modelled	Max 8-hour mean CO Max 1-hour mean CO Max 1-hour mean NO_2 Annual mean NO_2 Max 24-hour mean PM_{10} Annual mean PM_{10} Criteria: NEPM, DECC.
Approach	PIARC (2004), adjusted to reflect the NSW vehicle fleet and grades, speed, and %HDV.
Scenarios	• A base case (2010, no upgrade). • With the proposed upgrade in 2010. • With the proposed upgrade 2020.
Traffic data	Traffic flow data was calculated based on predicted annual average traffic flow data for the three scenarios. Hourly traffic volumes were calculated using a generic profile from traffic count data collected on the Pacific Highway north of Terranora Road in February 2007. For modelling purposes, the route (proposed upgrade and existing highway) was split into southern, mid and northern sections. Traffic on the on and off-ramps and on the existing Pacific Highway was also modelled as part of the proposed upgrade 2010 and 2020 scenarios.
Background air quality	No air quality monitoring data available for the study area. However, monitoring data collected by the Department of Environment and Climate Change at Newcastle swimming pool in Wallsend and at the Newcastle sportsground (on Dumaresq Street) is considered indicative of air quality in a coastal town like Banora Point.
Emission factors	Dust emission rates from US EPA (1995) *AP-42 Compilation of Air Pollutant Emission Factors* and the NSW Mineral Council (2000) Particulate Matter and *Mining Interim Report.* Vehicle emissions rates, using vehicle emission data from PIARC (2004).
Met/dispersion model(s)	CAL3QHCR
Receptors	Receptor locations were chosen to represent the residential areas closest to the proposed upgrade and positioned at ground level, at fixed distances of 0, 10, 20, 30 and 50 metres from the road in the following locations : Receptor Location 1: northbound carriageway close to the southern off-ramp. Receptor Location 2: northbound carriageway of the Old Pacific Highway, just north of Terranora Road. Receptor Location 3: north and southbound carriageways close to Short Street. Receptor Location 4: north and southbound carriageways close to Minjungbal Drive.
Model validation	Not specified
Construction assessment	Qualitative construction scenario.
Reference	Holmes Air Sciences (2008)

Table D-13 Pacific Highway Upgrade, Bulahdelah

Project (type of assessment)	Pacific Highway Upgrade, Bulahdelah
Project description	Around 8.5 km of dual carriageway.
Pollutants/metrics modelled	Max 8-hour mean CO Max 1-hour mean CO Max 1-hour mean NO_2 Max 24-hour mean PM_{10} Annual mean PM_{10} Annual mean benzene Criteria: NEPM, WHO, DEC, NHMRC.
Approach	Metropolitan Air Quality Study (1997) provided by DEC.
Scenarios	Only one scenario for proposed road works considered
Traffic data	Traffic flow data for 2008 and 2018
Background air quality	No monitoring undertaken specifically for this project, but there are data available from the DEC monitoring network and earlier data from north of Bulahdelah. The station closest to the route is near the Pacific Highway at Beresfield near Newcastle
Emission factors	Metropolitan Air Quality Study (MAQS) (Carnovale et al, 1997) and rates provided by the DEC.
Met/dispersion model(s)	CALINE 4 with BREEZE ROADS package used to assess impacts.
Receptors	Receptors were placed at fixed distances of 0 m, 10 m, 30 m and 50 m from sections of the roads closest to residences and other sensitive areas including Bulahdelah Central School and St. Joseph’s Primary School.
Model validation	Williams et al. (1994)
Construction assessment	Construction qualitatively assessed.
Reference	Holmes Air Sciences (2004)

Table D-14 M2 Upgrade

Project (type of assessment)	M2 Upgrade
Project description	Widening sections of the motorway and additional access/egress points.
Pollutants/metrics modelled	Max 1-hour mean NO_2 Max 8-hour mean CO Max 24-hour mean PM_{10} Max 24-hour mean $PM_{2.5}$ Criteria: DECCW.
Approach	A cumulative impact assessment has been undertaken to determine the combined effect of the project with other proposed activities within the region.
Scenarios	2021 no M2 upgrade 2021 with M2 upgrade
Traffic data	The Transurban Sydney Strategic Traffic Model (TUSTM)
Background air quality	CSIRO Lindfield Laboratories at West Lindfield, approximately 1.5 kilometres southeast of the intersection of Lane Cove Road and the M2 Motorway. For PM10 and PM2.5, data from other locations in Sydney has been assessed (Liverpool and Lucas Heights, and Magdala Park in North Ryde).
Emission factors	Provided by DECCW for light and heavy vehicles assume no improvement in vehicle exhaust standards to the assessment year of 2021.
Met/dispersion model(s)	TAPM, CAL3QHCR
Receptors	65 receptors including residential, commercial, institutional and recreational receptors locations along the length of the M2 Motorway.
Model validation	Not specified.
Construction assessment	Construction qualitatively assessed.
Notes	Air quality within the tunnel and associated with emission from the tunnel openings has been assessed. Modelled a 'do nothing' and 'upgrade' scenario.
Reference	Heggies (2009)

Table D-15 M80 Upgrade

Project (type of assessment)	M80 Upgrade Project. VIC
Project description	Widening the existing M80 freeway
Pollutants/metrics modelled	* NO_2 * PM_{10} Criteria from EPA's State Environment Protection Policy – Air Quality Management Intervention Levels.
Approach	VicRoads Screening Tool detailed in the "Technical Guidelines for Assessing the Air Quality Impacts of Road Developments" was used for the assessment of the impacts of the M80 Upgrade Project.
Scenarios	Modelled existing traffic volumes (2008) and estimated traffic volumes in 2021
Traffic data	Traffic volumes supplied by VicRoads
Background air quality	Measured NO_2 and PM_{10} concentrations at Footscray and Alphington for the years 2002 to 2007.
Emission factors	VicRoads Screening Tool detailed in the "Technical Guidelines for Assessing the Air Quality Impacts of Road Developments" was used for the assessment.
Met/dispersion model(s)	VicRoads Screening Tool
Receptors	17 residences located < 100 m to the M80
Model validation	Not specified.
Construction assessment	Not specified.
Reference	Bassett Consulting Engineers (2009)

Table D-16 Pacific Highway Upgrade, Tintenbar to Ewingsdale

Project (type of assessment)	The Project involves the construction and operation of approximately 17 km of dual carriageway including twin 430 m long tunnels, commencing from the northern section of the Ballina Bypass, through to Ewingsdale Road
Project description	Upgrade of the Pacific Highway from Tintenbar to Ewingsdale.
Pollutants/metrics modelled	Max 1-hour mean CO Max 1-hour mean NO_2 Max 1-hour mean PM_{10} Criteria: DECC, NEPM, EPA.
Approach	Use of a dispersion model that simulates worst-case meteorology.
Scenarios	With Project 2012 Without project 2012 With Project 2022
Traffic data	Traffic data supplied by Arup for 2012 and 2022; traffic counts south of Ivy Lane, south of Bangalow and north of Bangalow Road; Light and heavy vehicle traffic volumes by hour of day
Background air quality	Monitoring data have been collected by the RTA at the Pacific Highway near Coffs Harbour.
Emission factors	PIARC. Assessment is based on emission rates assuming that the roadway is flat. No potential future improvements in vehicle technology or fuel standards have been included in the PIARC emission estimates which will result in some overestimation of emission rates for future years. Assumed reductions in the proportion of older vehicles in the fleet has simulated some improvement to vehicle emissions in future years.
Met/dispersion model(s)	CALINE 4
Receptors	A total of 18 receptors, whereby at 3 locations, air quality was assessed at kerb, and 10, 20, 30, 50, and 100 m away from road.
Model validation	Not specified
Construction assessment	Construction qualitatively assessed.
Notes	Pollutant emissions have been estimated for each tunnel ventilation outlet and for all surface roads.
Reference	Holmes Air Sciences (2008)

Table D-17 Foxground and Berry Bypass, NSW

Project (type of assessment)	Foxground and Berry Bypass. NSW
Project description	Upgrade of 11.6 km of the Princes Highway between Toolijooa Road north of Foxground and Schofields Lane south of Berry, to achieve a four lane divided highway (two lanes in each direction) with median separation. The project includes bypasses of Foxground and Berry.
Pollutants/metrics modelled	Max 1-hour CO Max 8-hour CO Max 1-hour NO_2 Annual average NO_2 Max 24-hour average PM_{10} Annual average PM_{10} AQ criteria from WHO, NEPC and EPA.
Scenarios	For 2017, and 2037: Do Nothing Do Minimum
Traffic data	- Average speed by road type sourced from the Traffic and Transport Assessment Technical Paper (AECOM,2012) - Average Annual Daily Traffic (AADT) and VKT, for light and heavy vehicles, were sourced from the Traffic and Transport Assessment Technical Paper (AECOM, 2012). - Rate of fuel consumption calculated for each road type within the traffic impact footprint using the basic fuel-speed formula (Equation 1 in Austroads Guide to Project Evaluation Part 4: Project Evaluation Data part 6).
Background air quality	1997-2005 data: Croom Road in Albion Park, 2005-2007 data: Terry Reserve in Albion Park South
Emission factors	Vehicle emissions data from PIARC were adjusted to reflect NSW fleet. No future improvements in vehicle technology or fuel standards have been included in the emission estimates.
Met/dispersion model(s)	CAL3QHCR
Receptors	69 receptors
Model validation	Williams et. al. (1994)
Construction assessment	Construction semi-qualitatively assessed (emissions estimated but not modelling).
Reference	PAEHolmes (2012)

Table D-18 Pacific Highway Upgrade, Woolgoolga to Ballina

Project (type of assessment)	Pacific Highway Upgrade, Woolgoolga to Ballina. NSW
Project description	The Woolgoolga to Ballina upgrade would involve upgrading ~155 km of highway. Starting from the southern end, the project would ‘tie in’ to the northern extent of the Sapphire to Woolgoolga upgrade (about five kilometres north of Woolgoolga), which is currently being constructed. At its northern end, the project would tie in to the southern extent of the recently opened Ballina bypass.
Pollutants/metrics modelled	Max 1-hour CO Max 8-hour CO Max 1-hour NO_2 Annual average NO_2 Max 24-hour average PM_{10} Annual average PM_{10}
Approach	Assessment of greenhouse gas emissions as part of the Transport Authorities Greenhouse Group, 2011.
Scenarios	2016, and 2026 with and without the project.
Traffic data	Average daily traffic on the Pacific Highway at the time of monitoring was around 19,700 vehicles (RTA, 2004).
Background air quality	RMS monitored air quality at a site adjacent to the Pacific Highway at Korora between Korora Public School and the Korora Rural Fire Brigade, north of Coffs Harbour.
Emission factors	Emissions associated with traffic from the project have been calculated using RMS’ Tools for Roadside Air Quality (TRAQ).
Met/dispersion model(s)	TRAQ
Receptors	11 sections of the Pacific Highway.
Model validation	Not specified
Construction assessment	Construction qualitatively assessed.
Notes	Various scenarios were considered, in terms of the project’s intended year of opening (2016), 10 years after opening, and with and without the project.
Reference	NSW RMS (2012)

Appendix E - Description and evaluation of emission models

E.1 Overview

A spatial emissions inventory was developed for road traffic sources in the WestConnex GRAL domain. The modelling of emissions was required for the following components:

- Emissions from the proposed ventilation outlets of the project tunnel. These were calculated using the emission factors provided by PIARC (2012).
- Emissions from the traffic on the surface road network, including any new roads associated with the project. These were calculated on a link-by-link basis using an emission model developed by NSW EPA (2012b).

