Appendix E: Synergetics Air Quality Assessment

SYNERGETICS
ENVIRONMENTAL ENGINEERING

Air quality modelling of M5 East portal emissions

for

Roads and Traffic Authority of NSW

October 2006

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for

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Executive Summary

The M5 East motorway is a 10km long motorway connecting the M5 Motorway in south-western Sydney with the Eastern Distributor in south-eastern Sydney. A key feature of the M5 East is the main road tunnel, which comprises twin 4km, two lane tunnels between the tunnel entry and exit portals at Bexley Road, Earlwood and Marsh Street, Arncliffe. The M5 East was opened to traffic in December 2001.

A ventilation system is incorporated into the tunnel design to maintain the in-tunnel and ambient air quality within the goals specified in the project conditions of approval, which was issued on 9 December 1997 by the then Minister for Urban Affairs and Planning (Approval). The system is a recirculatory system, which involves the transfer of tunnel air between both main tunnels near the tunnel exits, the introduction of fresh air at an intake station, and the discharge of air containing vehicle exhaust emissions from a stack at Turrella. The ventilation system was designed to avoid portal emissions as far as practical.

The Roads and Traffic Authority of NSW (RTA) is considering a proposal for modifications to the M5 East project which generally comprise:

- a trial of controlled emissions from the Marsh Street and Bexley Road portals (proposed trial) to improve air quality in the M5 East tunnel; and
- the construction and operation of a pilot filtration plant for in-tunnel air.

As a consequence, the RTA is considering a proposal to request the Minister for Planning to modify the conditions of the Approval.

This report describes a study to model the dispersion of emissions from the M5 East tunnel portals by application of high quality computer modelling, known as computational fluid dynamics (CFD).

Specifically, the aims of the modelling exercise were to:

- determine the impact (if any) of portal emissions on ambient air quality and residences nearby the portals in the various portal emission scenarios;
- develop a control procedure that limits the contribution of the tunnel portal emissions for the residents around both the Marsh St and Bexley Road portals during the proposed trial so as to ensure compliance with both the air quality goals specified in the Approval and the more stringent Approved Methods for Modelling and Assessment of Air Pollutants in New South Wales (DEC NSW 2005); and
- carry out a health risk assessment to determine if the exposure risk for volatile organic compounds (VOCs) is below the relevant DEC NSW (2005) health risk assessment criteria.

For the purposes of the modelling, a broad range of pollutant assessment criteria, which are identified in Table 1 and Table 2, was considered. However, it is understood that the air quality goals specified in the Approval will remain the compliance goals for the purpose of the Approval, and those goals were also taken into account for the assessment the subject of this report.

From the modelling, a control strategy was developed that limited the contribution of particulate matter (PM_{10}) from portal emissions to a maximum of 5 $\mu g/m^3$ at all residences nearby the portals and limited the portal flow rate to 250m^3/s. This resulted in maximum modelled ground level concentration (GLC) and risk values at relevant residential receptors which are summarised in Table 10 (for criteria pollutants) and Table 11 (for volatile organic carbon compounds or VOCs).

It can be seen from these tables, that all of the modelled pollutant concentrations associated with portal emissions in accordance with the proposed control strategy are below relevant Department of Environment and Conversation (DEC NSW 2005) assessment criteria set to protect public health and, in particular, goals specified in the Approval. In addition, a screening level health risk assessment which was carried out for VOCs, on an individual-for-individual basis and an aggregate risk basis, indicates that VOC levels were also below the DEC NSW (2005) health risk assessment criteria.

A consequence of limiting the maximum contribution of PM_{10} to about 5 $\mu g/m^3$, which is predicted to occur in the order of 3 to 5 days per year, and the portal flow rate to 250m^3/s, also limits the contribution of all other pollutants at residential receptors nearby the portals. For example, the contribution of 24-hour PM_{10}, 1-hour NO_2 and 8-hour CO from portal emissions will be below 2.7$\mu g/m^3$, 23$\mu g/m^3$ and 0.18ppm respectively for 95% of the trial duration. Similarly, the annual average $PM_{10,}$, NO_2 and CO contribution associated with portal emissions will be limited to 0.6$\mu g/m^3$, 3.4$\mu g/m^3$, and 0.053ppm respectively.

The analysis carried out for the Bexley Road and Marsh Street portals is based on actual monitoring data. The worst case highest pollutant contributions are predicted to be experienced at residences nearby the Bexley Road portal. These levels are shown in Table 10 and Table 11. The greater separation distance between the residences and the main tunnel portal at Marsh Street results in greater dispersion of the discharges from the portal and modelling predicts a maximum ground level concentration at nearby residences approximately 30% lower than those at Bexley Road

1 Introduction

The M5 East motorway is a 10km long motorway connecting the M5 Motorway in south-western Sydney with the Eastern Distributor in south-eastern Sydney. A key feature of the M5 East is the main road tunnel, which comprises twin 4km, two lane tunnels between the tunnel entry and exit portals at Bexley Road, Earlwood and Marsh Street, Arncliffe. The M5 East was opened to traffic in December 2001.

A ventilation system is incorporated into the tunnel design to maintain the in-tunnel and ambient air quality within the goals specified in the project conditions of approval, which was issued on 9 December 1997 by the then Minister for Urban Affairs and Planning (Approval). The system is described in more detail in Chapter 2 of this report. Among other things, it involves the discharge of air containing vehicle exhaust emissions from a stack positioned at Turrella. The ventilation system was designed to avoid portal emissions as far as practical.

The Roads and Traffic Authority of NSW (RTA) is considering a proposal for modifications to the M5 East project which generally comprise:

- a trial of controlled emissions from the Marsh Street and Bexley Road portals (proposed trial) to improve air quality in the M5 East tunnel; and
- the construction and operation of a pilot filtration plant for in-tunnel air.

As a consequence, the RTA is considering a proposal to request the Minister for Planning to modify the conditions of the Approval.

The RTA asked Synergetics to model dispersion of emissions from the M5 East tunnel portals for a broad range of possible scenarios, by application of high quality computer modelling, known as computational fluid dynamic (CFD), and compare the modelled conditions with relevant assessment criteria in accordance with the Approval and the more stringent Approved Methods for Modelling and Assessment of Air Pollutants in New South Wales (DEC NSW 2005).

Specifically, the aims of the modelling exercise were to:

- determine the impact (if any) of portal emissions on ambient air quality and residences nearby the portals in the various portal emission scenarios;
- develop a control procedure that limits the contribution of the tunnel portal emissions for the residents around both the Marsh St and Bexley Road portals during the proposed trial so as to ensure compliance with both the air quality goals specified in the Approval and the more stringent Approved Methods for Modelling and Assessment of Air Pollutants in New South Wales (DEC NSW 2005); and
- carry out a health risk assessment to determine if the exposure risk for volatile organic compounds (VOCs) is below the relevant DEC NSW (2005) health risk assessment criteria.

This report describes the work that was undertaken and is laid out under the following headings.

- Description of tunnel operation
- Air pollutants and assessment criteria
- Sources and receptors
- Computer model selection and operation
- Modelling input data
- Results
- Concluding comments
- References

2 Description of tunnel operation

The ventilation system for the M5 East tunnel is a recirculatory system which involves the transfer of air between both main tunnels near the eastbound and westbound tunnel exits. The ventilation system essentially operates as two "U" shaped closed loops, ventilating each of the eastern and western ends of the twin tunnels.

A schematic of the tunnel (Figure 1) shows the layout of the tunnel and typical airflows. Fresh air is drawn into the tunnel approximately 600 metres east of the mid-point of each tunnel, from a dedicated air intake station on the surface at Duff Street. Some 550m^3/sec of fresh air is drawn in at Duff Street. Of this 550m^3/sec, some 375m^3/sec is drawn along the westbound "U" loop, in the direction of traffic flow through the tunnel towards the western portal. Approximately 150m before the air reaches the portal, it is drawn across to the adjacent eastbound tunnel through the cross-over vent which link both tunnels. Additional fresh air is drawn in through the exit portal. The tunnel air then flows with the eastbound traffic to the air extraction point, where the air travels along the 800 metre long exhaust tunnel to the ventilation stack at Turrella. The remaining 175m^3/sec from the Duff Street intake follows the eastbound "U" loop in a similar manner, with additional fresh air drawn in through each of the portal openings.

The ventilation air flow rates are controlled by means of fans mounted in the cross-over vents and mounted on the ceiling along the tunnel length. Three variable speed axial fans are mounted in the cross-over vents to control the amount of air passing between the two tunnels and the amount of air being drawn into the tunnels through the nearby portal openings. The ventilation system was designed to avoid ventilation air being exhausted from the tunnel portals as far as practical.

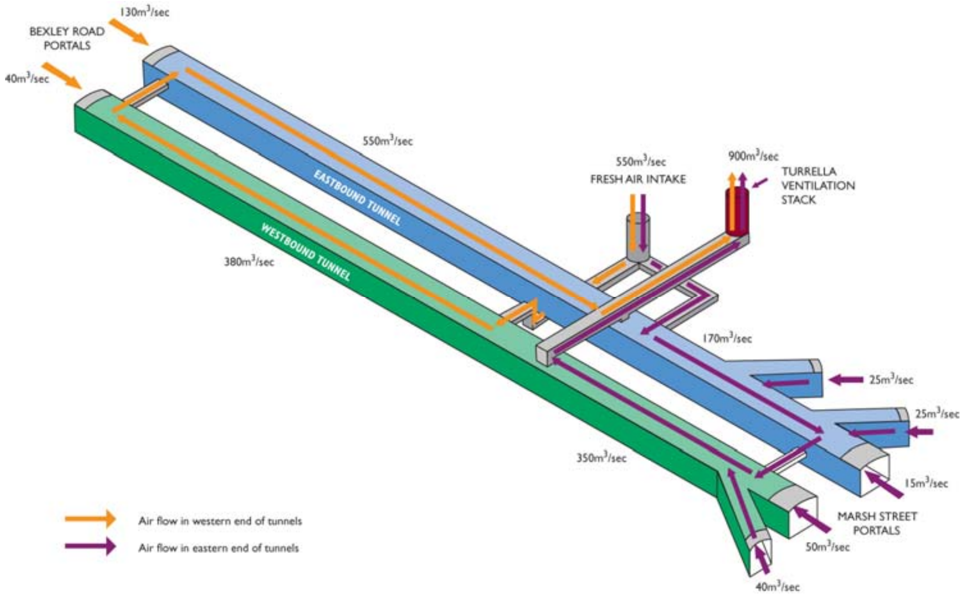

Figure 1. Schematic of tunnel showing designed air flow and traffic flow

3 Air pollutants and assessment criteria

The emissions from road tunnels are principally a combination of the ambient air which is drawn into the tunnel (including any pre-existing pollutants used for tunnel ventilation, plus pollutants generated by the vehicles travelling through the tunnel.

