6.1.9 Breakdown scenario

A semi-quantitative assessment was undertaken to consider a breakdown scenario and the potential emissions associated with such an event. The estimated vehicle emissions within the tunnel were calculated under each scenario for comparison with the results from 'with project – expected traffic flows 2029' scenario (scenario 2b).

The project was designed and would be managed to minimise the potential for prolonged congestion within the tunnels, and specifically includes the following features:

- A tunnel height of 5.3 metres, which is greater than other Sydney tunnels. This would reduce the likelihood of incidents involving over-height vehicles.
- An over-height detection system, which would comprise of an electronic over-height prior to the tunnel portals, vehicle presence detectors, and warning signs with lanterns, which would light up upon detection of an over-height vehicle.
- Provision of two vehicle cross passages, which would allow emergency response vehicles to bypass a congested tunnel.
- Wide shoulders to accommodate breakdowns and provide access by recovery and emergency vehicles.
- Ability for the in-take of air from tunnel support facilities along the alignment to bring in additional fresh air, if required.
- Tunnel barrier gates to prevent access in the event of a tunnel closure.
- CCTV and audible systems to detect and manage incidents.
- Monitoring of vehicle speeds and traffic management infrastructure to reduce or prevent vehicle access to the tunnels if congestion is experienced.

In the event of an incident, approaching traffic would be prevented from entering both the incident main alignment tunnel and the non-incident main alignment tunnel. Traffic flow and speeds would also be monitored, so that in the event that traffic flow starts to fall below 40 kilometres per hour, traffic closure responses would be in place before traffic speeds fall below 20 kilometres per hour.

The assumptions made in the assessment of the breakdown scenario are summarised below:

- The tunnel is completely blocked at one exit.
- The number of vehicles was assumed to be 2,800 PCU, which would represent the indicative number of vehicles that could be accommodated within one tunnel when the average speed drops below 20 kilometres.
- Vehicles would continue to enter the tunnel for a ten minute period, after which the tunnel would be closed to inbound traffic for the affected direction (that is, the northbound or southbound direction), which would prevent more vehicles from entering the tunnel.
- Vehicles within the tunnel would be idling continuously for 55 minutes. It was conservatively assumed that no vehicles would turn off their engines. In reality, the measures described above would prevent the tunnel from becoming full of vehicles, and drivers would be directed to turn off their engines.
- The operation of the ventilation system was assumed to be the same as that occurring during peak traffic flows. The jet fans may be turned on, but the volumetric flow rate of emissions from the tunnel ventilation outlets would remain the same.

Emissions calculations

Vehicle emissions were calculated using country specific factors prepared by the World Road Association (PIARC, 2012), based largely on European vehicle standards, incorporating pre-Euro engine classifications through to new Euro-6 classifications, together with the penetration of hybrid fuel and electric vehicles. These factors are the same as those used in the main modelling assessment.

In order to calculate the predicted emissions from the breakdown scenario, the following parameters and assumptions detailed in **Table 40** were used.

Table 40 Breakdown scenario assumptions

Parameter	Value
Maximum proposed tunnel length	9,000 metres
Maximum traffic flow	1,828 vehicles per hour (2,800 PCU)
Maximum traffic in tunnel during breakdown period (55 minutes)	511 vehicles

Results

Vehicle emissions within the tunnel were calculated based on the worst case breakdown scenario outlined above for the primary vehicle exhaust pollutants of concern (CO, NO_x and PM_{10}). The estimated emissions are detailed in **Table 41**. For comparative purposes, the estimated emissions for the 'with project – expected traffic flows' (northern ventilation outlet in 2029) are also presented (as the highest expected mass emission rates of the scenarios considered in this assessment). The numbers in parentheses represent the breakdown scenario emission rates expressed as a percentage of the 'with project – expected traffic flows' scenario (northern ventilation outlet in 2029).

Table 41 Predicted tunnel emissions under breakdown scenario (grams per second)

Scenario	Emission rates (grams per second)		
	CO	NOx	PM_{10}
Breakdown scenario	3.6 (74 per cent)	4.0 (69 per cent)	0.3 (74 per cent)
With project – forecast traffic flows (northern ventilation outlet, 2029)	4.84	5.81	0.36
N.B. The numbers in parentheses represent the emission rates expressed as a percentage of the calculated worst case emission rates for Scenario 2			

When compared to the 'with project – expected traffic flows' scenario (northern ventilation outlet, 2029), the results in **Table 41** show that, during a breakdown scenario, emissions of carbon monoxide, oxides of nitrogen and PM_{10} are all expected to be lower. Given the similarities between both scenarios, the modelling results for 'with project – expected traffic flows' scenario were considered applicable for the breakdown scenario. The predicted pollutant concentrations of the 'with project – expected traffic flows' scenario were shown to comply with applicable air quality criteria (refer to Error! Reference source not found.). Because the mass emission rates for the breakdown scenario are comparable to, but no greater than, the 'with project – forecast traffic flows' scenario, and the breakdown scenario would occur over a relatively short period, it is expected that the breakdown scenario would also comply with applicable air quality criteria.

6.1.10 Water treatment plant

An operational water treatment plant would be established at the motorway operations complex to treat groundwater inflow into the tunnels. Emissions to air associated with water treatment depend on the nature of the contamination of the water being treated and the treatment process. Primary air emissions associated with water treatment are odorous compounds, such as ammonia and volatile organic compounds, which are associated with aeration (primary treatment), aerobic digestion, sludge thickening, anaerobic digestion and sludge drying (NPI, 2011).

The nature of any odours would depend on the degree and type of any contamination present in the water. A management plan would be developed to address any odours should contamination be encountered and if odours arise. The plan would include identification of odours, identification of the extent to which the odours are detectable, and, if necessary, mitigation measures to reduce any odours affecting receivers. Such mitigation measures could include modifications to the operating process, or the installation of carbon filters to capture odorous compounds before they are emitted.

7.0 Mitigation and management measures

7.1 Construction mitigation and management measures

Construction emissions can generally be well managed through best practice management and mitigation strategies. A hierarchy of emission control is recommended as best practice, where prevention of emissions is the primary goal of management actions, followed by suppression and containment.

The management and mitigation measures described in the following table would be included in the Construction Environmental Management Plan(s) and associated sub plans for the project. As shown, the primary dust generating activities associated with the tunnel excavations (stockpiling and materials handling) would be undertaken within enclosures to minimise dust emissions.

Table 42 Proposed construction air quality management and mitigation measures

Proposed management and mitigation measures
General
Site inductions and ongoing toolbox talks would be provided to make construction workers aware of sound air quality control practices and responsibilities.
Construction activities would be modified, reduced or controlled during high or unfavourable wind conditions if they may potentially increase off-site dust emissions.
Control measures would be implemented to control dust emissions, which could include water carts, sprinklers, sprays and dust screens. The frequency of use would be modified to accommodate prevailing conditions.
Air filtration systems would be installed to filter particulate matter generated by underground works.
Management measures would be developed and implemented though the air quality environmental management plan to mitigate any odour emissions from the groundwater treatment plants or stockpiles, should they arise.
Disturbed areas would be stabilised as soon as practicable to prevent or minimise windblown dust.
Cutting of materials such as concrete slabs or bricks would be undertaken in a manner that minimises the generation of dust where possible, such as wetting of the cutting face.
Controls, such as rumble grids or wheel wash facilities, would be implemented to minimise the tracking of dirt onto public roads.
Hardstand areas and surrounding public roads would be cleaned, as required.
Speed limits would be posted and observed by all construction vehicles on the construction site.
All loaded haulage trucks would be covered at all times on public roads and on site where there is a risk of release of dust or other materials.
Haul trucks and plant equipment would be switched off when not in operation for periods of greater than 15 minutes.
Construction plant, vehicles and machinery would be maintained in good working order and in accordance with manufacturers' specifications.
Monitoring
A formal dust observation program would be implemented during construction, involving daily reviews of weather forecasts, observations of meteorological conditions and on site dust generation. This would inform mitigation measures or alterations to construction activities to be implemented during unfavourable weather conditions (such as dry weather and strong winds).

7.2 Operational mitigation and management measures

The project includes a well-designed ventilation system, including ventilation outlets for the effective and efficient dispersion of emissions. The modelling and assessment presented in this report demonstrated the high efficiency

of the ventilation system, which would achieve contributions to ambient air quality that are well below applicable air quality criteria, even under worst case operational and meteorological conditions.

Further opportunities to improve the performance of the project's ventilation system would be taken into account where reasonable and feasible during the detailed design of the project. This may include further modelling and analysis to confirm that the detailed design of the project would achieve air quality outcomes equivalent to or better than those predicted in this report.

During operation of the project, monitoring of key pollutants would be undertaken at the project's ventilation outlets and in the surrounding environment to confirm that the operation of the project is consistent with this assessment and within acceptable air quality limits. In the event that elevated concentrations of pollutants are detected, further consideration would be given to the application of additional reasonable and feasible mitigation measures.

An operational air quality management plan would also be developed to manage air quality within the project tunnels. This would include strategies for management of ventilation during emergencies.

7.3 Discussion of filtration

Air pollution control technology has been used in a limited number of tunnels in a few countries including Norway, Austria, Germany and Japan, as well as in the M5 East Motorway tunnel trial in Sydney. This technology includes the use of electrostatic precipitators to remove particles and catalytic and biological processes and adsorption technologies to remove nitrogen oxides.

Evidence to date suggests that the effectiveness of such measures is questionable when applied to road tunnels. These technologies are pollutant specific, only address local and not regional transport related air pollution, generate chemical waste and have significant capital and operational costs (NZ Transport Agency, 2013). The French government undertook an international assessment of the air in road tunnels (CETU, 2010), and concluded that filtration systems are:

> *'bulky and less cost-effective than conventional ventilation systems, both in terms of investment and operation. Generally-speaking, these systems are also energy-intensive given the surplus ventilation requirements.'*

There are a large number of factors influencing the decision as to whether a tunnel ventilation outlet should be fitted with mitigation equipment. The relevant factors, which were identified in a previous assessment of the M5 East road tunnel ventilation facility (AMOG, 2012), are:

- Whether unfiltered tunnel exhaust emissions are expected to adversely affect local air quality.
- Whether there are consistently high background pollutant concentrations in the local area, which would result in an increased risk of tunnel emissions affecting the surrounding environment.
- Whether the proposed mitigation equipment is effective.
- Whether the costs involved with the installation and operation of the mitigation equipment are justified given the factors outlined above.
- Whether there are other sources of pollution in the region that would result in a larger relative drop in emissions for a smaller cost.

This consideration of the costs and benefits of filtration was based on analysis of a filtration system similar to that trialled on the M5 East Motorway. That filtration system consisted of a combined electrostatic precipitator and activated carbon filtration device.

7.3.1 Predicted air quality

The emissions from the project were examined as part of this air quality impact assessment. The assessment found that the expected pollutant concentrations resulting from the project are low, with the expected incremental increases of PM_{10} and $PM_{2.5}$ being negligible at surrounding receivers. A small number of elevated pollutant concentrations were predicted for the worst case dispersion conditions over the three years of meteorology considered. For PM_{10} and $PM_{2.5}$, the maximum short term incremental increases (24 hour maximum concentrations) are expected to represent less than eight per cent of the applicable criteria, and less than two per cent of the existing background pollutant concentrations for the annual time period.

NO_2 emissions for the ventilation outlets are expected to be higher than the particulate emissions in terms of relative percentage of the criteria or background. Under normal operational conditions, the 1 hour NO_2 concentrations are expected to represent less than 30 per cent of the criterion under worst case dispersion conditions and less than three per cent of the criterion over a full year of emissions.

Concentrations of other pollutants, such as CO, VOCs and PAHs, are predicted to fall well below their respective criteria, and are not expected to be able to be discernable from existing concentrations.

Based on the findings of this assessment, the low levels of predicted pollutant concentrations do not indicate that further mitigation would be required for the operation of the tunnel. The predicted pollutant concentrations represent careful design of the ventilation system and ventilation outlets to achieve optimum exhaust velocities while minimising the potential for wake-effects on the plume when emitting from the ventilation outlet.

7.3.2 Background air quality

In cases where consistently high background pollutant concentrations are present, small incremental contributions from a project may result in additional exceedences of the EPA's impact assessment criteria. Additional exceedences are generally interpreted as equating to a greater potential for adverse impacts to occur. Such circumstances could support the need for additional mitigation, such as filtration.

Analysis of the background pollutant concentrations recorded at the OEH stations at Lindfield and Prospect and the project monitoring data do not suggest that this is the case. On an individual pollutant perspective the following was shown:

- PM_{10} and $PM_{2.5}$ concentrations from Lindfield and Prospect were found to exceed the ambient criteria nine and four times respectively in 2009, with no exceedences noted in 2010 and 2011. This excluded the 2009 dust storm data as it is an extreme event. The exceedences noted in 2009 were likely to be due to bushfires or unusual short term natural events, and are not considered to be representative of typical pollutant concentrations in the area as the average PM_{10} and $PM_{2.5}$ concentrations were well below the relevant criteria for all three years assessed.
- Monitoring data along the Pennant Hills Road corridor followed a similar trend to the Lindfield and Prospect data, with no exceedences recorded for PM_{10} or $PM_{2.5}$ and the average concentrations falling well below the long term criteria.
- Monitoring stations at Lindfield, Prospect and the project monitoring stations along the Pennant Hills Road corridor all recorded NO_2 values well below the 1 hour ambient criterion of 246 $\mu g/m^3$.
- The Prospect monitoring station and the monitoring stations along the Pennant Hills Road corridor recorded CO values well below the 1 hour ambient criterion of 30,000 $\mu g/m^3$. Peak CO concentrations of 2,602 $\mu g/m^3$ were recorded by the Pennant Hills Road monitoring stations compared to peak values of 3,625 $\mu g/m^3$ recorded at the OEH Prospect monitoring station.

Based on the data analysed for the region in which the ventilation outlets would be located, there is no compelling evidence indicating that the airshed is 'full' and in need of further project mitigation in the form of filtration to be fitted.

7.3.3 Mitigation equipment effectiveness

A study of the M5 East Tunnel filtration trial was undertaken by AMOG Pty Ltd in February 2012. The study found the following:

- Based on the results of three methods to establish the effectiveness of the system in reducing NO_2 emissions:
  - The DeNOx filter removed 55 per cent of the NO_2 from the air being treated. This was a much lower reduction efficiency than expected.
  - The NO_2 within the gas stream being treated was converted to NO and released into the environment. No NO_2 was retained within the filter medium.
  - The $DeNO_X$ filter only processed 14 per cent of the air in the westbound tunnel and, as such, would not have had a large effect on NO_2 levels in the overall tunnel. The authors found that "*Using activated carbon to reduce NO_2 in a tunnel will only slightly reduce total NO_X emissions from the stack*" (AMOG, 2012).
- The capture of particulates was evaluated through the analysis of the performance of the Electrostatic Precipitator (ESP) unit installed in the filtration building. The analysis found:
  - The ESP filter was found to remove approximately 65 per cent of the particulate matter from the tunnel air being treated. This was a much lower reduction efficiency than expected (80 per cent targeted).
  - Investigations into the cause of the lower reduction efficiency found that the ESP was not operating within its operating limits, and that modifications, such as expanding the collector plates or decreasing the air flow rate over the plates, may increase the effectiveness of the system.
- The authors concluded that mitigation equipment was operated for longer periods of time than is typical in other road tunnels and that it did not operate efficiently. The authors recommended that the system should cease operation in its current form and that alternative methods be sought for filtration.

Based on the investigation into the mitigation equipment effectiveness, it was concluded that the equipment is not an effective means by which pollution can be removed from a ventilation outlet. On this basis, given the factors above, the installation of this mitigation equipment is not recommended.

7.3.4 Cost of mitigation

The cost of the mitigation equipment (including retrofitting the equipment) was analysed as part of the AMOG study outlined above (AMOG, 2012). Cost estimates were based around the relative cost for the equipment to remove pollutants; that is, cost per tonne of pollution removed. The various capital and operating costs were calculated for the equipment and contrasted against industry standards for pollution capture. The costs were as follows:

- Cost of NO_2 removal was calculated at:
  - $4,014,000 per tonne if civil construction and machinery costs were amortised over 20 years and operating costs included.
  - $874,000 per tonne if operating costs only were included (civil construction and machinery costs excluded).
- Cost of particulate matter removal was calculated at:
  - $17,393,000 per tonne if civil construction and machinery costs were amortised over 20 years and operating costs included.
  - $3,787,000 per tonne if operating costs only were included (civil construction and machinery costs excluded).

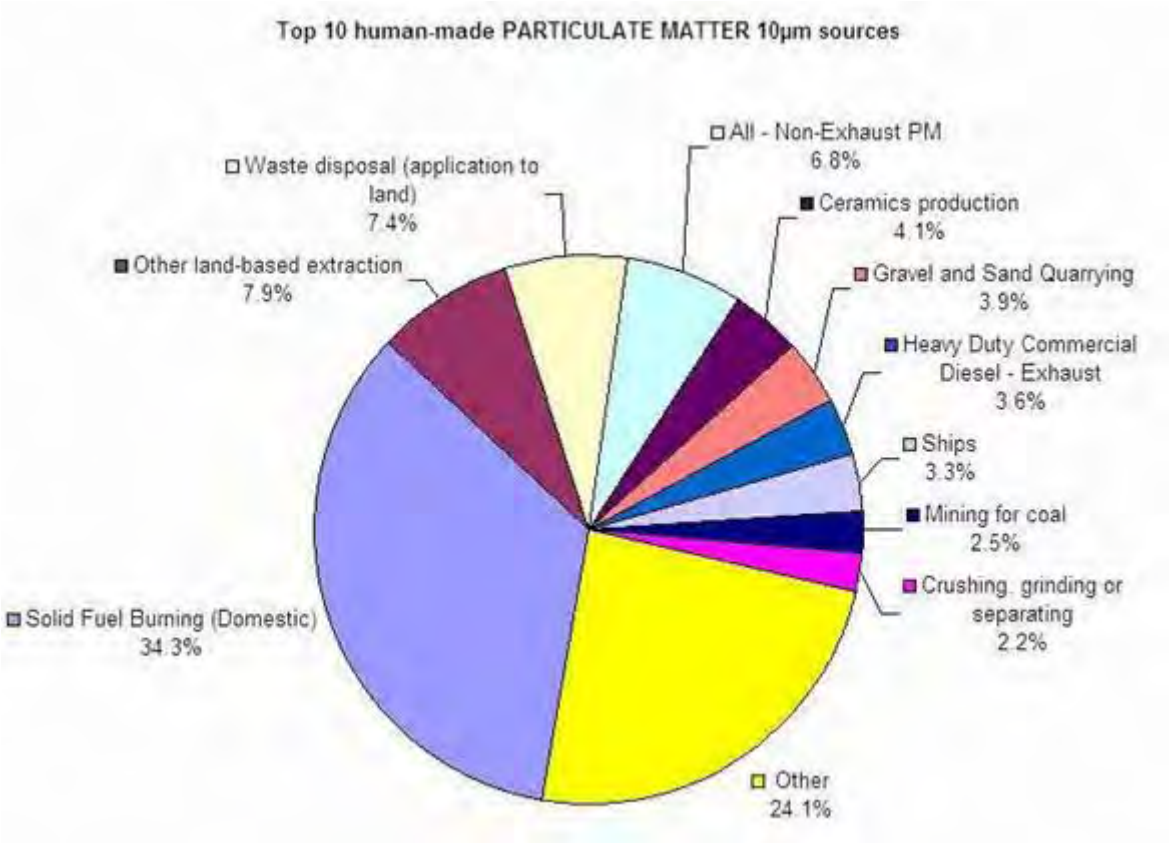
In comparison, the cost of removing particulate pollution using vehicle particulate filters ranges from $150,000 per tonne to $300,000 per tonne. The costs above suggest a high cost for a poorly operating mitigation solution.

7.3.5 Other sources of pollution in the area

In addition to the analysis focusing on the ability of the mitigation equipment to reduce the levels of pollution being emitted into the environment, it is worth considering whether there are other local sources of pollution that could

be mitigated to achieve the same, or better, improvements in air quality for the same or lower costs as filtering the project emissions.

According to the NSW EPA Air Emissions inventory (EPA, 2008), the largest source of PM_{10} pollution in the Greater Metropolitan Region of NSW is domestic solid fuel burning (34.3 per cent of overall PM_{10} emissions). As shown in the following graphic, heavy duty commercial vehicles (which are the major source of particulates emissions for the project) are a relatively minor contributor of particulates to the airshed, with their emissions estimated to represent only 3.6 per cent to particulate emissions in NSW.



Based on these broad data, programs targeting the reduction of emissions from areas such as solid fuel burning would have a far greater effect on reducing the State's PM_{10} emissions than installing mitigation equipment on a source which is contributing only minor levels of pollution to the environment.

In 2010, the then Department of Environment, Climate Change and Water engaged Sinclair Knight Merz (SKM, 2010) to undertake a study to identify and analyse a range of emissions abatement initiatives. In the Sydney region, 12 emissions reduction measures were identified, with associated costs ranging from $1,000 to $274,000 per tonne of PM_{10} removed. The cost of removing PM_{10} using particle filters was $151,000 per tonne. In contrast, two emissions reduction programs (the SmartWay program and shifting transport mode the cycling) were found to have a negative cost; that is, a cost benefit.

Roads and Maritime compared the M5 East Tunnel filtrations system against other pollution mitigation measures in terms of both costs and abatement of $PM_{2.5}$ emissions based on the findings of SKM (2010), who analysed the various costs and effectiveness of various air emission reduction actions, and AMOG (2012), who estimated the costs and effectiveness of the M5 East filtration system. As shown in **Table 43**, the costs of tunnel filtration were well above the costs of mitigating emissions from sources such as wood heaters, off-road vehicles, diesel locomotives and vehicle emission standards. Furthermore, the tunnel filtration removed only a fraction of $PM_{2.5}$ compared to the other measures.

In 2013, the EPA commissioned PAEHolmes to develop a valuation methodology to account for the health impacts associated with changes in particulate matter emissions (PAEHolmes, 2013). This study estimated the health benefit of removing one tonne of $PM_{2.5}$ in Sydney to be $280,000.

Nearly all of the particles removed in the M5 East Motorway trial consisted of $PM_{2.5}$. Based on the above valuation, the M5 East Motorway filtration trial had operational costs of more than ten times the estimated health benefit. All of the measures considered by the SKM (2010) study cost less than one tenth the cost of the M5 East Motorway filtration trial and would remove substantially more particulate matter, delivering a much greater health benefit than tunnel filtration. This is consistent with the conclusions of the National Medical and Health Research Council, which determined that the most effective method to manage air quality in and around tunnels is through vehicle fleet emission reductions (NHMRC, 2008).

Table 43 Comparison of particulate matter reduction measures

Reduction measures	Cost of reduction per tonne	Annual tonnes reduced
SmartWay program[1]	-$54,266,000	5
Two per cent transport mode shift to cycling	-$16,146,000	7
National emissions standards for wood heaters (1 g/kg)	$1,000	1,701
National emissions standards for wood heaters (3 g/kg)	$1,000	45
Emission limits for industry	$5,000	359
Tier 4 emissions standards for off-road vehicles and equipment	$12,000	31
Wood heaters – reduce moisture content of firewood	$20,000	93
Small engines (2 stroke to 4 stroke) recreational boating and lawn mowers	$39,000	261
Truck and bus diesel retrofit	$151,000	1
Diesel locomotive replacement (USEPA Tier 0 to Tier 2)	$156,000	53
Diesel locomotive replacement (USEPA Tier 0 to Tier 2) plus Tier 2 locomotives with selective catalytic reduction)	$191,000	72
Euro 5/6 emission standards for new passenger vehicles	$209,000	131
Recommission and electrify Enfield to Port Botany freight line	$244,000	3
Port Botany shore-side power	$274,000	11
M5 East Motorway tunnel filtration (operating costs only)	$3,800,000	0.2
M5 East Motorway tunnel filtration (total cost)	$17,400,000	0.2
Note: 1 USEPA's SmartWay Transport Partnership is a market-driven partnership aimed at helping businesses move goods in the cleanest most efficient way possible		

As a comparison, Roads and Maritime and the NSW EPA instigated a smoky vehicle strategy on the M5 East Motorway in 2006. This strategy involves the use of smoke detectors, video and still cameras to detect smoky vehicles. Fines and suspensions are issued to encourage vehicles to be repaired or removed from the road network. This strategy has proved to be effective in resulting in improvements to air quality within the M5 East Motorway tunnels, and, therefore, improvements in the quality of air is exhausted from the M5 East Motorway tunnels to the environment.

One measure of in-tunnel air quality is visibility, which is measured as an extinction coefficient. Visibility can be used as a measure of in-tunnel particulate matter using a conversion factor from the PIARC (2012). The PIARC definitions of extinction coefficients (visibility) are as follows:

- 0.003 m^{-1} means a clear air tunnel (visibility of several hundred metres).
- 0.007 m^{-1} approximates a haziness of in-tunnel air.
- 0.009 m^{-1} approximates a foggy atmosphere.
- 0.012 m^{-1} is the threshold value that should not be exceeded during operation and which results in a very uncomfortable in-tunnel atmosphere. At this level, however, visibility is normally sufficient to stop safely at an obstacle.

In 2004, prior to the implementation of the strategy, the extinction coefficient within the M5 East Motorway tunnels exceeded 0.004 m^{-1} in the most months. Contemporary data (from April 2013 to April 2014) show that the M5 East Motorway now operates with an extinction coefficient of less than 0.003 m^{-1} (that is, a clear air tunnel) for the majority of the time. The NorthConnex project would include smoky vehicle regulatory measures similar to those used for the M5 East Motorway. Further details on the improvement in air quality in the M5 East Motorway tunnels since the implementation of the smoky vehicle strategy and the NorthConnex strategy in relation to smoky vehicles are provided in **Section 7.3.4** of the EIS.

7.3.6 Summary

The pollutant concentrations predicted by the dispersion modelling do not indicate that tunnel filtration is warranted or that it would provide any benefit to the surrounding community. The ventilation outlets were designed to ensure little, if any, increase in exposure to vehicle emissions at receiver locations. Even if filtration was 100 per cent effective, if would be expected to deliver negligible benefits to the environment in terms of air quality. Greater improvements in air quality could be achieved through investment in programs targeting other emission sources that contribute higher levels of pollution to the surrounding environment.

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8.0 Conclusion

Roads and Maritime Services is seeking approval to construct and operate a tolled motorway linking the M1 Pacific Motorway at Wahroonga to the Hills M2 Motorway at the Pennant Hills Road interchange at Carlingford. The project would include twin tunnels approximately nine kilometres in length, which would generally follow the alignment of the existing Pennant Hills Road. The purpose of the project is to reduce congestion on Pennant Hills Road, particularly heavy vehicle traffic. This technical working paper assessed the potential effects on air quality associated with the construction and operation of the project.

The qualitative assessment of the effects of the construction works on local air quality determined that standard management measures would be sufficient to mitigate the effects of these works on local air quality and receivers.