Descriptions of these two models used, and evaluations of their performance, are provided in the following sections.

E.2 Model descriptions

E.2.1 PIARC model

E.2.1.1 Hot exhaust emissions

The guidance by PIARC (2012) provides hot exhaust emission rates (in grams per hour) for CO, NO_X and opacity. The emission rates were derived from the Handbook of Emission Factors (HBEFA) which is used in Germany, Austria, Switzerland and other European countries (INFRAS, 2010). The underlying emission data were obtained from tests on European vehicles conforming to European standards, and were filtered by PIARC to better represent in-tunnel driving behaviour. Appendix 3, Section 3.1 of the PIARC guidance presents aggregated emission rates for Australian vehicles. These are defined for a base year of 2010 and for the following vehicle types:

- Petrol cars.
- Diesel cars.
- Light commercial vehicles. These are referred to as 'LDVs' by PIARC.
- Diesel HGVs. These are referred to as 'trucks' by PIARC.

For each vehicle type the emission rates are presented as discrete values for different speeds (0 kilometres per hour to 130 kilometres per hour, in intervals of 10 kilometres per hour) and different road gradients (-6 per cent to +6 per cent, in intervals of 2 per cent). No guidance is provided on how to determine emission rates for intermediate speeds and gradients.

Opacity values are provided for both exhaust and non-exhaust particles, and these can be converted to $PM_{2.5}$. It is assumed by PIARC that $PM_{2.5}$ concentrations are directly proportional to opacity, with:

Equation E1

$$\mathbf{K = 0.0047 \times C_{PM2.5}}$$

Where:

K is the opacity (m^{-1})

$\mathbf{C_{PM2.5}}$ is the $PM_{2.5}$ concentration (mg/m^3)

Similarly, the opacity units for emission rates in the PIARC guidance (in m^2/h) are converted into $PM_{2.5}$ emission rates (in g/h) using a factor of 4.7 (i.e. 1 g/h = 4.7 m^2/h).

The influence of fleet renewal, and the introduction of vehicles conforming to more stringent emission standards, is taken into account using scaling factors for future years. These are presented for 2015 and 2020, relative to 2010. No scaling factors are provided for other years. The PIARC model also involves the use of altitude scaling factors, although these are set to unity below an altitude of 1,000 m, and no factors are provided for Australia as no major urban areas are at altitude.

E.2.1.2 Cold-start emissions

PIARC does not provide emission factors for cold-start emissions.

E.2.1.3 Primary NO_2 emissions

It is noted by PIARC that in previous years 90-95 per cent of the NO_X in vehicle exhaust was emitted as NO, but the implementation of diesel after-treatment systems such as oxidation catalysts, diesel particulate filters (DPFs) and selective catalytic reduction (SCR) systems have tended to increase the primary NO_2 fraction (termed f-NO_2). PIARC adds that in many European road tunnels NO_2 can be around 20-30 per cent of NO_X. Only on roads with very few cars with diesel engines will the NO_2 contribution be below 10 per cent. However, PIARC does not provide specific guidance on the fraction of NO_2 that should be used in Australia, or indeed elsewhere.

E.2.1.4 Non-exhaust PM emissions

PIARC notes that the quantification of non-exhaust PM emissions is highly uncertain. Whilst emissions due to abrasion processes correlate with traffic volume and speed, the quantity of resuspended particles is strongly related to the cleanness of the tunnel and whether the traffic is one-way or two-way. In the PIARC guidance it is assumed that the emission rates for non-exhaust $PM_{2.5}$ are dependent only upon the broad type of vehicle (LDV/HDV), and are constant per vehicle-km. There is an additional complexity in that non-exhaust particles are mainly larger than 1 µm in diameter, and do not strongly affect light extinction. However, it is assumed in the guidance that Equation E1 applies to non-exhaust particles as well as to exhaust particles (PIARC, 2012).

E.2.2 NSW EPA model

E.2.2.1 Hot running exhaust emissions

The NSW EPA method for calculating hot running emissions involves the use of matrices of base composite emission factors for the following cases:

- Five pollutants (CO, NO_X, PM_{10}, $PM_{2.5}$, THC)[1].
- Nine vehicle types: petrol passenger vehicles, diesel passenger vehicles, light-duty commercial petrol vehicles (<=3,500 kg), light-duty commercial diesel vehicles (<=3,500 kg), heavy-duty commercial petrol vehicles (>3,500 kg), rigid trucks (3.5-25 t, diesel), articulated trucks (> 25 t, diesel), heavy public transport buses (diesel only), and motorcycles. The composite emission factor for each vehicle type took into account VKT by age and the emission factors for specific emission standards.
- Five road types (residential, arterial, commercial arterial, commercial highway, highway/ freeway), to allow for differences in traffic composition and driving patterns.
- Nine model years (2003, 2008, 2011, 2016, 2021, 2026, 2031, 2036 and 2041). The year defines the composition of the fleet for each type of vehicle, allowing for technological changes. The base year for the inventory is 2008, and therefore the data for years after 2008 are projections.

The road types used in the NSW GMR emissions inventory have been mapped to RTA functional classes by EPA (Table E-1). Further information on the mapping of these categories is provided in the inventory report (NSW EPA, 2012b).

Each base composite emission factor is defined for a VKT-weighted average speed (the base speed) associated with the corresponding road type. Dimensionless correction factors – in the form of 6th-order polynomial functions – are then applied to the base emission factors to take into account the

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[1] It is assumed that $PM_{2.5}$ is equivalent to PM_{10}, which is appropriate for exhaust emissions.

actual speed on a road. According to EPA, the speed correction factors are valid up to 110 kilometres per hour for light-duty vehicles, and up to 100 kilometres per hour for heavy-duty vehicles.

Emission factors have also been provided by EPA for heavy-duty vehicles with and without the implementation of the Euro VI regulation.

Table E-1 Road types used in NSW EPA emissions inventory model

NSW GMR inventory road type	RTA functional class	Definition/description
Local/residential	Local road	Secondary road with prime purpose of access to property. Low congestion and low level of heavy vehicles. Generally one lane each way, undivided with speed limit up to 50 kilometres per hour. Regular intersections, mostly unsignalised, and low intersection delays.
Arterial	Sub-arterial and arterial	Connection from local roads to arterials. May provide support role to arterial roads for movement of traffic during peak periods. Distribute traffic within residential, commercial and industrial areas. Speed limit 50-70 kilometres per hour, 1-2 lanes. Regular intersections, mostly uncontrolled. Lower intersection delays than residential roads, but significant congestion impact at high volume: capacity ratio (V/C).
Commercial arterial	Arterial	Major road for purpose of regional and inter-regional traffic movement. Provides connection between motorways and sub-arterials/collectors. May be subject to high congestion in peak periods. Speed limit 60-80 kilometres per hour, typically dual carriageway. Regular intersections, many signalised, characterised by stop-start flow, moderate to high intersection delays and queuing with higher V/C.
Commercial highway	Arterial	Major road for purpose of regional and inter-regional traffic movement. Provides connection between motorways and sub-arterials/collectors. May be subject to moderate congestion in peak periods. Speed limit 70-90 kilometres per hour, predominantly dual carriageway. Fewer intersections than commercial arterial, with smoother flow but subject to some congestion at high V/C.
Highway/freeway	Motorway	High volume road with primary purpose of inter-regional traffic movement with strict access control (i.e. no direct property access). Speed limit 80-110 kilometres per hour, predominantly 2+ lanes and divided carriageway. Relatively free-flowing when not congested, slowing with congestion approaching V/C limit but minimal stopping.

The emission factor for a given traffic speed is calculated as follows:

Equation E2

$$\mathbf{EF_{HotSpd} = EF_{HotBasSpd} \times \frac{SCF_{Spd}}{SCF_{BasSpd}}}$$

Where:

$\mathbf{EF_{HotSpd}}$ is the composite emission factor (in g/km) for the defined speed

$\mathbf{EF_{HotBasSpd}}$ is the composite emission factor (in g/km) for the base speed

$\mathbf{SCF_{Spd}}$ is the speed-correction factor for the defined speed

$\mathbf{SCF_{BasSpd}}$ is the speed-correction factor for the base speed

Each speed-correction factor is a 6th order polynomial: **SCF = aV^6 + bV^5 +…+ fV + g**, where **a** to **g** are constants and V is the speed in kilometres per hour.

Some examples of the resulting emission factors are shown in the Figures below. Figure E-4 shows how NO_X emissions (per vehicle-km) from petrol cars vary as a function of average speed[2] on different road types. The data show that some types of road, notably arterial roads, are associated with higher emissions for a given average speed than others. Figure E-5 shows how emissions (again, per vehicle-km) of different pollutants from petrol cars will decrease in the future as emission-control technology improves. PM emissions from petrol vehicles are projected to be dominated by non-exhaust particles. Because these are unregulated the reduction in emissions in the future will be lower than for the other pollutants.

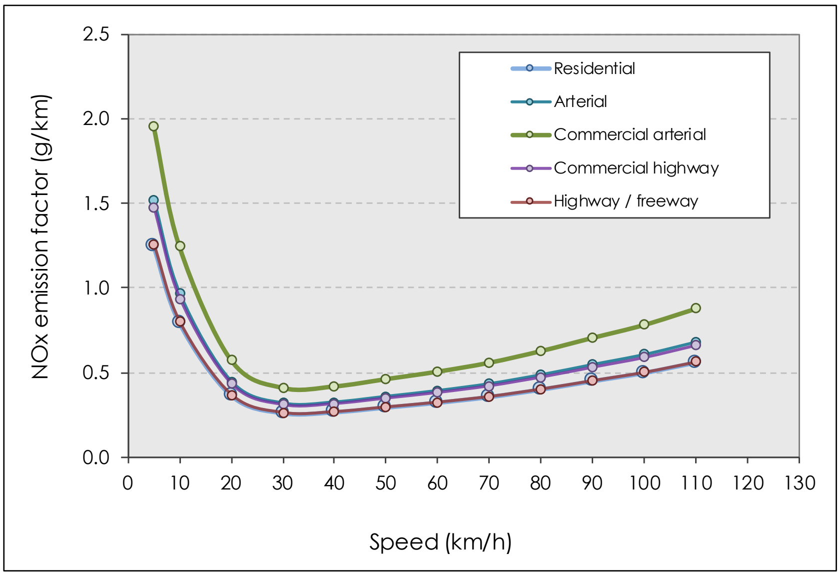

Figure E-1 **NO_X emission factors for petrol cars in 2014**

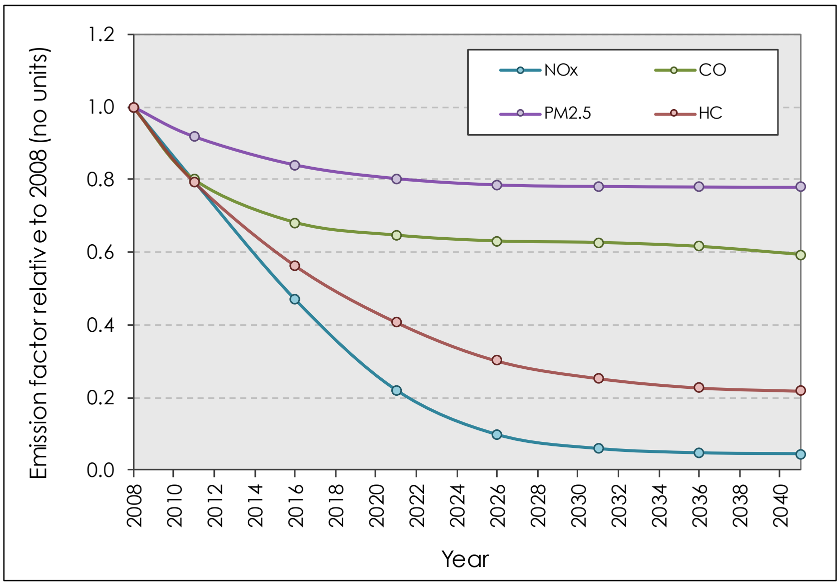

Figure E-2 **Emission factors for petrol cars at 80 kilometres per hour, normalised to 2008**

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[2] 'Average speed' should not be confused with 'constant speed'. The former is calculated for a driving cycle which includes periods of acceleration, deceleration, cruise, and idle, as encountered in real-world traffic.