The relevant pollutants and associated assessment criteria are drawn from the DEC NSW (2005) and the World Health Organisation (WHO 2000). In addition, advisory reporting goals (NEPC 2003) for $PM_{2.5}$ have been included. These pollutants are commonly grouped as either criteria pollutants or VOCs. Criteria pollutants are summarised in Table 1. VOCs are summarised in Table 2.

Whilst all of the criteria in Table 1 and Table 2 have been addressed for the purposes of modelling, Synergetics understands that the Approval conditions specify air quality goals which the operation of the M5 East tunnel must satisfy, and that those goals will remain the compliance goals for the purposes of the Approval. These goals have also been taken into account for the purposes of the assessment which is the subject of this report.

Table 1. Summary of ground level concentration assessment criteria for criteria pollutants

Criteria pollutant	Total or contrib.[a]	Stat.[b]	Avg. time	Reference	Modelling assess. level
NO_2	Total	100%	1-hour	Planning Approval Condition 71	256 µg/m^3 (0.125 ppm)
	Total	100%	1-hour	DEC NSW (2005, Table 7.1)	246µg/m^3 (12pphm)
	Total	100%	Annual	DEC NSW (2005, Table 7.1)	62µg/m^3 (3pphm)
Carbon monoxide (CO)	Total	100%	15-min	DEC NSW (2005, Table 7.1)	100mg/m^3 (87ppm)
	Total	n.s.[c]	15-min	WHO (2000) and Planning Approval Condition 70	100mg/m^3 (87ppm)
	Total	n.s.	30-min	WHO (2000)	60mg/m^3
	Total	100%	1-hour	DEC NSW (2005, Table 7.1)	30mg/m^3 (25ppm)
	Total	n.s.	1-hour	WHO (2000)	30mg/m^3 (25ppm)
	Total	100%	8-hour	DEC NSW (2005, Table 7.1)	10mg/m^3 (9ppm)
	Total	n.s.	8-hour	WHO (2000)	10mg/m^3 (9ppm)
Particulate (PM_{10})	Total	100%	24-hour	DEC NSW (2005, Table 7.1) and Planning Approval Condition 71	50µg/m^3
	Total	100%	Annual	DEC NSW (2005, Table 7.1)	30µg/m^3
Particulate ($PM_{2.5}$)	Total	n.s.	24-hour	NEPC (2003) advisory reporting standard	25 µg/m^3
	Total	n.s.	Annual	NEPC (2003) advisory reporting standard	8 µg/m^3

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[a] "Total" denotes the sum of the pre-existing background level plus the incremental contribution of the tunnel portal emissions, whereas "contrib." denotes that only the incremental contribution, i.e., the incremental concentration associated with emissions from the tunnel portal emissions alone.

[b] "Stat" refers to the statistical parameter that is compared against the modelling assessment level. For example 100% denotes the 100 percentile value, and 99.9% denotes the 99.9 percentile value.

[c] n.s. denotes “not specified”.

Table 2. Summary of criteria for volatile organic compounds (VOCs)

VOC	Total or contrib.	Stat.	Avg. time	Reference	Modelling assess. level
acetaldehyde	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.4a)	0.042mg/m^3 (0.023ppm)
	Contrib.	n.s.	annual	NSW Health (undated)	n.s.
acetone	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.2b)	22mg/m^3 (9.2ppm)
benzene	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.2a)	0.029mg/m^3 (0.009ppm)
	Contrib.	n.s.	annual	NSW Health (undated)	n.s.
benzo(a) pyrene	Contrib.	n.s.	annual	NSW Health (undated)	n.s.
1,3 butadiene	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.2a)	0.04mg/m^3 (0.018ppm)
cyclohexane	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.2b)	19mg/m^3 (5ppm)
ethylbenzene	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.2b)	8.0mg/m^3 (1.8ppm)
formaldehyde	Contrib.	n.s.	30-min	WHO (2000)	0.1mg/m^3
	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.2a)	0.02mg/m^3 (0.018ppm)
	Contrib.	n.s.	3-hour	NSW Health (undated)	n.s.
	Contrib.	n.s.	24-hour	NSW Health (undated)	n.s.
n-Hexane	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.2b)	3.2mg/m^3 (0.9ppm)
Poly Aromatic Hydrocarbons (PAHs)	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.2a and 7.2c)	0.0004mg/m^3
styrene	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.4a)	0.12mg/m^3 (0.027ppm)
toluene	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.4a)	0.36mg/m^3 (0.09ppm)
xylenes	Contrib.	99.9%	1-hour	DEC NSW (2005, Table 7.4a)	0.19mg/m^3 (0.04ppm)
Aggregate risk	Contrib.	n.s.	annual	DEC NSW (2005, Table 7.3)	1E-06

4 Sources and receptors

4.1 Bexley Road

The location of the portals at Bexley Road with respect to the local residential areas can be seen in Figure 2. There are residential areas to the north and north-east of the motorway. There are also a few residences to the south.

The residential area to the north is approximately 50m from the M5 Motorway with the closest residence approximately 100m from the portal opening. The residential area to the south is further away and less affected, being approximately 100m from the M5 Motorway and with the closest residence approximately 150m from the portal opening. The nearest residences to the north-east are approximately 50m from the portal.

Prevailing summer conditions are characterised by south east sea breezes tending north east during the day. In winter westerly winds dominate. Night-time flows are characterised by cold air drainage flows down the valley in an easterly direction.

A preliminary assessment of the dispersion and meteorological conditions suggested that winds with a southerly component produced the ground level pollutant concentrations of most concern. Because the plumes are largely ground based, the most affected residences are closest to the road canyon. A closely spaced (30m spacing) rectangular shaped modelling receptor grid was employed covering all relevant residences within the range of 0 to 150m of the portal.

4.2 Marsh Street

At the eastern end of the M5 tunnel, there are two two-lane main portals, and two one-lane ramp portals, one for each of the Marsh Street and Princess Highway on-ramp and off-ramp. The residential areas are generally west of the portal opening, with the nearest residences 150 to 200m from the main portal as shown in Figure 2.

Similarly for Bexley Road, prevailing summer conditions are characterised by south east sea breezes tending north east during the day. In winter westerly winds dominate. Night-time flows are characterised by cold air drainage flows down the valley in an easterly direction.

Wind directions modelled in detail for Marsh Street were east, south-east and south, corresponding to those that would likely disperse any portal emissions over residential areas. Unlike the Bexley portal, the residences were unevenly distributed. To ensure that the whole of the residential area was modelled a selection of individual residences covering all residences within 200m of the portal were modelled.

Figure 1. Aerial photograph of the region close to Bexley Road that was modelled

Figure 2. Aerial photograph of the region close to Marsh Street that was modelled

5 Computer modelling selection and operation

5.1 Model selection

Computational fluid dynamic (CFD) methods were employed to model the steady state pollutant emission from the M5 East portals assuming constant portal emissions.

CFD provides the most accurate and representative estimates of ground level concentrations for non-stack emission sources such as road tunnel portals.

CFD modelling involves the discretisation of a volume of air/fluid/solid and the explicit calculation of numerous parameters, such as the velocity, temperature and pressure concentration in respect of the medium being modelled, throughout the entire computational domain. Local flow regimes and flow details can be fully resolved by CFD, whereas empirically based dispersion models (e.g., AUSPLUME, CALPUFF, etc) cannot model the flow details.

State-of-the-art CFD modelling software, FLUENT Version 6.2[d], with current ISO 9001 certification and guaranteed model validity was used. Some features of the software used by Synergetics are described below.

- The corporate author of FLUENT is the largest supplier of CFD software in the world, with over one-third of the global CFD market, and is twice as big as its nearest competitor.
- The FLUENT modelling software has the largest array of industrially tested capabilities, with over 1,000 physical models. These models range from simple incompressible single phase steady state flow to transient turbulent multiphase flows with moving boundaries, heat transfer and species dispersion.
- The extensive range of turbulence models allows even the most complex flows to be modelled with confidence in solution accuracy. Gone are the days of trying to fit the simple k-epsilon turbulence model to all situations.
- Unlike many CFD codes, FLUENT provides a Body Fitted Coordinate (BFC) mesh around ANY complex three-dimensional geometry, using unstructured meshes. *No stair stepping approximations are required.*
- Unlike other CFD software packages, FLUENT has not been developed for any single specific application, such as internal combustion modelling. Rather, FLUENT software is a general purpose CFD solver, and as such, has been written and validated to solve a broad range of applications.
- The FLUENT modelling software fully supported by highly trained and experienced FLUENT support engineers. This support group constitutes the single largest repository of CFD knowledge in the world.

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[d] Synergetics has also been invited to review the beta release version 6.3 of FLUENT, although we do not use this for commercial applications.

5.2 Model operation

The portals and surrounding landscape, including buildings, roads and parkland, were created to a fine resolution (as fine as 0.3m) by dividing the modelling domain into a total of approximately 2 million computational cells. This resolution assures that the air flow patterns, large scale turbulence and pollutant dispersion through the portal opening and road canyon, and over the acoustic barriers, large buildings and surrounding topography are representative of full scale emission plume behaviour. The sub-grid scale boundary layer and turbulence were captured by suitable empirical approximations. For each cell, fluid momentum, pressure, temperature and pollutant concentration and dispersion were calculated governed by fundamental conservation equations with minimal simplifying assumptions, this delivers the most accurate and representative results practicable.

The modelling domain inlet boundary layer temperature, wind direction, velocity and turbulence profiles imposed on the CFD modelled domain can vary as a function of mean wind direction due to meteorological forcing modified by varying upwind topography, surface cover and surface temperature. Only the wind direction conditions that would impact most on local residential areas were examined in detail. A “sensitivity” analysis confirmed the appropriateness of those selected.

Stable atmospheric conditions occur when the potential temperature (i.e., relative to adiabatic) increases with increasing height. Stable conditions suppress turbulence and pollutant dispersion. However when an air mass is dominated by large scale and strong turbulence, such as those associated with the building and acoustic barrier wakes surrounding M5 East, even strongly stable temperature profiles have been found to be unimportant (Zhang, Aryar and Snyder, 1996). Consequently, for most of the time, the boundary layer will be well mixed and the potential temperature profile, relative to the adiabatic lapse rate of -0.01°C/m, can be assumed uniform. On this basis, a neutral potential temperature lapse rate of 0.0°C/m was modelled for neutral as well as unstable conditions.