A quantitative assessment of the operational stage of the project was undertaken using the CALPUFF suite of models, and was coupled with estimations of emissions along the surface roads from the CAL3QHCR model. The results of the dispersion modelling determined that concentrations of nitrogen dioxide, carbon monoxide, volatile organic compounds and PAHs would all be well below the applicable impact assessment criteria. While exceedences of the criteria for PM_{10} and $PM_{2.5}$ were predicted to occur, these were attributable to elevated background concentrations of these pollutants, with the project contributing only minor levels of particulates to the airshed. The estimated annual TSP concentrations, using the annual PM_{10} concentrations as a surrogate, were also determined to be well below the assessment criteria. As such, the project is considered unlikely to adversely affect local or regional air quality.

An assessment of changes to the air quality environment was also undertaken along the project corridor, which took into account the changes in traffic flows along Pennant Hills Road as a result of the project, and the improved dispersion of emissions from diverted traffic through ventilation outlets. This found that:

- In the case of both 24-hour average and annual average $PM_{2.5}$ concentrations, the project's ventilation outlets would effectively disperse emissions to very low levels in the surrounding environment. The peak contributions from the project would be around five to 10 per cent (24-hour average) and one to five per cent (annual average) of the advisory reporting standards for $PM_{2.5}$. Both of these percentages are well within the normal variability in background $PM_{2.5}$ concentrations.
- Substantial reductions in 24-hour average and annual average $PM_{2.5}$ concentrations were predicted to occur along the Pennant Hills Road corridor as a result of the project. Receivers along the road corridor were predicted to benefit from improvements in $PM_{2.5}$ concentrations (24-hour average) of around five to 20 per cent in as a result of the project. For annual average $PM_{2.5}$ concentrations, receivers along the road corridor are expected to benefit from improvements in $PM_{2.5}$ concentrations (annual average) of around five to 35 per cent in as a result of the project.

As such, the project is expected to result in a net improvement in air quality, taking into account substantial improvements in air quality along the Pennant Hills Road corridor balanced with less extensive, very low levels of increases in $PM_{2.5}$ concentrations around the northern and southern ventilation outlets.

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9.0 References

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Appendix A

Construction activities

Appendix A Construction activities

Construction works would include the excavation of the road tunnels and access tunnels, road widening works, demolition works, road and bridge construction, material storage and handling and wastewater treatment (groundwater). Around 2.6 million cubic metres of surplus spoil would be generated from the project, primarily from the tunnel excavations. Most of this material would be uncontaminated crushed sandstone and shale material classified as virgin excavated natural material (VENM), which can be reused or disposed of at disposal sites. Some materials excavated from construction sites may be contaminated; such contamination would be identified through soil sampling, and contaminated material would be disposed of at a licensed waste facility.

Construction emissions for large road projects are difficult to quantify due to the number of construction sites, the distribution of sites across a large geographical area, and the transitory nature of many individual construction activities at particular locations. Construction emissions can generally be well managed through best practice management and mitigation strategies. As such, the excavation and construction works were assessed qualitatively by describing the nature of the proposed work, the proposed plant and equipment, the potential emission sources and their potential emission levels. Proactive and reactive mitigation measures were then identified to reduce the likelihood of the works adversely affecting local air quality and receivers.

A description of the works is provided below.

High level construction activities associated with potential emissions to air

Component	Typical activities
Hills M2 Motorway integration works	- Establishment of work areas. - Earthworks associated the formation of the finished design levels for the additional lane, cuttings and embankments. - Bridge construction works, including piling. - General civil works. - Spoil handling and management, estimated at around 39,800m^3 of spoil. - Paving. - Exhaust emissions from the operation of construction vehicles and plant. - Surface site rehabilitation and restoration.
Windsor Road compound (C1), Darling Mills Creek compound (C2), Barclay Road compound (C3) and Yale Close compound (C4)	- Establishment of work sites. - Exhaust emissions from the operation of construction vehicles and plant. - Surface site rehabilitation and restoration.
Southern interchange and southern interchange compound (C5)	- Establishment of work areas, including vegetation removal and building demolition. - Earthworks associated with the formation of finished design levels, cuttings, cut-and-cover sections (including tunnel structures), and the excavation of decline ramps, main alignment tunnels, and shafts. - General civil works, including retaining walls. - Removal, storage and transport of around 613,900m^3 of spoil from construction activities. - Paving. - Exhaust emissions from the operation of construction vehicles and plant. - Construction of permanent operational ancillary facilities. - Surface site rehabilitation and restoration.

Component	Typical activities
Wilson Road compound (C6)	- Establishment of work site, including building demolition and vegetation clearance. - Earthworks associated with the formation of the finished design levels for the site and the excavation of the decline to the main alignment tunnels. - Removal, storage and transport of around 441,950m^3 of spoil from tunnelling activities. - Exhaust emissions from the operation of construction vehicles and plant. - Decommissioning and removal of construction-related buildings and plant. - Construction of permanent operational ancillary facilities. - Surface site rehabilitation and restoration.
Trelawney Street compound (C7)	- Establishment of work site, including building demolition and vegetation clearance. - Earthworks associated with the formation of the finished design levels for the site and the excavation of the decline to the main alignment tunnels. - Removal, storage and transport of around 492,200m^3 of spoil from tunnelling activities. - Exhaust emissions from the operation of construction vehicles and plant. - Decommissioning and removal of construction-related buildings and plant. - Construction of permanent operational ancillary facilities. - Surface site rehabilitation and restoration.
Pioneer Avenue compound (C8)	- Establishment of work site, including building demolition. - Construction of temporary structures, and paving for car parking areas. - Decommissioning and removal of construction-related buildings. - Surface site rehabilitation and restoration. - Exhaust emissions from the vehicles.
Northern interchange, the northern interchange compound (C9), Bareena Avenue compound (C10) and Junction Road compound (C11).	- Establishment of work areas, including vegetation removal and building demolition. - Earthworks associated with the formation of the finished design levels for the interchange, cuttings, cut-and-cover sections (including tunnel structures), and the excavation of on-ramps and off-ramps, shafts and the main alignment tunnels, - Removal, storage and transport of around 1,024,350m^3 of spoil from construction activities from the northern interchange compound. - General civil works. - Paving. - Exhaust emissions from the operation of construction vehicles and plant. - Decommissioning and removal of construction-related buildings and plant. - Construction of permanent operational ancillary facilities at the Bareena Avenue compound. - Surface site rehabilitation and restoration.

Tunnel excavation

The project would involve the excavation of two tunnels around nine kilometres in length for the main alignment and additional tunnels for on and off-ramps at both the northern and southern interchanges. Tunnel depth along the corridor would vary depending on geological constraints, with a maximum depth of around 90 metres below ground level, with shallower sections approaching the northern and southern portals. The tunnels would be around 14 metres in width.

It is anticipated that tunnel excavation would be undertaken using a number of road headers and surface miners, supported from multiple sites. A road header is an excavation machine consisting of a boom-mounted rotating cutter head mounted on bulldozer-style tracks, a loader device usually on a conveyor, and a crawler travelling track to move the machine forward into the rock face. A surface miner is a mechanically driven excavation machine capable of cutting, crushing and loading in one continuous process.

The mainline tunnels would be constructed using a heading and bench excavation method. The top heading would be excavated by a road header and the bench would be excavated by a surface miner operating behind the main face excavation. Localised blasting works may be carried out underground depending of the geological conditions encountered. Following tunnel excavation, ground support would be installed by way of tunnel lining.

Each of the tunnelling sites would require support services for the tunnelling activity including power supply, ventilation, water supply, construction water treatment plants, workforce facilities and spoil handling and removal.

In addition to the main alignment and on and off-ramp tunnels, pedestrian cross passages would be excavated between the main alignment tunnels at 120 metre intervals and vehicle cross passages would be excavated around the Wilson Road and Trelawney Street sites. These cross passages would be excavated using small road headers, excavators with rock hammer, drilling and blasting.

Construction program

Construction of the project is planned to begin in early 2015, with completion of construction in the fourth quarter of 2018. The total period of construction works is expected to be around four years. The indicative construction program is shown below.

Indicative construction program

Construction activity	Indicative construction timeframe																							
	2014				2015				2016				2017				2018				2019			
Site establishment					■	■	■	■	■	■														
Shaft excavations							■	■	■	■	■	■	■	■	■									
Tunnelling							■	■	■	■	■	■	■	■	■	■	■							
Tunnel lining											■	■	■	■	■	■	■	■						
Concrete pavement													■	■	■	■	■	■	■					
Tunnel mechanical and electrical fit-out												■	■	■	■	■	■	■	■	■	■			
Southern portal					■	■	■																	
Hills M2 Motorway integration works								■	■	■	■	■	■	■	■									
Northern portal								■	■	■	■	■	■	■	■	■	■	■						
M1 Pacific Motorway tie-in works								■	■	■	■	■	■	■	■	■	■	■	■					
Wilson Road tunnel support facility													■	■	■	■	■	■	■	■	■			
Trelawney Street tunnel support facility													■	■	■	■	■	■	■	■	■			
Southern ventilation facility												■	■	■	■	■	■	■	■	■				
Northern ventilation facility														■	■	■	■	■	■	■	■			
Motorway control centre												■	■	■	■	■	■	■						
Commissioning																					■	■	■	

Plant and equipment

Plant and equipment expected to be used during the construction the project include standard construction equipment, such as gantry cranes, fans, excavators, compressors, loaders, road sweepers, water carts, pumps, excavators, concrete agitators and dump trucks. The following table provides a list of plant and equipment likely to be used during construction of the project.

Indicative construction plant and equipment

Plant / equipment	Hills M2 Motorway integration	Southern interchange compound (C5)	Wilson Road compound (C6)	Trelawney Street compound (C7)	Northern interchange compound (C9)	Bareena Avenue compound (C10)
Surface						
100 tonne / 10 tonne gantry crane			✓	✓	✓	
160 kilowatt fan		✓(4)	✓(4)	✓(4)	✓(4)	
20 tonne excavator		✓	✓	✓		✓
24 tonne excavator		✓(2)	✓	✓	✓	
30 tonne excavator	✓(6)	✓	✓	✓		✓
Backhoe	✓(6)	✓	✓	✓		
Bobcat		✓	✓	✓		
80 tonne piling rig	✓(3)	✓	✓	✓		✓
Dozer	✓(6)					✓
Dump truck						✓(4)
25 tonne mobile crane		✓	✓	✓		✓
50 tonne mobile crane	✓(6)	✓	✓	✓		✓
100 tonne mobile crane		✓	✓	✓		✓
Hiab truck		✓	✓	✓		✓
10 tonne smooth drum vibrating roller	✓(6)	✓	✓	✓		✓
Compactor						✓
Grader	✓(6)					
Concrete saw / cutter	✓(4)					
Rock saw	✓(4)					
Hydraulic hammer / rock breaker	✓(6)					
Jackhammer	✓(6)					
Rock crusher	✓(6)					
Asphalt laying machine	✓(2)					
Truck	✓(10)					
Line marking machine	✓(2)					
Paving machine	✓(2)					
30 tonne gantry crane			✓	✓	✓	
60 kilowatt fan		✓				
Air compressor		✓(2)	✓(2)	✓(2)	✓(2)	
Bucket loader		✓(2)	✓	✓	✓	✓
100 tonne crawler crane		✓(2)	✓	✓	✓	
Grout plant / paddle mixer		✓(2)	✓	✓	✓	
Jumbo drill (shaft)		✓(2)	✓	✓	✓	
Road sweeper truck		✓	✓	✓	✓	✓
Skid steer loader		✓	✓	✓	✓	✓

Submersible pump		✓(8)	✓(6)	✓(6)	✓(6)	✓
Sump pump		✓(3)	✓(2)	✓(2)	✓(2)	✓(3)
Water cart	✓(2)	✓	✓	✓	✓	✓
Water treatment plant		✓	✓	✓	✓	
100 kilovolt ampere generator	✓(4)	✓	✓	✓		✓
Underground						
12 tonne mini excavator with hammer		✓	✓	✓	✓	
24 tonne excavator		✓	✓	✓	✓	
24 tonne excavator with diamond cutting tool		✓(2)	✓	✓	✓	
Booster pumps		✓	✓	✓	✓	
Bucket loader		✓(3)	✓(3)	✓(3)	✓(3)	
Colloidal grout mixer		✓	✓	✓	✓	
Concrete agitator		✓(4)	✓(4)	✓(4)	✓(4)	
Deduster (dry type) and fan		✓(4)	✓(5)	✓(5)	✓(5)	
25 tonne articulated dump truck		✓(7)	✓(6)	✓(6)	✓(6)	
Gate end box		✓(4)	✓(4)	✓(4)	✓(4)	
200 kilowatt roadheader (for cross passages)			✓	✓	✓	
300 kilowatt roadheader		✓(4)	✓(4)	✓(4)	✓(4)	
Rockbolting rig		✓(3)	✓(3)	✓(3)	✓(3)	
Shotcrete robot		✓(3)	✓(3)	✓(3)	✓(3)	
Skid steer loader			✓	✓	✓	
Water cart					✓	

Spoil and waste disposal

Based on the current project design, the project would generate around 2.6 million cubic metres of spoil. The spoil generated by the road headers would predominantly be transported to the extraction shaft sites via trucks within the tunnels. Where the excavation occurs close to the extraction points, the material would be transferred directly from the road headers. Smaller quantities of excavated spoil would remain in the tunnels.

The majority of stockpiling of spoil would occur within acoustic (noise-reducing) sheds. Front end loaders or excavators would be used to load the stockpiled materials onto haulage trucks (truck and dog trucks with around 30 tonne capacity) for transport off site. The stockpile would be approximately 2,400 cubic metres in size, representing between one and two days' excavation volumes.

Other waste streams which would be generated during construction of the project include:

- Demolition waste from existing structures and properties.
- Contaminated soil, which may be encountered during construction.
- General construction waste such as concrete, steel and timber formwork off-cuts.
- Vegetation waste from clearing.
- Plant and vehicle maintenance waste such as oils and lubricants.
- General office waste such as paper, cardboard, plastics and food waste.
- Sewage waste.

Spoil generation and disposal would occur throughout the majority of the four year construction period. A number of potential sites were identified for the disposal of spoil generated by the project. The final disposal location(s) would be determined during detailed design.

Construction vehicles

Construction vehicles required for the works are summarised in the following table. The numbers provided represent those required for the excavation phase, as they represent the highest vehicle numbers of all the working phases (vehicle numbers associated with the fit out phases are expected to be substantially lower than the excavation phase vehicle numbers).

Construction vehicle numbers

Site	Daily heavy vehicles*	Daily light vehicles*
Windsor Road compound (C1)	20	85
Darling Mills compound (C2)	50	20
Barclay Road compound (C3)	50	52
Yale Close compound (C4)	50	20
Southern interchange	740	165
Wilson Road compound	600	100
Trelawney Street compound	570	100
Pioneer Avenue compound	12	650
Northern interchange	720	100
Bareena Avenue compound	20	25
Junction Road compound	1	100

Emission sources

The proposed construction works may generate air pollutant emissions through earthworks; material stockpiling, handling and transport; demolition works; combustion emissions from plant and equipment; and wind erosion of exposed areas. Particulate emissions generated by underground works, including vehicle and blasting emissions, would be captured and filtered to an acceptable standard before being emitted through the ventilation systems. As the underground emissions would be controlled, surface works are considered to be the most important source of emissions associated with the construction works.

Equipment associated with excavating, handling or moving material -- such as road headers, excavators, jack hammers and piling rigs -- generate particulate emissions. Particulates are also emitted from exposed, unvegetated areas and uncovered stockpiles through wind erosion. Diesel and petroleum-powered plant and equipment are sources of pollutants such as particulates (PM_{10} and $PM_{2.5}$), nitrogen dioxide, carbon dioxide and VOCs through their exhaust (combustion) emissions. Electrically-powered plant and equipment do not generate combustion emissions.

The most substantial particulate emissions potentially generated by the construction works are those associated by surface earthworks, material stockpiles, wind erosion and wheel-generated dust from vehicles on unsealed roads. Off-road plant and equipment can generate substantial emissions of oxides of nitrogen and lesser amounts of carbon monoxide, particulates and VOCs. Passenger vehicles are also a source of these emissions. All emissions are expected to be confined to the local area surrounding the emission points, with no lasting effects on local air quality.

Motor vehicles and plant

The main sources of emissions from heavy vehicles, mobile excavation machinery and stationary combustion plants would be related to diesel combustion. Construction plant would generally be diesel-powered and would emit gaseous and particulate matter into the air. Road headers would be driven by mains power supply and would therefore not contribute the exhaust emissions.

Most of the emissions generated by combustion engines are emitted from the exhaust (NPI, 2008). Emissions from combustion engines are affected by the engine power, fuel consumption and distance travelled or operating hours.

The NPI (2008) provides emission factors for road transport vehicles (that is, cars, light and heavy goods vehicles and buses used on either sealed roads or on well-formed unsealed roads) and industrial (off-road) vehicles, such as heavy earth moving and construction equipment and a range of miscellaneous vehicles such as forklifts. According to these factors, diesel light goods vehicles emit the greatest amount of PM_{10} of all road vehicles on a volume-of-fuel-used basis; buses emit the greatest level of NO_X; petrol LGVs emit the greatest level of total

VOCs; and petrol cars have the highest emissions of benzene and 1,3-butadiene. Within each vehicle category, emissions of PM_{10} and $PM_{2.5}$ are very similar.

Wheeled tractors powered by diesel emit the highest level of particulates per kilowatt hour; forklifts have the highest emissions of carbon monoxide and VOCs; and diesel rollers have the highest emissions of oxides of nitrogen.

All plant and equipment used during construction would comply with the emissions concentration limits outlined in the *Protection of the Environment Operations (Clean Air) Regulation 2010*. As such, vehicular and plant emissions arising from the civil construction works are not likely to have a substantial effect on the surrounding air quality.

Emissions are minimised through switching engines off when not in use, maintaining vehicles in accordance with manufacturers' specifications, using fuel efficient vehicles and limiting the number of trips.

Earth moving, excavation and demolition

The operations commonly found in earth moving, excavation and demolition activities include:

- Worksite establishment activities such as vegetation clearing and earthworks.
- Demolition of buildings, structures and road pavement.
- General earthworks.
- Exposure of surfaces, which may be susceptible to wind erosion.
- Handling and stockpiling of spoil material.
- Vehicle movements on unsealed roads, resulting in wheel generated dust.
- Drilling and blasting.
- Tunnelling activities and tunnel ventilation during construction.
- Materials storage and handling.

Any operations that move or manipulate dusty material can be a source of particulate emissions. The NPI manual for fugitive emissions (NPI, 2012b) indicates that emission factors developed for mining are applicable to earth moving, excavation and demolition works associated with demolition and debris removal, site preparatory works and general material handling activities.

Katestone (2011) prepared a best practice guide for the management of mining emissions, which was based on the results of environmental audits conducted for coal mines within the Greater Metropolitan Region. The different mining activities were ranked according to their emission levels of TSP, PM_{10} and $PM_{2.5}$. The highest levels of particulates were generated from vehicle movements on unpaved roads and wind erosion of material stockpiles; these activities are similar to those associated with the proposed excavation works. As such, these activities would be expected to be primary potential emission sources for the proposed construction works.

The NPI specifies control efficiencies for various management and mitigation measures. As shown in the following table, the most effective mitigation strategy for wheel-generated dust is the sealing of roads, followed by watering at a rate of greater than two litres per square metre per hour. For wind erosion of stockpiles, total enclosure is considered to reduce 99 per cent of emissions. For this project, the majority of haul truck travel would be undertaken on sealed roads, and the stockpiles of material excavated from the tunnels would be stored within acoustic sheds in the majority of case. These actions would substantially mitigate emissions associated with the construction works.

Estimated control factors for various mining operations (NPI, 2012c)

Operation / Activity	Control method and emission reduction
Scrapers on topsoil	50 % control when soil is naturally or artificially moist
Dozers	No control
Drilling	99 % for fabric filters 70 % for water sprays
Blasting coal or overburden	No control
Loading trucks	No control
Hauling	50 % for level 1 watering (2 litres/m^2/h) 75 % for level 2 watering (> 2 litres/m^2/h) 100 % for sealed or salt-encrusted roads
Unloading trucks	70 % for water sprays
Loading stockpiles	50 % for water sprays 25 % for variable height stacker 75 % for telescopic chute with water sprays 99 % for total enclosure
Unloading from stockpiles	50 % for water sprays (unless underground recovery, where no controls are needed)
Wind erosion from stockpiles	50 % for water sprays 30 % for wind breaks 99 % for total enclosure 30 % for primary earthworks (reshaping/profiling, drainage structures installed) 30 % for rock armour and/or topsoil applied
Miscellaneous transfer and conveying	90 % control allowed for water sprays with chemicals 70 % for enclosure 99 % for enclosure and use of fabric filters
Wind erosion	30 % for primary rehabilitation 40 % for vegetation established but not demonstrated to be self-sustaining. Weed control and grazing control. 60 % for secondary rehabilitation 90 % for revegetation 100 % for fully rehabilitated (release) vegetation

It should be noted that the effects of control measures are multiplicative, so the implementation of a number of control measures increases the overall emission reductions.

There are a number of receivers located in the vicinity of the construction sites, which have the potential to be affected by dust emissions from above-ground works. The potential for dust emissions from above-ground construction works would be managed through standard mitigation measures identified in **Section 5.2**, such as water spraying of unsealed areas, wetting down of dust activities and progressive stabilisation works.

The underground tunnels would be required to be ventilated during construction in order to provide a safe working environment for the construction workforce. Tunnel ventilation would be provided at the four tunnel support sites, which are:

- The southern interchange compound (C5).
- The Wilson Road compound (C6).
- The Trelawney Street compound (C7).
- The northern interchange compound (C9).

This ventilation equipment would have dust extraction and filtration systems installed to minimise dust emissions. Additionally, as the road headers would require water for dust suppression while cutting rock, dust generation from tunnelling activities is expected to be minimal.

The primary pollutants emitted from the detonation of explosives used for blasting are carbon monoxide, hydrogen sulfide, sulfur dioxide, oxides of nitrogen and ammonia (NPI, 2012a). In addition to the emissions associated with the fuel detonation, particulates are also emitted.

As blasting would be undertaken on an intermittent basis and underground, the pollution emissions associated with these activities would be expected to be of short duration. Underground particulate blasting emissions would be captured by the tunnel filtration systems. As blasting works would only be carried out underground, the potential for dust impacts from this activity is negligible.

Water treatment

Water treatment plants are proposed for the southern interchange, Wilson Street compound, Trelawney Street compound and the northern interchange to treat groundwater extracted from the workings. Emissions to air associated with water treatment depend on the nature of the contamination of the water being treated and the treatment process. Primary air emissions associated with water treatment are odorous compounds, such as ammonia and VOCs, which are associated with aeration (primary treatment), aerobic digestion, sludge thickening, anaerobic digestion and sludge drying (NPI, 2011).

The nature of any odours would depend on the degree and type of any contamination present in the groundwater. As this is not currently known, a reactive management plan should be developed to address any odours if they arise. The plan should include identification of odours, identification of the extent to which the odours are detectable, and, if necessary, mitigation measures to reduce any odours affecting receivers if they arise. Such mitigation measures could include modifications to the operating process, or the installation of carbon filters to capture odorous compounds before they are emitted. The water treatment plants should be located as far from receivers as can feasibly be achieved.

Appendix B

Pollutant descriptions

Appendix B Pollutant descriptions

Particulate matter – PM_{10}, $PM_{2.5}$ and TSP

Airborne particles are commonly differentiated according to size based on their equivalent aerodynamic diameter. Particles with a diameter of less than or equal to 50 micrometres (μm) are collectively referred to as total suspended particulates (TSP). TSP primarily cause aesthetic impacts associated with coarse particles settling on surfaces, which also causes soiling and discolouration. These large particles can, however, cause some irritation of mucosal membranes; they pose a greater risk to health when ingested if they are contaminated. Particles with diameters less than or equal to 10 μm (known as PM_{10}) are primarily created through crushing and grinding of rocks and soil, and typically comprise soot, dirt, mould and pollen. These particles tend to remain suspended in the air for longer periods than larger particles (minutes or hours), and can penetrate into human lungs. Fine particulates (those with diameters less than or equal to 2.5 μm, known as $PM_{2.5}$) are typically generated from vehicle exhaust, bushfires and some industrial activities, and can remain suspended in the air for days or weeks. As these fine particulates can travel further into human lungs than the larger particulates and are often made up of heavy metals and carcinogens, fine particulates are considered to pose a greater risk to health.

Exposure to particulate matter has been linked to a variety of adverse health effects, such as respiratory problems (for example coughing, aggravated asthma, chronic bronchitis), lung damage and non-fatal heart attacks. Furthermore, if the particles contain toxic materials (such as lead, cadmium, zinc) or live organisms (such as bacteria or fungi), toxic effects or infection can occur from inhalation of the dust.

Particulate Matter – PM_1

There are a large number of studies establishing links between concentration of ambient aerosols level of air pollution and adverse health and environmental effects. While PM_{10} and $PM_{2.5}$ measures provide very important steps toward air quality assessment, it is also apparent that more accurate descriptors of the actual atmosphere are still needed. There is a growing consensus that PM_1 would be a more suitable size than $PM_{2.5}$ to assess health impacts; there is, however, a limited amount of data for the sub-micrometre ambient particle fraction available. Very little data currently exist relating to ambient PM_1 concentrations, and existing PM_1 data sets are restricted to measurements of limited time periods from field campaigns, and little information exists regarding the chemical compositions of these particles.

Small particles around 1 μm in size are affected by relative humidity, wind speed and traffic. Knowledge regarding this fraction of particulate matter includes the following points:

- Particles in 1 μm range are equally spread throughout air layer, and evenly spread regionally, meaning that fine particles in this size range are transported globally.
- Increasing humidity causes these particles to grow in size to the $PM_{2.5}$ due to hygroscopic growth; similarly, evaporation can cause particles to reduce in size again.
- As wind speed increases, dispersion of PM_1 is increased.
- As traffic increases, fine particles increase.

A study conducted in Austria (Gomiscek et al., 2004) determined that PM_1 counted for about 50 – 60 percent and $PM_{2.5}$ accounted for about 70 percent of all PM_{10}.

As no monitoring of PM_1 is currently conducted in Sydney, and no criteria for this fraction exist, PM_1 was not modelled in this assessment.

Carbon monoxide

Carbon monoxide (CO) is a colourless, odourless gas produced by the incomplete combustion of fuels containing carbon (for example, oil, gas, coal and wood). CO is absorbed through the lungs, where it reacts to reduce the blood's oxygen-carrying capacity. In urban areas, motor vehicles account for up to 90 per cent of all CO emissions.

Nitrogen dioxide

Nitrogen dioxide (NO_2) is a brownish gas with a pungent odour. It exists in the atmosphere in equilibrium with nitric oxide. The mixture of these two gases is commonly referred to as oxides of nitrogen (NO_x). As NO_x is a product of combustion processes, motor vehicles and industrial combustion processes are the major sources of ambient NO_x in urban areas. NO_2 can cause damage to the human respiratory tract, increasing a person's

susceptibility to respiratory infections and asthma. NO_2 can also cause damage to plants, especially in the presence of other pollutants such as ozone and sulfur dioxide. NO_x are primary ingredients in the reactions that lead to photochemical smog formation.