E.2.2.2 Gradient factors

Correction factors were applied to allow for the effects of road gradient on hot running emissions. NSW EPA did not develop gradient correction factors for the GMR inventory, but these were determined separately by Sinclair Knight Merz (SKM) for use in the TRAQ[3] model.

The gradient factors for TRAQ were taken from the (now superseded) version of the PIARC tunnel ventilation guidance of 2004, and therefore revised factors were determined using the emission rates in the PIARC guidance from 2012. For each gradient and speed, the gradient correction factor was determined by dividing the corresponding PIARC emission rate by the emission rate for zero gradient.

The gradient correction is introduced as follows:

Equation E3

$$\mathbf{EF_{HotGradCor} = EF_{HotSpd} \times G}$$

Where:

$\mathbf{EF_{HotGradCor}}$	is the composite emission factor (in g/km), corrected for road gradient
G	is the road gradient correction factor. Different values of **G** are used for each pollutant, vehicle type and speed.

No gradient corrections were applied to THC (any vehicles) or to PM emissions from petrol vehicles.

E.2.2.3 Cold-start emissions

The method for calculating cold-start emissions involved the application of adjustments to the base hot emission factors to represent the extra emissions which occur during ‘cold running’. The adjustments took into account the distance driven from the start of a trip, the parking duration and the ambient temperature. Cold-start emissions were only calculated for light-duty vehicles. No cold-start adjustment was made for PM. The amount of cold running was dependent on the road type, and no cold running was assumed for highways.

Cold-start emissions are therefore calculated as follows:

Equation E4

$$\mathbf{EF_{Cold} = EF_{HotBasSpd} \times (CS-1)}$$

Where:

$\mathbf{EF_{Cold}}$	is the cold-start emission factor (in g/km)
CS	is a cold start adjustment factor (>1). Different values of **CS** are used for each pollutant, vehicle type, road type and year.

E.2.2.4 Primary NO_2 emissions

No primary NO_2 emission factors were available for Australian vehicles. Primary NO_2 emissions were therefore determined by NSW EPA using the f-NO_2 values for the various vehicle types and emission standards that have recently been developed for the EMEP/EEA Air Pollutant Emission Inventory Guidebook and the COPERT 4 model (Pastramas et al., 2014).

E.2.2.5 Non-exhaust PM emissions

The method for non-exhaust PM_{10} and $PM_{2.5}$ emissions was drawn from the EMEP/EEA Air Pollutant Emission Inventory Guidebook (EEA, 2013), and included tyre wear, brake wear and road surface wear. Emission factors (in g/km) were provided for each vehicle type, road type and year. Information

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[3] TRAQ is an air quality screening model for roads that has been developed by Roads and Maritime.

was required for parameters such as vehicle load and number of axles, and the assumptions used for vehicles in the NSW GMR are described in NSW EPA (2012b).

E.2.2.6 Evaporative emissions

Evaporative emissions of VOCs are not included in the EPA model described here, although they are included in the more detailed full inventory model. The calculation of evaporative emissions is relatively complex, as it requires an understanding of temperature profiles, fuel vapour pressure, fuel composition, and operational patterns. Moreover, it is difficult to link evaporative emissions to traffic activity on specific road links, as running losses are only one component (for example, evaporative emissions also occur when vehicles are stationary). For these reasons evaporative emissions have been excluded from the model and the M4 East assessment. Ambient concentrations of VOCs are also very low, and the inclusion of evaporative emissions would be unlikely to result in adverse impacts on air quality.

E.2.3 Fleet data

In order to combine the emission factors in the models with traffic data, information was also required on the following:

- The fuel split (petrol/diesel) for cars (Figure E-6). This was assumed to be the same for all road types.
- The fuel split (petrol/diesel) for LCVs (Figure E-7). This was also assumed to be the same for all road types.
- The sub-division of HDVs into rigid HGVs, articulated HGVs and buses (Figure E-8).

These splits were provided for NSW EPA for the road types included in the EPA model, and as used in the GMR inventory. The values were based on VKT data from the Bureau of Transport Statistics Household Travel Survey, Strategic Travel Model, and Freight Movement Model (NSW EPA, 2012b and references therein).

An examination of vehicle registration (sales) data in NSW has recently been conducted by NSW EPA (Jones, 2015). Whilst there are some differences[4] between the geographical coverage and the definitions of vehicle groups, the EPA analysis has highlighted some discrepancies between the actual vehicle sales figures and the inventory projections.

Figure E-9 shows the diesel proportions for cars ('PC' = cars and people-movers) and SUVs.

NSW EPA note the following in relation to these data:

- The actual growth in diesel car sales has been lower than projected in the inventory. For example, the actual NSW-wide diesel proportion of sales in 2014 was 8 per cent, compared with a projection for 2014 in the inventory of 19 per cent. These data are shown by the blue lines.
- The proportions of new four-wheel-drive (4WD) vehicles that are diesel in the sales data are in good agreement with the inventory projections. These data are shown by the red lines.
- The proportion of passenger vehicles (PV = cars + people-movers + SUV) that are SUVs is underestimated in the inventory projections for 2014 at 29 per cent, compared with 37 per cent in the sales data. These data are shown by the green lines.

Figure E-10 shows the total passenger vehicle (PV) fleet (cars + people-movers + SUV) and light commercial vehicles (LCV).

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[4] The vehicle registration data to the end of 2014 were NSW-wide, whereas the inventory projection were for the GMR only. There may be some bias due to the different geographical areas (e.g. there may be more diesel vehicles and more SUV/4WD in regional areas). In addition, for LCVs the inventory defines these as GVM <=3500kg in line with the ADR's (i.e. primarily utes and vans), while the RMS rego data lists light trucks as those commercial vehicles with GVM <=4500 kg; thus there may be a bias again to diesel in the RMS as those vehicles 3.5t – 4.5t will be almost exclusively diesel.