The temperature profile during stable conditions cannot be determined with any accuracy without continuous detailed site-specific meteorological studies. In the absence of these site-specific studies, a stable potential temperature lapse rate of 0.02°C/m was modelled. This lapse rate corresponds to the stable E Pasquill-Gifford stability class (EPA Victoria, 1985).

On the basis of this assessment of stability, two potential temperature lapse rates of 0.0°C/m and 0.02°C/m were modelled.

Substantial variation in wind direction with height can occur particularly during stable temperature conditions and an urban ‘built-up’ area. These variations are very difficult to characterise without continuous and detailed site-specific meteorological studies. However, in all cases the wind direction variation will enhance dispersion. Consequently, a conservative assumption was to assume that the wind direction is constant with increasing height at the inlet of the model domain. Realistic wind shear is then taken into account by the CFD modelling.

Four wind velocities covering the range of atmospheric variability with emphasis on light wind conditions likely to result in maximum GLCs at the nearest residence for ground level sources were modelled, e.g., 1, 2, 4 and 6 m/s, referenced to a standard 10m high meteorological measurement height (U_{10m}).

Low wind velocities, and hence minimum dilution will result in the maximum concentration it is therefore important to model the change in wind speed with height. The modelled boundary layer profiles were derived from a power law of the form:

$$U = U_{ref}\left(\frac{z}{Z_{ref}}\right)^{0.2} \qquad (1)$$

Where: z - height above ground level (m)

U_{ref} and Z_{ref} – velocity U at reference height Z (usually 10m).

In cases such as this where the wind velocity profile is defined by a power-law, Richards and Hoxey (1993) recommend the use of the following expressions to define the total kinetic energy k and the eddy dissipation rate ε:

$$k = \frac{u_*^2}{\sqrt{C_\mu}} \qquad (2)$$

$$\varepsilon = \frac{u_*^3}{\kappa\,(z + z_0)}. \qquad (3)$$

The friction velocity is defined as:

$$u_* = \sqrt{\frac{\tau_0}{\rho}} \qquad (4)$$

where: τ_0 - shear stress (Pa)

ρ - density (kg/m^3)

κ - von Karman constant

z - height above ground level (m)

u_* - friction velocity (m/s)

z_0 - roughness length (m).

The total kinetic energy k and the eddy dissipation rate ε can be calculated by substituting for $C_\mu = 0.09$ (from Richards and Hoxey, 1993) and κ=0.41.

To determine the appropriate value for the constants, z_o and $u*$, ideally we would obtain a measurement of the surface shear stress directly at the site, or inferred from the wind velocity profile. In the absence of field data, z_o was chosen as 2.0m, which, is equivalent to urban residential districts (Seinfeld, 1998, p858). For simplicity, the value of the "friction velocity", $u*$ was obtained from Seinfeld (1998, pp.858) at a known velocity and height, i.e.;

$$u_* = \frac{\kappa u_{ref}}{\ln\left(\frac{z_{ref} + z_0}{z_0}\right)}. \qquad (5)$$

Modelling of stable conditions introduces special problems, particularly when dealing with the associated low wind velocities. Some researchers have found that even slight slopes under conditions of urban roughness and convective heat release can have an important effect on the mean velocity and turbulent kinetic energy profiles. Huang et al. (1993) found greater than 10% change in velocity for a slope of 0.005m/m, which is equivalent to the average slope over the modelled domain. Other effects such as localised convection from roadways and building surfaces can also be important at low wind velocities. However these effects are likely to be a second order effect and have been ignored for the purposes of this study.

For simplicity, a power law approximation to the PBL velocity profile is commonly chosen for stable profiles, i.e.:

$$u(z) = u_{ref}\left(\frac{z}{z_{ref}}\right)^{p} \qquad (6)$$

where: z_{ref} – reference height at which the velocity is defined (m)

u_{ref} – reference velocity at height H_{ref} (m/s)

p – stability dependent exponent.

The exponent p can be chosen over a range of stability categories to test the sensitivity of the inward flow profile to varying stability conditions. An advantage of the power law is that the full range of stability conditions can be modelled simply by adjusting the stability dependent exponent. For the purposes of this study, the value of p=0.40 was chosen to correspond to slightly stable conditions (e.g., EPA Victoria, 1985; Hanna et al, 1982) in an urban environment.

This simple expression does not provide a measure of the turbulence levels for stable conditions. For the purposes of this project, turbulence profiles were scaled from the levels determined for neutral conditions using plume dimensions corresponding to Pasquill-Gifford stability category of “E” at a typical distance downwind as the scaling factor. On this basis, a factor of 0.494 was calculated to scale the neutral “D” PG category turbulence levels to “E” PG class turbulence levels.

A purpose written “C” sub-routine incorporating these equations was used to set the boundary conditions for the CFD inlet domain for neutral conditions.

In total of over 100 CFD sets of conditions were modelled covering the full range of emission rate, emission temperature and meteorology encountered. The GLC were calculated at each grid locations adjacent to the Bexley Road portal for each pollutant for each of the sets of conditions that were modelled.

5.3 Data aggregation

Each 5-minute period in the consolidated dataset (refer to Section 6.5) was assigned a code corresponding to the most similar set of modelled conditions, providing concentration levels at each of the grid points surrounding the portal for a unit emission concentration. The 5-minute average concentration for each pollutant at each grid were determined by scaling the modelled results by the ratio of the actual in-tunnel concentration, calculated as discussed in Section 6.3 and the modelled concentration. Longer term averages for each grid point required for comparison with relevant ambient criteria were calculated by aggregating an appropriate number of 5-minute periods, i.e., 12 x sequential 5-minute periods for each 1-hour average, 96 x sequential 5-minute periods for 8-hour averages, 12 x sequential 5-minute periods for 24-hour averages and all 5-minute periods for 2005 for annual averages. This aggregation was carried out at increments of each respective averaging time for the whole of 2005.

5.4 Model uncertainty

The approach adopted includes a number of assumptions that will tend to provide conservative (high) values. Examples are outlined below.

- The assumptions regarding dispersion physics are conservative. For example, no pollutant depletion or removal mechanisms have been modelled. This is conservative as a substantial proportion of pollutants will be removed by rainfall, gravitational deposition, chemical transformation, adsorption, impaction (i.e., 100% reflection from solid surfaces internally and externally have been assumed) and other removal mechanisms. In particular the substantial dispersion and adsorption benefits afforded by trees have not been included.
- The aggregation methods are highly conservative. For example all modelled wind directions are represented by 45degree wind sector categories, which result in higher modelled concentrations. Similarly, the three portal emission temperature ranges: 0 to 5°C, 5 to 10°C and greater than 10°C were represented by the lower end of each category, i.e., 0, 5 and 10 °C respectively. Because lower plume temperature will artificially lower the plume height, this assumption will increase the maximum modelled GLC at residential receptors.

6 Modelling input data

6.1 Introduction

The basis for selection of the modelled meteorological, emission, background data and compilation of the data are described in this section.

6.2 Meteorological data

Meteorological data for each 5-minute period throughout the whole of the calendar year 2005 and background levels for the criteria pollutants, PM_{10}, CO and NO_2, were derived from the ambient monitoring stations located adjacent to the Bexley Road and Marsh Street portals, and are referred to as F1 and M1 respectively. A summary of the continuously measured parameters at F1 and M1 are provided in Table 3 below.

Table 3. Summary of continuous data sources

Monitor	Location	Parameters	Averaging time	Date commissioned
F1	Adjacent to Bexley Road portal	10m wind speed 10m wind direction 2m temperature 10m temperature PM_{10}, CO, NO_2 and NO_x	5-min	May 2004
M1	Adjacent to Marsh Street portal	10m wind speed 10m wind direction 2m temperature 10m temperature PM_{10}, CO, NO_2 and NO_x	5-min	May 2004

6.3 Emission data

Portal emission flow rate

To ensure that a conservatively high estimate of the ground level concentrations (GLC) during portal emissions are modelled, the portal out flow rate for the west bound portal at Bexley Road was set to a fixed value corresponding to the maximum design air flow rate of $390m^3/s$. Ventilation air was drawn into the east bound portal at a rate to maintain design airflow rates.

In summary the modelled flow rates for the Bexley Road portals were as follows.

- Bexley Road East bound 400 m^3/s inflow.
- Bexley Road West bound 390 m^3/s outflow.

In addition it was assumed that portal emissions at this rate are continuous between 5am and 7pm. Therefore, the modelled scenarios represent a conservative or credible worst case situation.

For the Marsh Street end, only the main east bound tunnel was modelled with portal emissions. A maximum outflow rate of 350m^3/s was modelled for Marsh Street from the main eastbound tunnel exit. The Marsh Street and Princess Highway off-ramps would continue to draw air into the tunnel. All other portal openings were modelled with ventilation air being drawn into the portals.

In summary, the modelled flow rates for the Marsh Street portals were as follows.

- Marsh Street East bound 350 m^3/s outflow.
- Marsh Street West bound 270 m^3/s inflow.
- Marsh Street off-ramp 130 m^3/s inflow.
- Princess Highway off-ramp 170 m^3/s inflow.

Portal emission temperature

The plume rise and hence the pollutant ground level concentration (GLC) will be highly sensitive to the temperature difference between the portal temperature and the ambient air temperature since the nature and extent of plume rise is associated with the relative plume temperature. An examination of this temperature difference for the full year of 2005 reveals that the instantaneous difference ranged from 0 to 20ºC, with the daily averages ranging from approximately 5 to 15 ºC as shown in Figure 3. An example of the effect of the substantial plume rise for a relatively modest 10ºC temperature rise is shown in Figure 4. This phenomenon was explicitly modelled for a range of temperature difference values covering the full range experienced, i.e., 0°C, 5°C, 10°C and 15°C. The temperature difference was included in the emissions database by subtracting the ambient temperature (as measured at F1) from the tunnel temperature (as measured at the Turrella stack) for each 5-minute period throughout the whole of the calendar year 2005.

