INVESTIGATION REPORT ET/IR304R

AIR QUALITY IMPACT OF THE EMISSIONS FROM THE M5 EAST TUNNEL

by

D.J. Williams, J.N. Carras, A. Saghafi,
P.C. Manins*, M.F. Hibberd* and P.J. Hurley*

CSIRO Division of Energy Technology,
North Ryde, NSW

*CSIRO Atmospheric Research, Aspendale,
Vic.

Report to the NSW Department of Urban Affairs and Planning

August 2000

DISTRIBUTION LIST

Chief of Division	1
R&D Operations Manager	1
Project Manager	1
Client	3 + e-copy
Other CSIRO Staff	5
This is copy number .5.. of .11..	D3 w

Limited Circulation

This document is not to be given additional distribution or to be cited in other documents without the consent of the Chief of Division of Energy Technology

Air Quality Impact of the Emissions from the M5 East Tunnel

CONTEXT and CONCLUSIONS

DUAP has requested CSIRO to advise:

1. whether the procedures and data used by Hyder Consulting to assess the air quality impacts of emissions from the M5 East tunnel vented through a single stack at Turrella are appropriate;
2. if the procedures and data have been used appropriately;
3. if the conclusions in the report are credible;
4. what stack height is required to meet the air quality goals;
5. other considerations.

We advise that, based on the information in the main Hyder Reports (2000a, b), further information supplied informally, and supplementary reports on modelling using 1998 meteorology (Hyder 2000c) and air quality modelling for incident management (Hyder 2000d) that:

1. The methods employed by the Consultants are appropriate for making an assessment of the impacts of emissions.
2. There are a number of points that we have not been able to satisfy ourselves about in reviewing the procedures employed. We believe the estimates of emissions are reasonable except for particles, which may be underestimated by a factor of two or more. We also believe the reliance on the wind tunnel results to support a claim that the numerical modelling is conservative, has not been justified.
3. The Hyder Reports conclude that predicted ground-level concentrations are below the Air NEPM Standards. We believe this may be the case for nitrogen dioxide if stack height and efflux velocities are appropriate (see point 5), but although the modelling shows that PM_{10} Standards are not exceeded, it is possible that at other times this may not be the case, principally because background PM_{10} levels are occasionally high, and because the emissions estimates used by Hyder Consultants may be too low. These exceedences may occur irrespective of the stack emissions, which, in principal, could increase the number of potential exceedences.
4. The 1998 background data for PM_{10} and NO_2 show generally similar peaks to those observed in the 1995 data, except for the maximum NO_2 value of 180 $\mu g\ m^{-3}$, which is substantially greater than the highest 1995 value of 136 $\mu g\ m^{-3}$. This indicates that conclusions based on Hyder's 1995 modelling may underestimate the potential for exceedence of the NEPM goals for NO_2. An unexplained feature of the 1998 glc predictions (Hyder 2000c) is that the highest stack contributions to PM_{10} levels are about 30% lower than those predicted using the 1995 meteorology. Although the results of modelling 1995 and 1998 are broadly similar, it must be noted that, there are data for other years that show higher concentrations, particularly for PM_{10}. As high PM_{10} is often associated with bushfires, some allowance is made in connection with exceedences. Nevertheless, some numerical modelling for these higher background occasions may provide a better estimate of the likely frequency of exceedence over a number of years.
5. In order to prevent exceedence of the NO_2 goal, which is predicted when using a conservative method for including background concentrations, we believe that the

effective plume height needs to be increased in light wind conditions. This can be achieved with a higher physical stack height (i.e. 35 m or higher) or the use of enhanced stack exit velocities at night (i.e. at hours 20-23) or a combination of both. For example, it has been shown that if stack exit velocities were to be increased for these hours (see Section 8 for details), then maximum ground level concentrations of NO_2 at these times would be below the guidelines, even for the 25 m stack height, and when using a conservative approach to inclusion of background concentrations. This may also reduce the frequency of PM_{10} exceedences.

6. We also believe the possibility of plume strike on tall buildings needs to be taken as a serious possibility and that building height restrictions be imposed in the region following modelling studies.
7. If further numerical modelling is undertaken, we recommend that the influence of thermal buoyancy and fan speed on plume rise should be included and that the background concentrations and plume strikes should be combined stochastically.

These conclusions are supported by the review presented here. In preparing it, we also have attempted to address residents and other citizens concerns raised at a meeting with DUAP on 14 June. This is largely achieved through a discussion of the inherent uncertainty in the estimates of ground level impacts from the Turrella plume.

Issues such as

- the adequacy or otherwise of the air quality goals
- the suitability of the stack location
- the advisability of treating the ventilation air to reduce emissions

were not included in the scope of the current review.

1. Introduction

The Hyder Reports (2000 a, b) present an impact assessment of the performance of the Turrella stack based on a modelling simulation using a numerical model called ISC3, a widely used numerical air pollution model from United States Environment Protection Agency. The results are supported by a physical modelling simulation performed in the Monash wind tunnel. The Reports develop the modelling assessment by dealing with each of the components described above. Here we review each of the components and reach conclusions about the appropriateness of the assessment presented in the Hyder Reports. An assessment of the information contained in the supplementary reports (Hyder 2000c, d) is included in the relevant sections of this review.

In arriving at estimates of ground level concentrations (glc) of pollutants, whether by physical or numerical modelling, there are a number of essential components that need evaluating:

- the estimates of traffic volumes
- the estimates of traffic emissions
- the emission flux from the stack to be located at Turrella
- the emission buoyancy flux from the stack
- the stack height
- terrain features
- meteorology
- background ground level concentrations.

Some of these components have a diurnal variability associated with them such as emission flux and the meteorology, others may have an inherent uncertainty, such as the emission flux and background PM_{10}. Some, such as background glc and traffic volumes and emissions are likely to vary over the years. In addition, assumptions that are inherent in the simulations to model the real world introduce further uncertainties.

The sections include:

- A review of the Hyder Reports' estimates of the emission flux from the stack by considering the estimates of traffic, the traffic emissions in the main M5 East tunnel, and the expected change in temperature of emissions due to the flow of hot exhaust gases through the 700 m long lateral tunnel to the Turrella stack.
- A review of the numerical modelling presented in the Hyder Reports, considering the meteorology used for the modelling, choice of background pollutant levels, terrain features and consideration of plume strikes on homes and tall buildings that might be located in the region.
- A review of the physical modelling presented in the Hyder Reports, which was said to be more representative of the real situation than the numerical modelling and therefore showing that the numerical modelling has a substantial factor of safety built into it.
- A statement of overall conclusions and recommendations to DUAP.

2. The Emission Flux

Estimation of the emission flux of a given pollutant at any time requires knowledge of the number of vehicles within the tunnel of each of the major engine and exhaust treatment technology classes, their speed, and their characteristic exhaust emission fluxes for the specified speed and grade along the tunnel.

2.1 Traffic Estimates

Hourly estimates of traffic in terms of passenger cars, LCVs, articulated and rigid trucks have been provided by the RTA. RTA advises that the M5 East tunnel will be managed as a component of the road network instead of being managed in isolation. From when the tunnel opens, traffic is expected to be near capacity. Maximum capacity of a single lane is ~ 2500 vehicles per hour (vph), hence a maximum total flow of ~ 5000 vph can be accommodated in the tunnel in any one direction. At 0700h, the number of vehicles, eastbound, is estimated at 4116 vph according to the Hyder Reports, and this is indeed close to design capacity. The number of heavy diesel vehicles within this flow is 429, which increases to a maximum of 508 at 1100h.

The heavy vehicle fleet is categorised into rigid trucks and semis (articulated trucks plus B doubles), the proportions of each being derived from a combination of data from RTA weighing stations in the Sydney region and Marulan plus traffic surveys in Bexley and St Peters. Data from the M5 tollway and the Bexley - St Peters surveys have been used to estimate the traffic flow and its diurnal variation; these data split the traffic into passenger and commercial vehicles. The estimates of the traffic flows, its diurnal profile and mix, appear to be well based. The major sources of any uncertainty would appear to be the numbers of rigid trucks and the split between articulated and B doubles.

The sensitivity of the emissions to the proportion of diesel traffic is explored in the next section.