Volatile organic compounds

Organic compounds with a vapour pressure at 20 °C exceeding 0.13 kPa are referred to as volatile organic compounds (VOCs). VOCs were implicated as a major precursor in the production of photochemical smog, which causes atmospheric haze, eye irritation and respiratory problems. VOCs are emitted from vehicle exhausts.

Three primary VOCs (benzene, toluene and xylenes) are components of petroleum and diesel fuel and are typically the focus for assessments of engine combustion emissions.

Benzene

Benzene is an airborne substance that is a precursor to photochemical smog. Benzene exposure commonly occurs through inhalation of air containing the substance. It can also enter the body through the skin, although it is poorly absorbed this way. Low levels of benzene exposure result from car exhaust.

Benzene is considered to be a toxic health hazard and a carcinogen. It has high acute toxic effects on aquatic life and long-term effects on marine life and agricultural crops. Human exposure to very high levels for even brief periods of time can potentially result in death, while lower level exposure can cause skin and eye irritation, drowsiness, dizziness, headaches and vomiting, damage to the immune system, leukaemia and birth defects.

Toluene

Toluene (methylbenzene) is a highly volatile chemical that quickly evaporates to a gas if released as a liquid. Due to relatively fast degradation, toluene emissions are usually confined to the local area in which it is emitted. Human exposure typically occurs through breathing contaminated air, but toluene can also be ingested or absorbed through the skin (in liquid form). Toluene usually leaves the body within twelve hours.

Short-term exposure to high levels of toluene can cause dizziness, sleepiness, unconsciousness and sometimes death. Long-term exposure can cause kidney damage and permanent brain damage that can lead to speech, vision and hearing problems, as well as loss of muscle and memory functions. The substance can cause membrane damage in plant leaves, and is moderately toxic to aquatic life with long-term exposure.

Xylenes

Xylenes are flammable liquids that are moderately soluble in water. They are quickly degraded by sunlight when released to air, and rapidly evaporate when released to soil or water. They are used as solvents and in petrol and chemical manufacturing.

Xylenes can enter the body through inhalation or skin absorption (liquid form), and can cause irritation of the eyes and nose, stomach problems, memory and concentration problems, nausea and dizziness. High-level exposure can cause death. The substances have high acute and chronic toxicity to aquatic life and can adversely affect crops.

Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs are a group of over 100 chemicals, which are formed through the incomplete combustion of organic materials, such as petrol. Exposure to these chemicals can cause a range of adverse reactions, including irritation of the eyes, nose and throat and skin. Exposure to very high levels can result in symptoms such as headaches, nausea, damage to the liver and kidneys, and damage to red blood cells. A number of PAHs were declared to be probably or possibly carcinogenic to humans by the IARC.

PAHs can attach to dust particles and be transported through the air. The compounds break down over days or weeks through chemical reactions in the atmosphere.

PAHs are moderately or highly acutely toxic to birds and aquatic organisms and moderately/highly chronic toxicity to aquatic life. Some can cause damage and death to crops. PAHs can bioaccumulate, and are moderately persistent in the environment.

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Appendix C

Ambient monitoring data review

Appendix C Ambient monitoring data review

Five air quality monitoring stations were commissioned within the study area to determine local pollution concentrations; the three ambient monitoring stations to represent general ambient air quality in the study area, and the two road monitoring stations to represent ambient air quality along Pennant Hills Road. At the time of the preparation of this report, data had been collected for a four month period (December 2013 to March 2014).

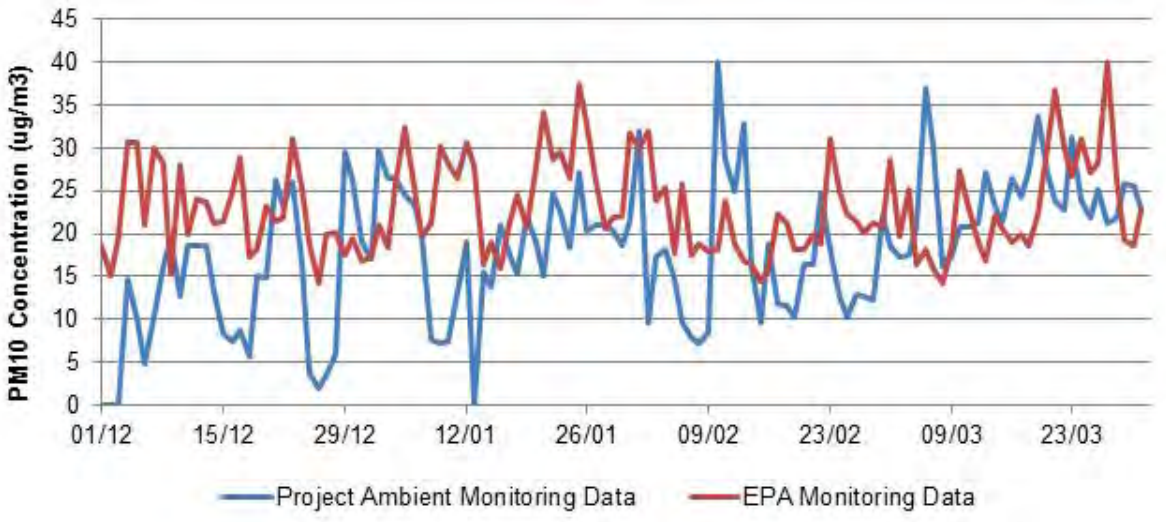
The dispersion modelling was undertaken for years 2009, 2010 and 2011, incorporating meteorological data measured by the OEH. As the data from the project monitoring stations did not cover the modelling period, they could not be used as ambient pollutant concentrations for the contemporaneous assessment of PM_{10} and NO_2. The data were, however, compared to OEH monitoring data to determine whether the OEH data adequately reflected local pollutant concentrations, or whether adjustment of the OEH data was required.

The two OEH monitoring stations located closest to the study area are at Prospect and Lindfield. Ambient pollutant data from these monitoring stations for the modelling period (2009 – 2011) were obtained. The data collected in December – March for each of the modelling years were compared to the project monitoring data from the ambient air quality monitoring stations. The maximum hourly concentrations of PM_{10} and NO_2 from either OEH station for the comparison period (December – March) were compared to the data recorded by the project ambient air quality monitoring stations. Statistical analyses of the hourly PM_{10} and NO_2 data were undertaken to identify whether the data sets are statistically different.

The results of a two sample t-test for PM_{10} are presented in the following table and figure. The t-test determined that the OEH and project ambient air quality monitoring stations are significantly different as the absolute value of the t statistic was greater than the critical t values. The pollutant concentrations recorded by the OEH are higher than the project monitoring data for the majority of the time as shown in the following chart. The conclusion was made, therefore, that the OEH data were satisfactory for use as conservative PM_{10} background concentrations in the assessment without any adjustment of the data.

Two-sample t-test assuming unequal variances – project ambient air quality monitoring stations vs OEH monitoring – PM_{10}

Parameter	Variable 1 (project community monitoring)	Variable 2 (OEH monitoring)
Mean	18.0	23.0
Variance	66.4	30.5
Observations	121.0	121.0
Hypothesised mean difference	0.0	
df	211.0	
t stat	-5.6	
P(T<=t) one-tail	0.0	
t Critical one-tail	1.7	
P(T<=t) two-tail	0.0	
t critical two-tail	2.0	

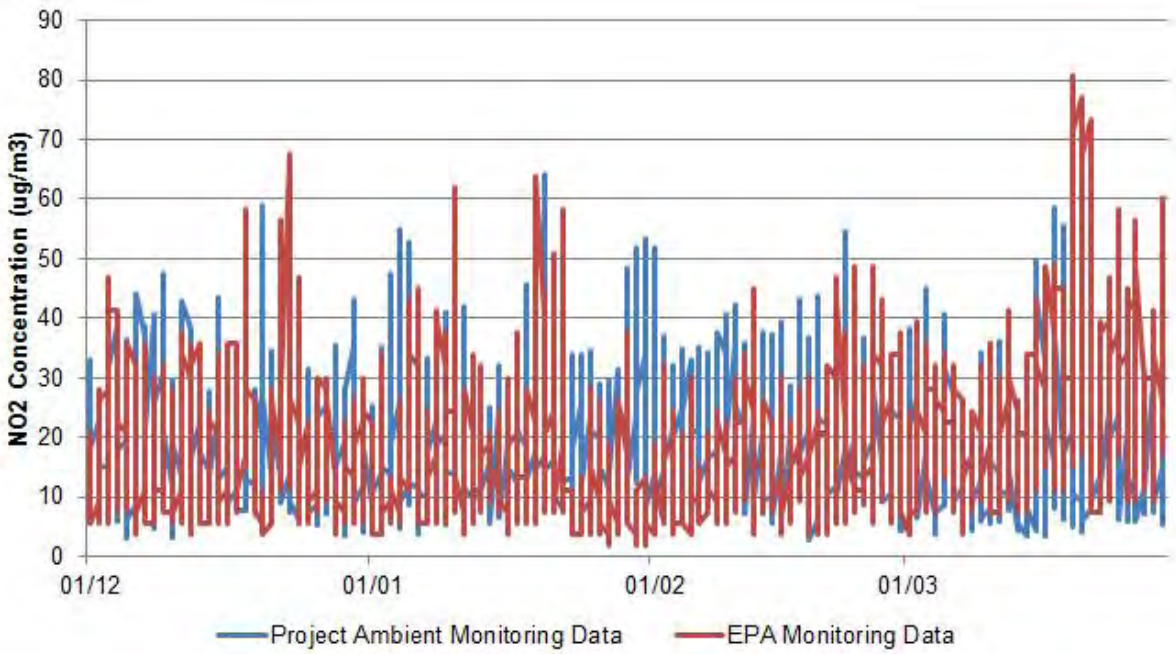


Comparison of project ambient air quality station data and OEH monitoring data – PM_{10}

The results of a two sample t-test for NO_2 are presented in the following table and chart. As the t statistic was greater than the critical t values, the data sets are statistically different. While the project monitoring data had marginally higher pollutant concentrations than the OEH monitoring for the majority of the time as shown in the following figure, the average percentage difference between the two data sets was only 0.7 per cent. As such, the OEH data were considered satisfactory for use as background pollutant concentrations in the assessment without any adjustment of the data.

Two-sample t-test assuming unequal variances – project ambient air quality monitoring stations vs OEH monitoring – NO_2

Parameter	Variable 1 (project community monitoring)	Variable 2 (OEH monitoring)
Mean	19.1	17.1
Variance	86.3	125.7
Observations	2598.0	2598.0
Hypothesised mean difference	0.0	
df	5021.0	
t stat	7.3	
P(T<=t) one-tail	0.0	
t critical one-tail	1.6	
P(T<=t) two-tail	0.0	
t critical two-tail	2.0	



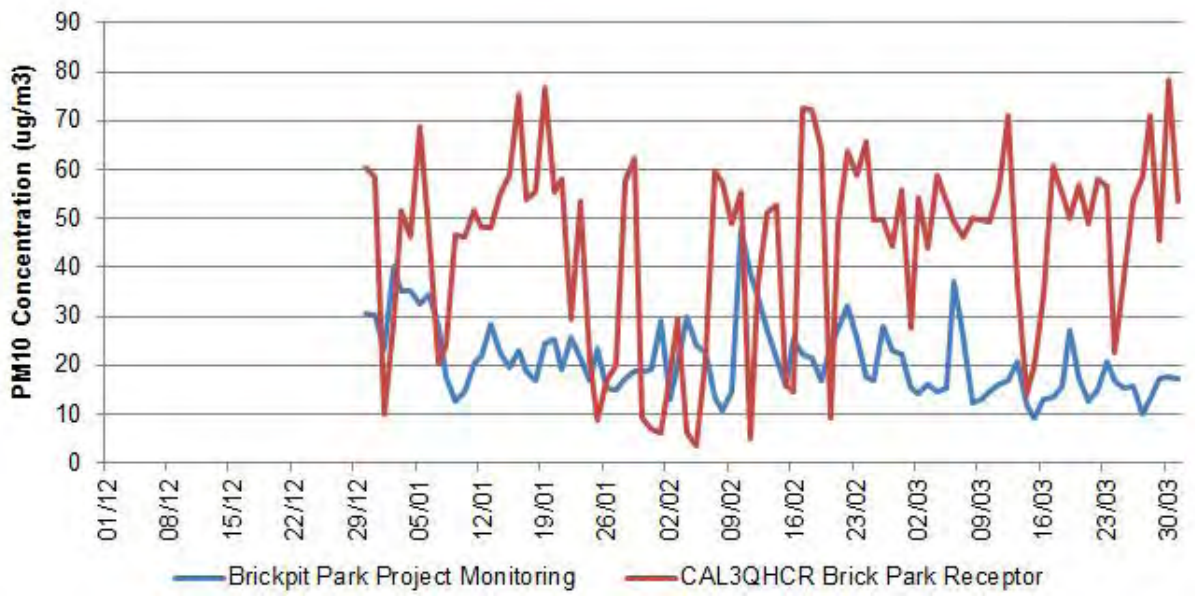
Comparison of Project ambient air quality station data and OEH monitoring data – NO_2

Similar to the assessment described above, an analysis was undertaken of the predicted surface road modelling (CAL3QHCR) concentrations to determine whether they adequately represent background pollutant concentrations for the receivers in proximity to the major arterial roads (Pennant Hills Road, M1 Pacific Motorway, Hills M2 Motorway) (road receivers) considered in the assessment. Receivers representing the locations of the two road monitoring stations were identified; the surface road modelling predictions for 2019 without the project, for these receivers were compared to the monitoring data. The 2019 data were chosen as they are the closest modelled year to the present, when monitoring data were collected (current traffic volumes were not assessed in this report). The results of the t-tests are provided for two PM_{10} and NO_2 data sets to represent the two project road monitoring stations (Brickpit Park and Observatory Park).

The results of the two sample t-test for PM_{10} are presented in the following table and chart for the PM_{10} Brickpit Park Road monitoring station and the CAL3QHCR Brickpit Park receiver. As the t statistic was greater than the critical t values, the data sets are statistically different. The road modelling data are greater than the project monitoring for the majority of the time as shown in the following figure. The road modelling data were, therefore, considered satisfactory for use as the PM_{10} background for the road receivers in the assessment without any adjustment of the data.

Two-sample t-test assuming unequal variances – Brickpit Park project road monitoring station vs CAL3QHCR Brickpit Park receiver – PM_{10}

Parameter	Variable 1 (Brickpit Park project road monitoring station)	Variable 2 (CAL3QHCR Brickpit Park receiver)
Mean	21.1	44.4
Variance	57.3	378.0
Observations	92.0	92.0
Hypothesised mean difference	0.0	
df	118.0	
t Stat	-10.7	
P(T<=t) one-tail	0.0	
t Critical one-tail	1.7	
P(T<=t) two-tail	0.0	
t critical two-tail	2.0	

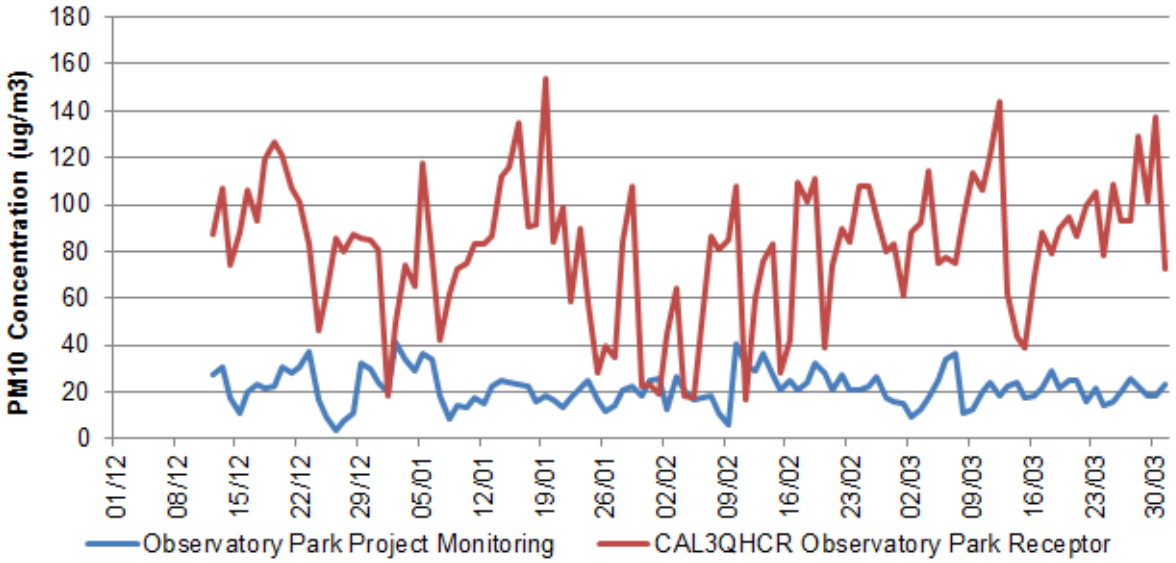


Comparison of Brickpit Park project road monitoring station data and CAL3QHCR predictions – PM_{10}

The results of the two sample t-test for the PM_{10} Observatory Park project road monitoring station and the CAL3QHCR Observatory Park road receiver are presented in the following table and chart. As the t statistic is greater than the critical t values, the data sets are statistically different. The road modelling data are greater than the project monitoring for the majority of the time as shown in the following figure. The predicted pollutant concentrations from the road modelling were, therefore, considered appropriate for use as conservative PM_{10} background concentrations for the road receivers in the assessment without any adjustment of the data.

Two-sample t-test assuming unequal variances – Observatory Park Road project road monitoring station vs CAL3QHCR Observatory Park receiver –PM_{10}

Parameter	Variable 1 (Observatory Park project road monitoring station)	Variable 2 (CAL3QHCR Observatory Park receiver)
Mean	21.6	81.4
Variance	56.3	874.0
Observations	110.0	110.0
Hypothesised mean difference	0.0	
df	123.0	
t Stat	-20.6	
P(T<=t) one-tail	0.0	
t critical one-tail	1.7	
P(T<=t) two-tail	0.0	
t critical two-tail	2.0	

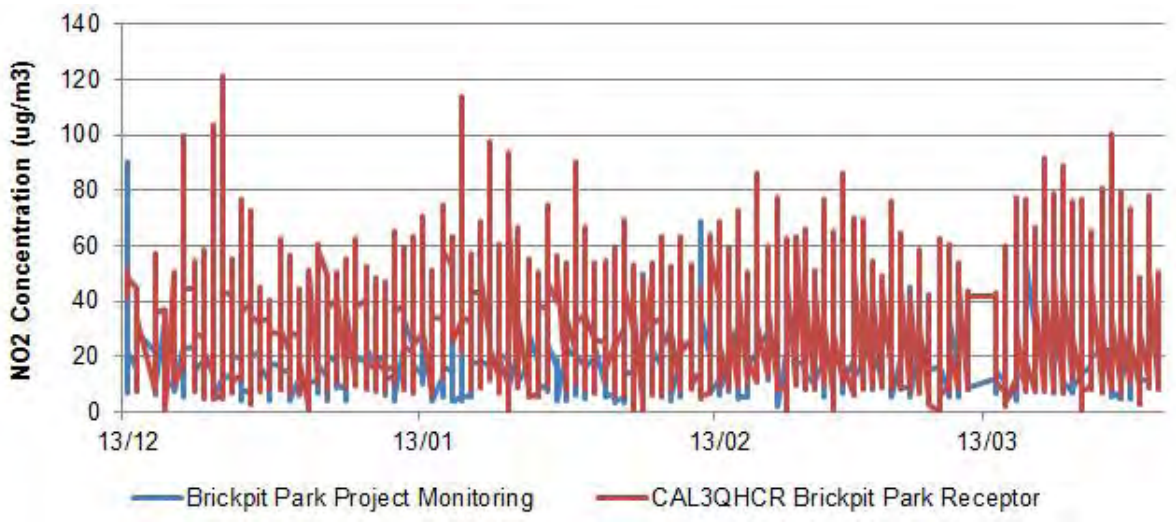


Comparison of Observatory Park project road monitoring station data and CAL3QHCR predictions – PM_{10}

The results of a two sample t-test for the Brickpit Park road monitoring station and the CAL3QHCR Brick Park road receiver are presented in the following table and chart. The results of the t-test show that the two data sets are statistically different. The road modelling predictions are greater than the project monitoring for the majority of the time as shown in the following figure. The road modelling predictions were, therefore, considered satisfactory for use as the NO_2 background concentrations for the road receivers in the assessment without any adjustment of the data.

Two-sample t-test assuming unequal variances – Brickpit Park Road project road monitoring station vs CAL3QHCR Brickpit Park receiver –NO_2

Parameter	Variable 1 (Brickpit Park project road monitoring)	Variable 2 (CAL3QHCR Brickpit Park receiver)
Mean	19.6	36.7
Variance	135.3	323.0
Observations	2263.0	2263.0
Hypothesised mean difference	0.0	
df	3874.0	
t stat	-38.2	
P(T<=t) one-tail	0.0	
t critical one-tail	1.6	
P(T<=t) two-tail	0.0	
t critical two-tail	2.0	

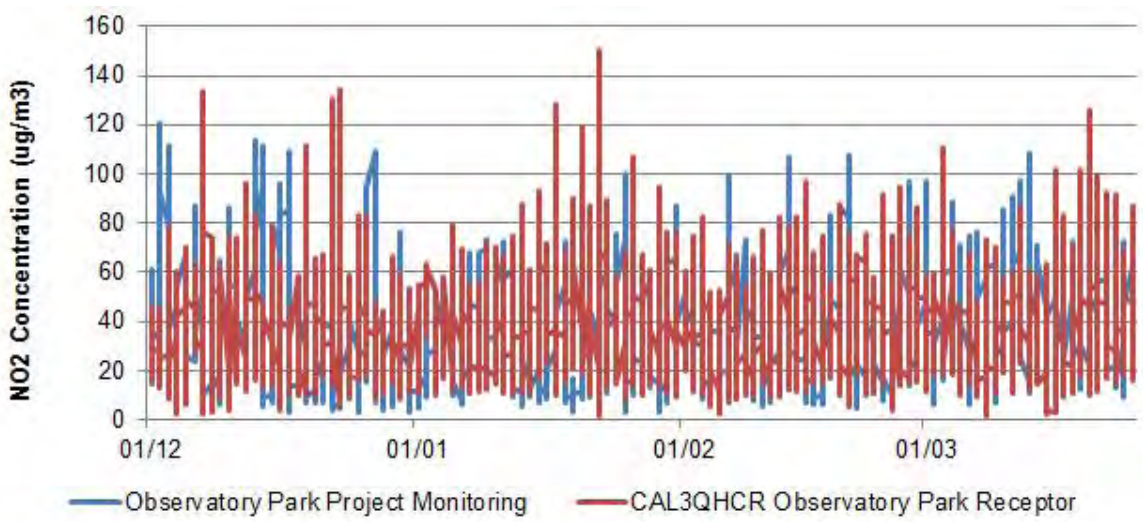


Comparison of Brickpit Park project road monitoring station data and CAL3QHCR predictions – NO_2

The results of the two sample t-test for the NO_2 Observatory Park Road project road monitoring station and the CAL3QHCR Observatory Park road receiver are presented in the following table and chart for NO_2. The results of the t-test showed that the two data sets are statistically different. The road modelling predictions are greater than the project monitoring data for the majority of the time as shown in the following figure. The road modelling predictions were, therefore, considered satisfactory for use as the NO_2 background concentrations for the road receivers in the assessment without any adjustment of the data.

Two-sample t-test assuming unequal variances – Observatory Park project road monitoring station vs CAL3QHCR Observatory Park receiver –NO_2

Parameter	Variable 1 (Observatory Park project road monitoring station)	Variable 2 (CAL3QHCR Observatory Park receiver)
Mean	31.6	42.9
Variance	387.5	398.6
Observations	2629.0	2629.0
Hypothesised mean difference	0.0	
df	5255.0	
t Stat	-20.8	
P(T<=t) one-tail	0.0	
t Critical one-tail	1.6	
P(T<=t) two-tail	0.0	
t Critical two-tail	2.0	



Comparison of Observatory Park project road monitoring station data and CAL3QHCR predictions – NO_2

Appendix D

Dispersion model details

Appendix D Dispersion model details

Dispersion modelling uses mathematical equations to characterise atmospheric processes, which disperse a pollutant emitted by a source. Based on emissions and meteorological inputs, dispersion models can be used to predict concentrations at selected downwind receiver locations. Air quality models are used to determine compliance with air quality standards. Two well-known and internationally used US EPA guideline models were used in this assessment - CALPUFF and CAL3QHCR. Details of both these models can be found on the US EPA SCRAM (Support Centre for Regulatory Atmospheric Modelling) Bulletin board. The models are addressed in Appendix A of the US EPA's Guideline on Air Quality Models (also published as Appendix W.pdf) of 40 CFR Part 51.

Dispersion models

Two dispersion models are recommended for regulatory assessments in Australia and New Zealand, which are CALPUFF and AERMOD. AERMOD has recently replaced AUSPLUME as the guideline model for all near-field, steady state modelling applications in Victoria. CALPUFF is recommended for use for all modelling applications where the steady state assumption does not apply; this includes complex terrain and coastal environments. A major difference between AERMOD and CALPUFF is in the models' treatment of meteorology. AERMOD is a 2-dimensional model where the effects of one single surface station and one single upper air station are assumed to be spatially uniform across the entire modelling region in its meteorological processor. In contrast, CALMET (CALPUFF's meteorological module) is a 3-dimensional model and is able to use the output of numerical prognostic meteorological models as well as multiple observation sites to assist in the development of three-dimensional wind fields.

Overview of the CALPUFF suite of models

The CALPUFF modelling system provides a non-steady state modelling approach, which evaluates the effects of spatial changes in the meteorological and surface characteristics. It offers the ability to treat stagnation, multiple-hour pollutant build-up, recirculation and causality effects, which are beyond the capabilities of steady-state models. The CALPUFF modelling system was adopted by the U.S. EPA as a guideline model for long range transport applications and, on a case-by-case basis, for near-field applications involving complex flows (Federal Register, April 15, 2003, pp 18,440-18,482). CALPUFF is also recommended by both the Federal Land Managers Air Quality Workgroup (FLAG, 2000, 2008) and the Interagency Workgroup on Air Quality Modelling (IWAQM, 1998). It was adopted for world-wide use by the United Nations International Atomic Energy Agency (IAEA). CALPUFF is widely used in many countries (over 100 countries) throughout the world, and has been incorporated as a regulatory model in several countries.

The CALPUFF modelling system includes three main components - CALMET, CALPUFF and CALPOST - and a large set of pre-processing programs designed to interface the model to standard, routinely-available meteorological and geophysical datasets. In simple terms, CALMET is a meteorological model, which develops hourly wind and temperature fields on a three-dimensional gridded modelling domain. CALPUFF is a transport and dispersion model, which advects 'puffs' of material emitted from modelled source, simulating dispersion and transformation processes along the way. In doing so, it uses the fields generated by CALMET. The primary output files from CALPUFF contain either hourly concentrations or hourly deposition fluxes evaluated at selected receiver locations. CALPOST is used to process these files, producing summaries of the results of the simulation.