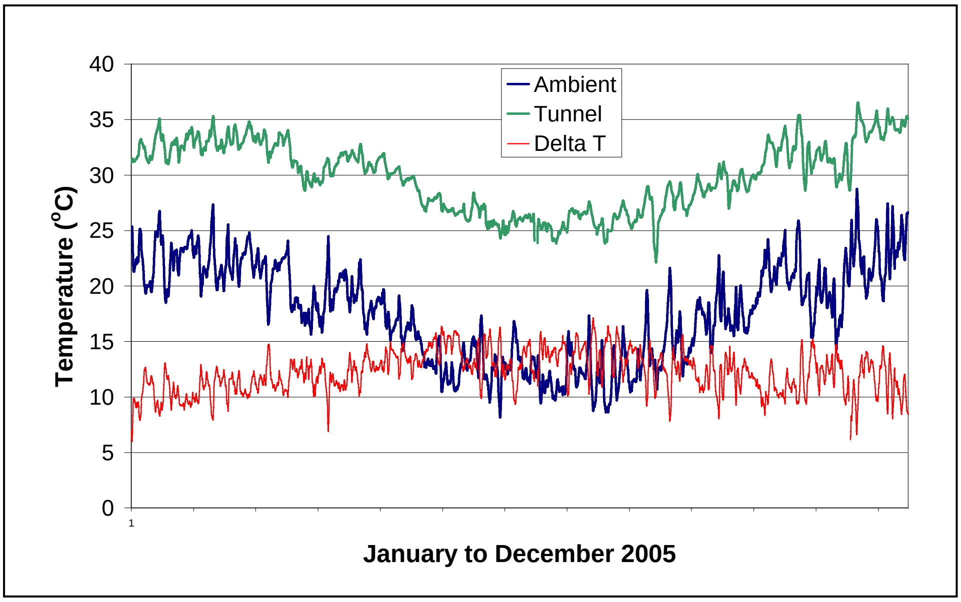

Figure 3. Daily average air temperature in the tunnel (Tunnel), daily average ambient air temperature at F1 (Ambient) and the difference between the two temperatures (Delta T).

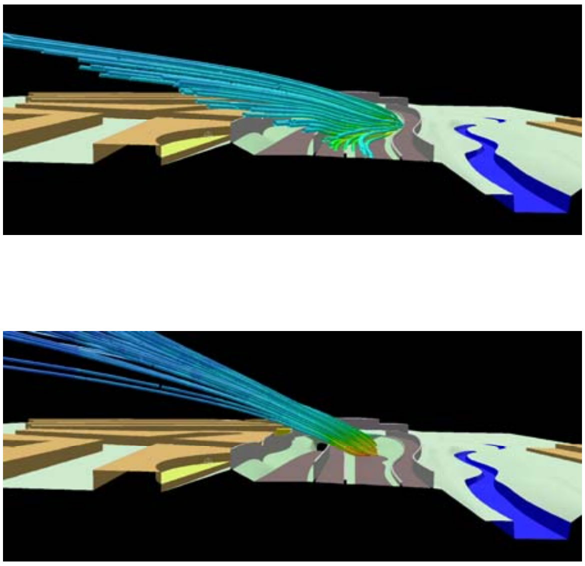

Figure 4. Bexley portal emission plume CFD modelled path-lines with 0 °C (upper figure) and 10°C (lower figure) temperature difference.

Portal emission concentration

Some of the emission parameters are measured continuously by sensors within the tunnel. A summary of the continuously measured data are summarised in Table 4.

Table 4. Summary of continuously measured emission parameters

Monitor	Location	Parameters	Averaging time	Date commissioned
AQS404 ASS 209 ASS201	Bexley Road portal WB tunnel	Flow rate, CO, NO and extinction (haze)	15-min	2001
AQS302 ASS104 ASS105	Marsh Street portal EB tunnel	Flow rate, CO, NO and extinction (haze)	15-min	2001
ANA090 ASS094 ASS090 PMT090 TCP090	Turrella exhaust stack	Flow rate, CO, NO, NO_2 and extinction (haze)	15-min	2001

CO, NO, extinction (an indicator of haze level) and flow rate are measured continuously by monitoring instrumentation within the tunnel at measurement locations in the vicinity of the tunnel portals and in the stack.

The CO measurement, in units of parts per million by volume (ppm), is available for each 15-minute period throughout the whole of the calendar year 2005 and has been used directly as the emission concentration.

In a similar manner to the meteorological data, the emission concentration for the pollutant can be obtained for each 15-minute period throughout the whole of the calendar year 2005. The pollutants that are not measured continuously are related to those that are, as explained further below, and can be estimated by multiplying one of the continuously measured pollutants by a suitable factor. Appropriate factors can be obtained by reference to relevant emissions databases.

For example, NO_2 is the product of reaction between NO and other chemicals in the atmosphere. This reaction is catalysed by sunlight. NO_2 levels are correlated with NO and are commonly estimated by multiplying by a factor dependent on the reaction time and sunlight. In the case of tunnel portal emissions, the maximum time between discharge from the tunnel and impact on residential areas occurs in seconds, even at low wind speeds, and there is minimal time for conversion from NO to NO_2, which usually takes place over a time scale of hours (DEC NSW 2005). A suitable factor of 0.1 was calculated from comparison of the simultaneous measurements of NO and NO_2 in the exhaust stack. This factor was applied to measured emission concentration at AQS404 to calculate the NO_2 emission concentration for each 15-minute period throughout the whole of the calendar year 2005.

Detailed iso-kinetic sampling tests on the Turrella stack emissions (HLA 2003). described a linear relationship between PM_{10} and the continuously measured extinction. This relationship was applied to estimate the PM_{10} emission concentration for each 15-minute period throughout the whole of the calendar year 2005.

A simple estimate of VOCs emissions was obtained by determining the ratio of VOC to CO for typical tunnel traffic (NSWRTA 2005) based on fleet average emission data for the year 2000 (NPI 2000), which indicates a ratio of VOC to CO of 0.082. To account for the reduction in vehicle VOC emissions over the period from 2005 to 2007, a factor of 0.74 was also applied to all VOCs, except for benzene for which a factor of 0.2 was applied to account for the reduction in maximum allowable benzene content in petrol from approximately 5% to 1% from 2000 to 2006.

The total VOC for each 15-minute period throughout the whole of the calendar year 2005 was determined on this basis. Individual VOCs of interest, i.e., 1,3 butadiene, benzene, formaldehyde and poly aromatic hydrocarbons (PAHs) were determined from mass fractions (NPI 2000) shown in Table 5. The individual PAHs were obtained from Lima, Farrington and Reddy (2005) in Table 6. The proportion of LPG, diesel and petrol powered vehicles were determined from NSW vehicle statistics (e.g., LPG Australia 2006).

Table 5. Summary of the mass fraction of total VOC represented by each individual VOC from NPI (2000).

VOC	**Mass Fraction**[e]			
	Petrol Exhaust	**Petrol Evaporative**[f]	**Diesel Exhaust**	**LPG Exhaust**
Acetaldehyde	0.00437[4]	n.s.	0.155	0.000615
Acetone	0.00286[4]	n.s.	0.0815	
Benzene	0.0658	0.0170	0.0101	9.43×10^{-6}
1,3-Butadiene	0.00649	0.00180	0.00115	0.0000552
Cyclohexane	0.00111	0.000713	0.000778	n.s.
Ethylbenzene	0.0150	0.00190	n.s.	n.s.
Formaldehyde	0.0156[g]	n.s.	0.0826	0.00178
n-Hexane	0.0155	0.0147	n.s.	n.s.
PAHs	0.00217[h]	n.s.	0.00667	n.s.
Styrene	0.00213	0.000308	n.s.	n.s.
Toluene	0.105	0.0224	0.0147	n.s.
Xylenes	0.0759	0.00992	0.0117	n.s.

Table 6. Summary of the mass fraction of total PAHs represented by each individual PAH from Lima, Farrington and Reddy (2005).

VOC	**Mass Fraction**			
	Petrol Exhaust	**Petrol Evap**	**Diesel Exhaust**	**LPG Exhaust**
anthracene (Anth),	0.003	n.s.	0.021	n.s.
benz[a]anthracene (BaA)	0.07	n.s.	0.048	n.s.
benzo[b]fluoranthene (BbF)	0.109	n.s.	0.038	n.s.
benzo[k]fluoranthene (BkF)	0.074	n.s.	0.034	n.s.
benzo[g,h,i]perylene (BghiP)	0.177	n.s.	0.021	n.s.
benzo[e]pyrene (BeP)	0.074	n.s.	0.033	n.s.
benzo[a]pyrene (BaP)	0.071	n.s.	0.016	n.s.
chrysene (Chry)	0.141	n.s.	0.132	n.s.
coronene (Cor)	0.04	n.s.	0	n.s.
dibenz [a,h]anthracene (DBA)	0.011	n.s.	0	n.s.
fluoranthene (Fla)	0.073	n.s.	0.172	n.s.
indeno[1,2,3-c,d]pyrene (IP)	0.017	n.s.	0	n.s.
phenanthrene (Phen),	0.032	n.s.	0.162	n.s.
pyrene (Py)	0.092	n.s.	0.302	n.s.

Airborne particles in road tunnels are derived from a wide range of sources including:

- pre-existing (background) particles contained within the tunnel ventilation air including urban smog, bushfire smoke, and local construction activity;
- vehicle exhausts;
- tyre wear;

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[e] Petrol and evaporative data derived from Duffy *et al* (1999), except where otherwise specified. Diesel data derived from Schauer et al (1999). LPG data derived from Parsons (1998).

[f] Evaporative emissions from LPG-fuelled vehicles contain mainly propane and butane (the main constituents of LPG) and no NPI substance (Nelson and Duffy 1998).

[g] Derived from Macauley (1990).

[h] Kahlili *et al* (1995).

- brake wear;
- clutch wear;
- corrosion products from vehicles and roadside furniture;
- soil and other particulate discharged from vehicle loads or vehicle surfaces;
- deposition, and re-suspension of deposited road dust;
- spores from micro-organisms on tunnel walls; and
- abrasion of the road surface itself.

The material which collects on the road surface, often referred to as 'road dust', may also contain exhaust particles and matter from a range of sources that are not related to road transport (e.g. crustal and vegetative material, and material from industrial/commercial /domestic activity). This road dust may subsequently be suspended or resuspended in the atmosphere as a result of tyre shear, vehicle-generated turbulence, and the action of the wind (Luhana et al 2004). To help characterise these $PM_{2.5}$ sources, representative estimates of the $PM_{2.5}$ fraction in the M5 tunnel are required. Data from HLA (2003) consists of 12 x 24-hour iso-kinetic particulate samples collected in accordance with a modified version of AS2724.3-1984 during January and February 2003 from the M5 East tunnel exhaust stack. These data were then analysed for particle size distribution (PSD) by the University of Newcastle. These data show that the average $PM_{2.5}$ in-tunnel concentration can be represented as 0.37 x PM_{10} by mass[i].