2.2 Traffic Emissions

The Hyder report used the PIARC methodology, which provides a tabulation of the emissions (g/h) of CO, VOC, NO_x and diesel PM_{10} for a range of speeds and road grades. The estimates are tabulated for petrol- and diesel-fuelled vehicles for a range of design regulations and are based on tests on European vehicles, mostly using chassis dynamometers. Whilst the PIARC methodology is state of the art, it must be borne in mind that there are significant uncertainties associated with this or other approaches. These are due, in part, to the relatively small size of databases, particularly emissions from in-use diesel traffic, and the degree to which drive cycle tests correspond to the real world.

We have compared the PIARC estimates with our own estimates based on Australian data for petrol and diesel vehicles and found them to be very similar (within the range of uncertainty that might be expected in such data) except possibly for diesel PM_{10} which we believe could be underestimated. To illustrate this we use a preliminary analysis of some data from a recently completed study of emissions from 80 in-use diesel-fuelled vehicles carried out for Environment Australia by ParsonsAustralia and CSIRO Energy Technology. (These data were not available to Hyder at the time of their estimates.)

A second by second analysis of particle emissions from in-use heavy-duty diesel vehicles for half maximum load (plus tare) was carried out in which the particle emission rates were binned according to the fraction of maximum test power experienced by the dynamometer. The vehicles were tested at half maximum load (plus tare) and the emissions were measured by a fast response monitor. The data are shown in Figure 1. The data point at eg 0.6 is the average emission rate for fractional maximum test powers ranging from 0.5 to 0.7 during a drive cycle and that for 0.8 covers the range 0.7 to 1. Negative power occurs during deceleration. The emission rate at 1 is an extrapolation of the data. The emission rates have been normalised so that the emission rate at zero power (-0.5 to +0.5 Pmax) is unity, and are shown in the attached figure for NC category heavy vehicles. Other categories show similar characteristics. The non-linear increase in emission is consistent with the increase in fuel/air ratio with increasing engine power.

PIARC emission rates for zero grade and 60 kph agree reasonable well with the Parsons data. Calculations suggest that at 60 kph, a HGV operates at about 20% of maximum power, but on a 6% grade it is at full power. The PIARC data have been overlaid on the attached figure by putting the PIARC emission rate for zero grade and 60 kph equal to the Parsons results at 0.2P and the estimate for 6% grade at P=1. The PIARC estimates are effectively linear with power. The difference between the two sets of data will depend on how the PIARC data overlay the Australian results and the degree of non-linearity in the emissions as a function of engine power - this awaits further study.

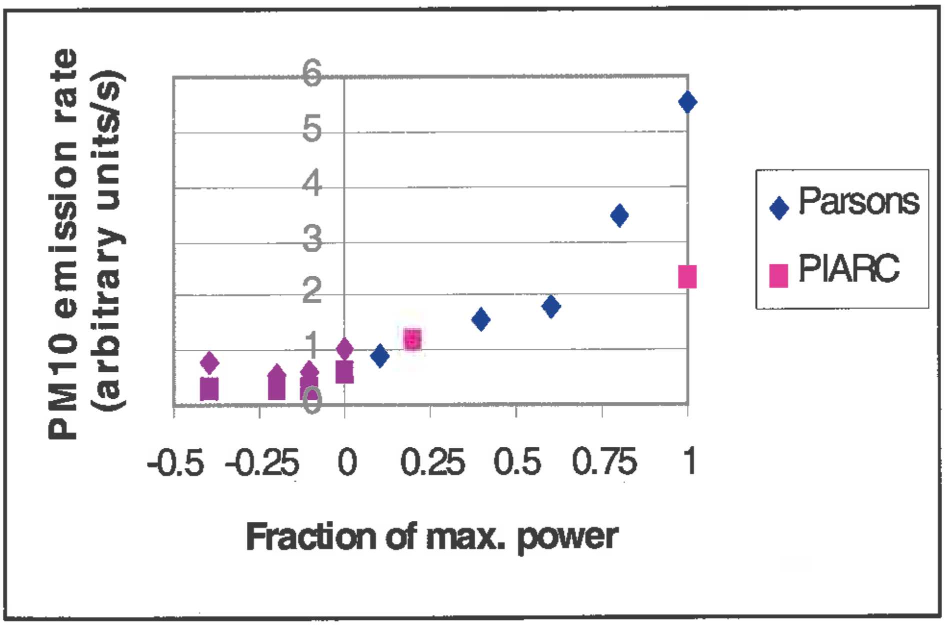

Figure 1. Variation of particle emission rate with applied power.

In our view, it is quite possible that actual PM_{10} emissions could be a factor of two or more higher than the PIARC estimates at full engine load as the majority of the emission will in fact, come from high power operation. It should be re-emphasised that this is new knowledge, not available to Hyder, but in view of the possible potential for exceedence this aspect needs to be taken into consideration.

The sensitivity of the estimates to the proportion of the heavy-duty diesel traffic is such that, using the PIARC methodology, a 20% increase in heavy vehicle traffic results in approximately a 20% increase in PM_{10} as most of this comes from heavy duty diesels with NO_x going up by ~10% at morning peak and ~16% in the middle of the day when diesel traffic is at a maximum. The impact on other emissions is very small.

With regard to the air toxic compounds, benzene, 1:3 butadiene, formaldehyde and acetaldehyde, knowledge of the emission factors is more uncertain than for CO, NO_x and VOCs. However, even taking this into account, the emissions are sufficiently low that the air quality goals are in no way threatened.

We conclude that the traffic emissions factors used in the Hyder Reports are appropriate except that they may underestimate present PM_{10} emissions by a factor of two or more.

The Reports point to the expected improvement of vehicle emissions with the introduction of Euro standards over the next seven years or more. They conclude that this means that year 2002 conditions in the tunnel are the worst case since improvements in emissions per vehicle will outweigh the increase in traffic overall. This seems to be a well-supported assertion for light and heavy diesel vehicles but at least for particle emissions from petrol vehicles the support is far from certain.

Indeed, Euro standards for petrol vehicles do not address particle emissions at all and they are not included in the M5 assessment. Euro4 diesel vehicles will emit no more than approximately 45 mg km^{-1} of particles. Evidence available to us (SAEA, 2000) is that in the near future, petrol vehicles are highly likely to use a technology called GDI (gasoline direct injection), a variant of the existing fuel injection technology available on most new cars. Although GDI gives a 20% improvement in fuel economy, it will lead to an increase of particle emissions of three to four times as great as present conditions (SAEA, 2000). Emissions would be in the range 40–60 mg km^{-1}, comparable to new diesel vehicles. Since petrol vehicles are, according to the Hyder Reports, likely to represent 60–76% of the fleet in the M5 tunnels, their contribution to particle emissions may need to be re-assessed.

We conclude that the assumption that the year 2002 represents worst case ('critical design conditions') may well be true for most pollutants but it may not be for particles.

2. 3 Buoyancy Flux of Emissions

An important aspect of modelling the ground level impact of stack plumes is the calculation of plume rise, which increases the effective stack height. This is due to a combination of momentum (due to the velocity and mass of the efflux) and thermal buoyancy due to temperature induced density difference between the emissions and the ambient air. In the numerical modelling, it has been assumed that the emissions will be 5°C cooler than ambient due to passage of the ventilation air through a tunnel. As is shown below, this is a conservative approach for the cooler part of the year, but it is worth examining this issue in more detail.

We have carried out a simple heat transfer calculation, assuming a rock temperature of 17°C, a tunnel of radius 7 m and a tunnel inlet gas temperature 10°C above rock temperature due to a combination of the temperature of the ambient air being sucked into the tunnel and heat release from the vehicle exhausts. Some measurements in the Sydney Harbour Tunnel showed that heat release from vehicles raised the ambient temperature by ~6°C (Williams, personal communication). For a *well-mixed* airflow of 800 m^3/s, the ventilation air reached rock temperature after about 600 m as shown in Figure 2. At slower flows, the distance will be shorter. It would appear, if these calculations are confirmed, that the exit temperature from the stack will be close to that of the rock at all times. The consequence of this is that during cold winter mornings at morning peak, when stable meteorology dominates and which can give rise to maximum impact at the ground, there will be a substantial positive thermal buoyancy to the plume.