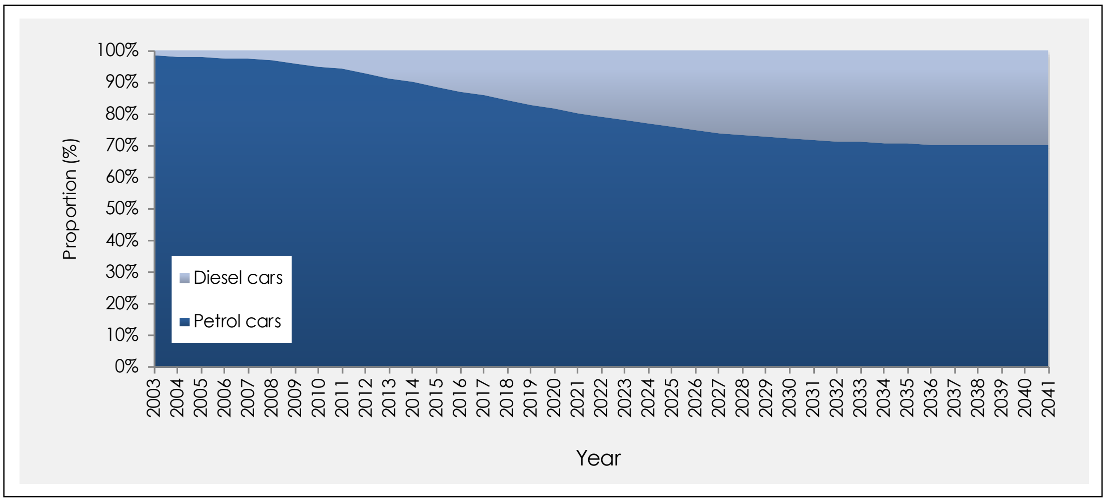

Figure E-3 **Fuel split for cars**

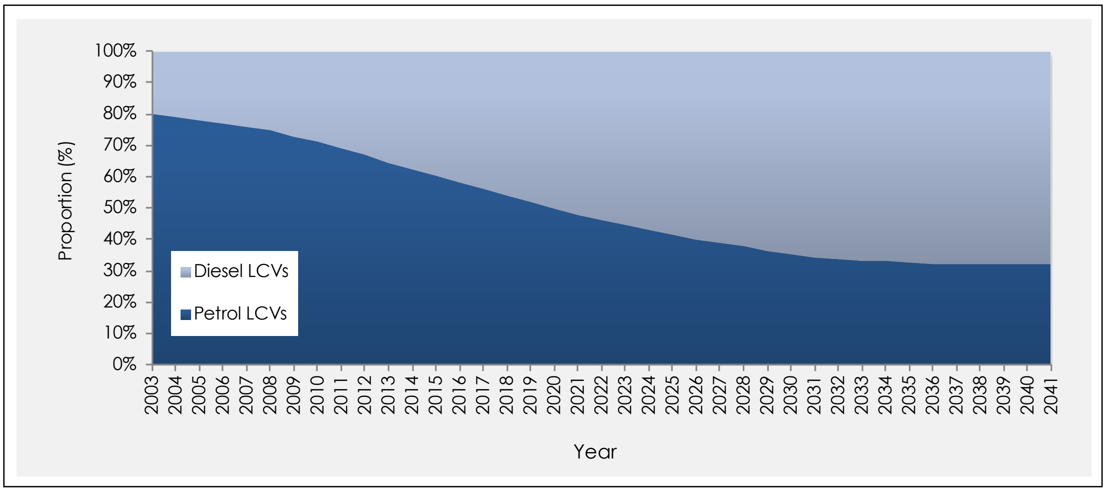

Figure E-4 **Fuel split for LCVs**

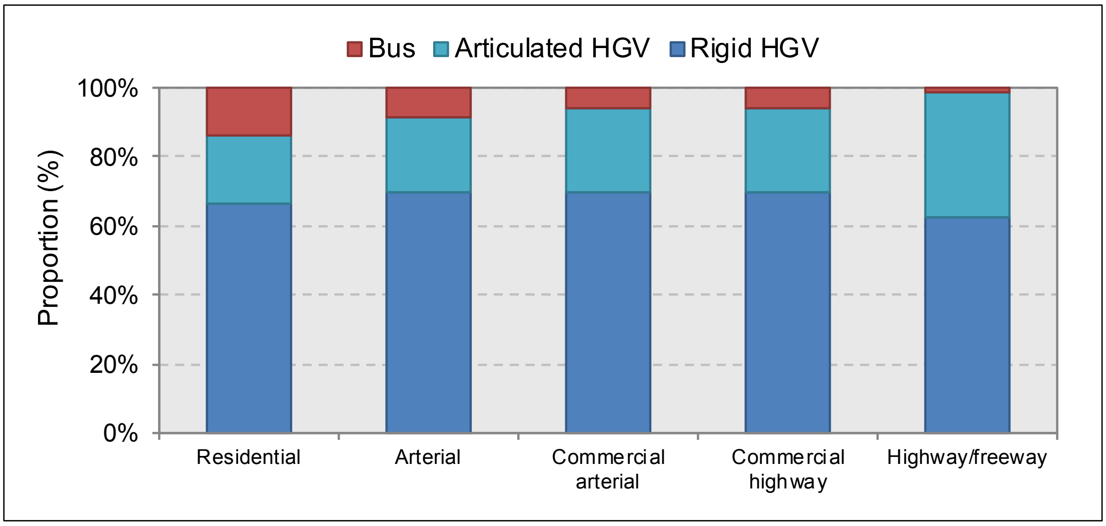

Figure E-5 **Vehicle type split for HDVs (year = 2021)**

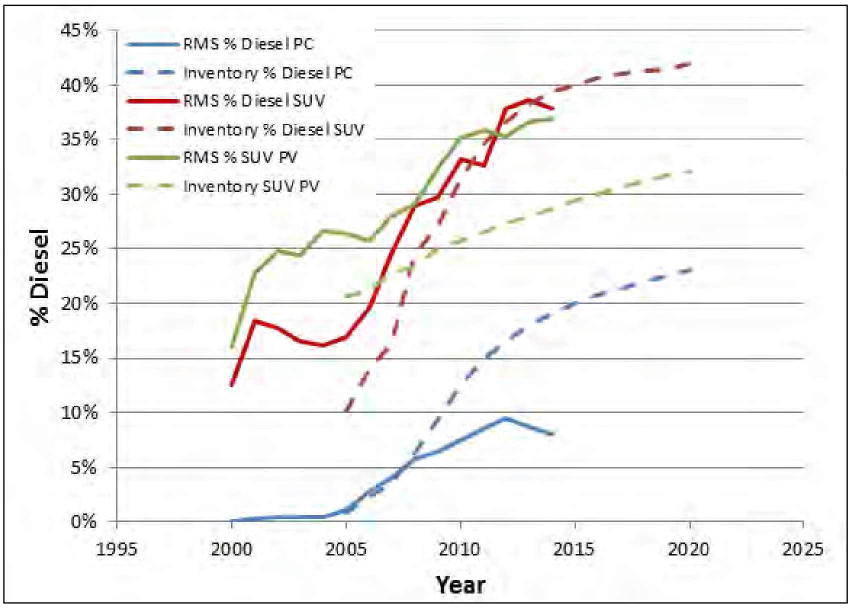

Figure E-6 **Diesel proportions for cars and SUVs**

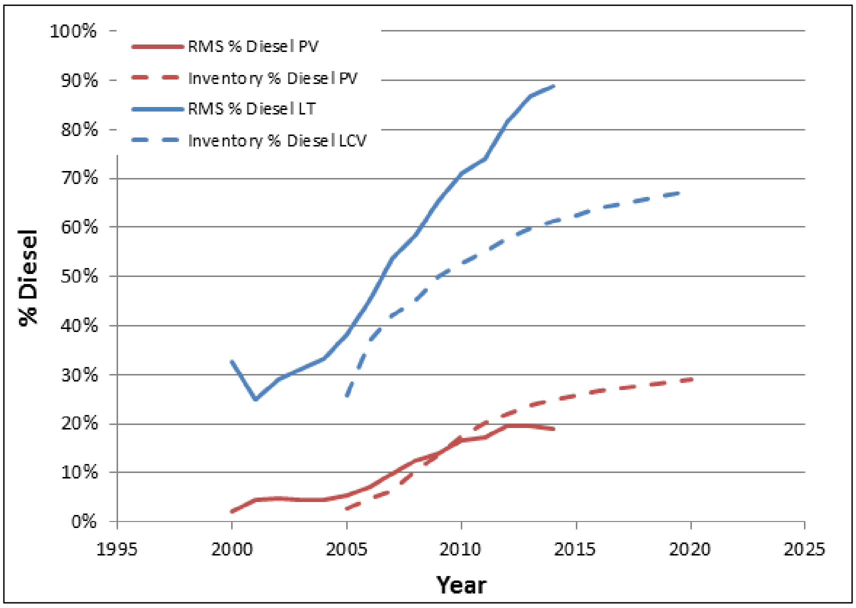

Figure E-7 **Diesel proportions for all passenger vehicles and light commercial vehicles**

In relation to these data, NSW EPA note the following:

- The proportion of total new passenger vehicles (cars, people-movers and 4WD/SUV) that are diesel is higher in the inventory projection for 2014 (25 per cent) than in the sales data (19 per cent).
- In contrast to cars, the actual diesel proportion of LCVs in 2014 (89 per cent) was substantially higher than the projection (61 per cent).

It was beyond the scope of this work to include these discrepancies in the M4 East assessment. NSW EPA is currently updating the emissions inventory, and the fleet information will be revised as part of this process.

E.2.4 Model summary

The algorithms in the PIARC and EPA models were converted into spreadsheet tools which could be readily used for air quality assessments of road projects, including the processing of data from the WestConnex traffic models. The content of each tool is summarised in Table E-2.

Table E-2 Summary of models

Parameter		Model	
		PIARC	EPA
Years		2010-2021(a)	2008-2041
Emission processes	Hot exhaust	✓	✓
	Cold-start	✗	✓
	Evaporative	✗	✗
	Non-exhaust	✓	✓(b)
Pollutants included	CO	✓	✓
	NO_X	✓	✓
	NO_2	✗	✓
	PM_{10}	✗	✓
	$PM_{2.5}$	✓	✓
	THC/VOC	✗	✓
	CO_2 (exhaust)	✗	✓
	CO_{2-e}	✗	✓
Vehicle categories	Petrol car	✓	✓
	Diesel car	✓	✓
	Petrol LCV	Combined	✓
	Diesel LCV		✓
	Petrol HGV	✗	✓
	Rigid HGV	✓(c)(d)	✓(e)
	Articulated HGV	✓(d)	✓(e)
	Bus	✓(c)(d)	✓(e)
	Motorcycle	✗	✓
Effects on emissions	Road type	✗	✓
	Average speed	✓	✓
	Road gradient	✓	✓(f)
Fuel splits for each year	Cars: petrol/diesel	✓	✓
	LCVs: petrol/diesel	✓	✓
Limitation of HGV speed to 100 km/h		✓	✓
Interpolation of emission factors for actual speed and road gradient		✓	✓
Calculations for any time period		✓	✓
Unlimited road links		✓	✓
Output units	Avg. g/vehicle-km	✓	✓
	g/h from traffic	✓	✓
	g/km/h from traffic	✓	✓

a) For the purpose of model evaluation, the data for 2021 were obtained by extrapolation of the PIARC year scaling factors for 2010-2020. It was considered inappropriate to extrapolate further into the future.
b) Based on full implementation of the method for non-exhaust PM in EEA (2013).
c) Rigid trucks and buses combined.
d) Based on simple scaling factors for an 'average' HDV.
e) Results available with and without ADR80/04 (Euro VI) for HDVs.
f) Using gradient scaling factors from PIARC (2012).

E.3 Model evaluation

E.3.1 Model comparison

E.3.1.1 Emission rates for zero per cent gradient

The PIARC and EPA emission rates were initially compared for a road gradient of 0 per cent. The emission rates for CO, NO_X[5] and $PM_{2.5}$ (both exhaust and non-exhaust) are shown in Figure E-11 to Figure E-18. For ease of comparison, the following assumptions were made in the calculation of these emission rates:

- The emission rates for LCVs were calculated using the PIARC and EPA models and were based on the fuel split for Australia in PIARC (2012) (i.e. 50 per cent petrol and 50 per cent diesel).
- The emission rates for HGVs calculated using the EPA model were based on the split between rigid and articulated vehicles for Australia in PIARC (2012) (i.e. 83 per cent rigid and 17 per cent articulated).
- For HGVs, separate emission rates were calculated using the EPA model for scenarios with and without the implementation of the Euro VI legislation. This only affected NO_X and exhaust $PM_{2.5}$.

It is worth repeating that:

- The PIARC method does not provide emission rates for 2031 and have therefore been assumed to the same as 2021.
- For cars and LCVs the valid speed range in the EPA approach is 5 to 110 kilometres per hour.
- The speed of HGVs has been restricted to 100 kilometres per hour in all models.

It is clear from these figures that the prediction of one model relative to the other depends on the pollutant, vehicle type, traffic situation and year being investigated. However, a more general overview of the behaviour of the different models can be obtained from the weighted results for a 'typical' highway tunnel traffic mix, as shown in Figure E-12, Figure E-14 and Figure E-18. For each pollutant the weighted emission rates were calculated based on a peak-hour traffic mix of 62 per cent petrol car, 7 per cent diesel car, 18 per cent petrol LCV, 10 per cent diesel LCV and 3 per cent HGV. These figures show the following:

- CO: In 2014 and 2021 the CO emission rates of the two models were similar at low speeds. For speeds between around 20 and 60 kilometres per hour the PIARC model tended to give higher emission rates than the EPA model. The EPA model gave significantly higher emission rates than the PIARC model at high speeds. In 2031 the EPA model gave lower emissions than the PIARC model at speeds below 70 km/h, but higher emissions at speeds above 70 km/h.
- NO_X: The PIARC and EPA models gave broadly similar NO_X emission rates for speeds below 40 kilometres per hour in all years. For 2014 and 2021 the EPA models gave the highest results for speeds above 40 kilometres per hour. For 2031 the models gave quite similar results.
- $PM_{2.5}$: For all years the PIARC model gave systematically higher total $PM_{2.5}$ emission rates than the EPA model. This was due to the conservative assumptions concerning non-exhaust PM in the PIARC model, although exhaust emissions in the PIARC model were also higher than those in the EPA model.

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[5] NO_2 is not included in the PIARC model.