Emissions from all vehicles are falling steadily. Benzene levels in petrol dropped from 5% to 1% from the beginning of 2006. Diesel vehicles (i.e., particularly $PM_{2.5}$ and NOx) for example are predicted to fall during the period from 2005 to 2010 as the more stringent Euro diesel vehicle emissions standards that were applied from 2002 and low sulphur and ultra–low sulphur diesel become available from January 2003 and January 2006 respectively (Minister for the Environment 2002). Hence all of these portal emission concentration measurements will be conservatively high as they were based on the higher levels of vehicle emissions prevalent during the years prior to the proposed trial.

6.4 Background data

As recommended by DEC NSW (2005), the background concentration of criteria pollutants were obtained from ambient monitoring data collected at the tunnel portals where possible. For example, 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.

By assuming that ambient $PM_{2.5}$ varies in proportion to the PM_{10}, the 5-minute average $PM_{2.5}$ background levels were calculated for the whole of 2005 by scaling the 5-minute average PM_{10} background levels at F1 by the ratio of the annual average $PM_{2.5}$ measurements (NSWEPA, 2002) to annual average PM_{10}.

Similarly, by assuming that ambient VOC levels vary in proportion to the CO level, the 5-minute average VOC background levels were calculated for the whole

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[i] Assuming a uniform particle density.

of 2005[j] by scaling the 5-minute average CO background levels at F1 by the ratio of annual average (or long term average where annual average was not available) VOC measurement to the annual average CO at F1. The annual average VOC measurements and references are summarised in Table 7. In all cases the maximum representative background levels were chosen[k].

Table 7. Summary of VOC background levels and references.

VOC	Measurement description	Annual background concentration (ppm unless specified)	Reference
acetaldehyde	According to NPI (2006) all reportable acetaldehyde is sourced from power stations located in Newcastle airshed, hence unlikely to contribute to the background in Earlwood.	0	NPI (2006)
acetone	Scaled from the ratio of reported NPI (2006) VOC to CO mass of emissions in the Sydney airshed.	0.000539	NPI (2006)
benzene	Maximum annual average in residential area.	0.0012	NSWEPA (2002)
Poly Aromatic Hydrocarbons (PAHs)	Annual average near a major road.	0.17ng/m^3	EPA Victoria (1991)
1,3 Butadiene	Scaled from the ratio of reported NPI (2006) VOC to CO mass of emissions in the Sydney airshed.	0.00009063	NPI (2006)
cyclohexane	Scaled from the ratio of reported NPI (2006) VOC to CO mass of emissions in the Sydney air-shed.	0.0001083	NPI (2006)
ethylbenzene	Highest overall mean in residential areas	0.0006	NSWEPA (1998)
formaldehyde	Overall mean CBD location	0.0032	NSWEPA (1998)
n-Hexane	Scaled from the ratio of reported NPI (2006) VOC to CO mass of emissions in the Sydney airshed.	0.0003021	NPI (2006)
styrene	Highest overall mean in residential areas	0.0006	NSWEPA (1998)
toluene	Highest overall mean in residential areas	0.0058	NSWEPA (1998)
xylenes	Highest overall mean in residential areas	0.0023	NSWEPA (1998)

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[j] Despite the determination of background levels for VOCs not being a prerequisite according to DEC NSW (2005, Section 5).

[k] For example in EPANSW (1998) measurements were available both near the western end of the tunnel at Earlwood and the eastern end of the tunnel at Botany. The highest of the residential levels were chosen.

6.5 Data compilation

The relevant data sets for the whole of 2005 were merged and matched by day and time to create a single dataset containing background, meteorology and emission concentrations for all parameters with greater than 95% coverage in time steps of 5-minutes, i.e.:

- ambient data from F1;
- ambient data from M1;
- meteorological data from F1;
- in-tunnel measurements from AQS404; and
- Turrella stack measurements.

7 Results

7.1 Air quality control strategy

The RTA instructed Synergetics Environmental Engineering to develop a control strategy that assures that the air quality associated with portal emissions meet all air quality assessment criteria in Table 1 and Table 2 at surrounding residences. The control strategy is such that portal emission rate and duration at any particular point in time will be dependent on certain conditions being met at that time. As a precautionary measure the RTA also instructed Synergetics to limit the contribution of PM_{10} to a maximum of 5 $\mu g/m^3$ at surrounding residences. This precautionary approach was adopted in order to limit potential exposure by limiting the total amount of portal emissions, providing a background level above portal emissions would not occur, and preventing portal emissions when meteorological conditions are not conducive to efficient pollutant dispersion.

The suggested control strategy requires portal releases to be reduced or stopped whenever the conditions shown in Table 8 occur.

Table 8. Bexley Road and Marsh Street meteorology trigger conditions

Portal	**Wind direction range (degrees relative to TN)**	**Wind speed range (m/s)**	**Atmospheric stability[1]**	**Portal temperature (differential °C)**
Bexley Road	SE Sector (122 to 190)	< 1.5	Unstable or Neutral	>10
	SE Sector (122 to 190)	> 1.5		<10
	N Sector (350 to 10)	< 5.0		> 10
	N Sector (350 to 10)	> 5.0		< 10
	NE Sector (58 to 90)	< 3.0		> 10
	W Sector (248 to 293)	1.5 to 3.0		all
Marsh Street	SE Sector 113 to 157deg	1.5 to 3.0		>10

The control strategy was tested against a whole year of data (calendar year 2005) and was found to meet the objectives. In addition, a continuous check that the control strategy is meeting its objectives will be carried out during the trial by monitoring the F1 and M1 monitoring stations adjacent to each portal. The Bexley Road and Marsh Street portal emissions will be reduced or stopped whenever the ambient levels at Bexley Road or Marsh Street approach the values shown in Table 9.

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[1] US denotes unstable (PG category A to D) and S denotes stable (PG category E and F) atmospheric stability. PG denotes Pasquill-Gifford stability category.

Table 9. Bexley Road and Marsh Street ambient concentration trigger conditions.

Pollutant	Trigger Level measured at Portal Monitor
PM_{10}	40μg/m^3 (24-hour continuous 1-hour rolling average)
NO_2	200μg/m^3 (1-hour continuous 1-hour rolling average)
CO	6ppm (8-hour continuous 1-hour rolling average)

In order for the portal emissions trial to operate in accordance with this report, all of the parameters identified in Table 8 and Table 9 will be monitored continuously and real time data will be available to the tunnel controllers. This would include, for example, monitoring temperature at the stack and both F1 and M1 so that the "temperature differential" can be calculated.

7.2 Calculated ground level concentration

The air quality control strategy that limited the contribution of PM_{10} to a maximum of 5 μg/m^3 resulted in maximum modelled ground level concentration (GLC) and risk values in residential areas associated for each pollutant identified in Table 1 and Table 2. The results are summarised in Table 10 for criteria pollutants and Table 11 for VOCs . It can be seen from these tables that all of the pollutant concentrations as a result of portal emissions are below their respective assessment criteria and, in particular, the goals specified in the Approval.

The range of modelled incremental contribution to 1-hour NO_2, 24-hour average PM_{10} and 8-hour CO respectively and predicted levels above background for the most sensitive residential receptors for portal emission rates[m] of 100, 250 and 390m^3/sec are shown in Figure 5, Figure 6 and Figure 7. These figures were obtained by sorting the modelled 1-hour average portal contribution at the receptor with the highest concentration for the whole of 2005 from highest to lowest concentration.

From Figure 6, for a portal emission rate of 250m^3/s, the maximum contribution of 24-hour PM_{10} is about 5 μg/m^3, which is predicted to occur in the order of 3 to 5 days per year. From Figure 5, Figure 6 and Figure 7 and Table 10, the contribution of 24-hour $PM_{10,}$ 1-hour NO_2 and 8-hour CO from portal emissions will be below 2.7μg/m^3, 23μg/m^3 and 0.18ppm respectively for 95% of the trial. Similarly the annual average $PM_{10,}$, NO_2 and CO contribution associated with portal emissions will be limited to 0.6μg/m^3, 3.4μg/m^3, and 0.53ppm respectively.

The worst case highest pollutant contributions are predicted to be experienced at residences nearby the Bexley Road portal. These levels are shown in Table 10 and Table 11. The greater separation distance between the residences and the tunnel portal at Marsh Street results in greater dispersion of the discharges from the portal and modelling predicts a maximum ground level concentration at nearby residences approximately 30% lower than those at Bexley Road

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[m] The concentration levels for the maximum portal emission rate of 390m^3/sec were modelled explicitly by CFD. The levels shown for 250 and 100m^3/sec were scaled from the data for 390m^3/sec.

Table 10. Summary of the maximum concentrations associated with each criteria pollutant at residences nearby Bexley Road.

Criteria pollutant	Total or contrib.[n]	Stat.	Avg. time	Reference	Modelling assess level	95% contribution[o] by portal flow rate (m^3/s)			Max contribution[p] by portal flow rate (m^3/s)			Total by[q] portal flow rate (m^3/s)		
						100	250	390	100	250	390	100	250	390
NO_2	Total	100%	1-hour	Planning Approval Condition 71	256 µg/m^3 (0.125 ppm)	6	23	36	33	127	198	115	191	200
	Total	100%	1-hour	DEC NSW (2005, Table 7.1)	246µg/m^3 (12pphm)	6	23	36	33	127	198	115	191	200
	Total	100%	Annual	DEC NSW (2005, Table 7.1)	62µg/m^3 (3pphm)	n.a.	n.a.	n.a.	0.9	3.4	5.3	36	38	40
CO	Total	100%	15-min	DEC NSW (2005, Table 7.1)	100mg/m^3 (87ppm)	0.08	0.20	0.32	1.2	3.1	4.8	8.7	8.8	9.0
	Total	n.s.[r]	15-min	WHO (2000) and Planning Approval Condition 70	100mg/m^3 (87ppm)	0.08	0.20	0.32	1.2	3.1	4.8	8.7	8.8	9.0
	Total	n.s.	30-min	WHO (2000)	60mg/m^3	0.08	0.20	0.32	1.0	2.5	4.0	5.3	5.3	5.3
	Total	100%	1-hour	DEC NSW (2005, Table 7.1)	30mg/m^3 (25ppm)	0.08	0.21	0.32	0.9	2.3	3.6	5.2	5.2	5.2
	Total	n.s.	1-hour	WHO (2000)	30mg/m^3 (25ppm)	0.08	0.21	0.32	0.9	2.3	3.6	5.2	5.2	5.2
	Total	100%	8-hour	DEC NSW (2005, Table 7.1)	10mg/m^3 (9ppm)	0.07	0.18	0.28	0.24	0.60	0.93	3.7	3.7	3.8
	Total	n.s.	8-hour	WHO (2000)	10mg/m^3 (9ppm)	0.07	0.18	0.28	0.24	0.60	0.93	3.7	3.7	3.8
PM_{10}	Total	100%	24-hour	DEC NSW (2005, Table 7.1) and Planning Approval Condition 71	50µg/m^3	1.1	2.7	4.3	2.0	5.0	8.0	40	40	40
	Total	100%	Annual	DEC NSW (2005, Table 7.1)	30µg/m^3	n.a.	n.a.	n.a.	0.2	0.6	0.9	20.8	20.8	20.9

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[n] "Total" denotes the sum of the pre-existing background level plus the contribution of the tunnel portal emissions, whereas "contrib." denotes that only the incremental contribution, i.e., the incremental effect from the tunnel portal emissions alone.