This buoyancy could enhance the effective stack height by 20 m or more. Whilst the reverse will be the case for summer afternoons, the higher dispersion rates, characteristic of neutral to unstable conditions at these times, means that the impact of negative buoyancy will be much less and also closer to the predictions of plume behaviour presented in the Hyder Reports.

As the degree of thermal buoyancy is proportional to the volume flow rate for a given temperature difference, it becomes quite small at the lowest fan speeds projected for minimum traffic flow so that there may well be only a small benefit for overnight plume strike conditions throughout the year.

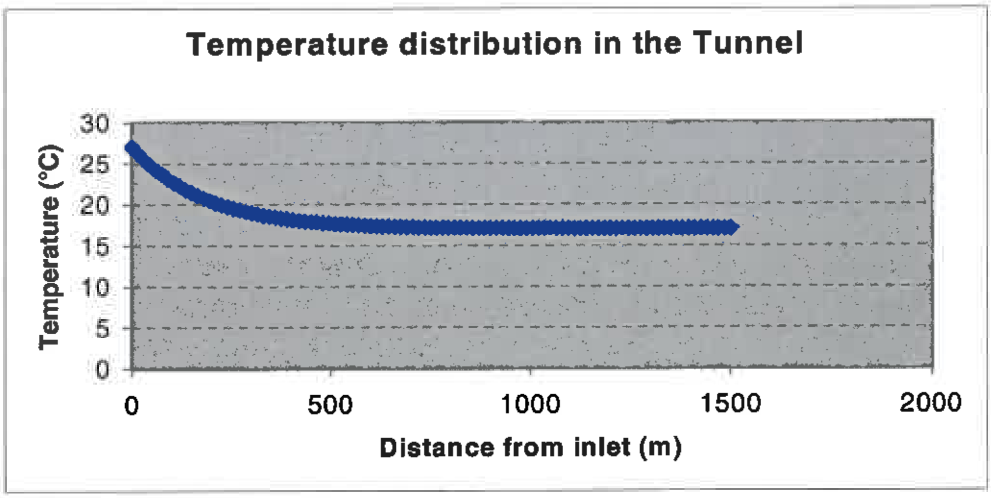

Figure 2. Effect of heat transfer within a road tunnel. Vent flow = 800 m^3/s.

3. Meteorological And Background Conditions

The Hyder Reports used surface meteorological conditions as measured at Earlwood Monitoring Station rather than as measured at the airport. We regard this as an appropriate selection of meteorology for the purpose of assessment of plume impacts where the conditions within a distance of a few kilometres of the stack are of concern.

Only one year of meteorological data was used (1995) in the main Reports (Hyder 2000a, b). While this is common practice, consideration of results from use of another year or more, given that they are available, would have led to an ability to assess the robustness of the predictions. For example, the supplementary report (Hyder 2000c) using 1998 meteorology shows that the ten highest 24-hour average PM_{10} contributions by the stack are substantially lower than in 1995. For the 25 m stack, the top ten values are on average 35% lower (range 30–45%), and for the 35 m stack they are on average 23% lower (range 18–30%) than those predicted using 1995 meteorology. Note that these differences are due solely to differences in the meteorology; the background is not included. We are surprised by the magnitude of these year-to-year differences, especially for 24-hour averages, and suggest that further work may be needed to confirm these results.

Background air pollution conditions were for the same year (1995) and location (Earlwood Monitoring Station) as the meteorology. We regard the use of background pollution data from the Earlwood Monitoring Station as appropriate in the circumstances but we also note that there could well be large local differences due to the regional terrain trapping local pollutants such as domestic wood smoke. The Hyder Reports note that data from some other years were influenced by broad-scale fires. However the Reports do not comment on the change in variation in the PM_{10} record halfway through the year as presented in Figure 5.2 of the Reports. Our inquiries of EPA NSW resulted in them noting that during 1995 the Earlwood TEOM was tested with various measuring heads, and other changes were made to try to reduce the sensitivity to vibration that TEOMs of that vintage were particularly subject to. EPA has provided us with data from 1998 as measured at Earlwood and these for 1-hour average NO_2 and 24-hour average PM_{10} are presented here in Figures 3 and 4.

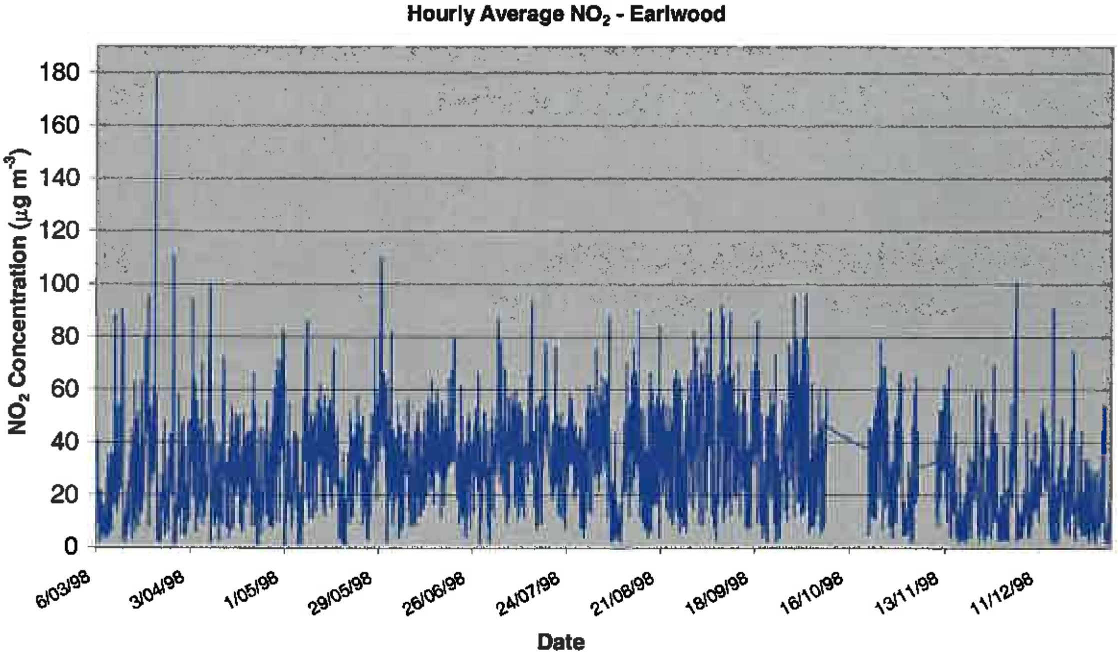

Figure 3. Nitrogen dioxide monitoring data for 1998 provided by EPA NSW.