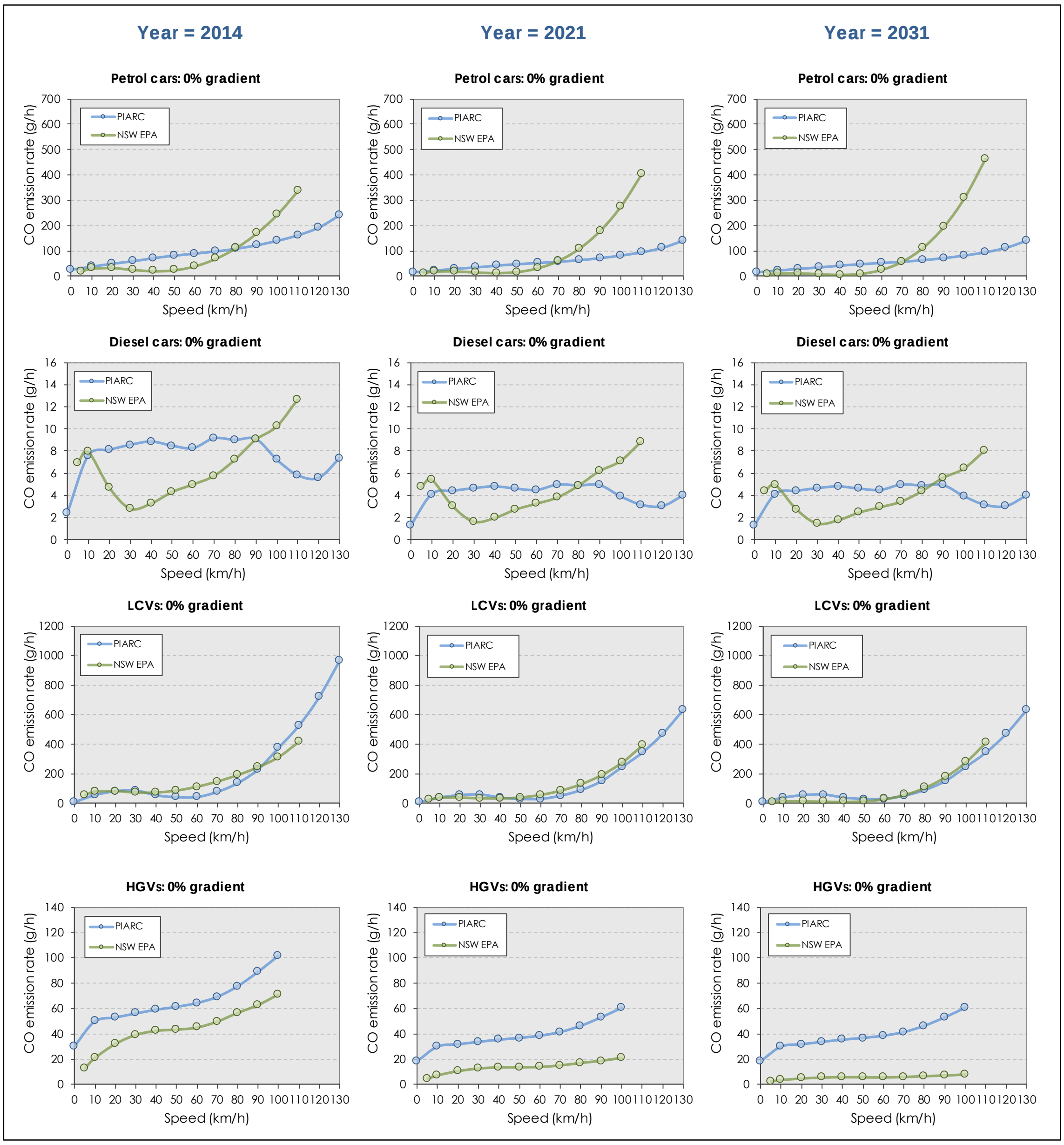

Figure E-8 CO emission rates at zero per cent gradient for 2014, 2021 and 2031

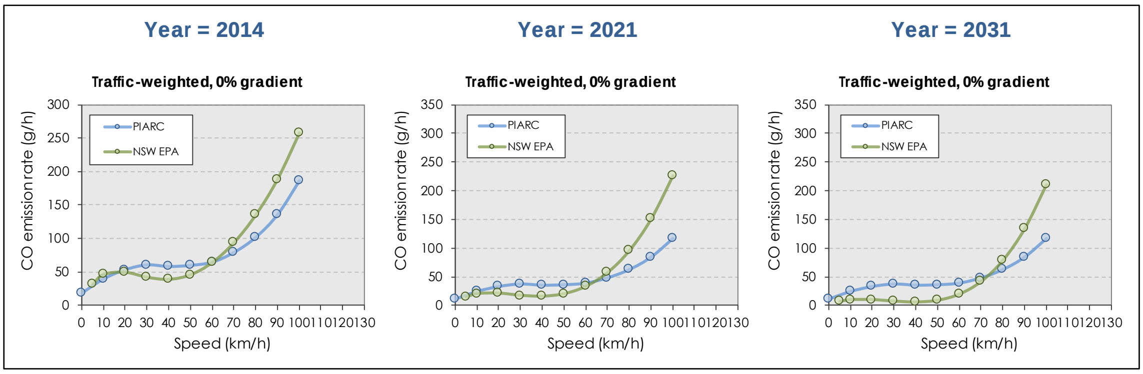

Figure E-9 Traffic-weighted CO emission rates at zero per cent gradient and highway traffic mix for 2014, 2021 and 2031

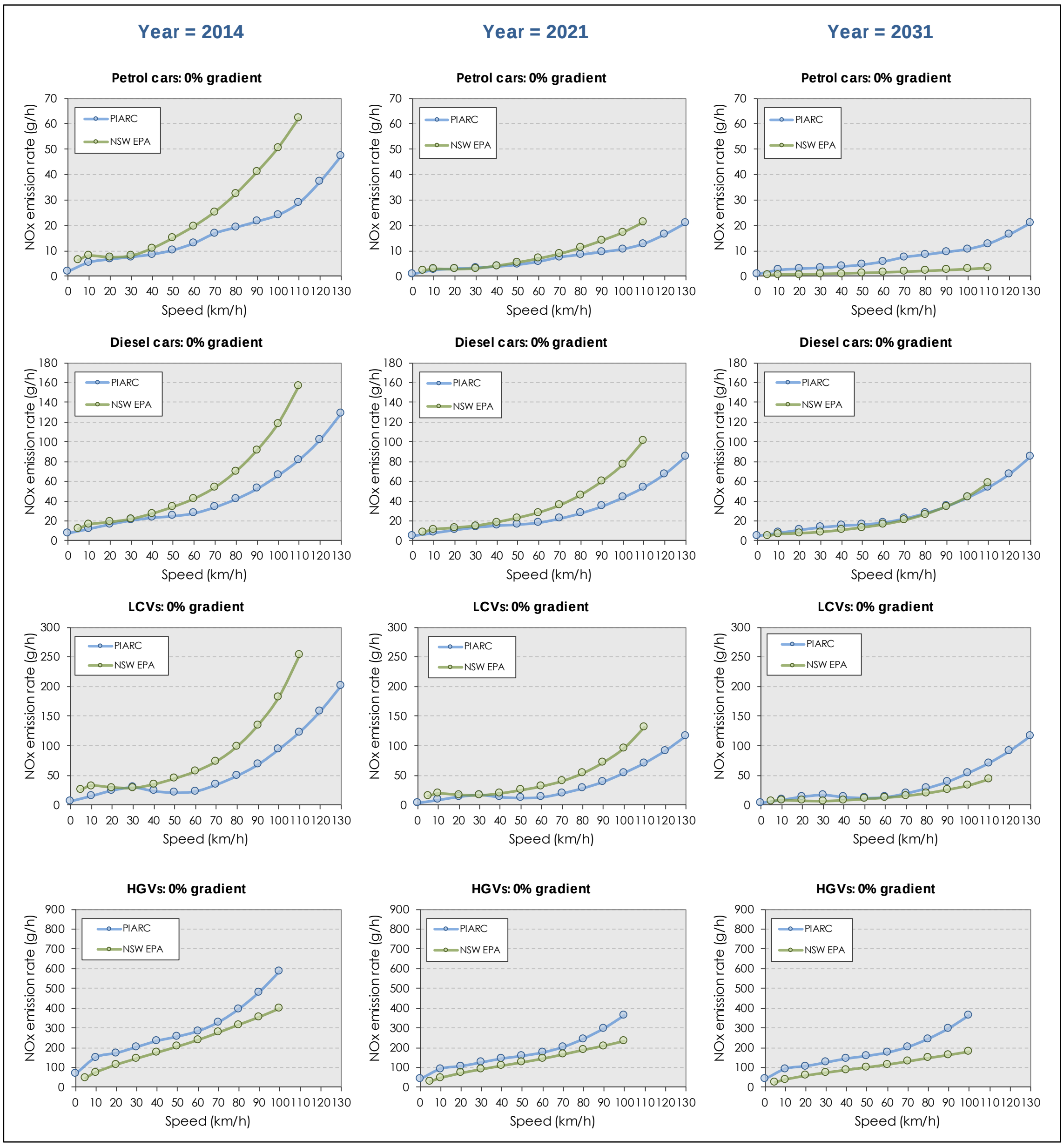

Figure E-10 NO$_X$ emission rates at zero per cent gradient for 2014, 2021 and 2031

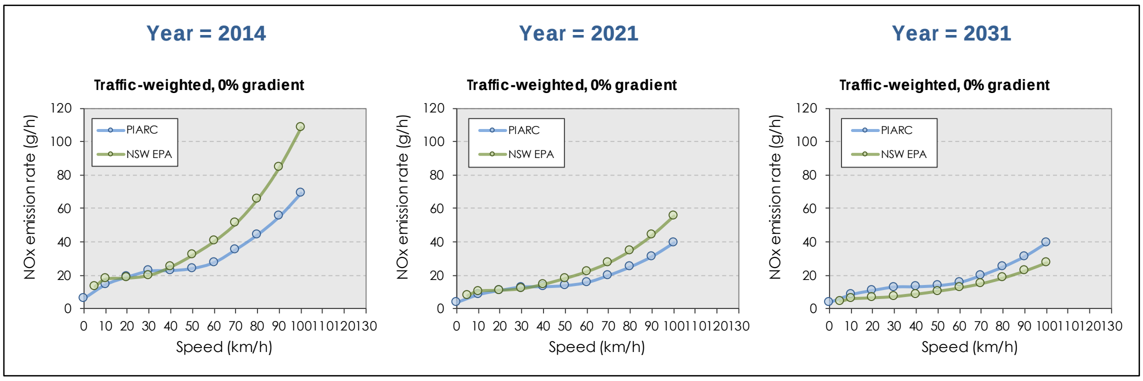

Figure E-11 Traffic-weighted NO$_X$ emission rates at zero per cent gradient for and highway traffic mix 2014, 2021 and 2031