[o] Calculated as the concentration level which is exceeded 5% or less of the trial duration.

[p] Calculated at the residence with the highest total concentration.

[q] The values shown at lower portal flow rates of 100 and 250m^3/s were estimated by scaling assuming that the plume behaved in a similar manner to a neutral buoyancy ground based source.

[r] n.s. denotes “not specified”.

$PM_{2.5}$[s]	Total	n.s.	24-hour	NEPC (2003) advisory reporting standard	25 µg/m^3	0.63	1.01	1.58	1.2	1.9	3.0	24.8	24.8	24.9
	Total	n.s.	Annual	NEPC (2003) advisory reporting standard	8 µg/m^3	n.a.	n.a.	n.a.	0.1	0.2	0.3	9.8	9.9	10

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[s] 5-minute background $PM_{2.5}$ levels were scaled from measured PM_{10} at F1 assuming a background annual $PM_{2.5}$ level of 10µg/m^3.

Table 11. Summary of the maximum concentrations associated with each VOC at residences nearby Bexley Road.

VOC	Total or contrib.[t]	Stat.[u]	Avg. time	Reference	Modelling assess level	Contribution[v] (mg/m^3) by flow rate (m^3/s)		
						100	250	390
acetaldehyde	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.4a)	0.042mg/m^3 (0.023ppm)	0.00038	0.00096	0.00149
	Contrib.	n.s.	annual	NSW Health (undated)	n.s.	0.000010	0.000024	0.000037
acetone	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.2b)	22mg/m^3 (9.2ppm)	0.00022	0.00055	0.00086
benzene	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.2a)	0.029mg/m3 (0.009ppm)	0.00080	0.00200	0.00312
	Contrib.	n.s.	annual	NSW Health (undated)	n.s.	0.000020	0.000050	0.000078
benzo(a) pyrene	Contrib.	n.s.	annual	NSW Health (undated)	n.s.	0.00000017	0.00000043	0.00000067
1,3 butadiene	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.2a)	0.04mg/m3 (0.018ppm)	0.00030	0.00074	0.00116
cyclohexane	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.2b)	19mg/m^3 (5ppm)	0.00007	0.00017	0.00026
ethylbenzene	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.2b)	8.0mg/m^3 (1.8ppm)	0.00060	0.00151	0.00235
formaldehyde	Contrib.	n.s.	30-min	WHO (2000)	0.1mg/m^3	0.00072	0.00179	0.00279
	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.2a)	0.02mg/m3 (0.018ppm)	0.00068	0.00170	0.00265
	Contrib.	n.s.	3-hour	NSW Health (undated)	n.s.	0.00047	0.00117	0.00182
	Contrib.	n.s.	24-hour	NSW Health (undated)	n.s.	0.00015	0.00037	0.00057

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[t] Total denotes the sum of the pre-existing background level plus the contribution of the tunnel portal emissions, whereas contrib. denotes that only the incremental contribution, i.e., the incremental effect from the tunnel portal emissions alone.

[u] All values for which the statistic is not specified (denoted as n.s.) in this table were assumed to be 99.9%.

[v] Calculated at the residence with the highest total concentration.

Table 11. (cont'd) Summary of the maximum concentrations associated with each VOC at any residence nearby Bexley Road.

VOC	Total or contrib.[w]	Stat.[x]	Avg. time	Reference	Modelling assess level	Contribution[y] (mg/m^3) by flow rate (m^3/s)		
						100	250	390
n-hexane	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.2b)	3.2mg/m^3 (0.9ppm)	0.00108	0.00269	0.00420
Poly Aromatic Hydrocarbons (PAHs)	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.2a and 7.2c)	0.0004mg/m^3	0.00000689	0.00001721	0.00002685
styrene	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.4a)	0.12mg/m^3 (0.027ppm)	0.00009	0.00022	0.00034
toluene	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.4a)	0.36mg/m^3 (0.09ppm)	0.00456	0.01140	0.01779
xylenes	Contrib.	99.9%	1-hour	DECNSW (2005, Table 7.4a)	0.19mg/m^3 (0.04ppm)	0.00308	0.00769	0.01199

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[w] Total denotes the sum of the pre-existing background level plus the contribution of the tunnel portal emissions, whereas contrib. denotes that only the incremental contribution, i.e., the incremental effect from the tunnel portal emissions alone.

[x] All values for which the statistic is not specified (denoted as n.s.) in this table were assumed to be 99.9%.

[y] Calculated at the residence with the highest total concentration.