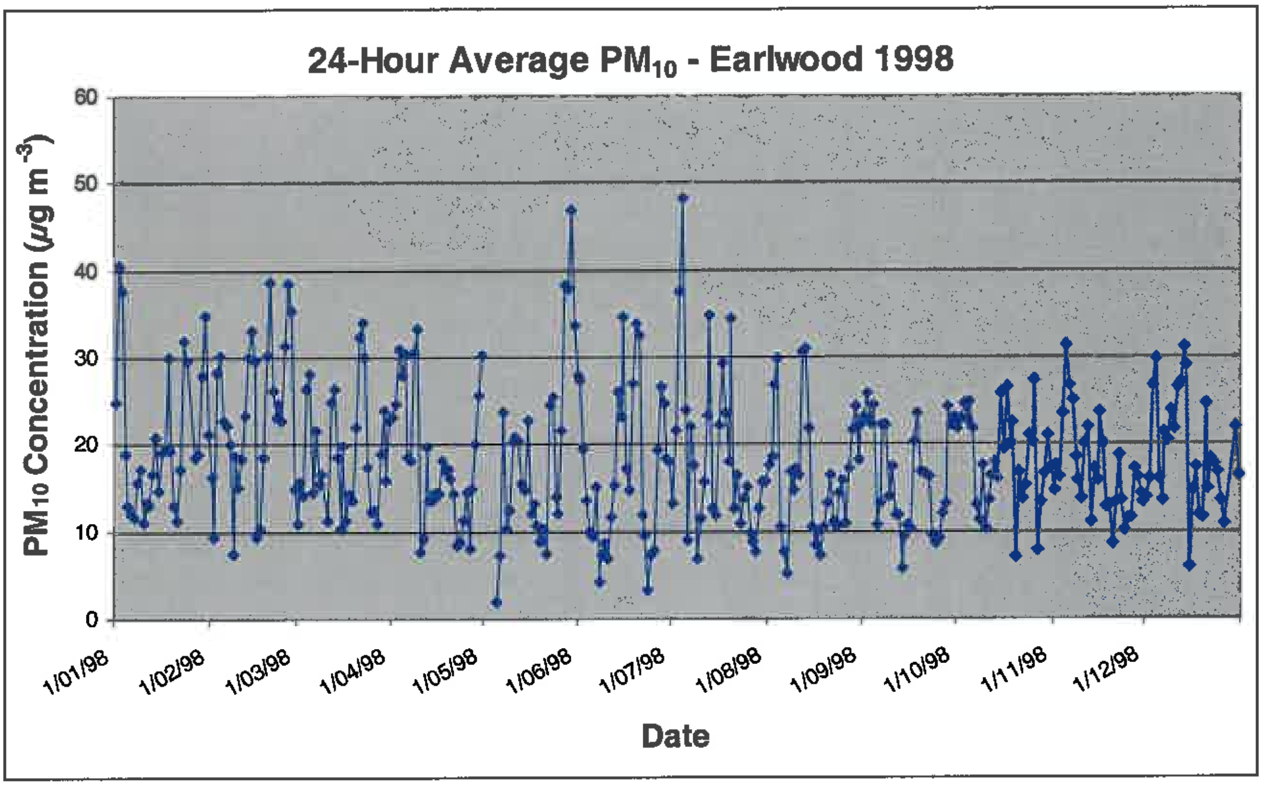

Figure 4. PM_{10} monitoring data for 1998 provided by EPA NSW.

We note that the 1998 NO_2 data indicate fewer values above 100 $\mu g\ m^{-3}$ than in 1995 although the peak value of 180 $\mu g\ m^{-3}$ is substantially higher than the peak of 136 $\mu g\ m^{-3}$ in 1995. The overall average levels are similar to 1995. For the 1998 PM_{10} data, it is clear that there is a much greater uniformity of fluctuations throughout the year than as reported for 1995. There are fewer excursions to higher values and these occur at about the same time (winter) as for 1995, but the overall average levels are about the same as for 1995.

The supplementary report (Hyder 2000c) of modelling results for PM_{10} for 1998 shows very similar peak cumulative 24-hour average PM_{10} concentrations as for 1995, due to the similarity in the peak background concentrations (see also section 5.2). There were no exceedences of the NEPM guideline of 50 $\mu g\ m^{-3}$, In all cases, the stack contribution on these top ten days was less than 3.5 $\mu g\ m^{-3}$, so that the fewer number of days with background concentrations above 45 $\mu g\ m^{-3}$ (two in 1998 compared to five in 1995) is the controlling factor for these extreme values. However if PM_{10} emissions were a factor of two or so higher, there would be exceedences.

The obvious differences between day-by-day levels of NO_2 and PM_{10} for 1995 and 1998 support a conclusion that we wish to make strongly: we do not agree with the approach followed in the Hyder Reports of attempting to simulate the cumulative air pollution effects hour by hour throughout the year by whatever modelling method selected and then adding the corresponding monitored background concentrations. Whilst we are aware of the approaches recommended by the USEPA, and that the NSWEPA had agreed to the use of the "Tier 3" approach of using hour-by-hour (day-by-day) background concentrations with the hour-by-hour (day-by-day) model predictions for NO_2, there is far too much variation in the real atmosphere for the

Tier 3 methodology to be considered conservative. It is far more informative to select background conditions that reflect the range of values that could be expected at a particular hour of day at a particular time of the year. In other words, instead of using a given measured background value derived from monitoring data, impose on this value a range which reflects the variability. We revisit this point in the review of the numerical modelling work, discussed in section 5.

Finally, we aware that there are monitoring data for other years that show higher background PM_{10} levels than 1995 or 1998. It is believed that high levels of PM_{10} are often associated with bushfires and while, under NEPM, some allowance is made by permitting five exceedences per year, it is likely that there that there would still be a number of occasions when background levels are higher than the periods modelled in this report. To better estimate any likely exceedences over a longer timeframe, it would be advisable to include such data in such an assessment.

4. Health Criteria used as Goals for Assessment of Impacts

The major goals used to judge the air pollution impacts of the M5 tunnel stack emissions are about the same as the recently agreed National Environment Protection Measure for Ambient Air Quality — the Air NEPM. Refer to the extensive discussion documented in the Air NEPM for the reasons for their selection (see http://www.nepc.gov.au). We believe these are appropriate design goals.

5. Review of Numerical Modelling of Impacts

5.1 General Impression of ISC3 Methodology

The model ISC3 was judged by EPA NSW and Hyder Consulting to be suitable to the task. We agree with that judgement. There are alternative modelling approaches that could have been used, which would have some advantages and some disadvantages compared to the approach used, but these alternatives have not been considered here.

The Hyder Reports would have been more readily appreciated if they had included more information about the options actually used, rather than just a general listing of the available options, for the modelling work. Similarly, a list of meteorological conditions and background ozone concentrations that were associated with the determined maximum stack concentrations would have helped us to understand the conditions that led to these values. Some of these issues (and others) have been addressed in subsequent informal question and answer sessions.

5.2 General Impression of ISC3 Results

NO_2 stack contributions are moderate compared to the air quality goal (up to 66% of the goal for the 25 m stack and up to 54% of the goal for the 35 m stack), without considering background values. Note that NO_x emissions may be overestimated by 10–20%, and plume rise underestimated overnight and in winter, according to our judgement.

NO_2 maximum stack concentrations are dominated by values during hours 21, 22 and 23, on nearby elevated terrain of height up to 45 m above the stack base (see Figure 5), under light wind conditions (1–3 m s^{-1}), and for stable atmospheric conditions (Pasquill-Gifford stability category E–G).

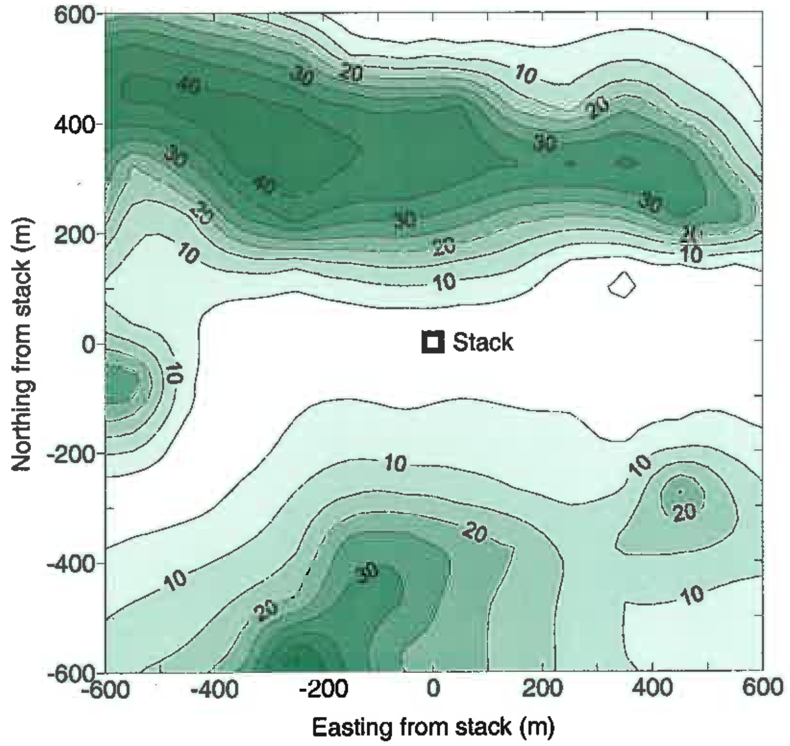

Figure 5. Topography of the region around the stack.