CALMET overview

CALMET is a diagnostic meteorological model, which produces three-dimensional wind fields based on parameterised treatments of terrain effects such as slope flows and terrain blocking effects. Meteorological observations are used to determine the wind field in areas of the domain within which the observations are representative. Fine scale terrain effects are determined by the diagnostic wind module in CALMET.

The CALMET meteorological model consists of a diagnostic wind field module and micrometeorological modules for overwater and overland boundary layers (Scire et al., 2000a). When using large domains, the user has the option to adjust input winds to a Lambert Conformal Projection coordinate system to account for the Earth's curvature. The diagnostic wind field module uses a two-step approach to the computation of the wind fields (Douglas and Kessler, 1988). In the first step, an initial-guess wind field is adjusted for kinematic effects of terrain, slope flows, and terrain blocking effects to produce a Step 1 wind field. The second step consists of an objective analysis procedure to introduce observational data into the Step 1 wind field in order to produce a final wind field. An option is provided to allow gridded prognostic wind fields to be used by CALMET, which may better represent

regional flows and certain aspects of sea breeze circulations and slope/valley circulations. The prognostic data (as a 3D.DAT file) can be introduced into CALMET in three different ways;

- As a replacement for the initial guess wind field.
- As a replacement for the Step 1 field.
- As observations in the objective analysis procedure.

The techniques used in the CALMET model are briefly described below.

Step 1 wind field

Kinematic effects on terrain: CALMET uses the approach of Liu and Yocke (1980) to evaluate kinematic terrain effects. The domain-scale winds are used to compute a terrain-forced vertical velocity, subject to an exponential stability-dependent decay function. The kinematic effects of terrain on the horizontal wind components are evaluated by applying a divergence-minimisation scheme to the initial guess wind field. The divergence minimisation scheme is applied iteratively until the three dimensional divergence is less than a threshold value.

Slope flows. Slope flows are computed based on the shooting flow parameterisation of Mahrt (1982). Shooting flows are buoyancy-driven flows, balanced by advection of weaker momentum, surface drag and entrainment at the top of the slope flow layer. The slope flow is parameterised in terms of the terrain slope, distance to the crest and local sensible heat flux. The thickness of the slope flow layer varies with the elevation drop from the crest.

Blocking effects. The thermodynamic blocking effects of terrain on the wind flow are parameterised in terms of the local Froude number (Allwine and Whiteman 1985). If the Froude number at a particular grid point is less than a critical value and the wind has an uphill component, the wind direction is adjusted to be tangential to the terrain.

Step 2 wind field

The wind field resulting from the adjustments of the initial guess wind described above is the Step 1 wind field. The second step of the procedure involves the introduction of observational data into the Step 1 wind field through an objective analysis procedure. An inverse-distance squared interpolation scheme is used, which weighs observational data heavily in the vicinity of the observational station, while the Step 1 wind field dominates the interpolated wind field in regions with no observational data. The resulting wind field is subject to smoothing, an optional adjustment of vertical velocities based on the O'Brien (1970) method, and divergence minimisation to produce final Step 2 wind fields.

Overview of CALPUFF

CALPUFF is a non-steady-state puff dispersion model. It accounts for spatial changes in the meteorological fields, variability in surface conditions such as (elevation, surface roughness, vegetation type, etc.), chemical transformation, wet removal due to rain and snow, dry deposition and terrain influences on plume interaction with the surface. CALPUFF can simulate the effects of time- and space-varying meteorological conditions on pollutant transport, transformation and removal. CALPUFF contains algorithms for near-source effects, such as building downwash, transitional plume rise, partial plume penetration, sub-grid scale terrain interactions, as well as longer range effects, such as pollutant removal (wet scavenging and dry deposition), chemical transformation, vertical wind shear, overwater transport and coastal interaction effects. It can accommodate arbitrarily-varying point source and gridded area source emissions. The major features of CALPUFF model are detailed below (after Scire et al., 2002).

Major features of the CALPUFF model

- Source types:
    - Point sources (constant or variable emissions).
    - Line sources (constant or variable emissions).
    - Area sources (constant or variable emissions).
    - Volume sources (constant or variable emissions).
- Non-steady-state emissions and meteorological conditions:
    - Gridded 3D fields of meteorological variables.

  - Spatially variable 3D fields of mixing height, friction velocity, convective velocity scale, Monin-Obukhov length, precipitation rate.
  - Vertically and horizontally-varying turbulence and dispersion rates.
  - Time-dependent source and emissions data.
- Efficient sampling functions:
  - Integrated puff formulation.
  - Elongated puff (slug) formulation.
- Dispersion coefficient options:
  - Direct measures of sigma v and sigma w.
  - Estimated values of sigma v and sigma w based on similarity theory.
  - PG dispersion coefficients (rural areas).
  - McElroy Pooler dispersion coefficients (urban areas).
  - CTDM dispersion coefficients (neutral/stable).
- Vertical wind shear :
  - Puff Splitting.
  - Differential advection and dispersion.
- Plume Rise:
  - Partial penetration.
  - Buoyant and momentum rise.
  - Stack tip downwash effects.
  - Vertical wind shear.
  - Building downwash effects.
- Building downwash:
  - Huber-Snyder method.
  - PRIME downwash.
  - Schulman Scire method.
- Dry deposition:
  - Gases and particulate matter.
  - Three options:
    - Full treatment of space and time variations of deposition with a resistance model.
    - User-specified diurnal cycles for each pollutant.
    - No dry deposition.
- Overwater and coastal interaction effects:
  - Overwater boundary layer parameters.
  - Abrupt change in meteorological conditions, plume dispersion at coastal boundary.
  - Plume fumigation.
  - Option to introduce sub grid scale TIBLs into coastal grid cells.
- Chemical transformation options:
  - Pseudo-first-order chemical mechanism for SO2, SO4, NOx HNO3 and NO3 (MESOPUFF II method).

- User specified diurnal cycles of transformation rates.
- No chemical conversion.
- Wet Removal.
- Scavenging coefficient approach.
- Removal rate a function of precipitation intensity and precipitation type.

Overview of CAL3QHCR

CAL3QHCR is a CALINE3-based model with queuing and hot spot calculations and with a traffic model to calculate delays and queues that occur at signalised intersections. The CALINE3 model on which it is based is a steady-state Gaussian dispersion model designed to determine air pollution concentrations at receiver locations downwind of highways located in relatively uncomplicated terrain.

The CAL3QHC model can predict carbon monoxide and other inert pollutant concentrations from motor vehicles at roadway intersections. The model includes the CALINE-3 line source dispersion model and a traffic algorithm for estimating vehicular queue lengths at signalised intersections. CALINE-3 was designed to predict air pollutant concentrations near highways and arterial streets due to emissions from motor vehicles operating under free flow conditions. CALINE-3, however, does not permit the direct estimation of the contribution of emissions from idling vehicles. CAL3QHC was developed to enhance CALINE-3 by incorporating methods for estimating queue lengths and the contributions of emissions from idling vehicles. The model permits the estimation of total air pollution concentrations from both moving and idling vehicles. CAL3QHC requires details on roadway geometries, receiver locations, meteorological conditions and vehicular emission rates. In addition, the model requires other parameters such as signal timing data and information describing the configuration of the intersection being modelled.

The CAL3QHCR model is an enhanced version of CAL3QHC, which can process up to a year of hourly meteorological data. Vehicular emissions, traffic volume, and signalisation data can be specified for each hour of a week. Furthermore, the latest version also accommodates up to 5,000 receivers and 5,000 sources (previously 60 receivers and 120 sources). In order to accommodate the large number of receivers associated with this assessment, the CAL3QHCR model was considered to be the most appropriate choice for modelling the traffic movements on roadways external to the tunnels. The line source model predicts pollutant concentrations based on the Gaussian diffusion equation. CAL3QHCR was used to predict concentrations of carbon monoxide, nitrogen dioxide and particulate matter (PM) in this assessment.

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Appendix E

Terrain and land use data

Appendix E Terrain and land use data

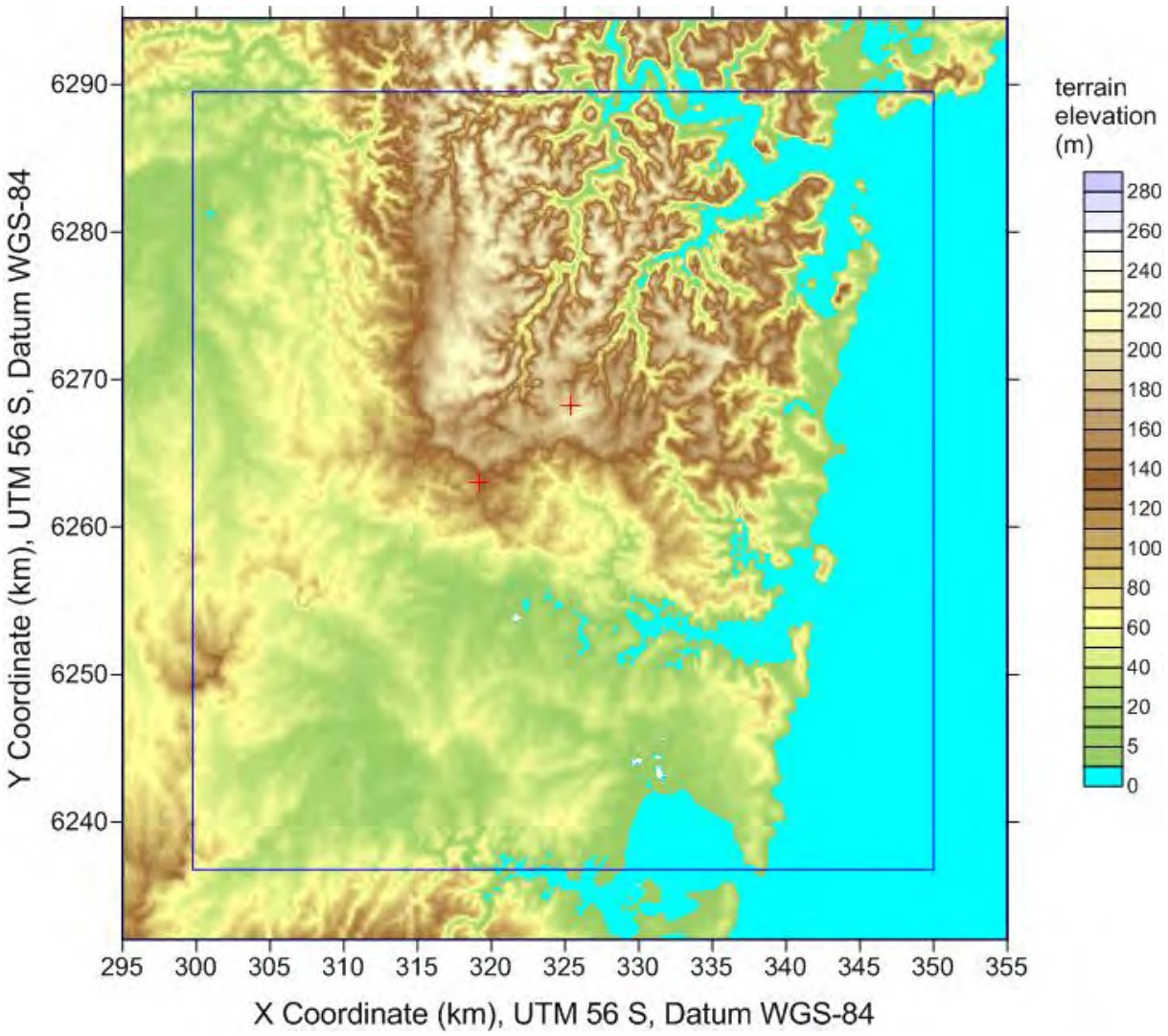
Gridded terrain elevations for the modelling domain were derived from the Shuttle Radar Topography Mission (SRTM) 3 arc-second or around 90 metre resolution data. The SRTM data represent a near-global digital elevation model (DEM) of the earth generated using radar interferometry. Data are provided in files covering one degree by one degree blocks of latitude and longitude. All elevations are in metres referenced to the WGS84/EGM96 geoid. SRTM terrain data were extracted from four files S34E150.HGT, S34E151.HGT, S35E150.HGT and S35E151.HGT which are available for download from the USGS website

Land use data within the study area were derived from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) and supplied to AECOM by the Department of Environment and Heritage.

This data set was compiled using the nationally agreed land use mapping principles and procedures of the Australian Land Use and Management (ALUM) Classification version 7. The land use dataset was collected as part of State and Territory mapping programs and the Australian Collaborative Land Use and Management Program (ACLUMP). The data over the country vary according to year (1997 to 2009) and scale (1:25,0000 to 1:250,000). The land use database was recently updated in November 2012 and includes a combined 50 metre raster for Australia including new data for Tasmania, Victoria, parts of southwest Western Australia and parts of Queensland. While there are no new data for New South Wales, edge-matching errors were corrected.

All contributing polygon datasets were re-gridded and mosaicked to minimise sampling errors. NODATA voids were filled with Australian Bureau of Statistics meshblocks land use attributes with modifications based on 1:250,000 scale topographic data for built up areas published by Geoscience Australia in 2006, land tenure data compiled by the Bureau of Rural Sciences (BRS) in 2007 and native and plantation forest data compiled by BRS in 2007. The following figure shows the land use data over the model domain at 250 m grid resolution.

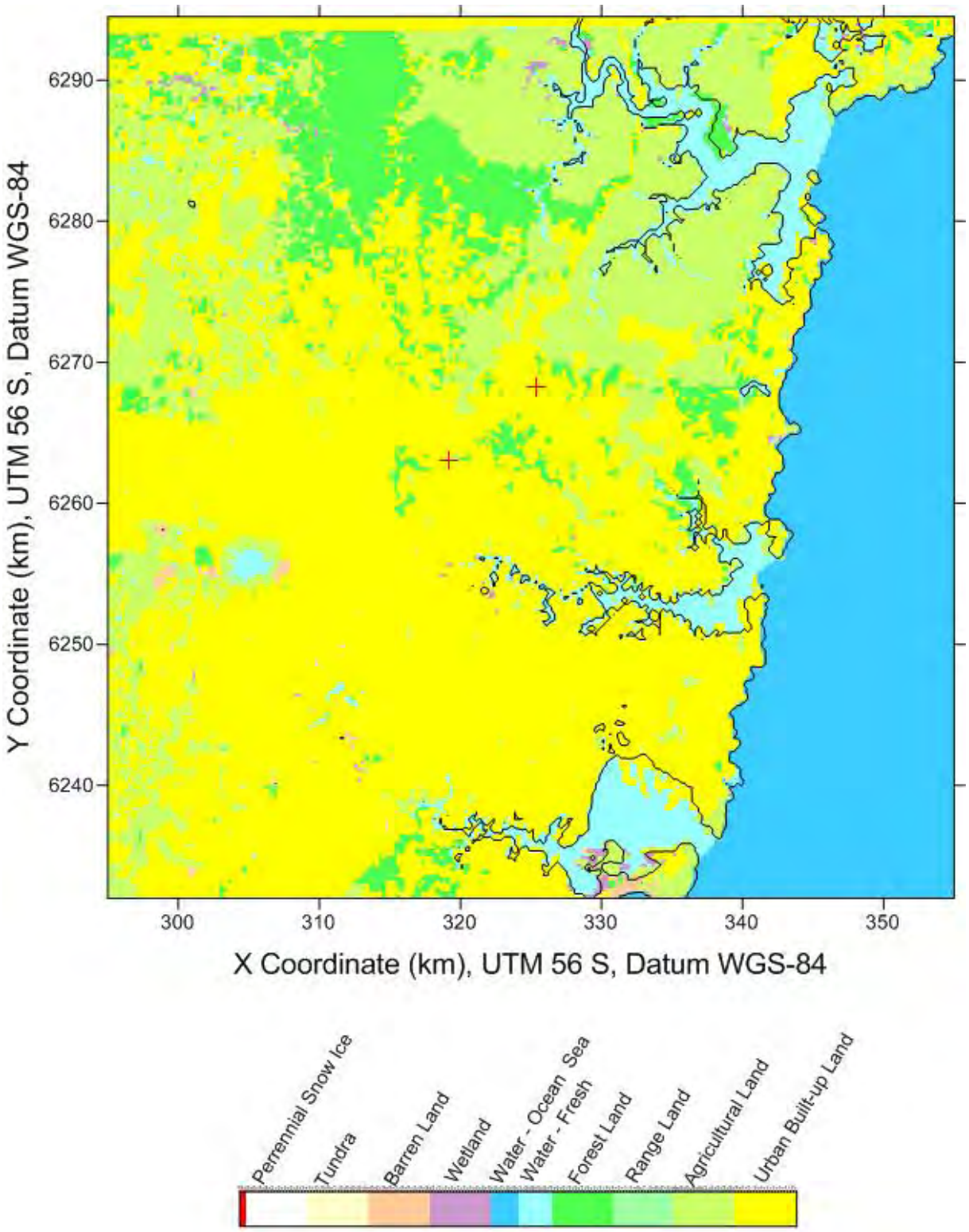
Land use within the study area primarily consists of urban areas with occasional rangeland and forest land areas as shown in the following figure.



Terrain elevations over the modelling domain

Terrain elevations were determined from 90 metre SRTM data. Red cross hairs mark the ventilation outlet locations at the southern and northern ends of the tunnels according to the design scenarios. The blue rectangle delineates the computational model domain, which is a subset of the meteorological model domain.

The land use data used in this application is different to the default land use data used in TAPM and for most CALMET model applications outside the United States, which is the USGS one kilometre land use data. Until recently, the USGS one kilometre global land use data set was the most readily available data set for air quality applications. Limitations of these data set, however, include its age (more than 20 years old), coarse resolution (between 900 metres and 1.2 kilometres), and the fact that it is categorised according to the North American land use category system, which does not correspond to all relevant Australian land use types. For air quality modelling purposes where a grid system is used, such as CALMET and TAPM, the underlying dominant land use is an important function of plume transport. The inclusion of the Australian land use data set is, therefore, an important relevant addition to this modelling application as the data are recent, relevant and of a very fine resolution. In this application, specific surface characteristics, albedo, roughness length and leaf area index for the Sydney basin were determined from Gero and Pitman (2006) for bushland, agricultural land, dense urban, new urban and established urban areas. Bushland is described as natural vegetation (primarily around 20 metre trees with 40 per cent cover). Agricultural land incorporates all agricultural activity in western Sydney, which is mostly pasture for grazing or market gardens. Urban categories are split into dense urban (which is confined to the city core and Parramatta CBD), new urban (newly established residential suburbs lacking mature trees), and established urban (residential suburbs with mature trees).



Dominant land use within the study area

The one metre terrain elevation contour is shown. Red cross hair symbols mark the locations of the ventilation outlets at the southern and northern ends of the tunnels. The dominant land use categories are urban areas – mostly established residential areas - and the agricultural land is mostly market gardens and pasture. Specific surface characteristics for Sydney region were derived from Gero and Pitman (2006).

Appendix F

Meteorological data

Appendix F Meteorological data

Representativeness of years

Representative is defined as the extent to which a set of measurements taken at the collection site spatially and temporally reflects the actual conditions at the application site. The collected meteorological data should closely mimic the conditions affecting the transport and dispersion of pollutants in the area of interest as determined by the locations of the source/receivers being modelled. Representativeness of meteorological data depends on the following factors:

- Character and complexity of the terrain in the source surroundings and between the source and the meteorological monitoring or observing site
- Proximity of the meteorological monitoring site to the source;
- Instrumentation and exposure of the meteorological monitoring site; and
- Quality, completeness, and period of record of the meteorological data.

The spatial representativeness of the data can be adversely affected by large distances between the source and receivers of interest and the complex topographic characteristics of the area. Temporal representativeness is a function of the year-to-year variations in the weather conditions.

In this study, meteorological input data were taken from the BOM and OEH. The data are of good quality and although none of the monitoring stations are expressly close to the source, their combined contributions of variables paired in space and time meant that the full spatial and temporal variability of the flow was captured across the modelling domain. All data sets for all three years had less than 10 per cent missing data, i.e., more than 90 per cent capture. When one station is missing data for a particular hour, the model will use the meteorological conditions from the next nearest station for that hour.

Period of record

Studies have demonstrated that variability of model estimates due to the meteorological data input was adequately reduced if a five year period of meteorological input was used. Based on these findings, the US EPA stated that a minimum of five years of meteorological data must be modelled. Consecutive years from the most recent, readily available five year period are preferred. If the data are recorded on site, however, then at least one year or more years of data are deemed as sufficient. This criterion was developed on the use of ISC and AERMOD, which are steady state Gaussian plume models that require only one surface station as meteorological input.

In Australia, DEC (2005) specifies that at least one year of site specific meteorological data must be used (Level 2 assessment). These data must be 90 per cent complete, that is with no more than 876 hours missing per year. If site-specific meteorological data are not available, at least one year of site-representative meteorological data must be used. These data should be either collected at a meteorological monitoring station or generated from a prognostic model such as TAPM, and the data must be correlated against a longer-duration site-representative meteorological database of at least five consecutive years. It must be established that the data adequately describe the expected meteorological patterns at the site under investigation.

For this assessment, modelling was conducted using three years of meteorological data to ensure the meteorological conditions assessed were representative of local conditions. A brief summary of each of the years with respect to climatic history is provided below.

Brief climate summary of 2009

The year 2009 was the warmest year on record for the state of NSW. It had the warmest year on record for average minimum temperatures and fourth warmest year for average maximum temperatures. The year 2009 was the ninth consecutive year with below average rainfall and the thirteenth consecutive year with above average min and max temperatures.

The annual average rainfall in NSW for 2009 was 484.0 millimetres. This is below the average of 559 millimetres. Inland areas and the southern half of the NSW coast recorded below average rainfall. In contrast, the Mid North Coast recorded well above average falls for the year, with Coffs Harbour in particular flooding five times.

The generally warm conditions were exacerbated by three extreme heat events in 2009; a heatwave at the end of January/early February in southwest NSW, extreme heat during August in northern NSW and an exceptional

heatwave - both in strength and duration - in November across all of NSW. These extremely warm conditions also contributed to the recording of the warmest winter and warmest spring on record for NSW.

NSW experienced two large and extensive dust storms. The most extreme storm occurred on 23 September 2009, and resulted in reduced visibility at many locations. On the morning of the 23 September 2009, visibility in Sydney was reduced to 400 metres over much of the city. A thick layer of red dust coated all exposed surfaces with many flights delayed or cancelled at Sydney Airport. The dust originated from South Australia and western NSW, and affected areas as far north as Cairns. A few days later, strong winds on 25 September 2009 again caused elevated dust levels, reducing visibility to 800 metres at 3 pm at Broken Hill, with the dust extending to Sydney by the morning of 26 September 2009. More dust storms of lesser extent occurred in October 2009.

Brief climate summary of 2010

The year 2010 was the wettest year on record for NSW and the ninth consecutive year with above average minimum temperatures. A total of 803.14 millimetres of rainfall was recorded in NSW during 2010, which was well above the average of 559.0 millimetres, and made 2010 the third wettest year on record. This is the highest rainfall recorded in the state in over fifty years, following the very strong La Niña events in 1956 (829.52 millimetres) and 1950 (908.45 millimetres), and slightly higher than the rainfall recorded during strong La Niña events in the 1970s. In addition, 2010 was the wettest year on record for the Murray-Darling Basin with a total rainfall of 794.27 millimetres, which was slightly higher than the previous record set in the La Niña of 1956 (786.53 millimetres).

The wet conditions were the result of a very strong La Niña event in the Pacific Ocean combined with combination with a negative Indian Ocean Dipole event, both of which bring increased rainfall to Australia. In particular, Spring 2010 was the wettest on record for both NSW and Australia, with above average rainfall for six consecutive months (July – December) in addition to high rainfall in February and March as the 2009 El Niño event broke down.

NSW had close to average temperatures during 2010, with mean temperatures only 0.06 °C above the 1961-1990 average. This was significantly cooler than 2009, which was the warmest year on record in NSW, and was the coolest year since 1996. In general, years of high rainfall (and most La Niña years) have lower daytime maximum temperatures. The cooler temperatures in 2010 were primarily due to La Niña. This year was, however, significantly warmer than the previous strong La Niña years in 1974 and 1956, which had mean temperatures 0.51 °C and 1.17 °C below average respectively. This demonstrates the fact that although individual years may show variability, the underlying warming trend has not stopped, with global average temperatures in 2010 likely to be among the three hottest years on record (http://www.wmo.int/pages/mediacentre/press_releases/pr_904_en.html).

The eastern seaboard of NSW continued to have above average temperatures during 2010, with Sydney Observatory Hill recording mean maximum temperatures of 22.6 °C, 0.9 °C above average.

Brief climate summary of 2011

The year 2011 was warm and wet as La Niña ended and another cycle began. La Niña brought the fourth wettest two-year period on record for NSW, close to average maximum and minimum temperatures, and the fifteenth consecutive warm year for NSW.

A total of 660.9 millimetres of rain was recorded in 2011, which was above the historical average of 552.8 millimetres and the 12th wettest year on record. The year was substantially drier than 2010 (815.1 millimetres), but otherwise the wettest year since 1988, when 689.4 millimetres fell. The high rainfall during 2011 was associated with the lingering impacts of the strong 2010 La Niña event, in addition to a weak La Niña, which developed towards the end of the year.

The average maximum temperature in NSW was 0.3 °C above average during 2011, which made it warmer than 2010 but otherwise the coolest year since 2000. Temperatures were generally within 1 °C of average across the state, despite the increased rainfall during the year, with coolest conditions recorded along the coast. Temperatures were particularly cool as the 2010 La Niña broke down during autumn, which was the 10th coolest on record and the coolest since 1995, while temperatures were well above average between July and September under drier conditions as well as a weak positive Indian Ocean Dipole event.

Very cold conditions returned during December, which was the fourth coolest on record for NSW, as well as the third coldest for maximum temperatures, which were 2.5 °C below average. This was associated with cloudy conditions, cool southerly winds, and a lack of hot days. The average temperature in December was 28.1 °C, almost 1 °C lower than recorded in November. November was recorded as being warmer than December on only

three previous occasions, most recently in 2009 when November was 5 °C above average. Interestingly, in NSW, five days during November had temperatures above 40 °C compared to just two days in December.

An average minimum temperature of 11.0 °C was recorded in NSW during 2011, which was 0.3 °C above the historical average. Temperatures were warm during the first part of the year, particularly along the coast, with well above average temperatures in January and February. This included a record five consecutive nights above 24 °C in Sydney between the second and sixth of February. Nights were also very warm during August, while November was the sixth warmest on record for minimum temperatures. In comparison, nights were cold during the middle of 2011, including the fourth coldest May on record for NSW, while December was 0.9 °C below average.

The statewide average temperature in NSW was consequently 0.3 °C above average at 17.6 °C, making 2011 the fifteenth consecutive warm year for NSW.

Meteorological evaluation

Rigorous tests exist to evaluate the performance of prognostic meteorological performance. The aim of any evaluation exercise is to determine whether and to what extent confidence may be placed in the prognostic meteorological data that are used as inputs to emission and dispersion models.

The two specific objectives of meteorological evaluation are to:

- Determine if the prognostic meteorological data represent a reasonable approximation of the actual meteorology that occurred during the modelling period; and
- Identify and quantify the existing biases and errors in the prognostic meteorological predictions in order to allow for a downstream assessment of how the air quality modelling results are affected by issues associated with the meteorological data.