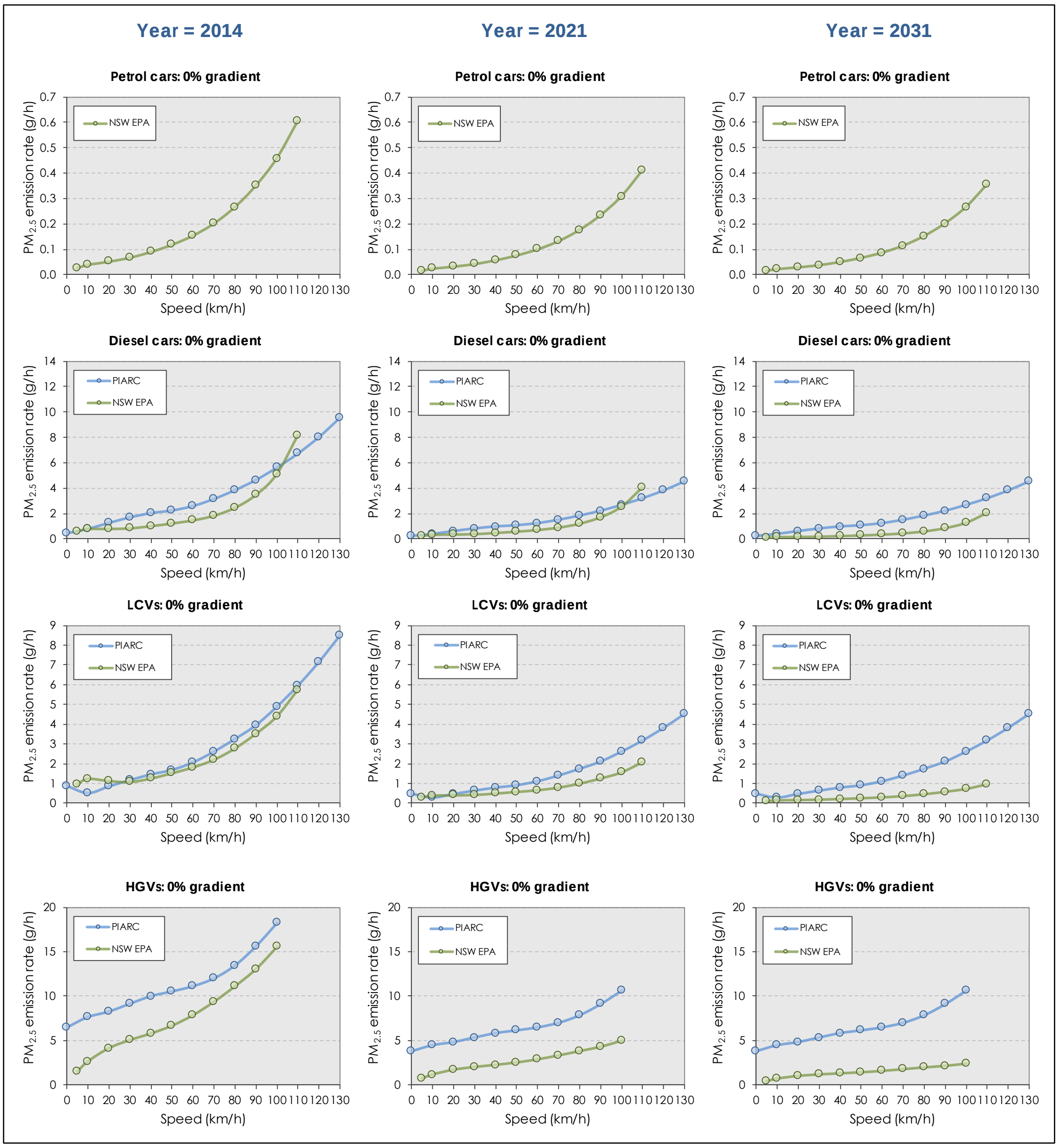

Figure E-12 Exhaust $PM_{2.5}$ emission rates at zero per cent gradient for 2014, 2021 and 2031

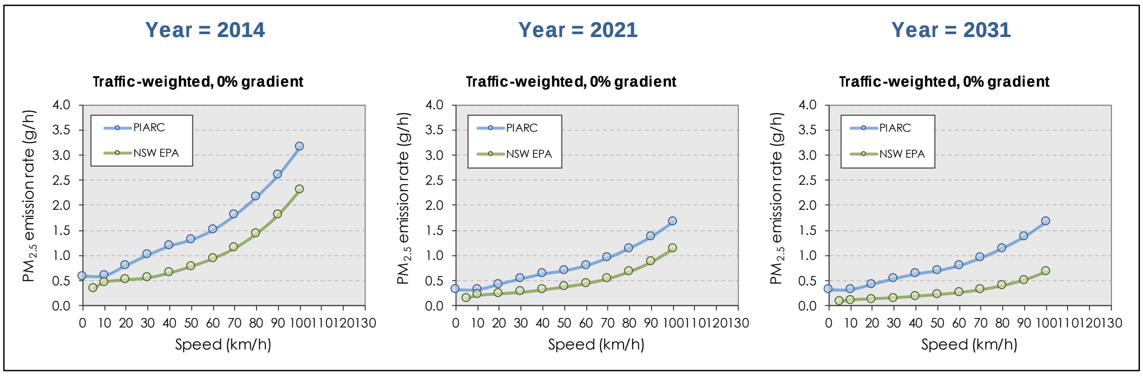

Figure E-13 Traffic-weighted exhaust $PM_{2.5}$ emission rates at zero per cent gradient and highway traffic mix for 2014, 2021 and 2031

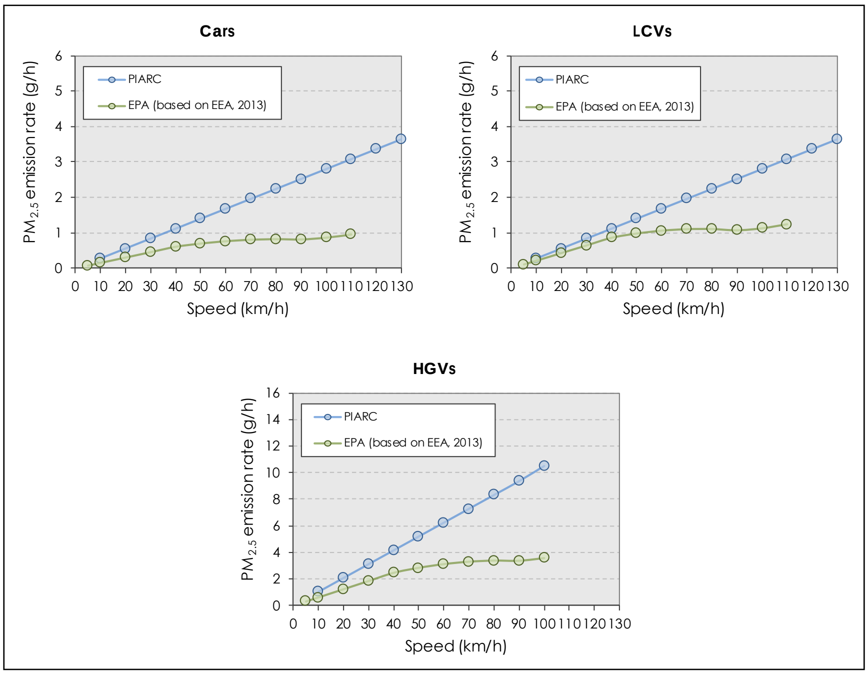

Figure E-14 Non-exhaust $PM_{2.5}$ emission rates at zero per cent gradient for 2014, 2021 and 2031

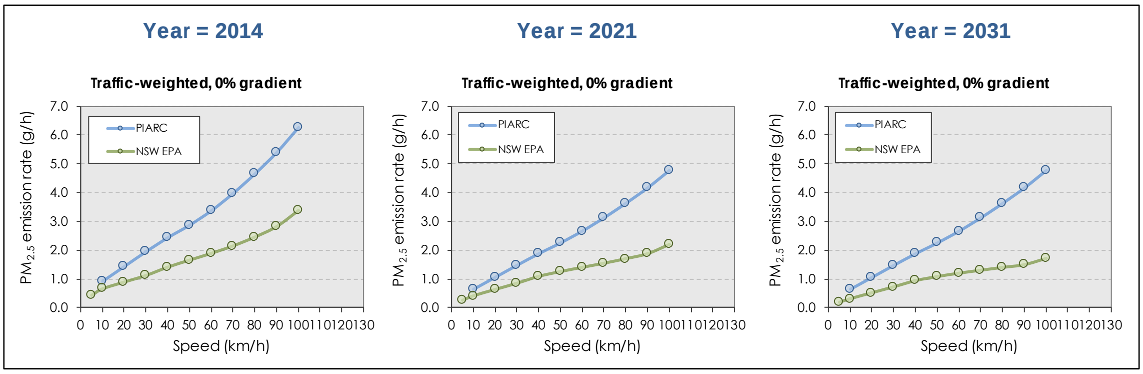

Figure E-15 Traffic-weighted total $PM_{2.5}$ emission rates at zero per cent gradient for highway traffic mix 2014, 2021 and 2031

E.3.2 Model validation

E.3.2.1 Performance of PIARC model

The accuracy of the PIARC model at representing vehicle emissions (CO, NO_X and $PM_{2.5}$) in the Lane Cove Tunnel was recently investigated by Boulter and Manansala (2014). The ventilation conditions in the tunnel result in all vehicle emissions being released from the ventilation outlets. No pollution is released from the tunnel portals. This makes it possible to compare the predicted mass emission rate (in g/h) for the traffic in each direction of the tunnel with the observed emission rate in the corresponding ventilation outlet. The same data (from October and November 2013) were used in the M4 East assessment to re-evaluate the accuracy of the PIARC model, as some changes to the implementation of the models by Pacific Environment had been made. The pollutants NO_2 and PM_{10} were also included in this part of the work, where possible.

The predicted and observed emission rates in the Lane Cove Tunnel were compared using a linear regression approach. In Figure E-21 separate results are shown for each pollutant and each direction in the tunnel; the eastbound tunnel is predominantly uphill, and the westbound tunnel is predominantly downhill. In each graph the dashed red line represents a 1:1 ratio between the predicted and observed emission rates, and the solid lines show the linear regression fits to the data, forced through the origin[6]. The $PM_{2.5}$ predictions are shown with and without the non-exhaust component. The average quotients of the predicted and observed values are given in Table E-3.

Some general patterns were apparent in the results for the PIARC model:

- There was generally a strong correlation between the predicted and observed emission rates for CO, NO_x and $PM_{2.5}$, with R^2 between 0.76 and 0.93. The strong correlations were due in large part to the narrow range of operational conditions (*i.e.* traffic composition, speed) in the Lane Cove Tunnel. In fact, the modelled emission rates were more or less directly proportional to the traffic volume. The variability in the regression plots was therefore linked to the variability of the measurements in the ventilation outlets with traffic volume.
- Different regression slopes were obtained for the eastbound and westbound directions. The eastbound tunnel has a net uphill slope which would increase engine load and emissions, whereas in the downhill westbound tunnel engines would tend to be under lower load, with some newer vehicles possibly having very low fuelling. Such effects may not be adequately reflected in the gradient adjustments in the models.
- On average, the PIARC model **overestimated** pollutant emissions in the tunnel. This is likely to be due in part to the following:
    - The inherent over-prediction built into the PIARC gradient factors, as well as other conservative assumptions.
    - The tunnel environment itself affecting emissions. The piston effect and any forced ventilation in the direction of the traffic flow may combine to produce an effective tail wind that reduces aerodynamic drag on the vehicles in the tunnel (John et al., 1999; Corsmeier et al., 2005).
- The model overestimated $PM_{2.5}$ emissions by a wider margin (a factor of between 2.6 and 4.3) than CO and NO_X. When exhaust emissions of $PM_{2.5}$ are relatively low (i.e. in the westbound tunnel), the overestimation of total $PM_{2.5}$ emissions as a ratio is much greater than when exhaust emissions are relatively high (i.e. in the eastbound tunnel). This confirms that that **the emission rates for non-exhaust $PM_{2.5}$ in the PIARC model are very conservative**. It can be seen from Figure E-21 that the $PM_{2.5}$ predictions of the PIARC model are still generally conservative (by a factor of around 1.5) even when the non-exhaust component is excluded.

The differences between the predicted and observed emission rates are influenced not only by errors in the emission factors in the model, but also the assumptions concerning the fleet composition and age distribution. Moreover, there are inherent errors in the outlet concentration and air flow measurements.

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[6] As the outlet emission rates were adjusted for the background contribution, and there were no other in-tunnel emission sources, it was considered acceptable to run the regression model with the constant constrained to zero.