PM_{10} stack contributions could be said to be small compared to the air quality goal (up to 23% of the goal for the 25 m stack and up to 13% of the goal for the 35 m stack), without considering background values. However, PM_{10} emissions may actually be two or more times higher than assumed in the Hyder Reports so the observation that the glcs are small may not be correct. Some mitigation would be possible due to enhanced plume rise overnight from heat transfer in the vent tunnel (Section 2.3) or by increasing the stack exit velocities in the late evening, however an exploration of this would require further modelling (and extra care with ISC3 would be required due to the way it switches between buoyant and momentum plume rise).

Maximum concentrations of other pollutants considered are below air quality goals,

5.3 Degree of Conservatism of the Modelling Approach

ISC3 is generally considered to be a conservative model, as stated in the Hyder Reports, but no substantiating evidence is presented, nor is an assessment of the degree of conservatism attempted except to point to the physical modelling — but see below (Section 6).

The modelling approach used in the assessment is not necessarily conservative in every aspect, and a list of assumptions and whether they are conservative or not is given below.

Conservative Assumptions:

- General dispersion assumptions;
- Complex terrain algorithms;
- Building wake screening algorithms;
- Conversion of available NO to NO_2 using available O_3 background;
- Assume a negatively buoyant plume at all times, especially in winter;
- Comparing maximum concentrations to air quality goal, without accounting for allowed exceedences of the goals (e.g. for the Air NEPM this is one day per year for NO_2, and five days per year for PM_{10}).

Non-Conservative Assumptions:

- Cannot handle calm winds or recirculation of pollutants by local winds;
- Vertical extrapolation of surface conditions to plume height in complex terrain;
- Hour-by-hour addition of model concentration with effective background concentration for NO_2;
- Day-by-day addition of model concentration with background concentration for PM_{10};
- Ignore the expectation that the plume may be substantially negatively buoyant during summer days;
- Ignores hydrocarbon contribution to photochemical production of NO_2 and O_3;
- Ignores secondary formation of PM_{10} through photochemical reactions;
- Ignores possibility of plume strikes on tall buildings that may exist now or be proposed at a later date.

In general, the conservative assumptions should out-weigh the non-conservative assumptions, but, in particular, the use of hour-by hour effective NO_2 backgrounds is potentially the largest of the non-conservative assumptions. This may not be such a problem for PM_{10}, due to the use of 24 hour averages, rather than hourly averages.

In order to explore the use of alternative (more conservative) backgrounds, we selected monthly maximum backgrounds from the 1995/96 NO_2 record as reported and added them to the predicted maximum NO_2 stack values. The results for the top ten stack contributions listed in Hyder Report for the 25 m stack option are: 296, 296, 291, 282, 277, 270, 269, 269, 257, and 250 $\mu g\ m^{-3}$; and for the 35 m stack option are: 263, 260, 260, 252, 238, 238, 236, 223, 217 and 214 $\mu g\ m^{-3}$.

These top values for the 25 m stack are mostly over, and for the 35 m stack are at or slightly over, the air quality goal for NO_2. It could be argued that this approach is too conservative, and something like using observed daily maximum or monthly maximum by hour of the day would be preferable. This consideration illustrates the difficulty in deciding how to add measured backgrounds to modelled values, when models are generally not considered capable of accurately predicting hour-by-hour concentrations.

6. Review of Physical Modelling of Impacts

6.1 Overview of Physical Modelling Results

The physical modelling was carried out in the Monash wind tunnel with a 1:400 scale model using a 1:5 velocity ratio, and hence a 1:80 timescale ratio. The Reynolds number of the modelled stack efflux ranged from 280 to 4400 depending on the efflux velocity. We believe these values are sufficiently high for these dispersion studies. Stack heights of 25 and 35 m were modelled. Most of the measurements were undertaken in neutral conditions, but stable conditions (PG stability F) were used for one series and weakly convective conditions (PG stability C) for another series of measurements.

A 90-second averaging period was used for the concentration measurements. This is equivalent to 2 hours in the atmosphere, but because of the fixed wind direction in the wind tunnel, these averages are equivalent to the 1-hour averages predicted by the mathematical modelling where the wind direction and speed changes each hour. We note that the physical modelling results are not used to predict 24-hour averages, because of the dominant influence of changes in wind speed and direction over such averaging times. All of the wind tunnel results are reported as dispersion ratios. This is the ratio of the concentration observed at the receptor to that in the stack gas.

The overall quality of the presentation of the physical modelling results in the Hyder Reports is poor. There are over 200 pages of Figures in each Report showing results from each of the individual tests, but almost no summary plots other than Figure 8. In order to interpret the physical modelling results, contour plots of maximum dispersion ratios (Figures 6 and 7) have been extracted to determine the internal consistency and the influence of the topography. At each location, the maximum dispersion ratio has been extracted from the Figures in the Reports. Note that the contouring has been done to assist in visualising the results and no significance should be given to contour lines in regions where there are no data.

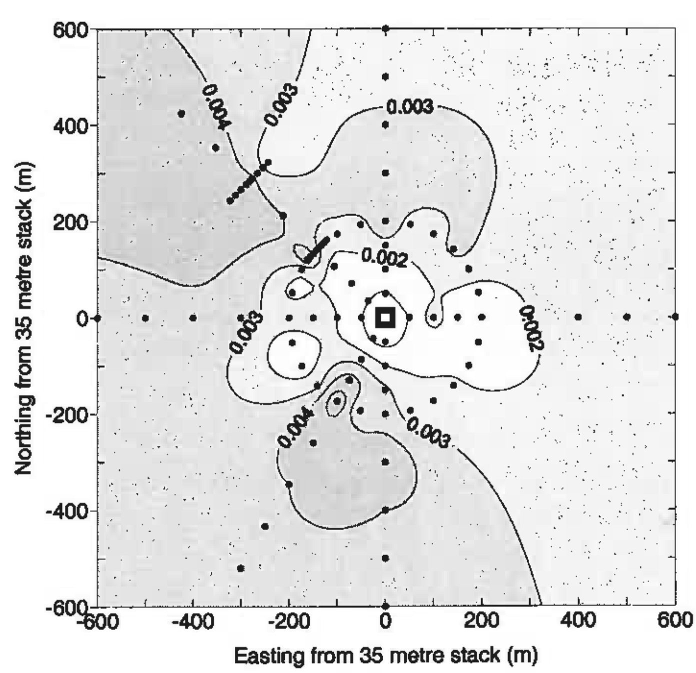

Figure 6 Contour map of the maximum dispersion ratios based on measurements (at the sites indicated by dots) in the physical modelling of neutral flow conditions for the 35 m stack.

Both contour plots (Figures 6 and 7) show good internal consistency between the data measured in the various series for each stack, although the data for the 25 m stack appear to be slightly noisier. In both cases, the maximum dispersion ratios are observed 200–300 m downwind from the stack, possibly slightly further downwind for the higher stack. The peaks tend to occur on the hills to the north and south, as indicated by the topographic contours shown in Figure 5.

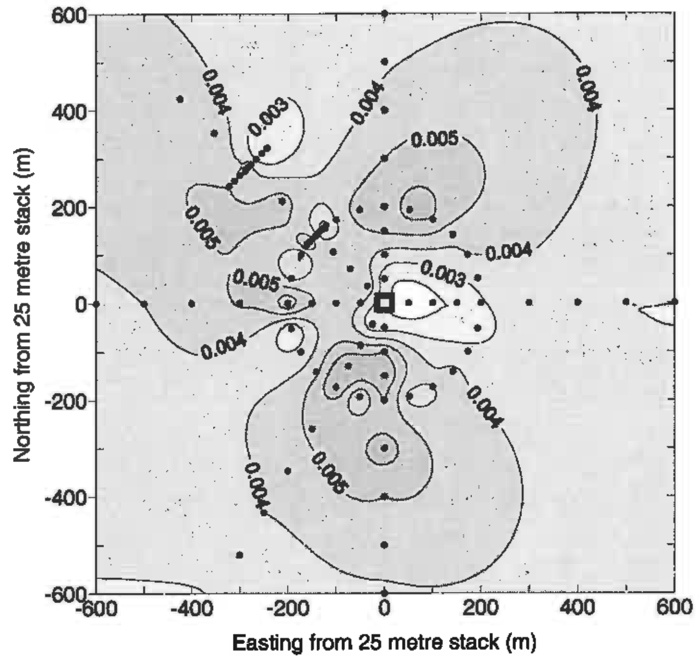

Figure 7. Contour map of the maximum dispersion ratios measured at each site (indicated by dots) in the physical modelling of neutral flow conditions for the 25 m stack.