Statistical evaluation

Several statistical measures are typically calculated as part of a meteorological model evaluation. These measures are calculated for wind speed, wind direction, temperature, and humidity at the surface. Examples of the suite of statistical performance measures that are routinely used include scalar and vector mean wind speeds, standard deviations in measured and observed winds, root mean square errors (RMSE) (total plus systematic and unsystematic components), two model skill measures, the Index of Agreement (IOA), and the mean and standard deviations in modelled and observed wind speeds.

The statistical measures considered in this study are described below. The statistics used to evaluate meteorological model performance are all given in absolute terms; that is, wind speed error is given in metres per second rather than percentage error.

Mean (average) value: eg mean observation and mean prediction

Bias error (B): calculated as the mean difference in prediction-observation pairings with valid data within a given analysis region and for a given time period (hourly or daily) as described by the following equation:

$$B = \frac{1}{IJ}\sum_{j=1}^{J}\left|\sum_{i=1}^{I}\left(P_j^i - O_j^i\right)\right.$$

Gross error (E): or absolute error. Calculated as the mean *absolute* difference in prediction-observation pairings with valid data within a given analysis region and for a given time period (hourly or daily) as described by the following equation.

$$E = \frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}\left|P_j^i - O_j^i\right|$$

Root mean square error (RMSE): calculated as the square root of the mean squared difference in prediction-observation pairings with valid data within a given analysis region and for a given time period (hourly or daily) as described by the following equation:

$$RMSE = \left[\frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}\left(P_j^i - O_j^i\right)^2\right]^{1/2}$$

The RMSE, as with the gross error, is a good overall measure of model performance. Since large errors are weighted heavily due to squaring, however, large errors in a small sub region may produce a large RMSE even though the errors may be small and quite acceptable elsewhere.

Systematic root mean square error (RMSEs): calculated as the square root of the mean squared difference in *regressed* prediction-observation pairings within a given analysis region and for a given time period (hourly or daily) as described by the following equation:

$$RMSE_S = \left[\frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}\left(\hat{P}_j^i - O_j^i\right)^2\right]^{1/2}$$

where the regressed prediction is estimated for each observation from the least square fit described above. The RMSEs estimates the model's linear (or systematic) error; as such, the better the regression between predictions and observations, the smaller the systematic error.

Unsystematic root mean square error (RMSEu): calculated as the square root of the mean squared difference in prediction-regressed prediction pairings within a given analysis region and for a given time period (hourly or daily) as described by the following equation:

$$RMSE_U = \left[\frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}\left(P_j^i - \hat{P}_j^i\right)^2\right]^{1/2}$$

The unsystematic difference is a measure of how much of the discrepancy between estimates and observations is due to random processes or influences outside the legitimate range of the model. A "good" model will provide low values of the RMSE, explaining most of the variation in the observations. The systematic error should approach zero and the unsystematic error should approach RMSE since:

$$\mathrm{RMSE}^2 = \mathrm{RMSE_S}^2 + \mathrm{RMSE_U}^2$$

It is important that RMSE, RMSES, and RMSEU are all analysed. For example, if only RMSE is estimated (and it appears acceptable) it could consist largely of the systematic component. This error might be removed through improvements in the model inputs or use of more appropriate options, thereby reducing the error transferred to the dispersion model. On the other hand, if the RMSE consists largely of the unsystematic component, this indicates that further error reduction may require model refinement (new algorithms, higher resolution grids, etc.), or that the phenomena to be replicated cannot be fully addressed by the model. It also provides error bars that

may be used with the inputs in subsequent sensitivity analyses. Generally a good/reasonable performance will provide low values of RMSE, explaining most of the variation in the observations. The RMSEs should approach zero and the unsystematic error RMSEu should approach RMSSE since $RMSE^2 = (RMSES)^2 + (RMSEU)^2$

Index of agreement (IOA): calculated following the approach of Willmont (1981). This metric condenses all the differences between model estimates and observations within a given analysis region and for a given time period (hourly and daily) into one statistical quantity. It is the ratio of the total RMSE to the sum of two differences – between each prediction and the observed mean, and each observation and the observed mean as described by the following equation:

$$IOA = 1 - \left[\frac{IJ \cdot RMSE^2}{\sum_{j=1}^{J}\sum_{i=1}^{I}\left|P_j^i - M_o\right| + \left|O_j^i - M_o\right|} \right]$$

Viewed from another perspective, the index of agreement is a measure of the match between the departure of each prediction from the observed mean and the departure of each observation from the observed mean. Thus, the correspondence between predicted and observed values across the domain at a given time may be quantified in a single metric and displayed as a time series. The index of agreement has a theoretical range of 0 to 1, the latter score suggesting perfect agreement.

Benchmarks

The model evaluation results were compared against the following benchmarks, developed by Emory et al. (2001) and Tesche et al. (2001b).

Benchmarks for MM5 modelling evaluation

Statistical Method	Wind Speed	Wind Direction	Temperature	Humidity
IOA	≥ 0.6	-	≥ 0.8	≥ 0.6
RMSE	≤ 2 m/s	-		
Mean Bias	± ≤ 0.5 m/s	≤ 10^0	≤ ± 0.5 K	< ± 1 g/kg
Gross Error	-	≤ 30^0	≤ 2 K	≤ 2 g/kg

It must be noted that simply meeting the performance goals cannot be considered an adequate demonstration of the model, and that performance can only be gauged from the results of many different analyses and tests.

Statistical evaluation of MM5 data vs observations for 2009, 2010 and 2011

All years analysed met the IOA benchmark for wind speed. The IOA developed by Willmott (1981) is a standardised measure of the degree of model prediction error and varies between 0 and 1, where 1 indicates perfect agreement. The IOA is often thought as the best indicator of overall model performance. The 12 km MM5 data showed a positive wind speed bias for all years. This is not unexpected for MM5 model data. The strongest wind bias was observed for 2011.

For wind direction, all the years met the benchmark requirements for the Bias statistic. The models were slightly higher than the benchmark statistics for the Gross Error indicating some randomness to the MM5 data that is not in the observation data. Both temperature and humidity met all the benchmark criteria for all three years.

Neither the wind speed and direction statistics are unexpected due to the 12 kilometre data used in the model.

Statistical evaluation between MM5 and 5 observation stations for 2009, 2010 and 2011 for wind speed, direction, temperature and specific humidity.

Wind Speed (m/s)

Years Modelled	IOA	BIAS	RMSE	RMSES/RMSE	Gross Error
Mean					
2009	0.64	0.80	2.27	0.83	1.86
2010	0.62	0.98	2.33	0.85	1.94
2011	0.62	1.05	2.28	0.85	1.90
Fraction meeting benchmark					
2009	0.65	0.30	0.33		
2010	0.56	0.25	0.30		
2011	0.62	0.17	0.33		
Total no. days	365	365	365	365	365

Wind Direction (deg)

Years Modelled	BIAS	Gross Error
Mean		
2009	-4.86	51.51
2010	-6.87	48.16
2011	-7.02	53.61
Fraction meeting benchmark		
2009	0.31	0.20
2010	0.34	0.24
2011	0.26	0.13
Total no. days	365	365

Temperature (K)

Years Modelled	IOA	BIAS	Gross Error	RMSE	RMSES/RMSE
Mean					
2009	0.81	-0.50	2.09	2.53	0.73
2010	0.82	-0.36	1.94	2.36	0.70
2011	0.79	-0.29	2.00	2.43	0.71
Fraction meeting benchmark					
2009	0.65	0.25	0.62		
2010	0.64	0.30	0.64		
2011	0.59	0.31	0.60		
Total no. days	365	365	365	365	365

Specific humidity (g/kg)					
Years Modelled	**IOA**	**BIAS**	**Gross Error**	**RMSE**	**RMSES/RMSE**
Mean					
2009	0.48	0.210	1.29	1.53	0.81
2010	0.49	-0.02	1.26	1.49	0.80
2011	0.47	0.22	1.35	1.60	0.83
Fraction meeting benchmark					
2009	0.27	0.65	0.87		
2010	0.28	0.66	0.88		
2011	0.24	0.59	0.83		
Total no. days	365	365	365	365	365

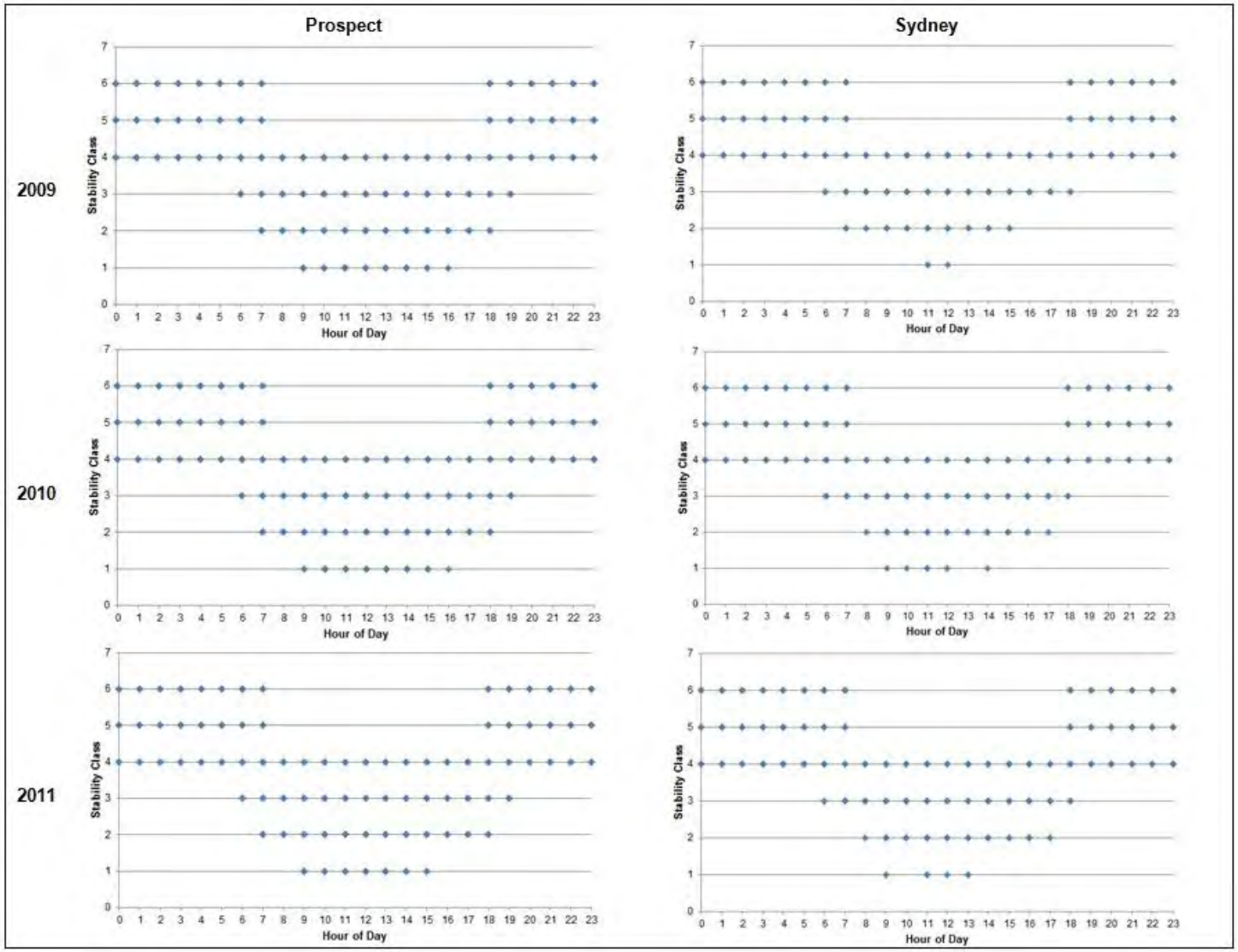
Stability class

Stability is a measure of the convective properties of a parcel of air. Stable conditions occur when convective processes are low, while unstable conditions are associated with stronger convective processes, which are associated with potentially rapid changes in temperature. Stable atmospheres occur when a parcel of air is cooler than the surrounding environment, so the parcel of air (and any pollution within it) sinks. Conversely, unstable atmospheres occur when a parcel of air is warmer than the surrounding environment, making the parcel of air buoyant and, subsequently, leading to the parcel of air rising.

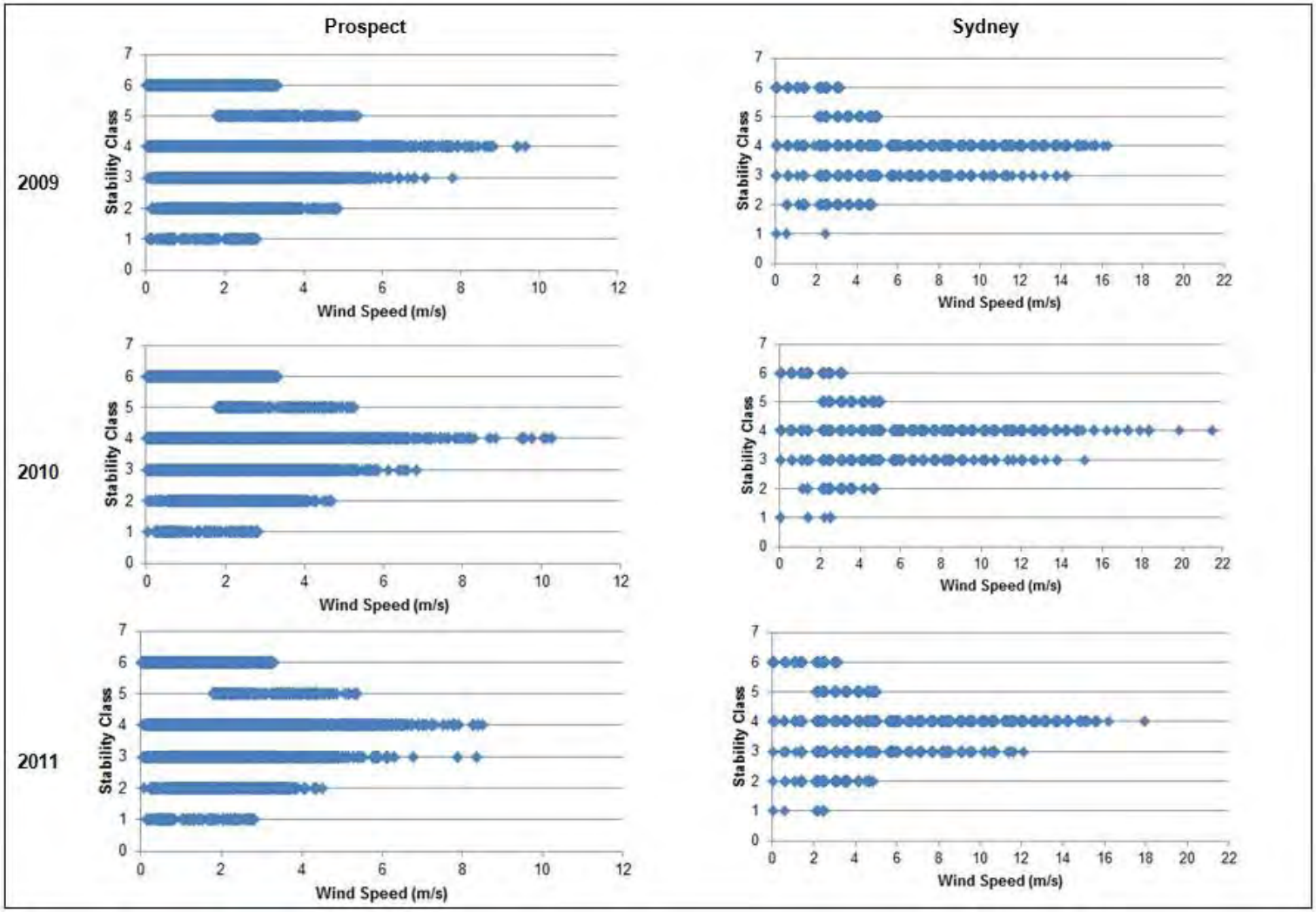
Stability class data extracted from the CALMET files at locations representing the Prospect and Sydney Airport monitoring stations were analysed. The following charts indicate stability classes designated as 1 to 6, which correspond to the Pasquill-Gifford A – F stability class designations (1 corresponds to A class and 6 corresponds to F class). Classes A, B and C (or 1, 2 and 3) represent unstable conditions, with class A representing very unstable conditions and C representing slightly unstable conditions. Class D (4) stability corresponds to neutral conditions, which are typical during overcast days and nights. Classes E and F (5 and 6) correspond to slightly stable and stable conditions respectively, which occur at night.

The stability class data were charted for time of day as shown in the first of the following charts. As expected, the stability classes indicate stable conditions during the night hours and neutral and unstable conditions during the day.

The stability classes were then plotted by wind speed as shown in the second of the following charts. The plots show the typical patterns of wind speed by stability class as expected. The wind speeds logged at Sydney were higher than those recorded at Prospect, but both sites displayed the same pattern, where, as expected, the highest wind speeds were associated with neutral conditions.



Stability classes by hour of day – Prospect and Sydney, 2009 – 2011

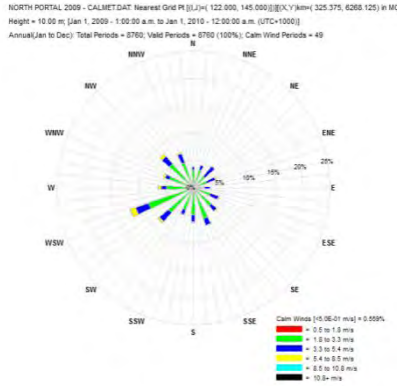


Stability classes by wind speeds – Prospect and Sydney, 2009 - 2011

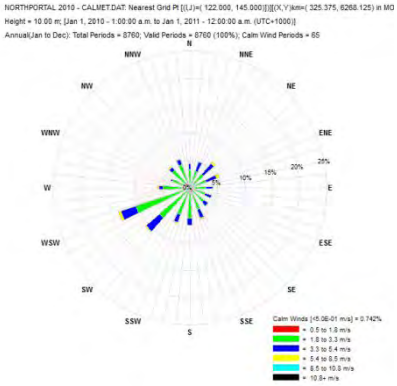
Wind roses

Wind roses extracted from CALMET for the northern and southern ventilation outlet locations are provided below, and are followed by wind roses for each of the BOM and OEH site used in the modelling for each of the three years. For evaluation purposes, the roses for each station are shown side by side for each of the three years. Year by year intercomparison in this way provided a simple method to evaluate the suitableness of each year analysed. The wind roses are split by season and by time of day into morning (7 am – 11 am), afternoon (12 pm – 6 pm), evening, (7 pm – 12 am) and night (1 am – 6 am). Wind direction is taken as the direction of the wind bar toward the centre of the rose.

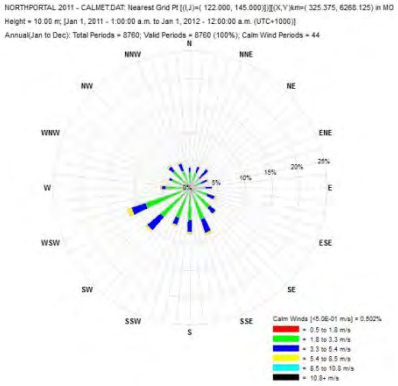
Annual, seasonal and diurnal wind roses for northern ventilation outlet for 2009, 2010, 2011 (CALMET-generated data)



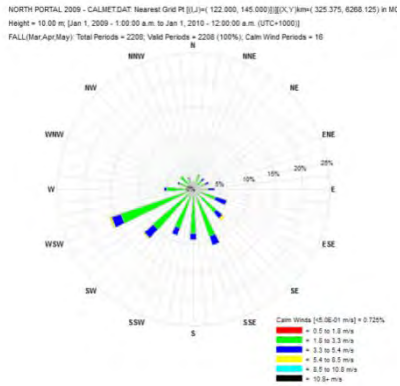
Annual – 2009, northern ventilation outlet



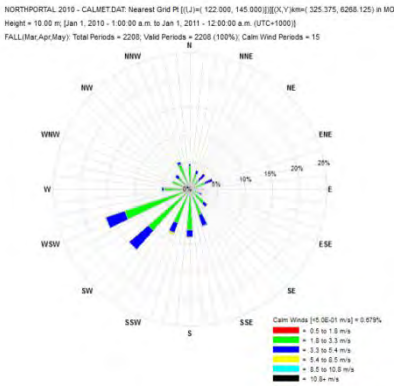
Annual – 2010, northern ventilation outlet



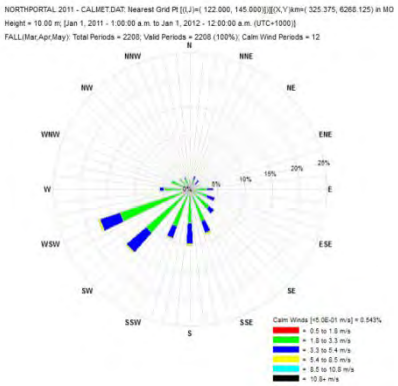
Annual – 2011, northern ventilation outlet



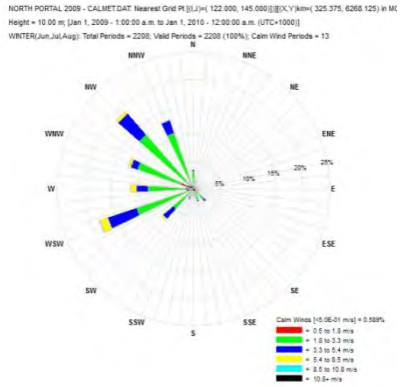
Autumn – March, April, May 2009, northern ventilation outlet



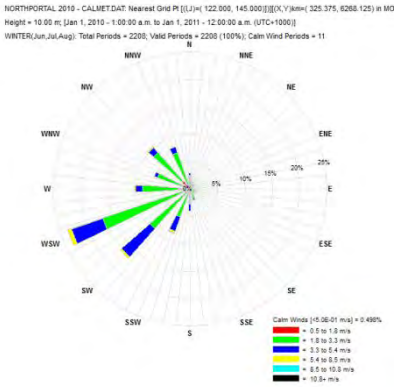
Autumn – March, April, May 2010, northern ventilation outlet



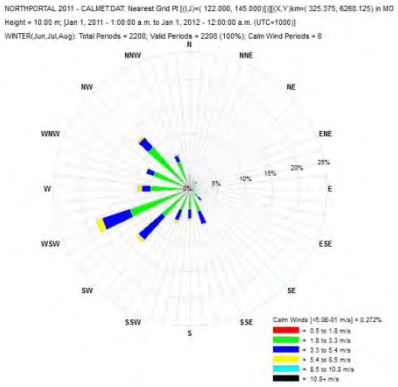
Autumn – March, April, May 2011, northern ventilation outlet



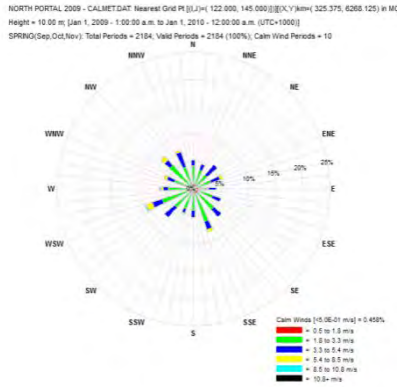
Winter – June, July, August 2009, northern ventilation outlet



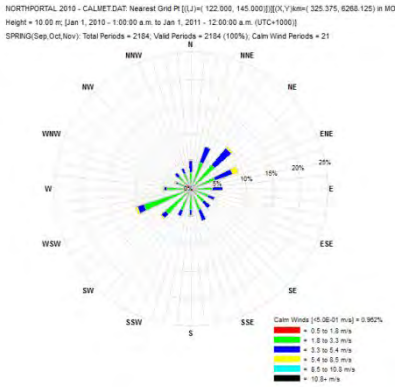
Winter – June, July, August 2010, northern ventilation outlet



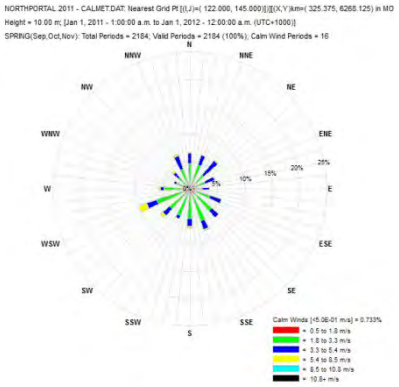
Winter – June, July, August 2011, northern ventilation outlet



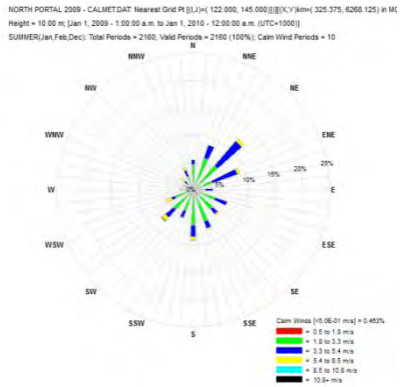
Spring –Sep, Oct, Nov, 2009, northern ventilation outlet



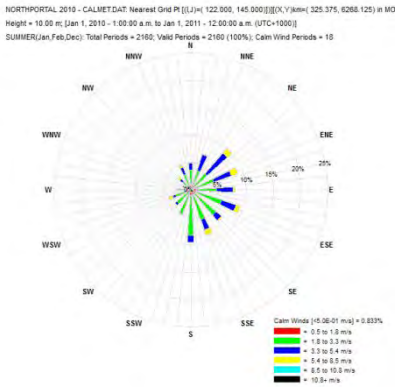
Spring –Sep, Oct, Nov, 2010, northern ventilation outlet



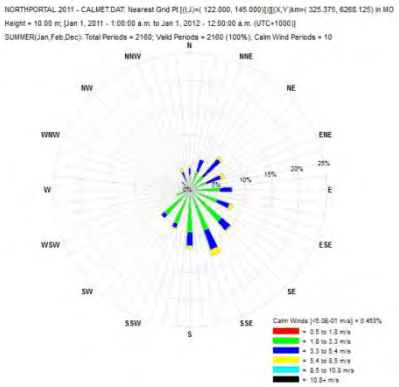
Spring –Sep, Oct, Nov, 2011, northern ventilation outlet



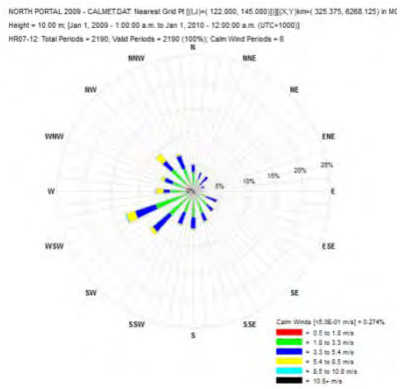
Summer –Dec, Jan, Feb, 2009, northern ventilation outlet