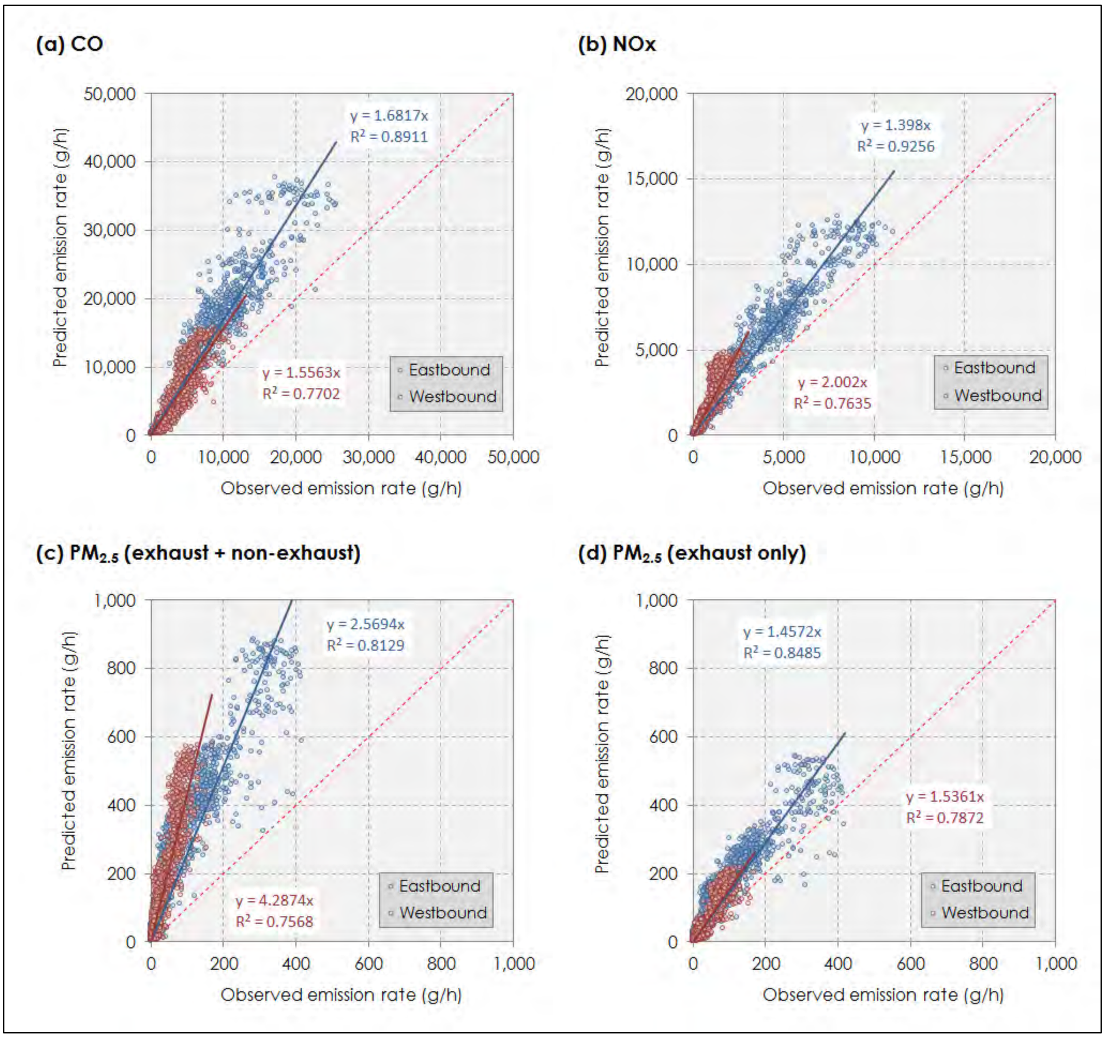

Figure E-16 Predicted vs observed emission rates – PIARC model

Table E-3 Summary of predicted vs observed emission rates

Methodology	Predicted emission rate / observed emission rate				
	CO	NO_X	NO_2	PM_{10}	$PM_{2.5}$
Eastbound					
PIARC	1.68	1.40	Not calculated	Not calculated	2.57
Westbound					
PIARC	1.56	2.00	Not calculated	Not calculated	4.29

E.3.2.2 Performance of NSW EPA model

A corresponding analysis was undertaken for the EPA model. The regression plots are shown in Figure E-24. The average quotients of the predicted and observed values are given in Table E-4.

The performance of the EPA model was similar to that of the PIARC model, with similar correlation coefficients. The EPA model gave a larger overestimation of emissions than the PIARC model for CO, NO_X and NO_2, and a smaller overestimation for $PM_{2.5}$.

Interestingly, in the westbound tunnel the NO_2 data had more scatter than the NO_X data, and a low correlation coefficient was obtained. This is in part due to the relatively low emissions in the westbound tunnel and is possibly also a consequence of the measurement technique (chemiluminescence), which does not generally respond well to NO_2 concentrations which fluctuate rapidly on short timescales. The NO_X measurements are less affected by this problem, and ought to be more reliable.

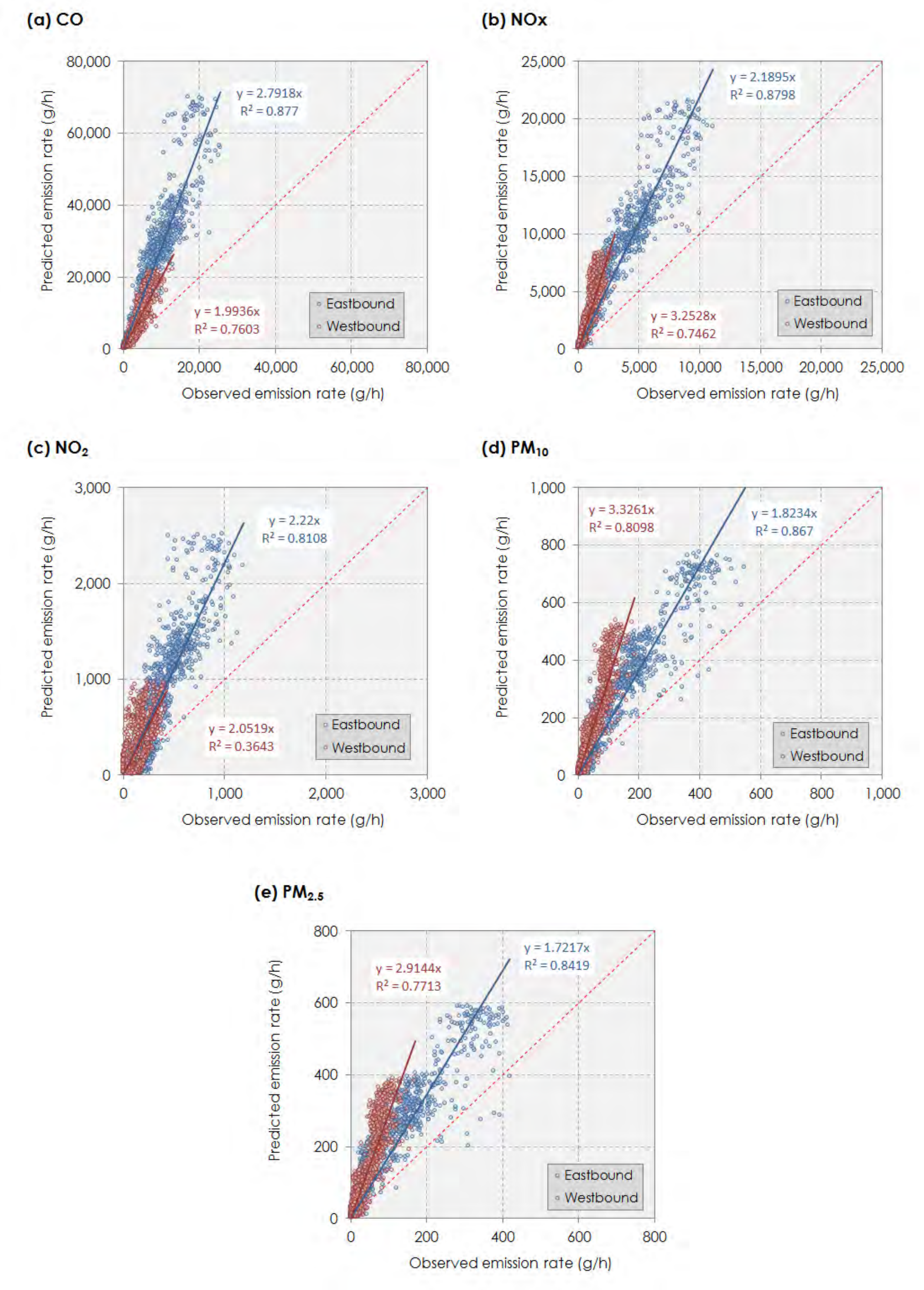

Figure E-17 **Predicted vs observed emission rates – EPA model (with PIARC gradient scaling factors)**

Table E-4 Summary of predicted vs observed emission rates

Methodology	Predicted emission rate / observed emission rate				
	CO	NO_X	NO_2	PM_{10}	$PM_{2.5}$
Eastbound					
NSW EPA	2.79	2.19	2.22	1.82	1.72
Westbound					
NSW EPA	1.99	3.25	2.06	3.32	2.91

E.3.2.3 Emission factors by vehicle type

A multiple linear regression (MLR) approach was used to determine mean emission factors (in g/km) for LDVs and HDVs based on the adjusted outlet emission rates (CO, NO_X, PM_{10} and $PM_{2.5}$). Multiple linear regression can be used to test how well a dependent variable can be predicted on the basis of multiple independent variables. The inputs to the MLR were the hourly mean emission factor for the traffic (dependent variable) and the corresponding numbers of LDVs and HDVs in the tunnel each hour (independent variables). A similar MLR method has been used in various studies to derive emission factors (e.g. Imhof et al., 2005; Colberg et al., 2005). The following regression model was applied to derive the emission factors:

Equation E5

$$\mathbf{EF_{total} = (N_{LDV} \times EF_{LDV}) + (N_{HDV} \times EF_{HDV}) + c}$$

where:

$\mathbf{EF_{total}}$ = the hourly mean emission factor for all traffic in the tunnel, as determined from the tunnel ventilation outlet measurements (g/km/h)

$\mathbf{N_{LDV}}$ = the number of LDVs in the tunnel per hour (vehicles/hour)

$\mathbf{N_{HDV}}$ = the number of HDVs in the tunnel per hour (vehicles/hour)

$\mathbf{EF_{LDV}}$ = the emission factor per LDV in the tunnel (g/vehicle.km)

$\mathbf{EF_{HDV}}$ = the emission factor per HDV in the tunnel (g/vehicle.km)

c = a constant (intercept on y-axis)

The hourly mean emission factor for all traffic in the tunnel was obtained by dividing the emission rate by the length of the main line tunnel (3.61 km), with the on- and off-ramps being ignored. The emissions on the ramps were negligible (less than around 2 per cent) compared with the emissions on the main lines.

As the outlet emission rates had already been adjusted to allow for the background contribution, and as there were no other in-tunnel emission sources it was considered acceptable to run the regression model with the constant constrained to zero.

The overall mean observed and predicted emission factors for LDVs, HDVs and all traffic (weighted for traffic volume) are shown in Table E-5, and the predicted/observed ratios are given in Table E-6.