6.2 Uncertainty in dispersion ratios

An estimate of the uncertainty in the measured dispersion ratios can be obtained from the repeat measurements at the same site in different test series listed in the Hyder Reports. The comparison in Table 1 indicates differences of up to 40%. This is consistent with the above contour plots of the maximum dispersion ratios, and helps to explain some of the apparently anomalous points for the 25 m stack. The magnitude of these discrepancies is also consistent with the statement in the Hyder Reports that 1-hour averages in the atmosphere are likely to be within ±50% of the concentrations predicted from the model data.

Table 1. Estimates of differences in physical modelling of similar conditions (V = 9 m s^{-1}, wind speed 10 m s^{-1} at sites 200 m downwind from the 25 m stack).

Direction from stack	Dispersion ratios	Relative difference between measurements
0°	0.056, 0	
90°	0.0028, 0.0018	44%
180°	0.0047, 0.0052	10%
210°	0.0037, 0.0056	40%
270°	0.0023, 0.0032	32%
315°	0.0047, 0.0039	19%

6.3 Stable vs. neutral flow conditions

For the wind speeds and stack efflux velocities producing the highest dispersion ratios, the physical modelling showed remarkably little change in the maximum dispersion ratios at ground level when the flow conditions were changed from neutral to stable, as shown by our analysis presented in Figure 8. This is all the more surprising because the stability of 0.077 K m^{-1} used in the physical modelling is twice as large as that assumed in the corresponding mathematical modelling. This lack of influence of stability was not commented on in the report, although it has been explained in later communication with Hyder as being due to high low-level turbulence in the high wind speed conditions. It should be noted that at lower wind speeds and higher efflux velocities, the modelling results do show significantly lower glcs in stable conditions.

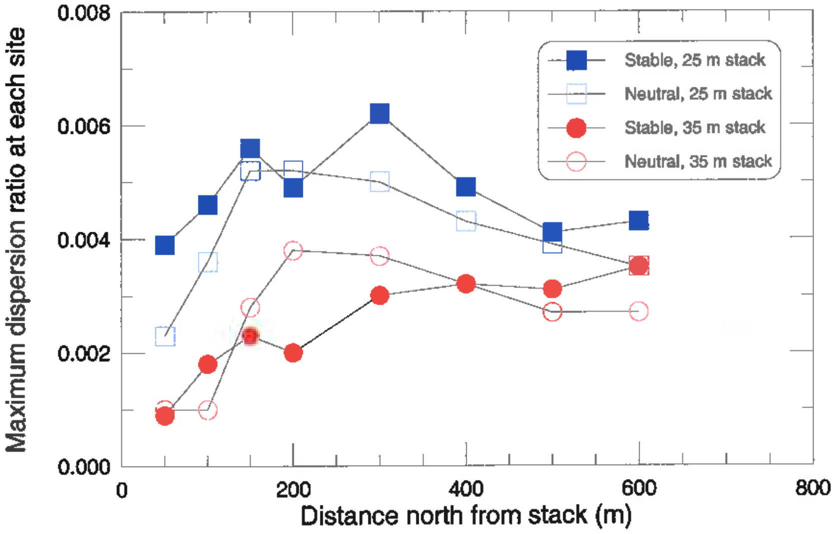

Figure 8. Comparison of maximum dispersion ratios for neutral and stable flow conditions as measured in the physical modelling for a southerly wind.

Some doubt about the reliability of the wind tunnel measurements in stable conditions is indicated by our analysis presented in Figure 9, which compares the vertical profiles measured 400 m downwind from the stack in neutral and stable conditions at the same efflux velocity and wind speed. Although the plume is not mixed to the ground as effectively in stable conditions, the figure shows that more of the plume is transported to higher levels in the stable case than in the neutral case. For the stack height of 35 m, the plume released into the stable environment is distributed more evenly between elevations of 25 m and 125 m, and the concentration at 125 m is more than five times greater than in the neutral case. This is counter to our expectation that stable conditions should inhibit vertical transport of the plume.

Moreover, a simple pollutant flux estimate using the concentration profiles in Figure 9 and assuming a power law velocity profile shows more than twice as much pollutant flux in the stable case as in the neutral case. The shapes of the upper parts of the concentration profiles also suggest that this difference would be greater if measurements had been made to higher elevations. If both profiles are on the plume centreline, there would need to be considerably more horizontal dispersion in the neutral case (against expectations) in order to match the pollutant fluxes in the two cases. This surprising result suggests a lack of consistency between the emissions for the two cases.

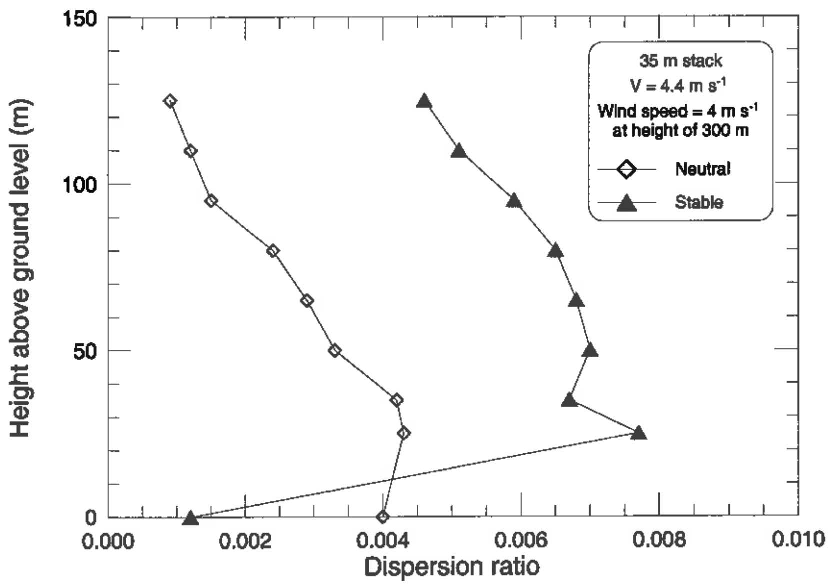

Figure 9. Comparison of vertical concentration profiles for neutral and stable flow conditions at sites 400 m downwind from the stack. The neutral profile was measured NW from the stack, and the stable profile due north of the stack.

We conclude that the physical modelling for neutral flow conditions is close to reality for the modelled conditions. However, the lack of data for wind speeds below 4 m s^{-1} (equivalent to 2.7 m s^{-1} at 10 m above ground level) is a significant limitation of the physical modelling. In particular, it makes it impossible to compare the physical modelling with the mathematical modelling at the wind speeds as low as 1 m s^{-1}, which existed at the times of the highest glcs predicted by the mathematical modelling.

We also conclude that the reliability of the wind tunnel simulation of the very important stable conditions is unclear. This is because the vertical concentration profiles indicated greater vertical transport of the plume in stable conditions than in neutral conditions, which is against expectations of weaker vertical dispersion (transport) in stable conditions.

7. Comparison between physical and numerical modelling

The comparison in the Hyder Reports between the physical and mathematical modelling used to support an assertion that the numerical modelling is conservative by a factor of two or more is based on comparing maximum dispersion ratios at various efflux velocities. However, there is no indication in Table 4.1 of Part 3 of the Hyder Reports of the wind speeds nor stability classes corresponding to the reported ratios for the mathematical modelling.

Furthermore, the minimum wind speed in test series 1–5 of the physical modelling was equivalent to 2.7 m s^{-1} (at 10m above ground level), although Appendix C1 of the Hyder Reports shows that the actual ambient wind speed at Earlwood is below 3 m s^{-1} for 50% of the year, and wind speeds at the times of the highest glcs predicted by the mathematical modelling were often as low as 1 m s^{-1}. (Note that the wind speeds quoted for the physical modelling in the Hyder Report are at 300 m, whereas the mathematical modelling uses wind speeds 10 m above ground level; these are assumed to be a factor of 1.48 smaller). Figure 10 shows that the lack of lower wind speeds undermines the comparison between the maximum dispersion ratios obtained from the physical and mathematical modelling. The values at 2.7 m s^{-1} were taken to be the maximum dispersion ratios, but with all the curves rising at this point, it is most likely that higher dispersion ratios would have been measured at lower wind speeds. While recognising that the wind tunnel may not be able to operate at lower wind speeds, we point out that comparisons between the physical and mathematical modelling are only valid if done for equivalent conditions.