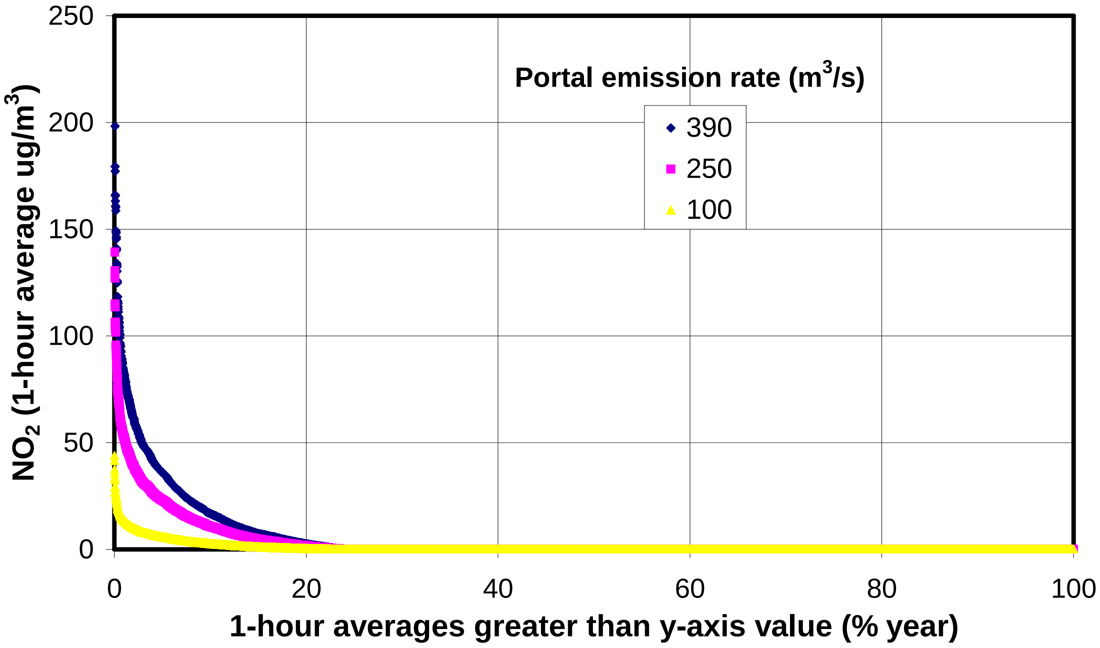

Figure 5. Frequency of portal emission incremental contribution for NO_2

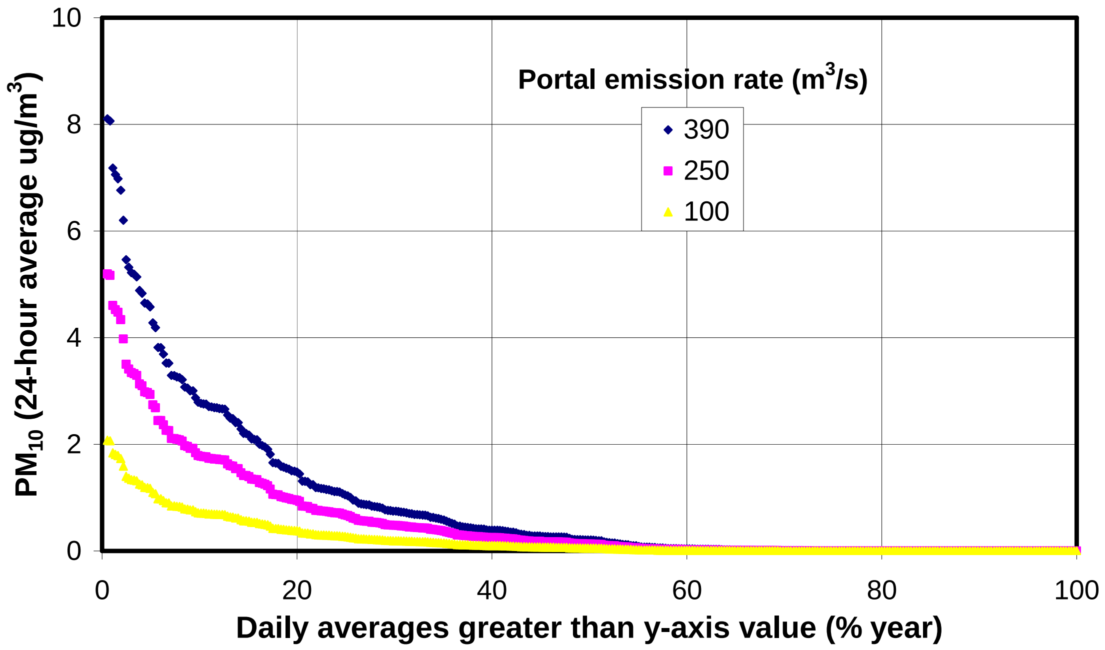

Figure 6. Frequency of portal emission incremental contribution for PM_{10}

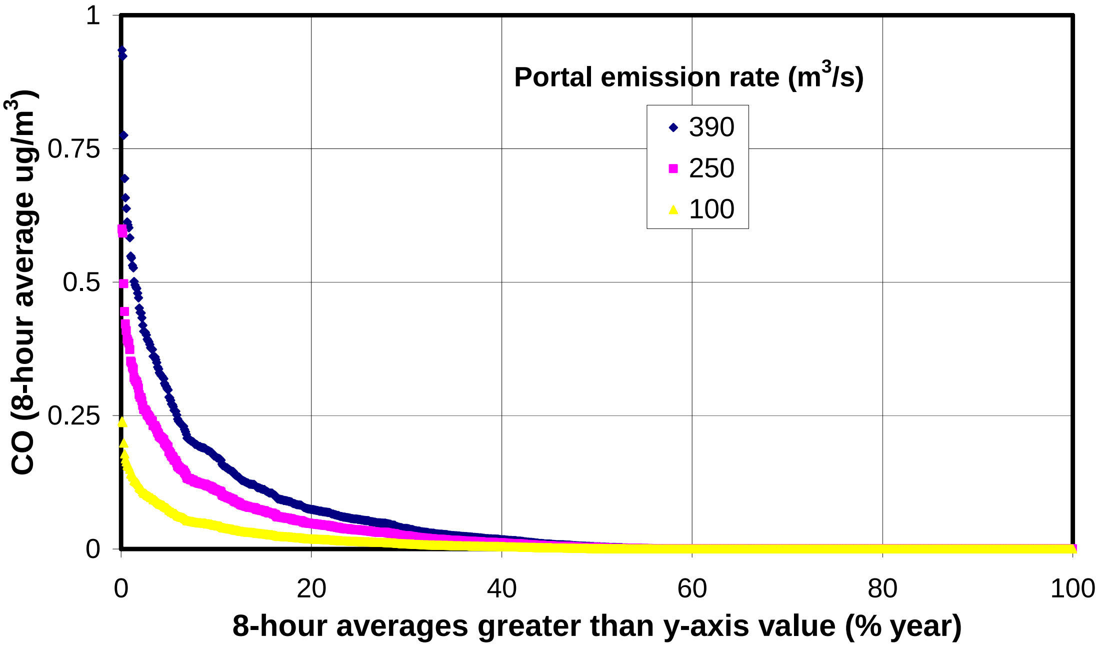

Figure 7. **Frequency of portal emission incremental contribution for CO**

7.3 Health risk assessment

A basic screening level health risk assessment was carried out to assess compliance with the health risk criteria for VOCs in Table 2. The most conservative (highest) screening level unit risk factors for inhalation from USEPA (2006) or from OEHHA (2003) were applied to the modelled annual average concentration for each substance.

Table 12. Unit risk factors for VOCs.

VOC	**IRIS (USEPA 2006) Inhalation Unit Risk (μg/m^3)$^{-1}$**	**OEHHA (2003) Inhalation Unit Risk (μg/m^3)$^{-1}$**
acetaldehyde[z]	2.2E-06	2.7E-06
acetone	n.s.	n.s.
benzene	7.8E-06	2.9E-05
benzo[a]pyrene	8.8E-04[aa]	1.1E-03
1,3-Butadiene	3.0E-05	1.7E-04
CO	n.s.	n.s.
cyclohexane	n.s.	n.s.
ethylbenzene	n.s.	n.s.
formaldehyde	1.3E-05	6.0E-06
n-Hexane	n.s.	n.s.
NO_2	n.s.	n.s.
PAHs[bb]	8.8E-04	1.1E-03
PM_{10}	n.s.	n.s.
$PM_{2.5}$	n.s.	n.s.
styrene	n.s.	n.s.
toluene	n.s.	n.s.
xylenes	n.s.	n.s.

Table 13. Unit risk factors for individual PAHs.

VOC	**OEHHA (2003) Inhalation Unit Risk (μg/m^3)$^{-1}$**
anthracene (Anth),	n.s.
benz[a]anthracene (BaA)	1.1E-04
benzo[a]pyrene (BaP)	1.1E-03
benzo[b]fluoranthene (BbF)	1.1E-04
benzo[e]pyrene (BeP)	n.s.
benzo[g,h,i]perylene (BghiP)	n.s.
benzo[k]fluoranthene (BkF)	1.1E-04
chrysene (Chry)	1.1E-05
coronene (Cor)	n.s.
dibenz [a,h]anthracene (DBA)	1.2E-04
fluoranthene (Fla)	n.s.
indeno[1,2,3-c,d]pyrene (IP)	1.1E-03
phenanthrene (Phen),	n.s.
pyrene (Py)	n.s.

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[z] Although only listed as an odorous pollutant in DECNSW (2005, Table 7.4a), acetaldehyde was included in the risk assessment to provide additional conservatism.

[aa] Provisional inhalation toxicity values have been developed by NCEA 1995. Also listed on RAIS database.

[bb] The unit risk factors for individual PAHs were used as they gave more conservative high estimates of risk.

The health risk assessment is based on an assumption of continuous exposure for a 70-year period. Vehicle emission levels have dropped markedly and are likely to continue to drop over the next 70-year exposure period due to ongoing initiatives[cc]. An estimate of the rate of change in annual VOC concentration with time was based on trends in vehicle emission standards over the period from 1976 to 2006. From these data, the ratio of the average VOC emissions during the period from 2007 to the average VOC emissions in 2077 was calculated as 10.2% of the 2007 value.

The risks were then calculated as summarised in Table 14.

Table 14. Summary of the maximum modelled risk values associated with each VOC and PAH at the residences nearby Bexley Road.

VOC/PAH	**Max. modelled value by[dd] flow rate (m^3/s) [ee]**		
	100	250	390
formaldehyde	1.03E-08	2.58E-08	4.02E-08
benzene	5.87E-08	1.47E-07	2.29E-07
1,3 Butadiene	1.28E-07	3.2E-07	4.99E-07
anthracene (Anth),	0	0	0
benz[a]anthracene (BaA)	4.01E-09	1E-08	1.56E-08
benzo[a]pyrene (BaP)	2.48E-09	6.2E-09	9.68E-09
benzo[b]fluoranthene (BbF)	1.62E-09	4.04E-09	6.3E-09
benzo[e]pyrene (BeP)	0	0	0
benzo[g,h,i]perylene (BghiP)	0	0	0
benzo[k]fluoranthene (BkF)	3.3E-09	8.26E-09	1.29E-08
chrysene (Chry)	1.7E-10	4.25E-10	6.63E-10
coronene (Cor)	0	0	0
dibenz [a,h]anthracene (DBA)	1.97E-09	4.92E-09	7.68E-09
fluoranthene (Fla)	0	0	0
indeno[1,2,3-c,d]pyrene (IP)	3.83E-09	9.59E-09	1.5E-08
phenanthrene (Phen),	0	0	0
pyrene (Py)	0	0	0
Aggregate	2.17E-07	5.42E-07	8.46E-07

[cc] The portal emission concentration measurements will continue to fall. For example the maximum permitted level of benzene in petrol dropped from 5% to 1% from the beginning of 2006. Diesel vehicles (i.e., particularly PM2.5 and NOx) for example are predicted to fall during the period from 2005 to 2010 as the more stringent Euro diesel vehicle emissions standards that were applied from 2002 and low sulfur and ultra–low sulfur diesel become available from January 2003 and January 2006 respectively (Minister for the Environment 2002). The NSWRTA is implementing an air quality improvement plan (Roozendaal 2006) to further reduce emissions from the M5 East Tunnel consisting of: video identification of pollution-causing heavy vehicles and the Clean Fleet Program; Increased ventilation flows with an extra 12 fans and a trial of filtration technology. The NSW EPA (DECNSW 2006) is implementing a broad reform program for vehicles to reduce emissions comprising, fuel quality standards, new vehicle standards, low volatility fuel program, emissions testing for cars, reduced vehicle use and alternative fuels.

[dd] The values shown at lower portal flow rates of 100 and 250m^3/s were estimated by interpolation assuming that the plume behaved in a similar manner to a neutral buoyancy ground based source.

[ee] A null value “0”was used for substances where OEHHA (2003) reported that there were insufficient data to characterize the potential risk.

Both the individual VOC risk and aggregate risk were found to be below the 1E-06 DECNSW (2005) risk assessment criterion as detailed in Table 2.

In addition, the health risks associated with the predicted maximum increase in PM_{10} (including $PM_{2.5}$) have been estimated (Holmes, 2006) to be:

- a 1 in 20 million and 1 in 32 million risk of mortality for the most exposed individual for the PM_{10} and $PM_{2.5}$.contributions respectively

- a 1 in 3.8 million and 1 in 4.7 million risk of daily hospital admission for asthma in a young person between 5 and 34 years for the PM_{10} and $PM_{2.5}$.contributions respectively (Holmes, 2006).

8 Concluding comments

CFD modelling was undertaken in accordance with The Approved Methods for Modelling and Assessment of Air Pollutants in New South Wales (DEC NSW 2005) to determine the potential impact of a portal emissions trial at the M5 East tunnel on the ambient air quality in nearby residential areas. A screening level health risk assessment was also carried out.

From the modelling a control strategy was developed that limited the contribution of PM_{10} to a maximum of 5 $\mu g/m^3$ at nearby residences and the portal flow rate to $250m^3/s$. This resulted in maximum modelled ground level concentration (GLC) and risk values at relevant residential receptors for each of the pollutant assessment criteria identified in Table 1 and Table 2. The results are summarised in Table 10 for criteria pollutants and Table 11 for VOCs . It can be seen from these tables that all of the modelled pollutant concentrations as a result of portal emissions in accordance with the proposed control strategy are below the assessment criteria and, in particular, the goals specified in the Approval.

A consequence of limiting the contribution of PM_{10} to about 5 $\mu g/m^3$, which is predicted to occur in the order of 3 to 5 days per year, and the portal flow rate to $250m^3/s$, also limits the contribution of all other pollutants at residential receptors. For example the contribution of 24-hour $PM_{10,}$ 1-hour NO_2 and 8-hour CO from portal emissions will be below 2.7$\mu g/m^3$, 23$\mu g/m^3$ and 0.18ppm respectively for 95% of the trial duration. Similarly the annual average $PM_{10,}$, NO_2 and CO contribution associated with portal emissions will be limited to 0.6$\mu g/m^3$, 3.4$\mu g/m^3$, and 0.053ppm respectively.

This analysis was carried out for the Bexley Road and Marsh Street portal based on actual monitoring data. The worst case highest pollutant contributions are predicted to be experienced at residences nearby the Bexley Road portal. These levels are shown in Table 10 and Table 11. The greater separation distance between the residences and the tunnel portal at Marsh Street results in greater dispersion of the discharges from the portal and modelling predicts a maximum ground level concentration at nearby residences approximately 30% lower than those at Bexley Road.

Using the model-derived calculations of key (indicator) pollutants, the screening level health risk assessment found that both the individual volatile organic compound risk and aggregate risk were found to be below relevant assessment criteria of 1E-06 described by DECNSW (2005).