Table E-5 Emission factors by vehicle type and direction

Direction	Pollutant	LDV (g/vehicle.km)			HDV (g/vehicle.km)			All traffic (g/vehicle.km)[a]		
		Observed	PIARC	NSW EPA	Observed	PIARC	NSW EPA	Observed	PIARC	NSWEPA
Eastbound	CO	1.47	2.75	4.61	3.66	0.79	1.09	1.62	2.71	4.48
	NO_X	0.29	0.57	1.18	8.42	8.82	6.93	0.61	0.89	1.39
	NO_2	0.06	N/A	0.14	0.37	N/A	0.85	0.08	N/A	0.16
	PM_{10}	0.01	N/A	0.04	0.36	N/A	0.31	0.03	N/A	0.05
	$PM_{2.5}$	0.01	0.05	0.03	0.32	0.35	0.27	0.02	0.06	0.04
Westbound	CO	0.72[b]	1.21	1.53	-[c]	0.48	0.48	0.78	1.18	1.49
	NO_X	0.13	0.27	0.51	1.07	2.81	2.78	0.18	0.37	0.60
	NO_2	0.03	N/A	0.06	0.03	N/A	0.34	0.03	N/A	0.07
	PM_{10}	0.01	N/A	0.03	0.08	N/A	0.21	0.01	N/A	0.04
	$PM_{2.5}$	0.01	0.04	0.02	0.07	0.13	0.17	0.01	0.04	0.03

(a) Weighted for traffic volume.
(b) Based on regression for LDV only (see point (c) below).
(c) Multiple regression analysis did not result in a valid emission rate.

Table E-6 Predicted/observed emission factors by vehicle type and direction

Direction	Pollutant	LDV (predicted/observed)		HDV (predicted/observed)		All traffic (predicted/observed)[a]	
		PIARC	NSW EPA	PIARC	NSW EPA	PIARC	NSW EPA
Eastbound	CO	1.9	3.1	0.2	0.3	1.7	2.8
	NO_X	1.9	4.0	1.0	0.8	1.5	2.3
	NO_2	N/A	2.4	N/A	2.3	N/A	2.1
	PM_{10}	N/A	3.0	N/A	0.9	N/A	1.9
	$PM_{2.5}$	5.2	3.2	1.1	0.8	3.0	1.9
Westbound	CO	N/A	N/A	N/A	N/A	1.5	1.9
	NO_X	2.0	3.8	2.6	2.6	2.0	3.2
	NO_2	N/A	2.2	N/A	11.6	N/A	2.2
	PM_{10}	N/A	3.9	N/A	2.7	N/A	3.3
	$PM_{2.5}$	5.8	3.3	2.0	2.6	4.4	2.9

(a) Weighted for traffic volume.

It has already been observed that both the PIARC and EPA models overestimated emissions in the Lane Cove Tunnel. It was noted by Boulter and Manansala (2014) that this is due in large part to the use of conservative gradient scaling factors. These additional results show that:

- For LDVs the predicted emissions were higher than the observed emissions in both the eastbound and westbound tunnels, except for NO_2 in the westbound tunnel for which the values predicted using the PIARC model and the observed values were the same.
- For HDVs, emissions of CO, NO_X, PM_{10} and $PM_{2.5}$ in the eastbound tunnel were underestimated by the models, whereas emissions of NO_2 were overestimated. In the westbound tunnel the predicted emissions were either equal to or higher than the observed emissions.

E.3.2.4 Primary NO_2 emissions

Inside a road tunnel most of the NO_2 in the air is primary in origin; it is emitted directly from vehicle exhaust pipes rather than being formed in the tunnel atmosphere. Whilst it is possible that certain reactions could lead to the formation of NO_2 in longer tunnels, the NO_2/NO_X proportion in the air from the ventilation outlets of most tunnels ought to provide a reliable indication of the overall average NO_2/NO_X proportion in vehicle exhaust (Boulter et al., 2007). The measurements from the Lane Cove Tunnel ventilation outlets provided useful information on primary NO_2 emissions from the vehicles in the tunnel, and the observed values of *f*-NO_2 calculated from the MLR analysis are given in Table E-7. The corresponding values for the NSW EPA model are also shown.

The average measured values of *f*-NO_2 for all vehicles were 13 per cent in the eastbound tunnel and 17 per cent in the westbound tunnel. The models were broadly in agreement with the measurements on average, giving a value of around 12 per cent (the same method for calculating NO_2 was used in both models). However, the models did not reproduce the observed difference in *f*-NO_2 between LDVs and HDVs. For the former, *f*-NO_2 was underestimated, whereas for the latter it was overestimated.

Table E-7 Primary NO_2 values

Vehicle type	Model	Eastbound			Westbound		
		NO_X (g/vkm)	NO_2 (g/vkm)	*f*-NO_2	NO_X (g/vkm)	NO_2 (g/vkm)	*f*-NO_2
LDV	Observed	0.29	0.06	**19%**	0.13	0.03	**19%**
	NSW EPA	1.18	0.14	**12%**	0.51	0.06	**11%**
HDV	Observed	8.42	0.37	**4%**	1.07	0.03	**3%**
	NSW EPA	6.93	0.85	**12%**	2.78	0.34	**12%**
All Vehicles(a)	Observed	0.61	0.08	**13%**	0.18	0.03	**17%**
	NSW EPA	1.39	0.16	**12%**	0.60	0.07	**11%**

(a) Weighted for traffic volume.

As noted in Appendix B, a recent update of the evidence for vehicles on the road in Sydney was provided by Boulter and Bennett (2015). Although a range of different data sets and methods were used, the level of agreement in both the *f*-NO_2 values and the trend was found to be good. The evidence suggested that there has been a gradual increase in *f*-NO_2 in recent years for highways, from less than 10 per cent before 2008 to around 15 per cent in 2014. It was also concluded that the approach of incorporating the European values for *f*-NO_2 in models for Sydney produced a satisfactory agreement with measurements.

Appendix F - Existing air quality and background concentrations

F.1 Introduction

When predicting the impact of any new or modified source of air pollution, it is necessary to take into account the way in which the emissions from the source will interact with existing pollutant levels. Defining these existing levels and the interactions can be challenging, especially in a large urban area such as Sydney where there is a complex mix of sources. Pollutant concentrations can fluctuate a great deal on short time scales, and substantial concentration gradients can occur in the vicinity of sources such as busy roads. Meteorological conditions and local topography are also very important; cold nights and clear skies can create temperature inversions which trap air pollution near ground level, and local topography can increase the frequency and strength of thee inversions. In the case of particulate matter, dust storms, natural bush fires and planned burning activities are often associated with the highest concentrations (SEC, 2011).

This Appendix provides the results of a thorough analysis of the air quality monitoring data that were available for the study area. The analysis was based on measurements conducted during the 11-year period between 2004 and 2014, the principal aim being to **establish background pollutant concentrations** for use in the M4 East assessment, taking into account the factors identified above. The analysis dealt with temporal and spatial patterns in the data, and contributed to the general understanding of air quality in Sydney.

This approach was in accordance with the NSW Approved Methods, which states:

> 'Including background concentrations in the assessment enables the total impact of the proposal to be assessed. The background concentrations of air pollutants are ideally obtained from ambient monitoring data collected at [or as close as possible to] the proposed site.' (NSW DEC, 2005)

Background concentrations were determined for the following pollutants and metrics, as these are especially relevant to road transport:

- CO – one-hour mean
- CO – rolling 8-hour mean
- NO_X – annual mean
- NO_X – one-hour mean
- PM_{10} – annual mean
- PM_{10} – 24-hour mean
- $PM_{2.5}$ – annual mean
- $PM_{2.5}$ – 24-hour mean

Background concentrations of NO_2 and O_3 were also determined. These were not included in the actual assessment of the project, and were only used to test the NO_X-to-NO_2 conversion methods developed in Appendix G.

For air toxics the NSW Approved Methods do not require the consideration of background concentrations. However, some data have been presented to demonstrate that prevailing concentrations in Sydney are very low.

F.2 Monitoring sites

The siting and classification of air quality monitoring stations is governed, as far as practicable, by the requirements of Australian Standard AS/NZS 3580.1.1:2007 - Methods for sampling and analysis of ambient air - Guide to siting air monitoring equipment. The Standard recognises that air quality is monitored for different purposes, and for convenience it classifies monitoring sites as follows based on functional requirements:

- Peak sites. These are located where the highest concentrations and exposures are expected to occur (such as near busy roads or industrial sources).
- Neighbourhood sites. These are located in areas which have a broadly uniform land use (e.g. residential or commercial zones), and can be used to characterise general trends in air quality.
- Background sites. These sites are located in urban or rural areas to provide information on air quality away from specific sources of pollutants such as major roads or industry.

The Standard also recognises that, in practice, a given site may serve more than one function.

Considerations when siting a monitoring station include the possibility of restricted airflow caused by vicinity to buildings, trees, walls, *etc.*, and chemical interference due to, for example, local industrial emissions.

Air pollutants and meteorological parameters – such as temperature, wind speed and wind direction – are usually measured on an automatic and continuous basis, and such monitoring is conducted at several locations across Sydney. To support the M4 East assessment, data were obtained for the monitoring sites and periods listed in Table F-1. The locations of these sites are shown in Figure F-1.

Until relatively recently, almost all of the air quality monitoring in Sydney has focussed on background locations within urban agglomerations but away from specific sources such as major roads. The monitoring sites in Sydney that are operated by NSW OEH are located in such environments, and have provided a long and vital record of regional air quality. The closest active OEH monitoring sites to the WestConnex scheme were those at Chullora, Earlwood and Rozelle. These sites were between around three and four kilometres from the M4 East project. The OEH sites at Lindfield, Liverpool, Randwick and Prospect were further away (between around 11 and 17 kilometres from the M4 East project), but were still considered important in terms of characterising air quality in the Sydney region.

RMS has established several long-term monitoring stations in response to community concerns relating to the ventilation outlet of the M5 East tunnel, and to monitor operational compliance of the tunnel with ambient air quality standards. Four of the RMS sites (CBMS, T1, U1, X1) were in the vicinity of the ventilation outlet. Sites U1 and X1 were located on a ridge to the north of the outlet, in the region of the predicted maximum impact. However, the impacts of the outlet at the monitoring sites are very small in practice, and these could effectively be considered as urban background sites. Two RMS sites (F1 and M1) were much closer to busy roads near the M5 East tunnel portals.

Consideration was also given to shorter-term data from other RMS air quality monitoring stations. Several monitoring sites were established for the NorthConnex project (AECOM, 2014a), with data being available from December 2013 to January 2015. Data were also available from an additional RMS roadside site ('Aristocrat'), located near the junction of Epping Road and Longueville Road. The Aristocrat site was only operational between 2008 and 2009, but given the low number of roadside monitoring sites in Sydney the data were valuable to the analysis.

WestConnex Delivery Authority (WDA) has established five monitoring stations in the M4 East area to support the development and assessment of the project. WDA commissioned Pacific Environment to operate and maintain the monitoring network. The M4 East network includes one monitoring station at an urban background site and four stations that are located to characterise population exposure near busy roads. The first station became operational in August 2014, and the others later in the year.

For the purpose of the analysis, the air quality monitoring data were separated according to site type. Given the main purpose of the work described in this Chapter (i.e. to determine background concentrations for the project assessment), the emphasis was placed on the background monitoring sites. However, the air quality data from the monitoring sites near roads (shown as shaded cells in Table F-1) have been used for the development of empirical NO_X-to-NO_2 conversion methods (Appendix G) and/or dispersion model evaluation (see Appendix J). For convenience, all the monitoring sites which have been used in the assessment are summarised in this single location.

The time period covered by the project-specific monitoring sites was too short for them to be included in the characterisation of background air quality, although the data from the urban background site for the project was used to examine the representativeness of the OEH and Roads and Maritime sites for this purpose. The data for the project-specific roadside sites are summarised in Appendix J.