We conclude that with the data provided in the Hyder Reports it is impossible to make a valid comparison between the physical and mathematical modelling. This is in part because of the absence of physical modelling at wind speeds below 2.7 m s^{-1} for neutral conditions, and also because of the problems with the physical modelling of stable conditions. However, if the wind speeds, directions and stability classes corresponding to the maximum dispersion ratios for each efflux velocity (Table 4.1 of Part 3 of the Hyder Reports) were available, it may be possible to make a comparison for conditions for which both physical and mathematical modelling results were obtained. At present it is not possible to appeal to the physical modelling to prove that the numerical model predictions are conservative estimates of real-world conditions with the M5 East stack operating.

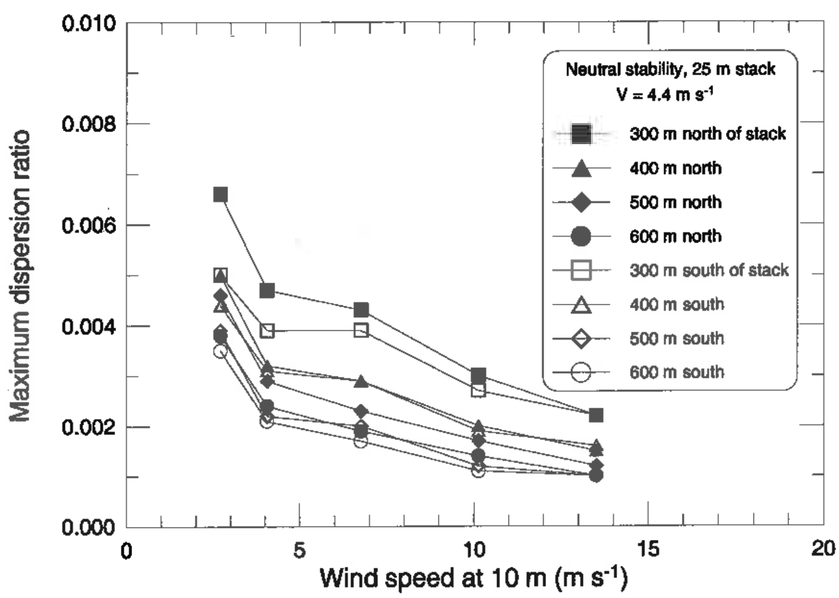

Figure 10. Examples showing the limitation of the maximum dispersion ratios determined from the physical modelling. In each modelled case, the maximum dispersion ratio value was taken to be the value at a wind speed of 2.7 m s^{-1}. However, with all the curves rising at the lowest wind speed, it is most likely that higher dispersion ratios occur at lower wind speeds. (Data from the physical modelling, Figures 18, 20, 22, 24, 50, 52, 54, and 56 of the Hyder Report for 25 m stack.)

8. Stack Height Considerations

8.1 Stack Heights of 25 and 35 m

The effect of changing the stack height on the maximum dispersion ratios is shown in Figure 11 for the physical modelling. The Figure plots the ratio of results from the modelled 35 m stack to the modelled 25 m stack. Increasing the stack height from 25 m to 35 m generally reduces the concentrations by about 50% within 200 m of the stack (the exception 100 m east of the stack is probably due to an unfavourable combination of errors). The locations with slightly larger dispersion ratios (400 m NW and 600 m SW of the stack) correspond to elevated regions, and probably reflect an increase in plume impact. Note that these results are for neutral stability.

From the numerical modelling, if stack height was increased from 25 m to 35 m, maximum ground level concentrations (stack contributions only) would be reduced by a factor of 0.8 (a factor range of 0.74-0.85, based on eight of the top ten maximum NO_2 stack concentrations common to the 25 m and 35 m stack data in the Hyder Reports). This sensitivity is in general agreement with the physical modelling, even though the modelled conditions differ in the ways described above.

We conclude that with the stack exit conditions listed in the main Hyder Reports (2000a, b), the higher stack height (35 m) would be advantageous, especially given that conservative methods of including background NO_2 (hour-by-hour addition is not necessarily conservative), would increase the total NO_2 closer towards the air quality goals.

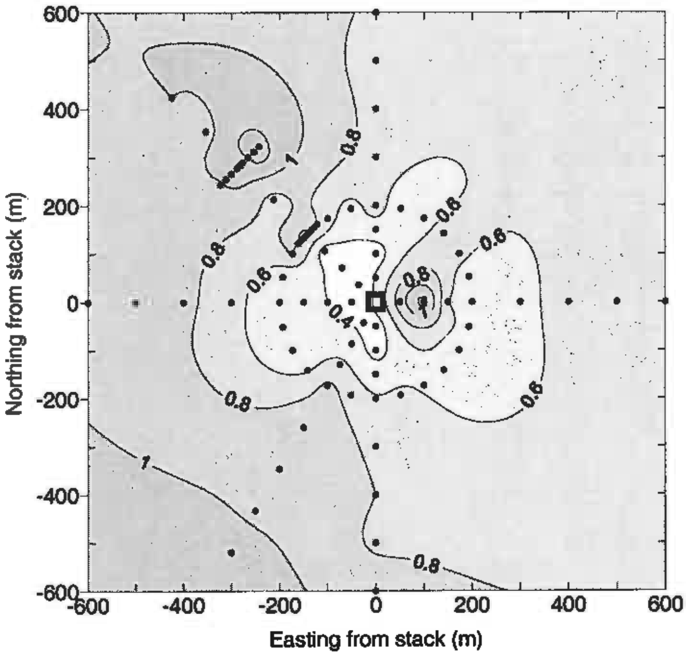

Figure 11. Contour map of the ratio of maximum dispersion ratios for the 35 m and 25 m stacks for neutral flow conditions as determined by the physical modelling.

8.2 Stack Height and Plume Strikes

Given that the highest concentrations are expected to occur as impacts on nearby terrain (approximately 500 m from the stack), and that this terrain is up to 45 m above the physical stack height, it would be advantageous to have an effective plume height (stack height – stack tip downwash + plume rise height increment) that was at least 50 m above the stack base. This could be achieved either by having a physical stack height of 50 m with the current diurnal pattern of stack exit velocities, or by using a combination of physical stack height and a modified diurnal profile of stack exit velocities in order to achieve a minimum plume height of 50 m. This second option is briefly explored below.

If stack exit velocity was increased for hours 21, 22 and 23 (currently 5.4, 4.5, 2.5 m s^{-1} respectively), then ten (nine) of the top ten listed maximum stack concentrations, listed in the Hyder Report for a 25 m (35 m) stack, would decrease due to an increase in the effective plume height (see Figure 12). Note that stack-tip downwash is important when the ratio of the exit velocity to the wind speed at stack height becomes less than a ratio of 1.5, and this is predicted to be having a significant effect on maximum stack concentrations, particularly at hours 21–23.

The effect on maximum NO_2 ground level concentration of increasing stack exit velocity for hours 21 and 23 has been explored in the Hyder report (2000d) on air quality modelling for incident management. It was shown that by increasing the stack exit velocity from 5.4 m s^{-1} to 9.0 m s^{-1}, the ground level concentration due to the 25 m stack for hour 21 on 29/10/95 was decreased from 169.1 to 111.6 $\mu g\ m^{-3}$. When using the conservative maximum monthly background approach, this results in a cumulative concentration of 225 $\mu g\ m^{-3}$. It was also shown that by increasing the stack exit velocity from 2.5 m s^{-1} to 4.5 m s^{-1}, the ground level concentration due to the 25 m stack for hour 23 on 08/10/95 was decreased from 164.1 to 110.5 $\mu g\ m^{-3}$. When using the conservative maximum monthly background approach, this results in a cumulative concentration of 224 $\mu g\ m^{-3}$. These results illustrate that simply by increasing the stack exit velocity for certain night-time hours (e.g. hours 20-23), the air quality goals for NO_2 can be achieved, even for the 25 m stack, and when using a conservative approach to include background NO_2 concentrations.