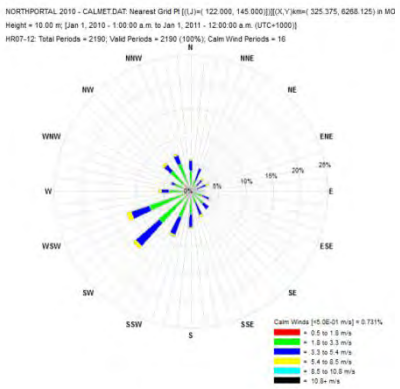
Summer –Dec, Jan, Feb, 2010, northern ventilation outlet



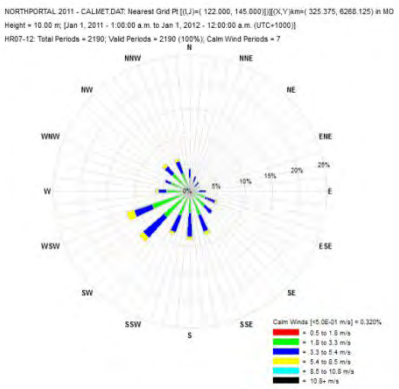
Summer –Dec, Jan, Feb, 2011, northern ventilation outlet



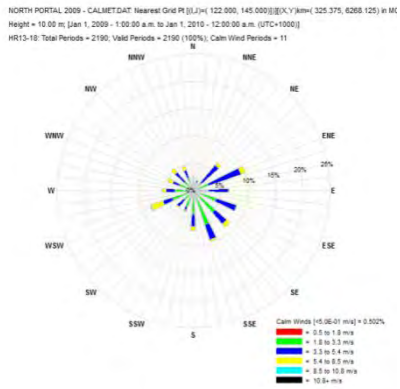
Morning (7am – 11am), 2009 northern ventilation outlet

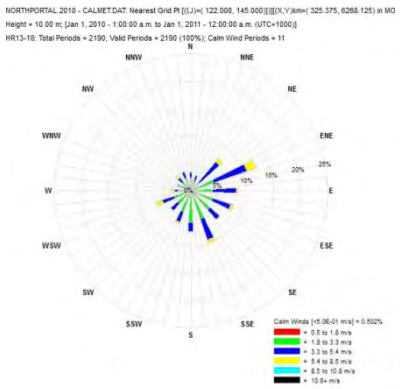


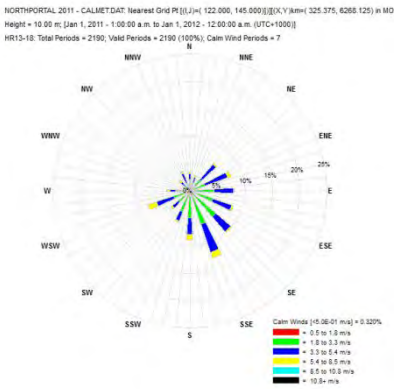
Morning (7am – 11am), 2010 northern ventilation outlet



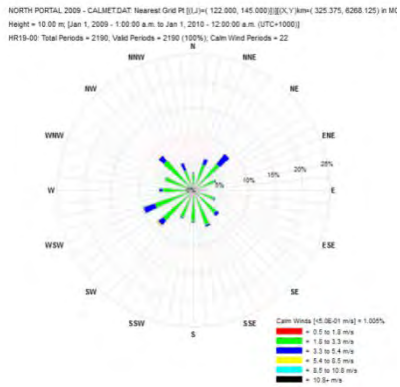
Morning (7am – 11am), 2011, northern ventilation outlet



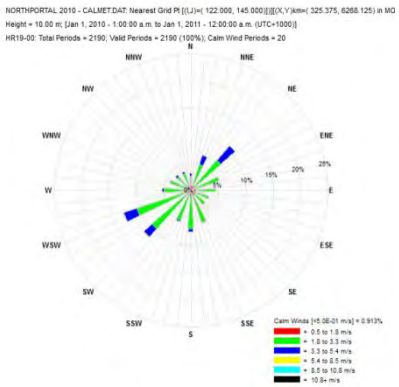




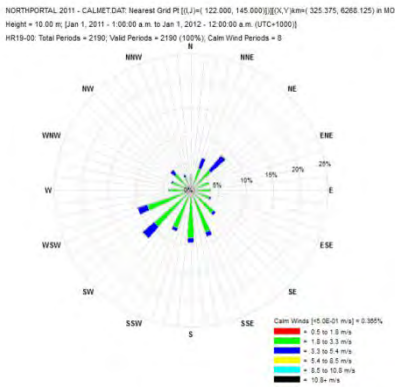
Afternoon (12pm – 6pm), northern ventilation outlet, 2009



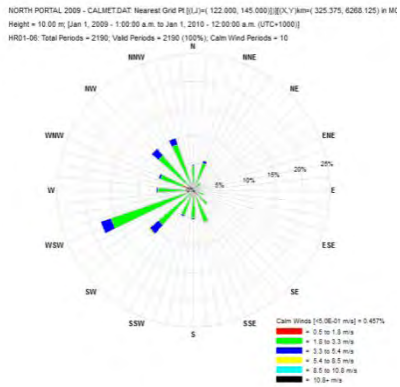
Afternoon (12pm – 6pm), northern ventilation outlet, 2010



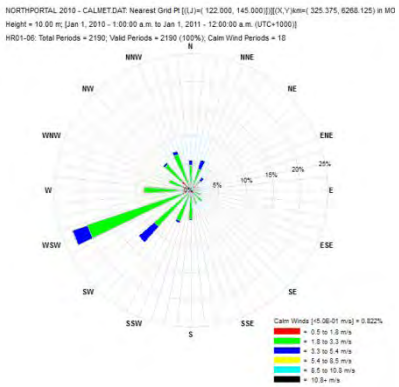
Afternoon (12pm – 6pm), northern ventilation outlet, 2011



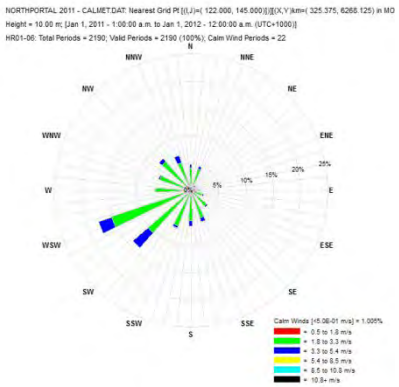
Evening (7pm – 12am), northern ventilation outlet, 2009



Evening (7pm – 12am), northern ventilation outlet, 2010



Evening (7pm – 12am), northern ventilation outlet t, 2011

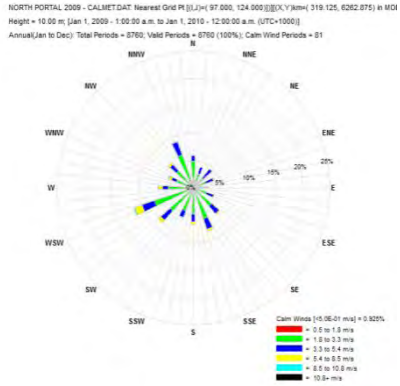


Night (1am – 6am), northern ventilation outlet, 2009

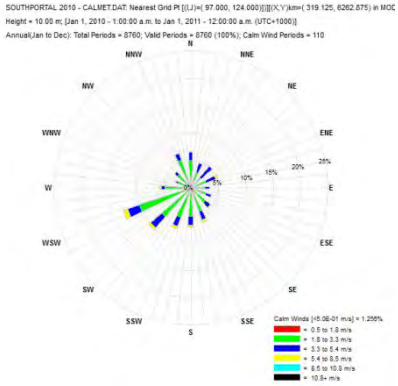
Night (1am – 6am), northern ventilation outlet, 2010

Night (1am – 6am), northern ventilation outlet, 2011

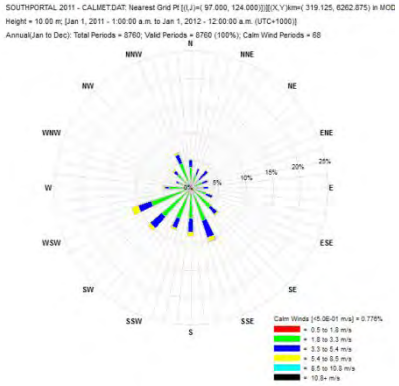
Annual, seasonal and diurnal wind roses for southern ventilation outlet for 2009, 2010, 2011 (CALMET-generated data)



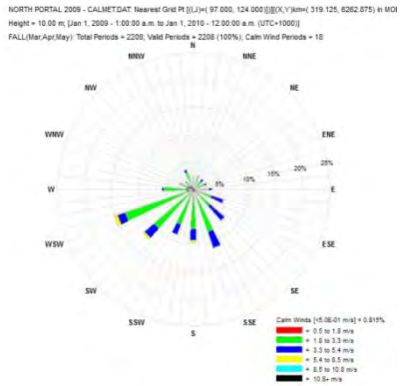
Annual – southern ventilation outlet, 2009



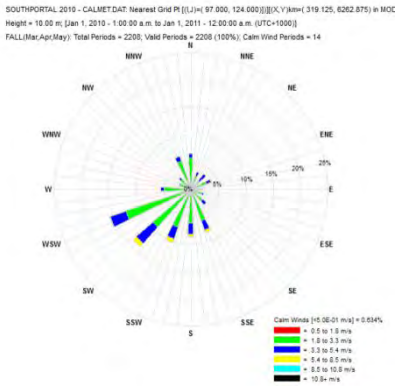
Annual – southern ventilation outlet, 2010



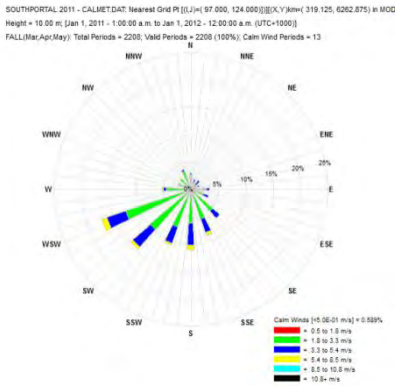
Annual –southern ventilation outlet, 2011



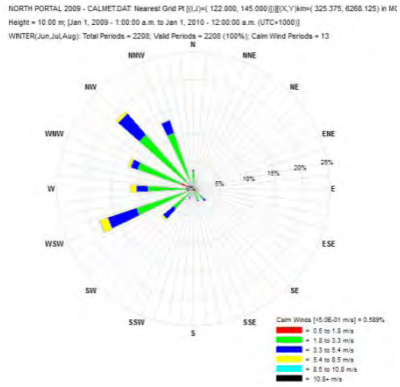
Autumn –southern ventilation outlet, 2009



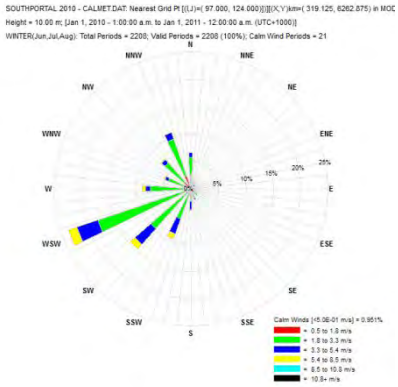
Autumn –southern ventilation outlet, 2010



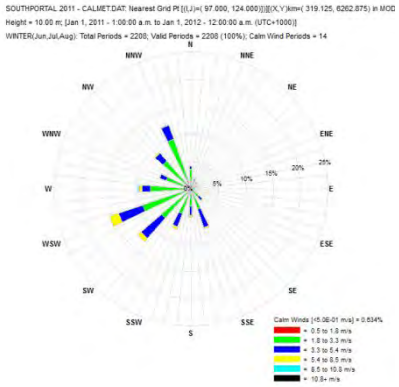
Autumn –southern ventilation outlet, 2011



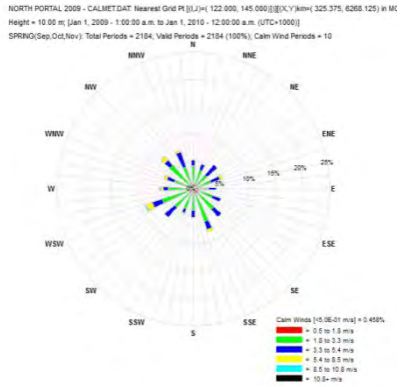
Winter –southern ventilation outlet, 2009



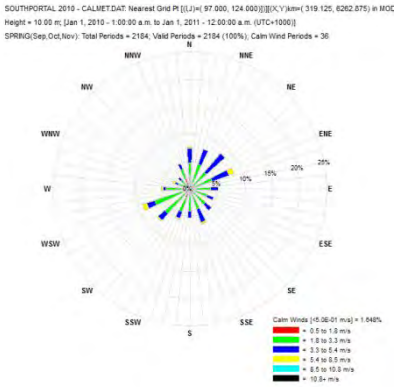
Winter – southern ventilation outlet, 2010



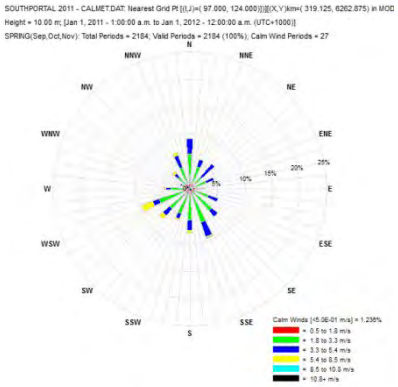
Winter – southern ventilation outlet, 2011



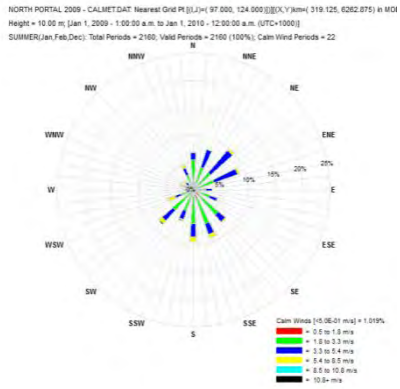
Spring – southern ventilation outlet, 2009



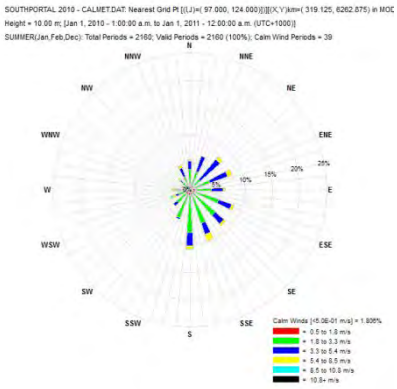
Spring – southern ventilation outlet, 2010



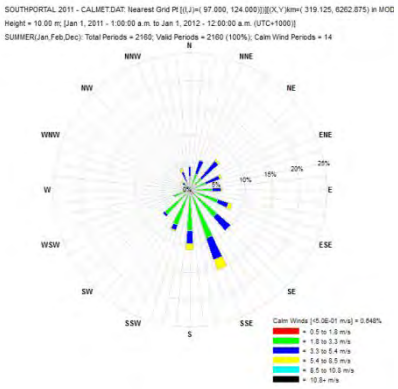
Spring – southern ventilation outlet, 2011



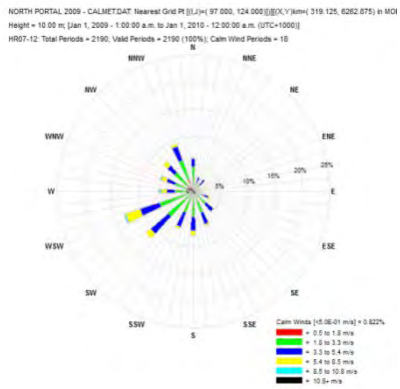
Summer –southern ventilation outlet, 2009



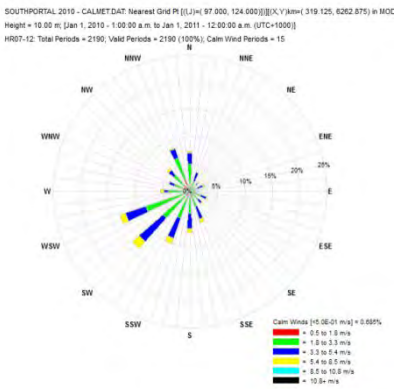
Summer – southern ventilation outlet, 2010



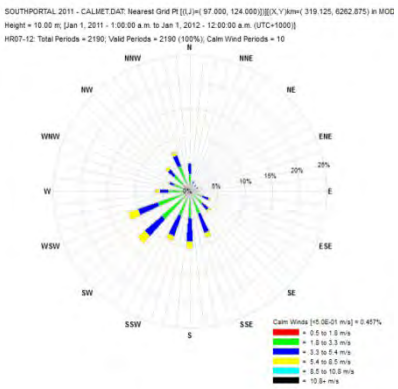
Summer –southern ventilation outlet, 2011



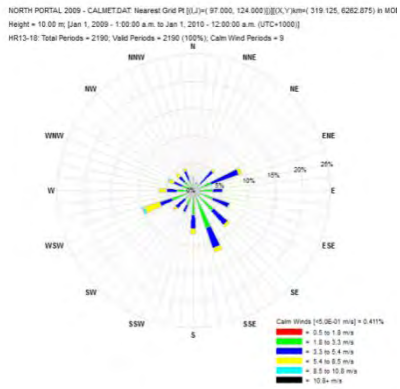
Morning (7am – 12pm) – southern ventilation outlet, 2009

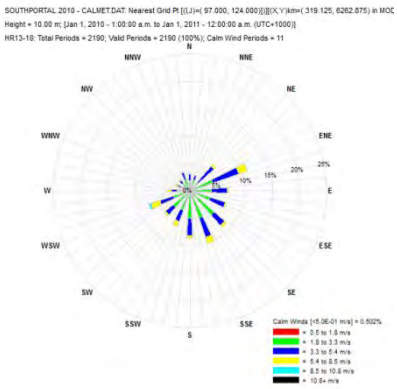


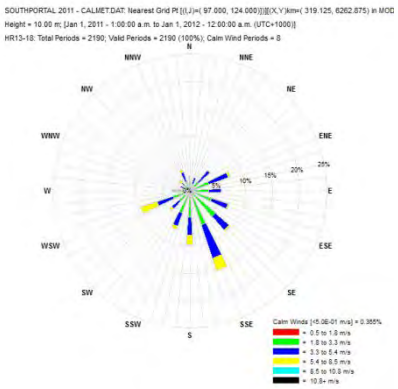
Morning (7am – 12pm) – southern ventilation outlet, 2010



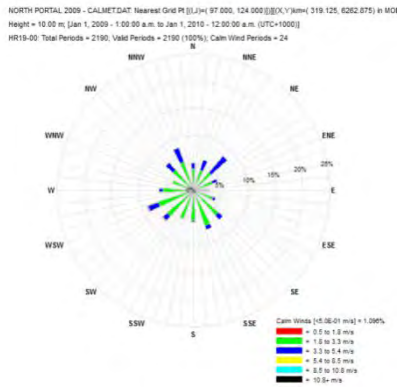
Morning (7am – 12pm) – southern ventilation outlet, 2011



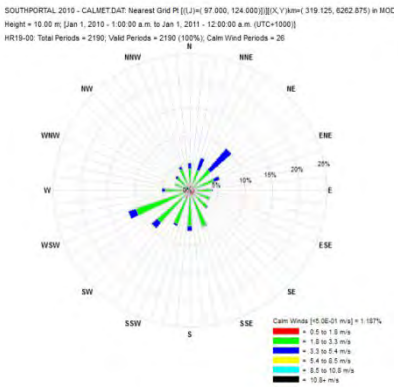




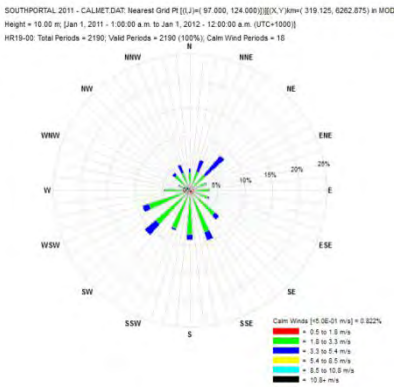
Afternoon (1pm – 6pm – southern ventilation outlet, 2009



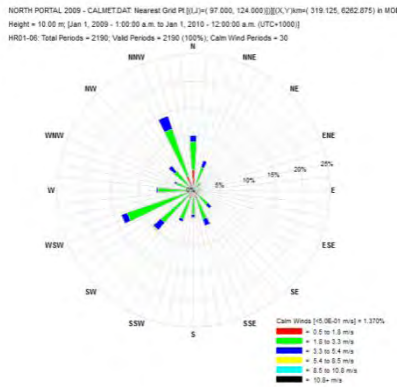
Afternoon (1pm – 6pm) – southern ventilation outlet, 2010



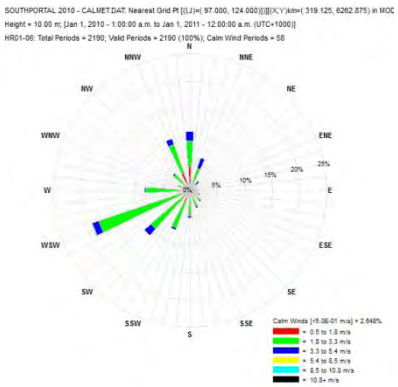
Afternoon (1pm – 6pm) – southern ventilation outlet, 2011



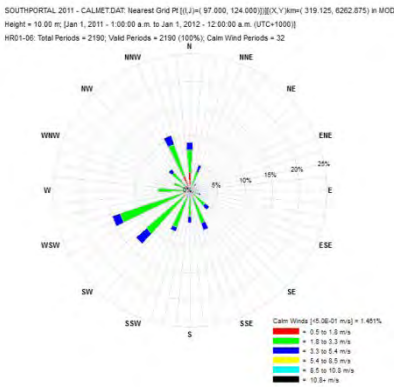
Evening (7pm – 12am) – southern ventilation outlet, 2009



Evening (7pm – 12am) – southern ventilation outlet, 2010



Evening (7pm – 12am) – southern ventilation outlet, 2011

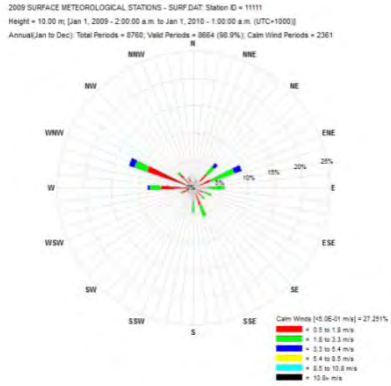


Night (1am – 6am) – southern ventilation outlet, 2009

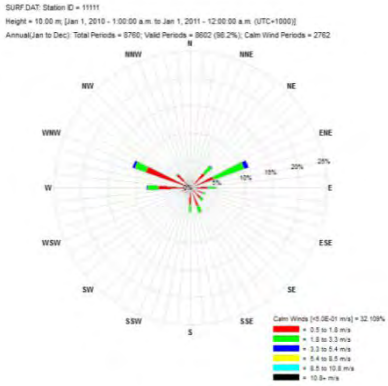
Night (1am – 6am) – southern ventilation outlet, 2010

Night (1am – 6am) – southern ventilation outlet, 2011

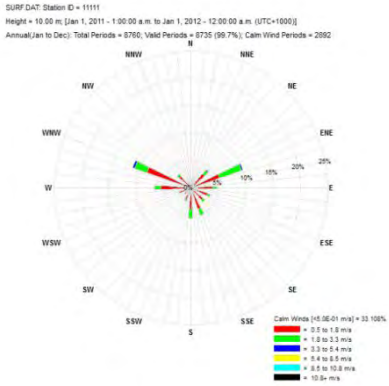
Annual, seasonal and diurnal wind roses for Lindfield Meteorological Station for 2009, 2010, 2011 (Measured data)



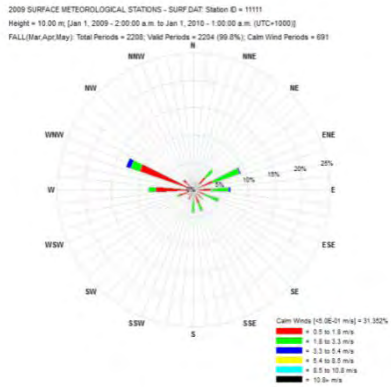
Annual – 2009, Lindfield



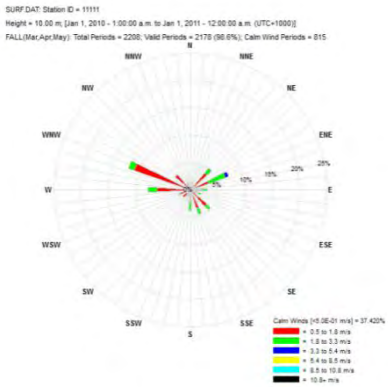
Annual – 2010, Lindfield



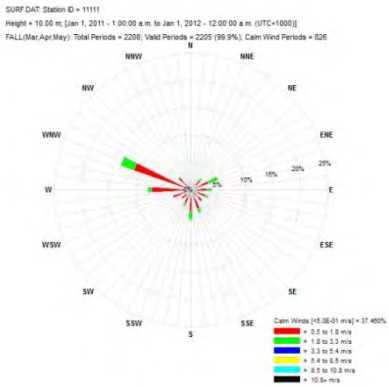
Annual – 2011, Lindfield



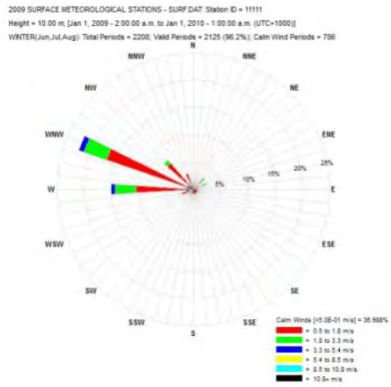
Autumn – March, April, May 2009, Lindfield



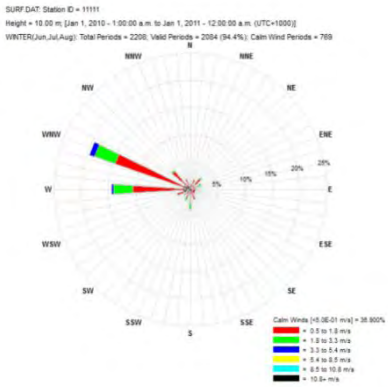
Autumn – March, April, May 2010, Lindfield



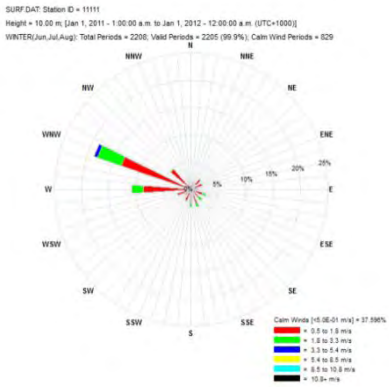
Autumn – March, April, May 2011, Lindfield



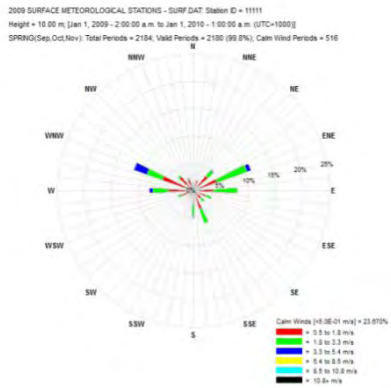
Winter – June, July, August 2009, Lindfield