9 References

Australian Government 2004, Department of Transport and Regional Services, Australian Design Rules for Road Vehicles as at Determination 5 of 2003 and Determination 1 of 2004, ADR 79/00 Emission Control for Light Vehicles, 79/01 Emission Control for Light Vehicles, Commonwealth of Australia 2004, ISBN: 0-646-43560-4

CARB 1993, Air Resources Board. Acetaldehyde as a toxic air contaminant. www.oehha.ca.gov/air/toxic_contaninants/html/Acetaldehyde.htm

CARB 1998, Findings of the Scientific Review Panel on “The report on diesel exhaust,” adopted at the panel’s April 22, 1998 meeting.

CARB 2005, Air Toxics Host Spots Program Risk Assessment Guideline (2005) California EPA. Office of Environmental Health Hazard Assessment. Air Toxicology and Epidemiology Division. May 2005.

DEC NSW 2005, Approved methods for the modelling and assessment of air pollutants in New South Wales, Department of Environment and Conservation (NSW), August 2005, 59-61 Goulbourn Street, Sydney, NSW, 2000.

DIPNR 2003, Transport and Population Data Centre Commercial Transport Study Classified Vehicle Count Study, Prepared for the Transport and Population Data Centre by CFE Information Technologies (Final Report September 2003), NSW Department of Infrastructure, Planning and Natural Resources Transport and Population Data Centre, 2003, ISBN 0 7313 2827 2, REPORT 2003/5, October 2003

Duffy B.L, Nelson P.F., Ye Y. and Weeks I.A. 1999, Speciated hydrocarbon profiles and calculated reactivities of exhaust and evaporative emissions from 82 in-use light-duty Australian vehicles, Atmospheric Environment, Volume 33, Number 2, January 1999, pp. 291-307(17)

EPA Victoria, 1991, PAH, PM10, Total Particulate Matter and Lead Measurements at Debney’s Park Estate, Flemington, 1990-1991, Vic Roads Study

EPA Victoria 1985, *Plume calculation procedure*, Environment Protection Authority of Victoria, Publication 210, March 1985.

EPA Victoria 1999, Ausplume *Gaussian Plume Dispersion Model – Technical Users Manual*, Environment Protection Authority of Victoria , Publication 671, December 1999,

Hanna S.R., Briggs G.A. and Hosker R.P. 1982, *Handbook on atmospheric diffusion*, US Department of Energy, DOE/TIC-11223.

HAS 2006, *M5 East portal monitoring analysis*, February 2006, Holmes Air Sciences, Suite 2B, 14 Glen Street, Eastwood, NSW.

Holmes K 2006, Personnal communication Monday 9 October 2006, Holmes Air Sciences, Suite 2B, 14 Glen St. Eastwood NSW 2122.

HLA 2003, ‘Air Quality Monitoring Program, M5 East Tunnel Exhaust’ prepared by HLA Envirosciences Pty Ltd, 12 May 2003.

Huang, G, Kawahara, Y. and Tamai, N. 1993, ‘Application of Reynolds-stress model to the study of heat island structure over a slightly inclined terrain’, *Journal of Wind Engineering and Industrial Aerodynamics*, Vols 46 and 47, pp705-712.

Kahlili, N. R., Scheff, A. P. and Holsen, T. M. (1995). "PAH source fingerprints for coke ovens, diesel and gasoline engines, highway tunnels, and wood combustion emissions", Atmos. Environ., vol 29, no 4, pp 533-542.

Lima A.L.C., Farrington J.W. and Reddy C.M. 2005, Combustion-Derived Polycyclic Aromatic Hydrocarbons in the Environment—A Review Environmental Forensics, 6:109–131, 2005.

Luhana L, Sokhi R, Warner L, Mao H, Boulter P, McCrae I, Wright J and Osborn D, Characterisation of Exhaust Particulate Emissions from Road Vehicles, October 2004, European Commission – DG TrEn, 5th Framework Programme Competitive and Sustainable Growth Sustainable Mobility and Intermodality Report No.2000-RD.11091

Macauley D. J. (1990). Measurement of Carbonyl Emissions from Unleaded Fuelled Vehicles, Report No SRS 90/009, Environment Protection Authority of Victoria, Melbourne.

Matzoros A. and van Vliet D. (1992). "A Model of Air Pollution from Road Traffic, Based on the Characteristics of Interrupted Flow and Junction Control: Part 1 - Model Description", Transpn. Res.-A, vol 26A, no 4, pp 315-330.

Minister for the Environment 2002, Report to the NEPC on the implementation of the National Environment Protection (Diesel Vehicle Emissions) Measure for New South Wales by the Hon Bob Debus MP, Minister for the Environment for the reporting year ended 30 June 2002.

NCEA 1995, National Center for Environmental Assessment (NCEA). *RAGS: Region 4 Bulletins, Human Health Risk Assessment* (Interim Guidance) (November 1995).

Nelson P. F. and Duffy B. L. (1998). "Composition of Exhaust and Evaporative Hydrocarbon Emissions from an In-Service Dual Fuel LPG/Petrol Passenger Vehicle", Clean Air, vol 32, no 1, pp 28-32.Parsons (1998). National Pollutant Inventory, Estimation of Motor Vehicle Emission Factors, prepared for Queensland Department of Environment, Brisbane.

NEPC 2003, Variation to the National Environment Protection (Ambient Air Quality) Measure, June 2003, NEPC Service Corporation, Level 5, 81 Flinders Street, Adelaide SA 5000, (08) 8419 1200, exec@ephc.gov.au..

NPI 2000, National Pollutant Inventory, Australian Government, Department of the Environment and Heritage – Emissions Estimation Technique Manual for Motor Vehicles, 22 November – Version 1.0, http://www.npi.gov.au/handbooks/aedmanuals/pubs/motorvehicles.pdf

NPI 2006, National Pollutant Inventory, Australian Government, Department of the Environment and Heritage, http://www.npi.gov.au/

NSWEPA 2002, 'Ambient Air Quality Research Project (1996-2001) – Dioxins, Organics, Polycyclic Aromatic Hydrocarbons and Heavy Metals', New South Wales EPA

NSW Health undated, NSW Health submission to the proposed modification of conditions of consent on the M5 East motorway.

NSWRTA 2005, M5 EAST FREEWAY RTA REPORT 6 IN-TUNNEL AIR QUALITY AND TRAFFIC DATA REPORT October 2005.

OEHHA 1992, Office of Environmental Health Hazard Assessment. Proposed identification of 1,3-butadiene as a toxic air contaminant. Part B. Health assessment. Hazard Identification and Risk Assessment Branch. Berkeley, CA.

OEHHA 2003, *Air Toxics Hot Spots Program Risk Assessment Guidelines - The Air Toxics Hot Spots Program Guidance Manual for Preparation of Health Risk Assessments*, August 2003, California Environmental Protection Agency, Office of Environmental Health Hazard Assessment

Pitts, J. 1993, California EPA. Air Resources Board- Acetaldehyde as a toxic air contaminant. Executive summary. http//www.oehha.ca.gov/air/toci_contaminants/html/Acetaldehyde.htm

Planning Approval 1997, Planning Approval for the M5 East issued by the Minister for Urban Affairs and Planning on 9 December 1997.

Richards, P.J. and Hoxey, R.P. 1993, 'Appropriate boundary conditions for computational wind engineering models using the k-ε turbulence model', Journal of Wind Engineering and Industrial Aerodynamics, Vol.46and47, pp145-153.

Schauer C, Neissner R, Poschl U 2003, Polycyclic aromatic hydrocarbons in urban air particulate matter: decadal and seasonal trends, chemical degradation and sampling artefacts. Environ Sci Technol. 37:2861-8.

Schauer J J, Kleeman M J, Cass G R, Simoneit B R T 1999, Measurement of Emissions from Air Pollution Sources. 2. C1 through C30 Organic Compounds from Medium Duty Diesel Trucks Environ. Sci. Technol., 33 (10), 1578 -1587, 1999.

Seinfeld, J.H. and Pandis S.N. 1998, Atmospheric chemistry and physics – from air pollution to *climate change*, John Wiley and Sons.

Sjogren M, Li H, Banner C, Rafter J, Westerholm R, Rannug U 1996, Influence of physical and chemical characteristics of diesel fuels and exhaust emissions on biological effects of particle extracts: a multivariate statistical analysis of ten diesel fuels. Chem Res Toxicol. 9:197-207.

Svanberg P-A and Lindskog A 1997. Air quality in Sweden the summer 1996 and winter 1996/1997. IVL report B-1272 L97/176. Institute of Water- and Air Pollution Research. Stockholm, Sweden. In Swedish.

U.S. EPA. 2002, Health assessment document for 1,3-butadiene. Office of Research and Development, Washington, DC. EPA/600/P-98/001.

USEPA 2006. Integrated Risk Information System (IRIS). U.S. EPA. Accessed August 20, 2006. http//www.epa.gov/iris

Westerholm R, Christensen A, Tornqvist M, Ehrenberg L, Rannug U, Sjogren M, Rafter J, Soontjens C, Almen J, Gragg K 2001, Comparison of exhaust emissions from Swedish environmental classified diesel fuel (MK1) and European Program on Emissions, Fuels and Engine Technologies (EPEFE) reference fuel: a chemical and biological characterization, with viewpoints on cancer risk. Environ Sci Technol. 35:1748-54.

Westerholm RN, and K.-E. Egebäck KE (1994). *Exhaust emissions from light- and heavy-duty vehicles: Chemical composition, impact of exhaust after treatment, and fuel parameters*. Environ Health Perspect 24:1179-1186.

Westlake P 2006, Personal communication Phil Westlake, Market Development Manager, ph02-93194733, LPG Australia, Sydney, NSW.

WHO 2000, *Air quality guidelines for Europe, Second edition*, WHO regional publications, European series no. 91, 2000.

World Health Organization/International Programme on Chemical Safety 2001, Concise International Chemical Assessment Document No. 30, 1,3-Butadiene: Human Health Aspects. pp. 4-5.

Zhang, Y.Q., Arya, S.P. and Snyder, W.H. 1996, 'A comparison of numerical and physical modelling of stable atmospheric flow and dispersion around a cubical building', *Atmospheric Environment*, Vol.30, No.8, pp1327-1345.

Zielinska B, Sagebiel J, McDonald JD, Whitney K, Lawson DR 2004, Emission rates and comparative chemical composition from selected in-use diesel and gasoline-fuelled vehicles. J Air Waste Manag Assoc. 54:1138-50.