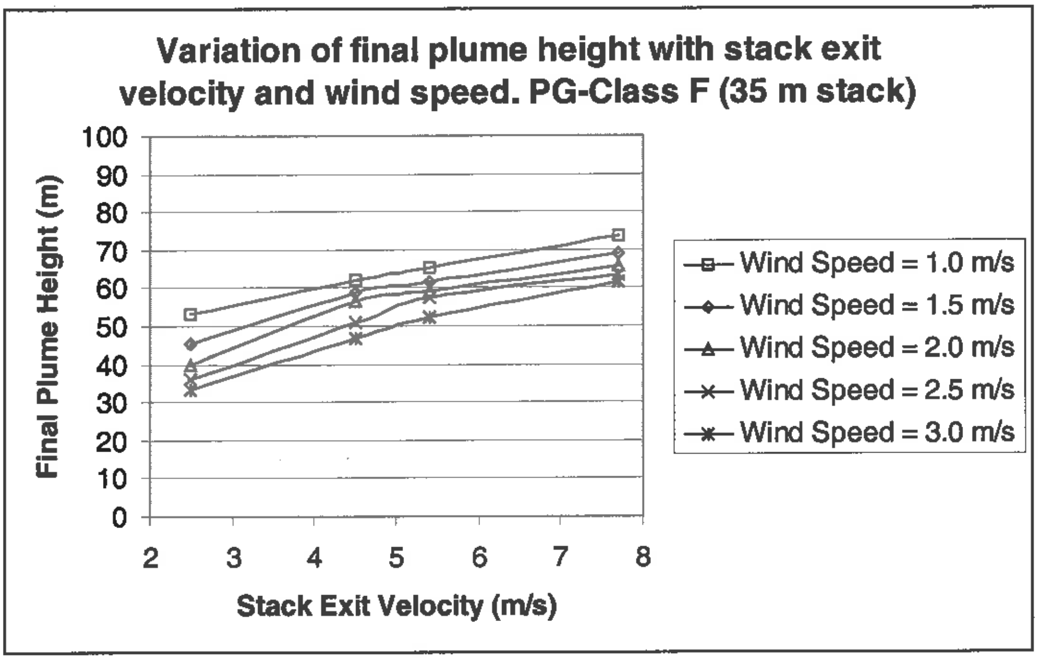

Figure 12. Sensitivity test of final plume height to stack exit velocity for the 35 m stack.

Another factor that determines the effective stack height is thermal buoyancy. In the numerical modelling it was assumption that the exit temperature is 5°C below ambient, ie negative. As indicated in section 2.3, the exit temperature of the ventilation air is likely to be at surrounding rock temperature (~17°C), even allowing for heat release from the vehicle exhausts. For the winter period, at high ventilation flow rates, this could represent a substantial positive buoyancy, and hence higher effective stack height. It is noteworthy that if ventilation flows were enhanced to gain extra momentum rise as discussed above, there would also be extra thermal rise in cold conditions. In summer, the effect will be reversed, but this is much less significant, as highly dispersive convective conditions are likely to be present.

As it is quite possible that another 20 m of plume rise could result from thermal buoyancy, a more detailed assessment of heat transfer within the tunnel and its impact on the effective stack height should be undertaken, particularly if there are strong community or other objections to the higher stack height.

9. Recommendations

Whilst the Hyder Reports have presented a reasonable estimate of the air quality impacts of emissions from the M5 East tunnel, there are some gaps and clarifications that could benefit from some extra modelling work, because of the potential for exceeding air quality goals. These concern:

- a revised procedure for combining background concentrations with the plume footprint to account for variability in background concentrations
- the combined effect of fan speed and thermal buoyancy on effective stack height, and hence glcs
- the use of monitoring datasets for other years to better quantify the potential exceedence of air quality goals. It is acknowledged that these may not be as complete as those used by Hyder, but may widen the representativeness of the assessment.

10. References

Hyder, 2000a. M5 East Motorway driven tunnel services - mainline tunnel air quality (25 m stack). Document # WCR018, revision D. Report by Hyder Consulting.

Hyder, 2000b. M5 East Motorway driven tunnel services - mainline tunnel air quality (35 m stack). Document # WCR020, revision B. Report by Hyder Consulting.

Hyder, 2000c. Draft of results: 1998 Meteorology Assessment by ANE, Ref # 032.7.

Hyder, 2000d. M5 East Motorway Mainline Tunnel – Air quality modelling for incident management plan; Results and recommendations. Ref. # 032, revision 00 (draft). Report by Hyder Consulting.

SAEA, 2000. Response to Request for Comment on Environment Australia's Review of Fuel in Quality Requirements for Australian Transport Study. Society of Automotive Engineers, Australasia — Energy and Environment Committee Chair, Professor Harry Watson

Appendix - Responses to Community Questions

1. To what extent has the background ambient concentration in the tunnel been taken into consideration. For example it appears that a fixed value of $25\mu g/m^{-3}$ is assumed. However on worst days the ambient levels in the tunnel would be much higher. To what extent could this affect the predictions?

The addition of emissions from the vehicle fleet into the tunnel air swamp any background levels sucked into the ventilation air.

2. How much benzene will come out of the exhaust stack per day?

About 2.3 grams

3. What is the source of PM10 in the ambient air? Is it mainly motor vehicle emission related or solid fuel? Is there a different particle size distribution between the different sources and how would this change affected residents with the stack?

The major contributor to high PM_{10} *levels is from burning vegetation, mostly domestic wood fires, but with spasmodic episodes of bush fires either wild or prescribed. These are ingested into the lung in similar fashion to diesel soot.*

4. Concern about the poor correlation between the numerical and physical modelling.

This has been addressed in our review report, and follow-up response to comments.

5. What extent of local air quality improvements are likely as a result of increasing the stack height?

This has been addressed in our report.

6. How valid is the Marulan truck percentage information which formed the basis of the trucks using the tunnel? Would this be a conservative assumption?

This has been addressed in the report.

7. How relevant are the new Californian air quality goals?

This is outside the scope of our review

8. To what extent can air quality impacts be reduced further (even if the goals are met) to minimise impacts to the greatest extent possible?

See answer to question Number 17 below.

9. Would the potential increase in diesel trains on the East Hills line change the background air quality?

Unable to comment

10. If the tunnel is at capacity, is there a major safety issue for motorists in the tunnel? That is, the ventilation design assumes motorists in front of a fire can escape. However if the tunnel is full this is not possible.

This was not an issue addressed by our study, however, we have been informed by the RTA that this aspect is an important part of their tunnel management strategy

11. What proportion of NO_2 is in the stack emissions?

Approximately 10% of total NO_x

12. Concern about the build up of particulate matter in the ventilation shaft particularly if large chunks get dislodged.

If soot, that has built up on surfaces, gets dislodged, it is generally in larger particle sizes, ie greater than 10 microns.

13. Appropriateness of single year background data. Is 1995 a representative year? (I expect this would be covered in detail in your report.)

Yes, this is covered in both the Hyder reports and ours. Recently, modelling for 1998 data has been undertaken and the results reviewed in this report .

14. Should there be an error statement? How would this affect the conclusions?

Placing errors on modelling is difficult, but we have addressed the degree of conservatism of the modelling approach in our report, and we have raised some issues concerning various components of the study, which we understand are currently being addressed by the consultants. If a statement can be made that the modelling is conservative, then this would be adequate to address these concerns.

15. To what extent is particle mass an appropriate surrogate for particle frequency?

Not an easy question to answer. Fine atmospheric particles tend to coagulate and end up with a similar distribution of sizes, so that mass is a fairly good surrogate.

16. How valid is the PIARC data for the M5 East situation?

PIARC is state of the art methodology, any concerns are addressed in the report

17. To what extent can air quality impacts be reduced further even if the goals are met to minimise impacts? That is, the project should not be designed to pollute up to the goals.

Theoretically, a reduction in concentrations could be obtained by increasing the effective plume height (via stack height, stack exit velocity, stack exit temperature), or by reducing emissions. The degree to which some of these measures are explored is up to the regulatory authorities. For pollutants that already have a high background concentration (such as PM10), even zero emissions from the M5 development would still result in concentrations close to the goals due to existing background concentrations.