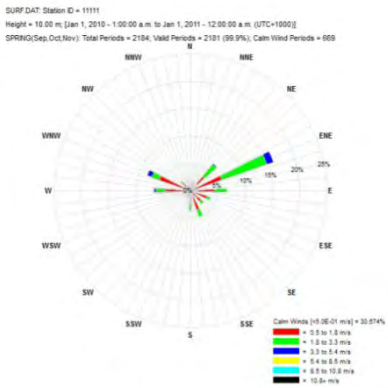


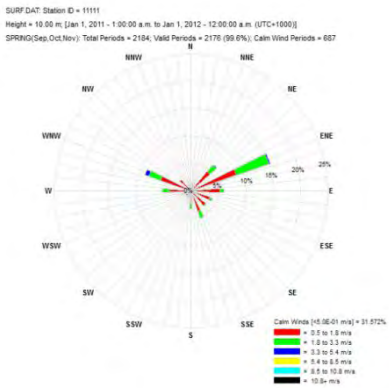
Winter – June, July, August 2010, Lindfield



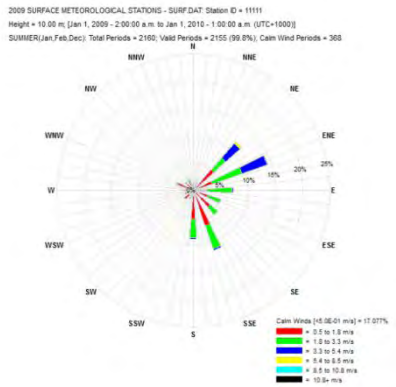
Winter – June, July, August 2011, Lindfield



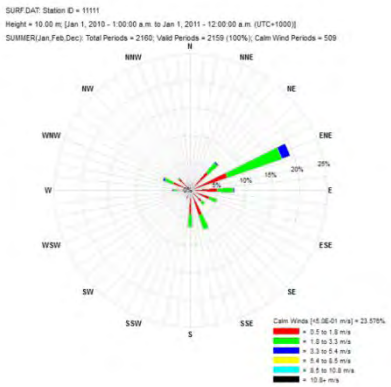




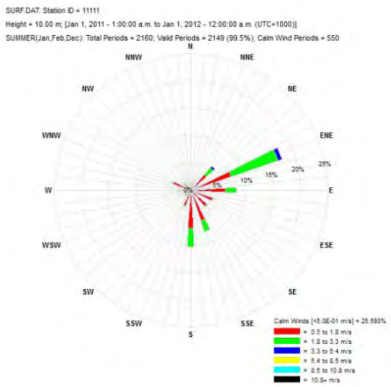
Spring –September, October, November, 2009



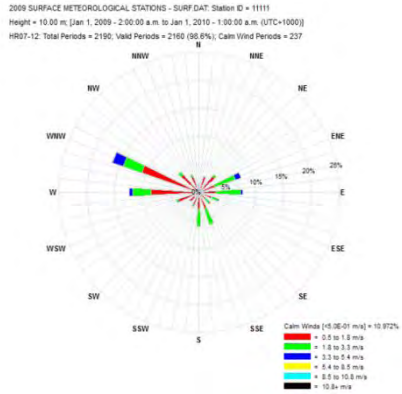
Spring –September, October, November, 2010



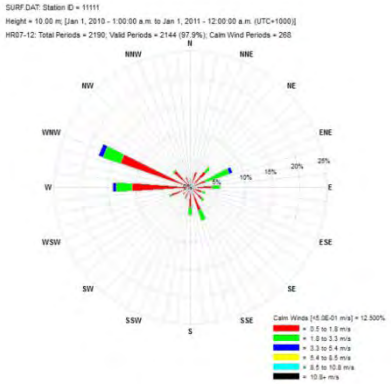
Spring –September, October, November, 2011



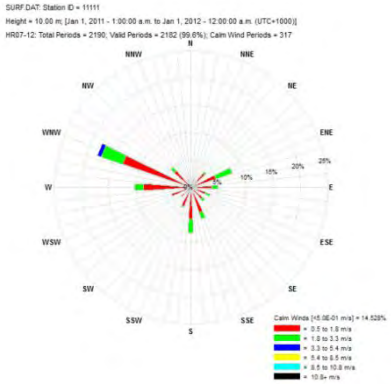
Summer –December, January, February, 2009, Lindfield



Summer –December, January, February, 2010, Lindfield



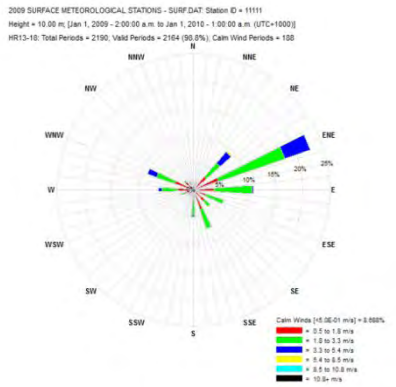
Summer –December, January, February, 2011, Lindfield

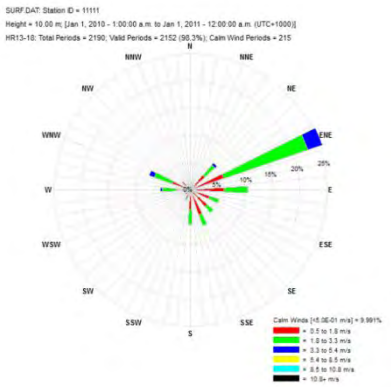


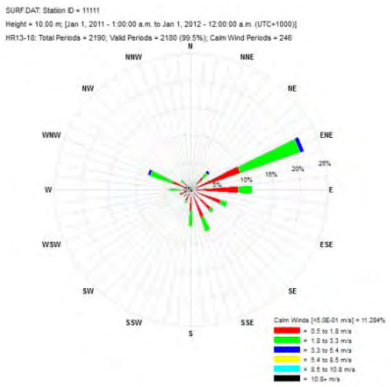
Morning (7am – 12pm), Lindfield, 2009

Morning (7am – 12pm), Lindfield, 2010

Morning (7am – 12pm), Lindfield, 2011







Afternoon (1pm – 6pm), Lindfield, 2009

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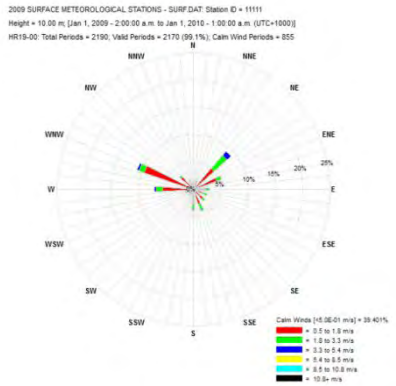
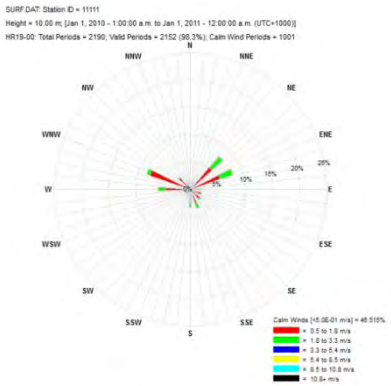
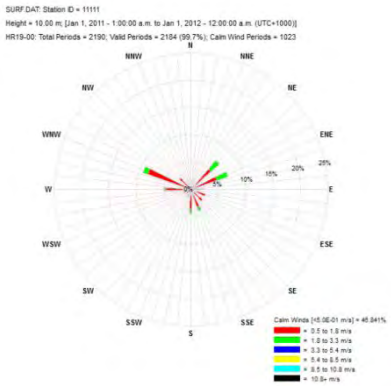
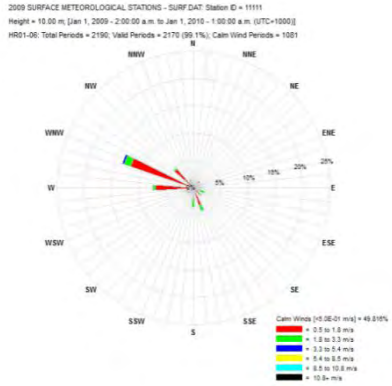
Afternoon (1pm – 6pm), Lindfield, 2011





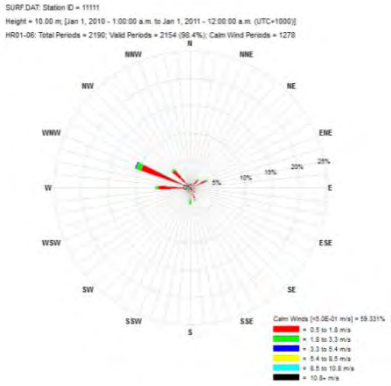


Evening (7pm – 12am), Lindfield, 2009



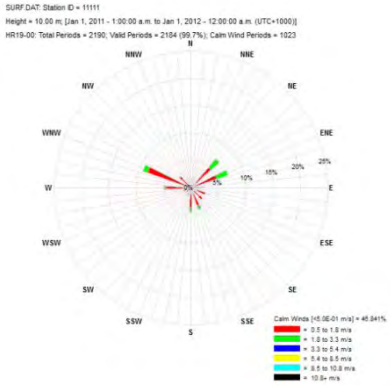
Night (1am – 6am), Lindfield, 2009

Evening (7pm – 12am), Lindfield, 2010



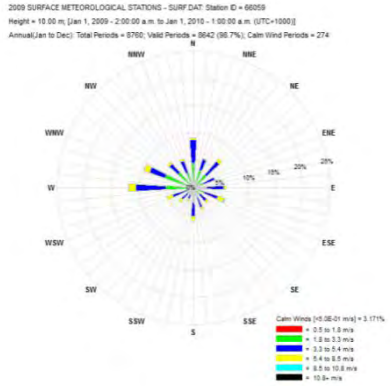
Night (1am – 6am), Lindfield, 2010

Evening (7pm – 12am), Lindfield, 2011

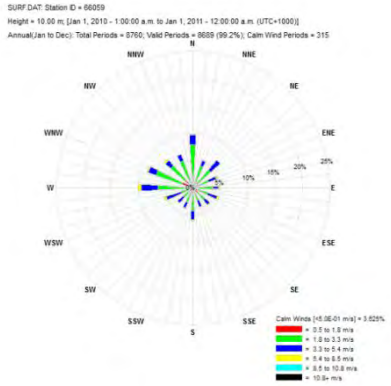


Night (1am – 6am), Lindfield, 2011

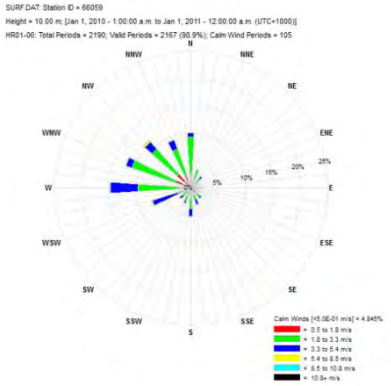
Annual, seasonal and diurnal wind roses for Terrey Hills Meteorological Station for 2009, 2010, 2011 (Measured data)



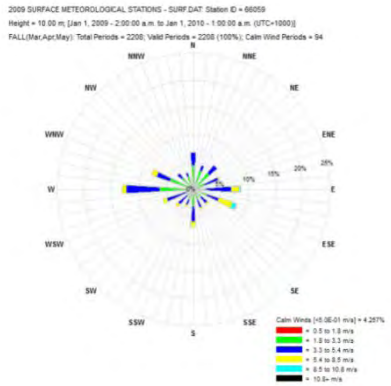
Annual – Terrey Hills (66059), 2009



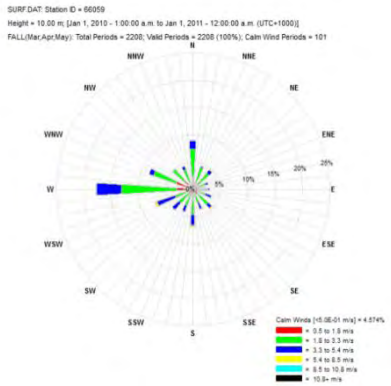
Annual – Terrey Hills (66059), 2010



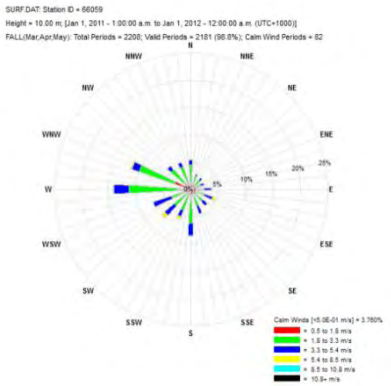
Annual –Terrey Hills (66059), 2011



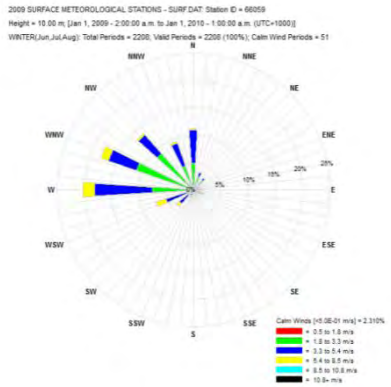
Autumn –Terrey Hills (66059), 2009



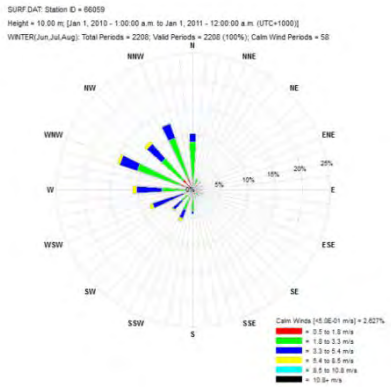
Autumn –Terrey Hills (66059), 2010



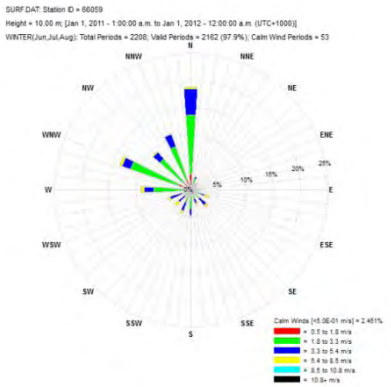
Autumn –Terrey Hills (66059), 2011



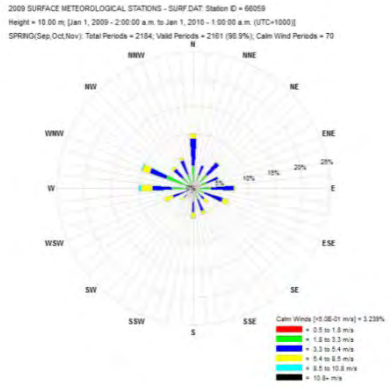
Winter –Terrey Hills (66059), 2009



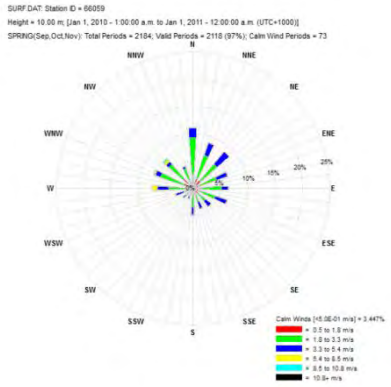
Winter – Terrey Hills (66059), 2010



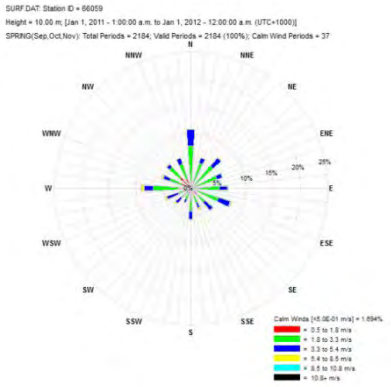
Winter – Terrey Hills (66059), 2011



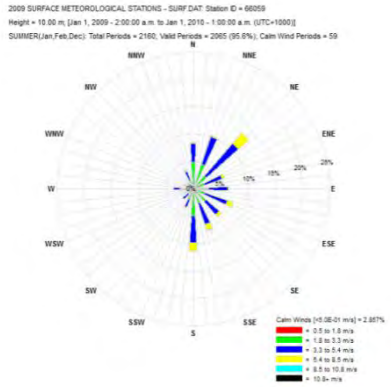
Spring – Terrey Hills (66059), 2009



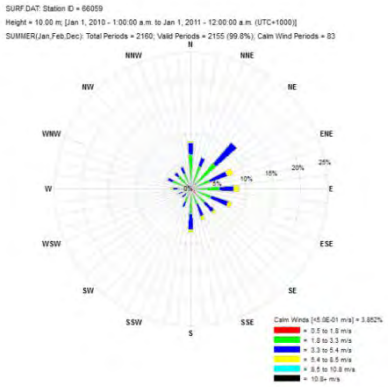
Spring – Terrey Hills (66059), 2010



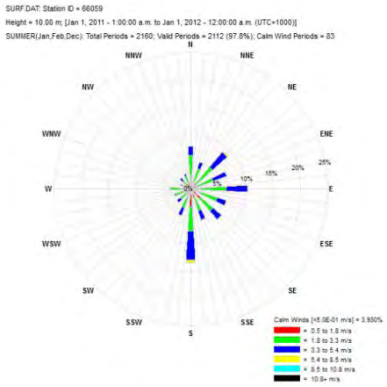
Spring – Terrey Hills (66059), 2011



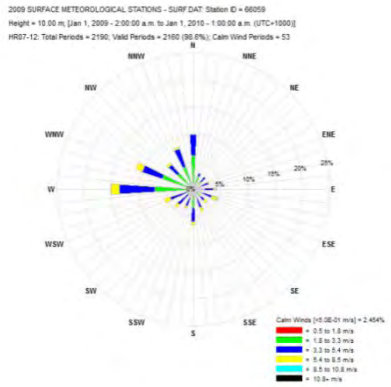
Summer –Terrey Hills (66059), 2009



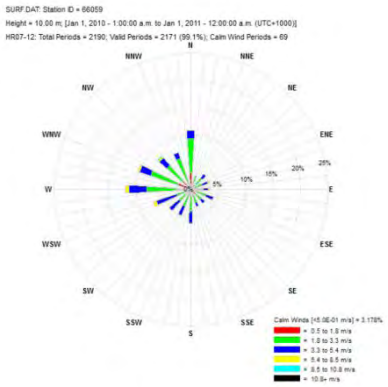
Summer – Terrey Hills (66059), 2010



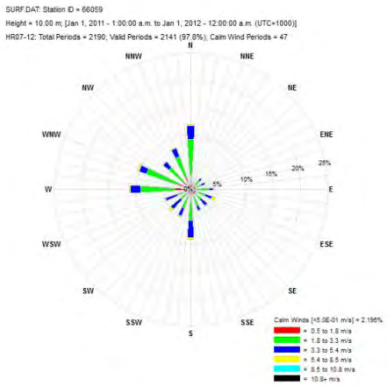
Summer –Terrey Hills (66059), 2011



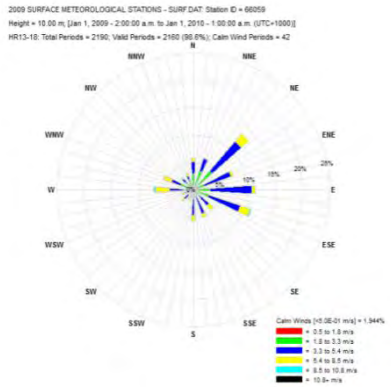
Morning (7am – 12pm) – Terrey Hills, 2009



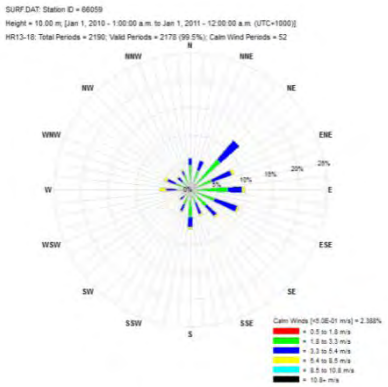
Morning (7am – 12pm) – Terrey Hills, 2010



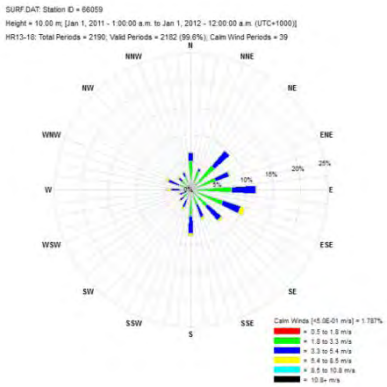
Morning (7am – 12pm) – Terrey Hills, 2011



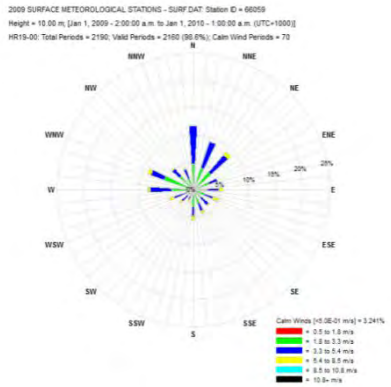
Afternoon (1pm – 6pm) – Terrey Hills, 2009



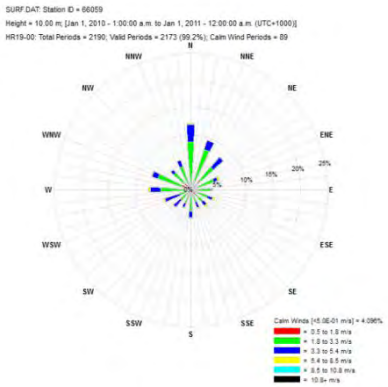
Afternoon (1pm – 6pm) – Terrey Hills, 2010



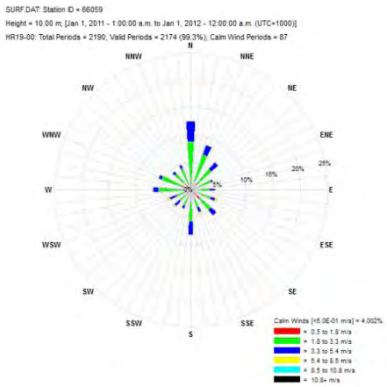
Afternoon (1pm – 6pm) – Terrey Hills, 2011



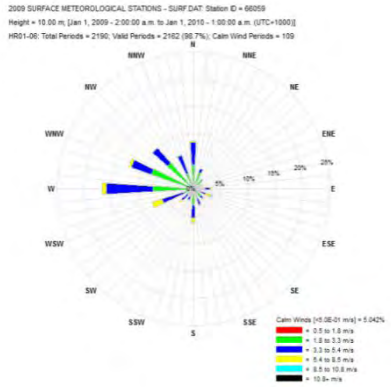
Evening (7pm – 12am) – Terrey Hills, 2009



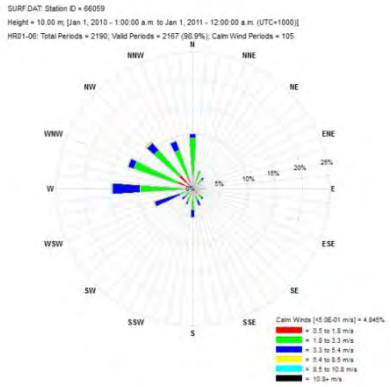
Evening (7pm – 12am) – Terrey Hills, 2010



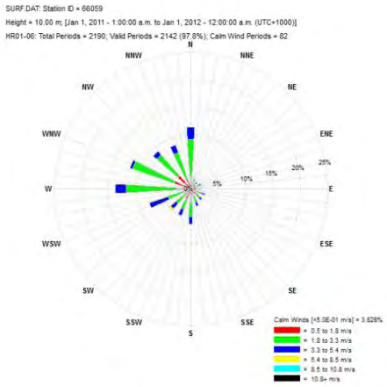
Evening (7pm – 12am) – Terrey Hills, 2011



Night (1am – 6am) – Terrey Hills, 2009

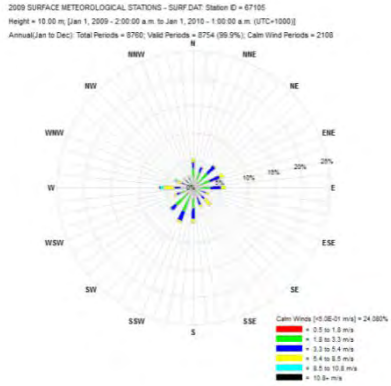


Night (1am – 6am) – Terrey Hills, 2010

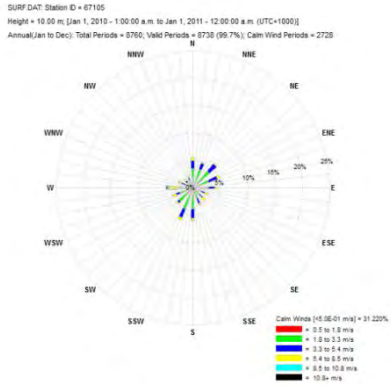


Night (1am – 6am) – Terrey Hills, 2011

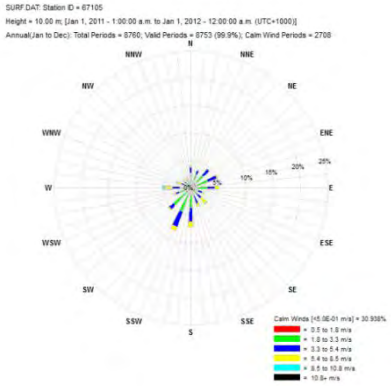
Annual, seasonal and diurnal wind roses for Richmond Meteorological Station for 2009, 2010, 2011 (Measured data)



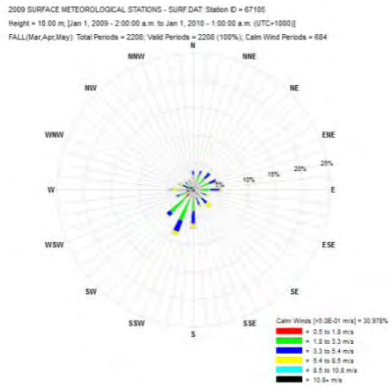
Annual – Richmond RAAF, 2009



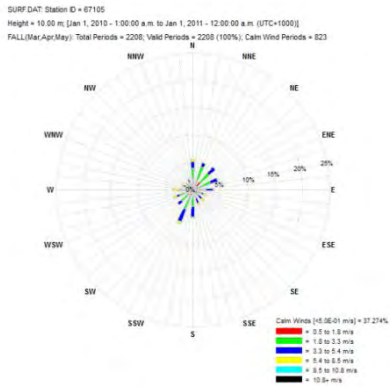
Annual – Richmond RAAF, 2010



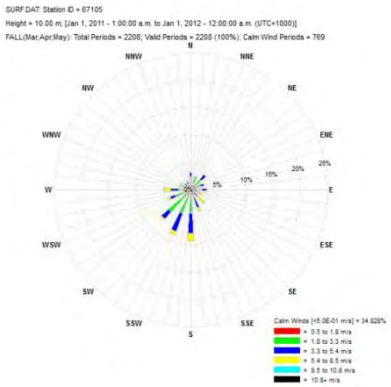
Annual – Richmond RAAF, 2011



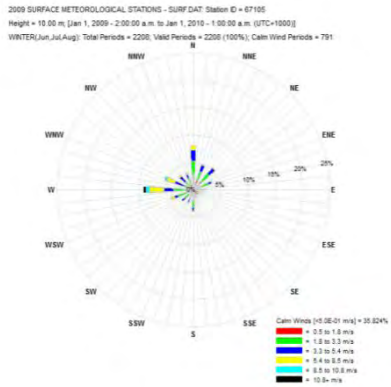
Autumn –Richmond RAAF, 2009



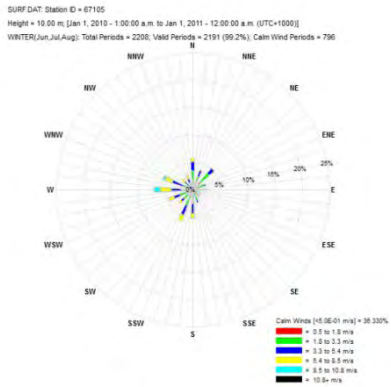
Autumn –Richmond RAAF, 2010



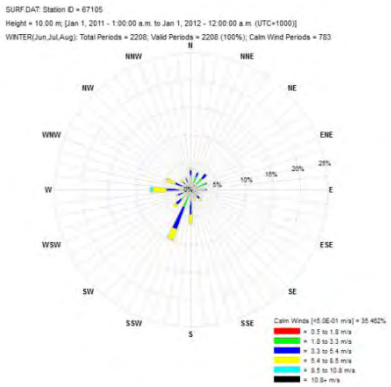
Autumn –Richmond RAAF, 2011



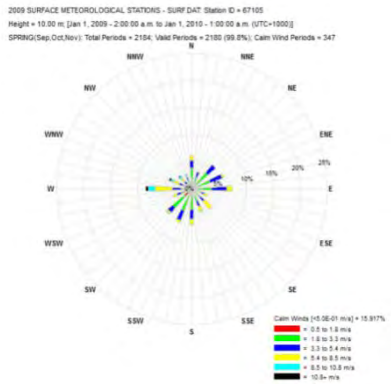
Winter – Richmond RAAF, 2009



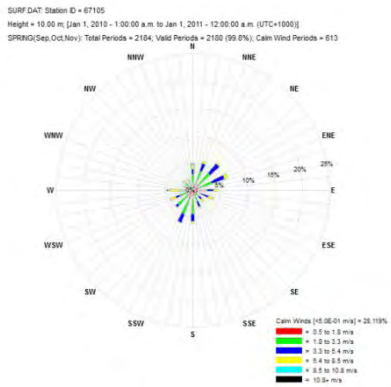
Winter – Richmond RAAF, 2010



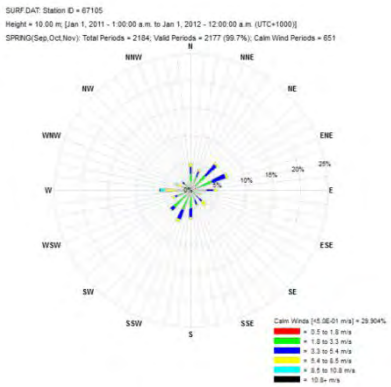
Winter – Richmond RAAF, 2011



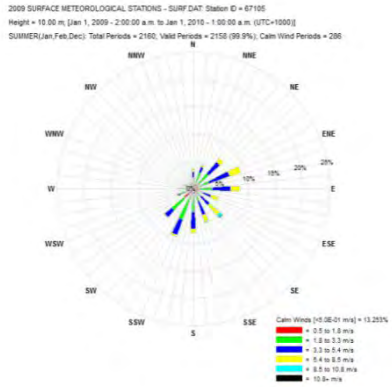
Spring – Richmond RAAF, 2009



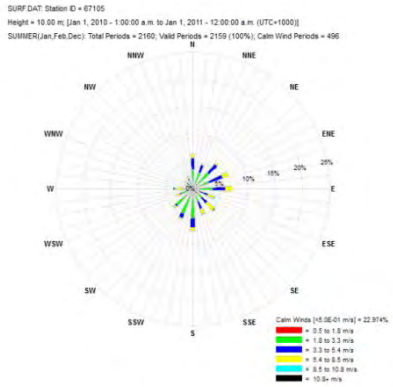
Spring – Richmond RAAF, 2010



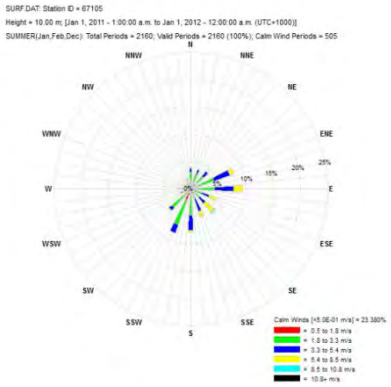
Spring – Richmond RAAF, 2011



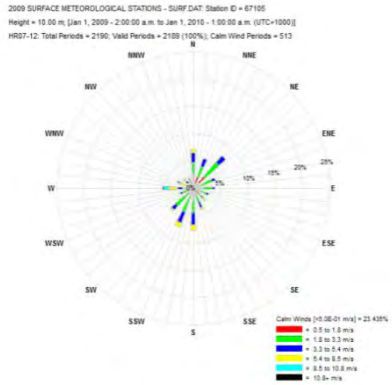
Summer –Richmond RAAF, 2009



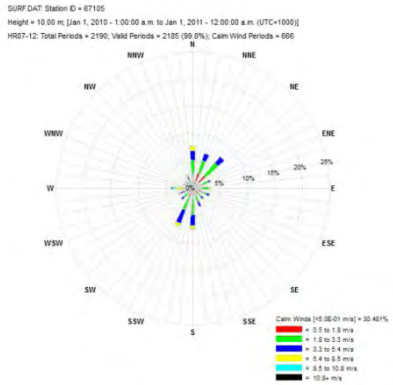
Summer –Richmond RAAF, 2010



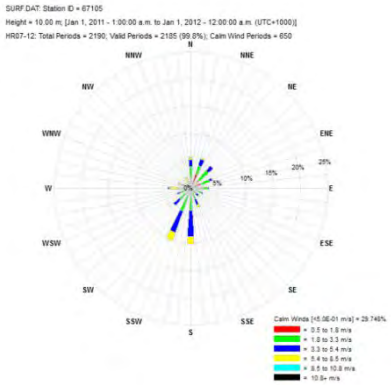
Summer –Richmond RAAF, 2011



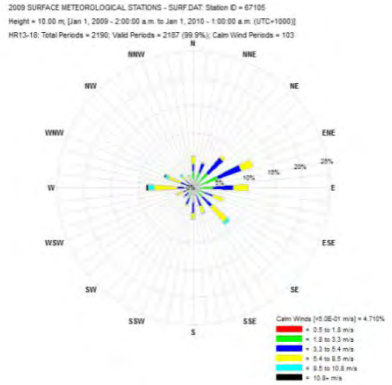
Morning (7am – 12pm) – Richmond, 2009



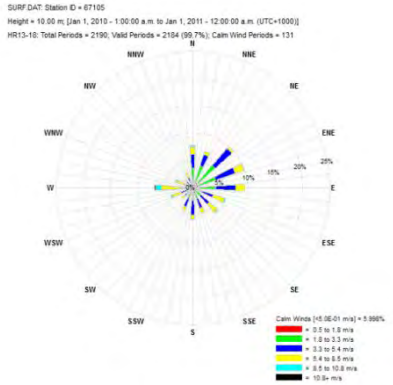
Morning (7am – 12pm) – Richmond, 2010



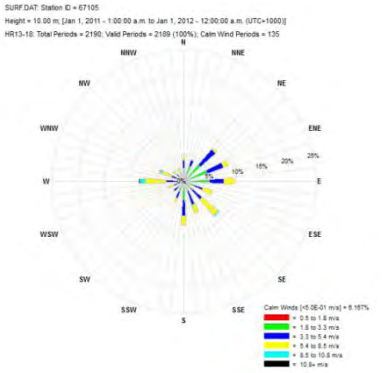
Morning (7am – 12pm) – Richmond, 2011



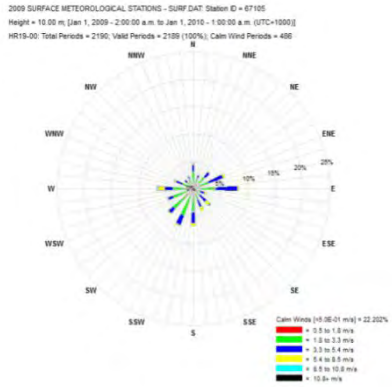
Afternoon (1pm – 6pm) – Richmond, 2009

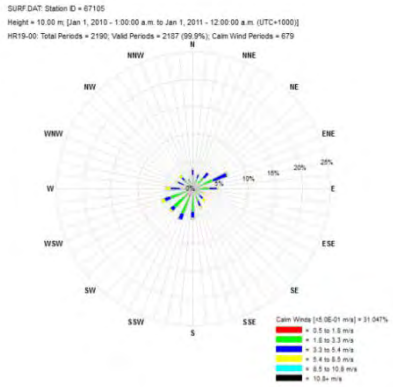


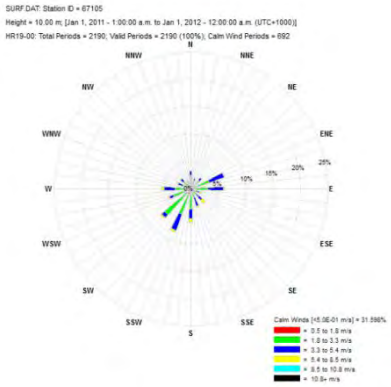
Afternoon (1pm – 6pm) – Richmond, 2010



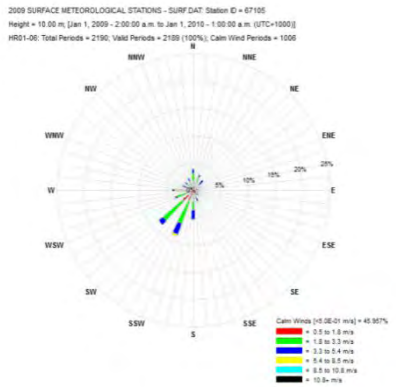
Afternoon (1pm – 6pm) – Richmond, 2011



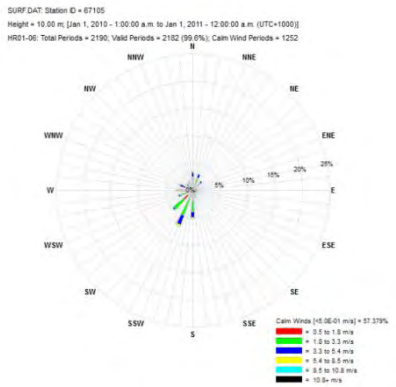




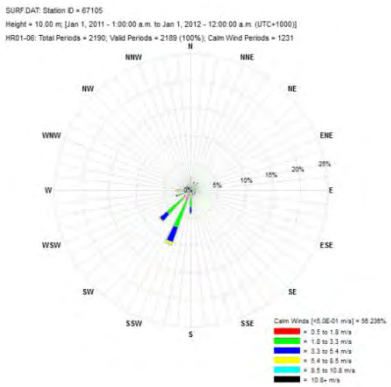
Evening (7pm – 12am) – Richmond, 2009



Evening (7pm – 12am) – Richmond, 2010



Evening (7pm – 12am) – Richmond, 2011

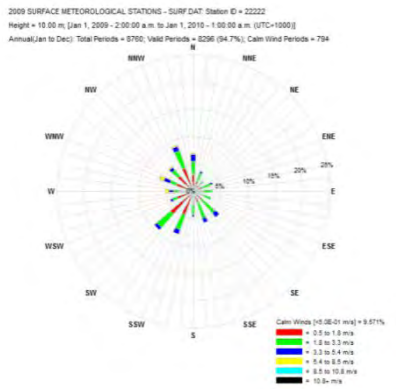


Night (1am – 6am) – Richmond, 2009

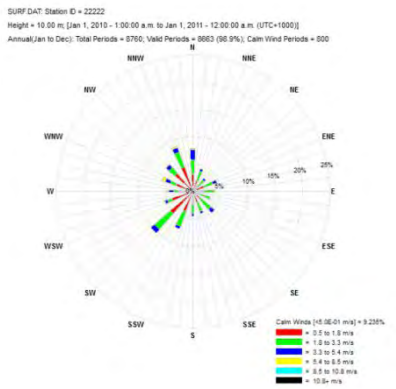
Night (1am – 6am) – Richmond, 2010

Night (1am – 6am) – Richmond, 2011

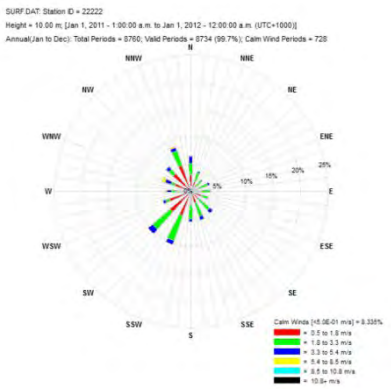
Annual, seasonal and diurnal wind roses for Richmond Meteorological Station for 2009, 2010, 2011 (Measured data)



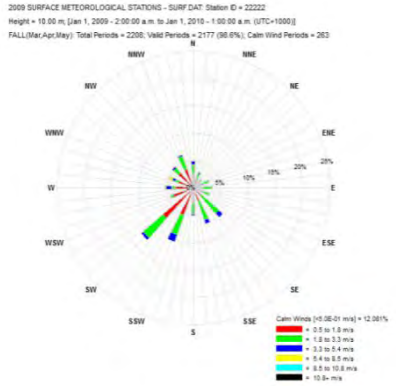
Annual – Prospect , 2009



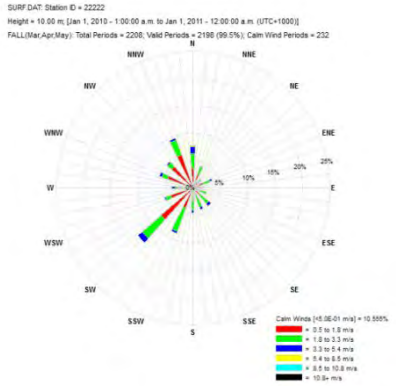
Annual – Prospect , 2010



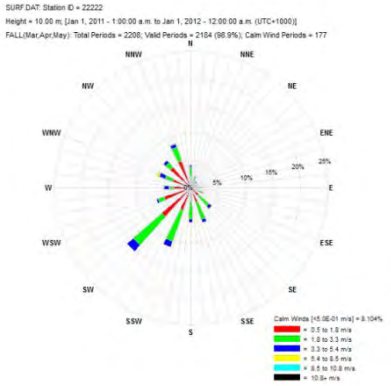
Annual – Prospect , 2011



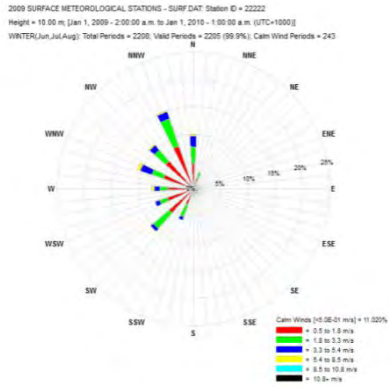
Autumn –Prospect , 2009



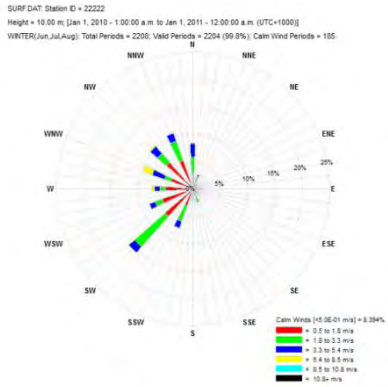
Autumn –Prospect , 2010



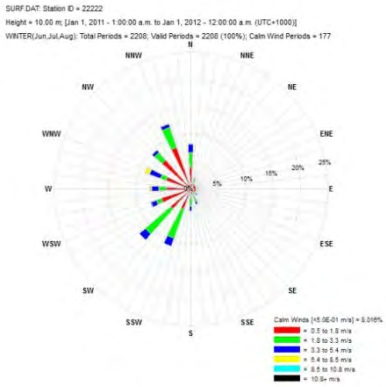
Autumn –Prospect , 2011



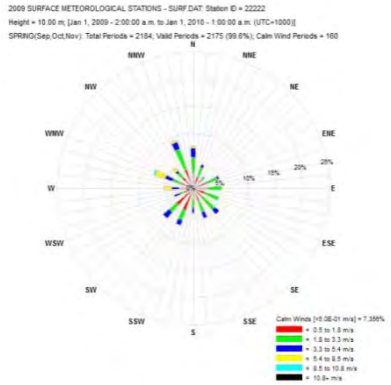
Winter – Prospect , 2009



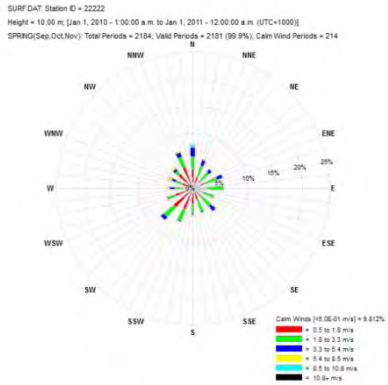
Winter – Prospect , 2010



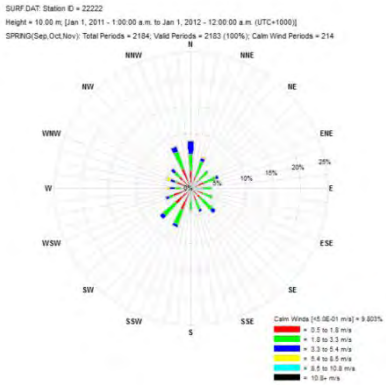
Winter – Prospect , 2011



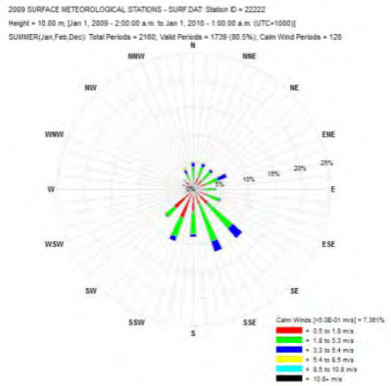
Spring – Prospect , 2009



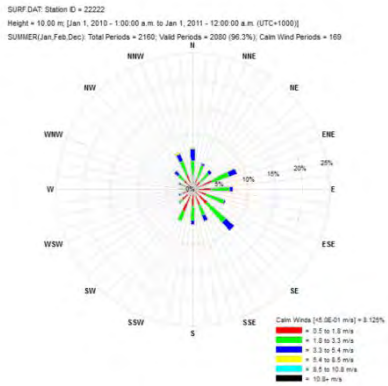
Spring – Prospect , 2010



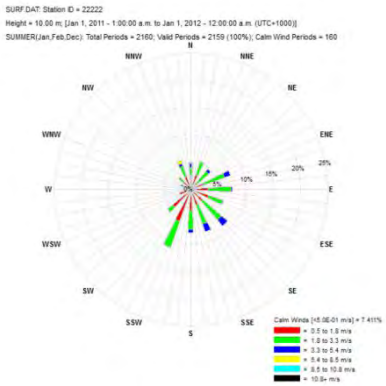
Spring – Prospect , 2011



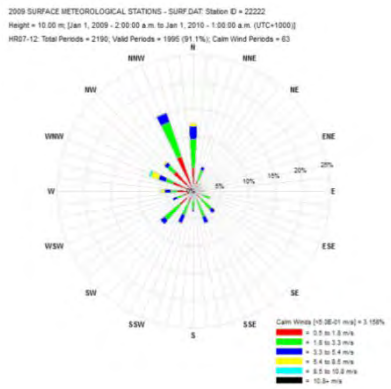
Summer –Prospect , 2009



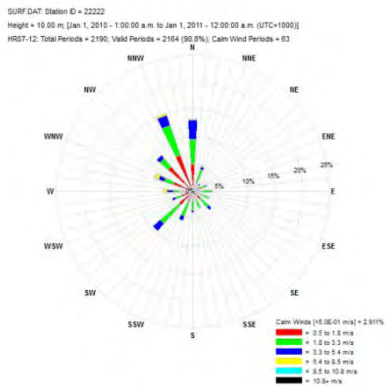
Summer –Prospect , 2010



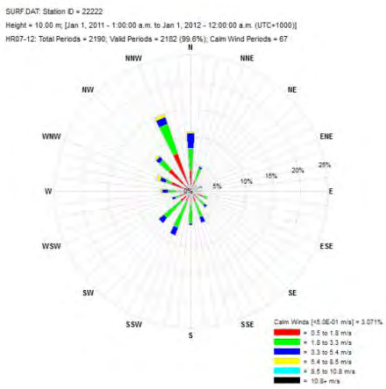
Summer –Prospect , 2011



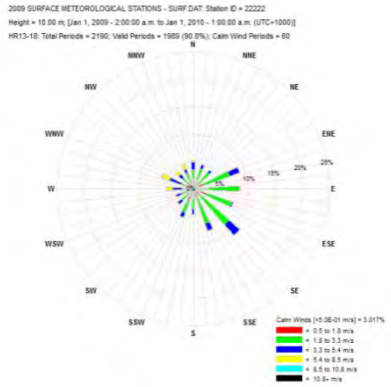
Morning (7am – 12pm) – Prospect, 2009



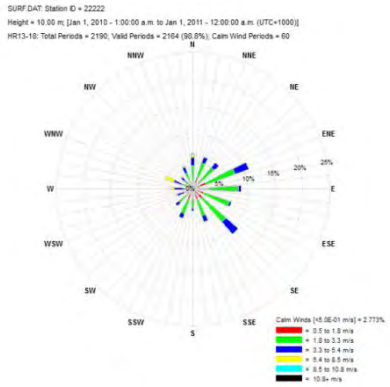
Morning (7am – 12pm) – Prospect, 2010



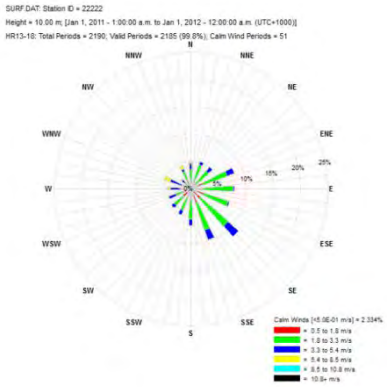
Morning (7am – 12pm) – Prospect, 2011



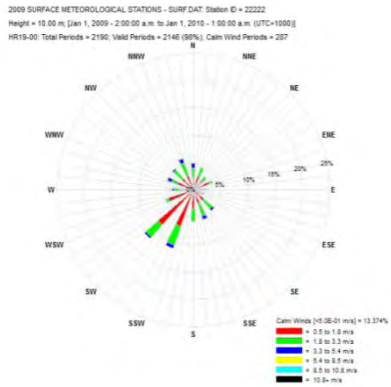
Afternoon (1pm – 6pm) – Prospect, 2009



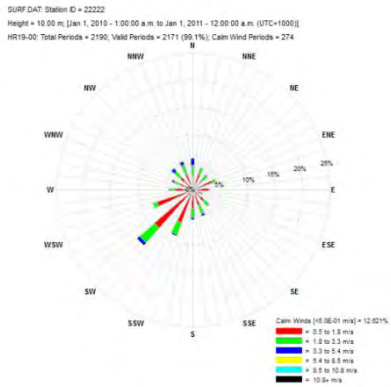
Afternoon (1pm – 6pm) – Prospect, 2010



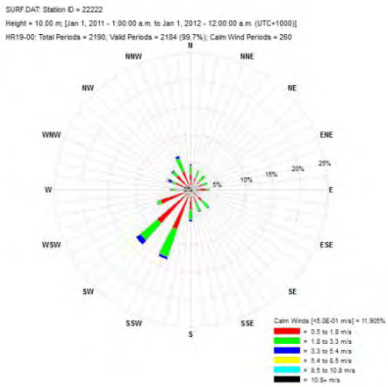
Afternoon (1pm – 6pm) – Prospect, 2011



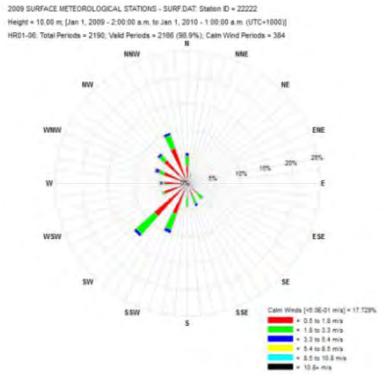
Evening (7pm – 12am) – Prospect, 2009



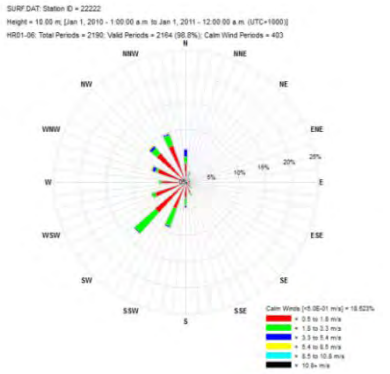
Evening (7pm – 12am) – Prospect, 2010



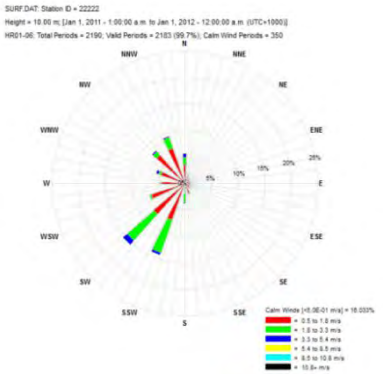
Evening (7pm – 12am) – Prospect, 2011



Night (1am – 6am) – Prospect, 2009

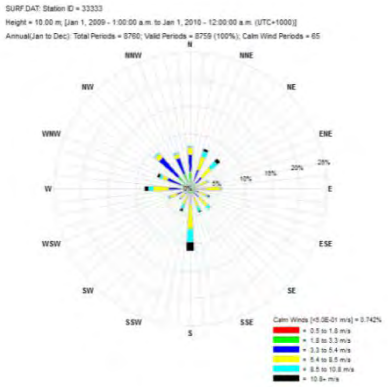


Night (1am – 6am) – Prospect, 2010

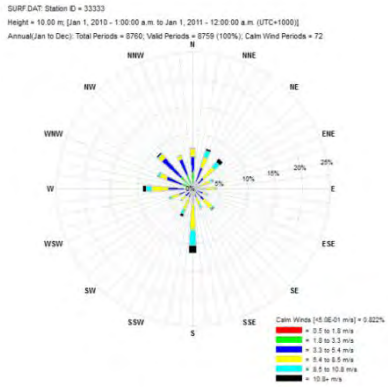


Night (1am – 6am) – Prospect, 2011

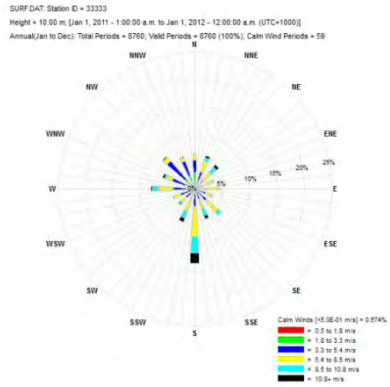
Annual, seasonal and diurnal wind roses for Sydney Airport Meteorological Station for 2009, 2010, 2011 (Measured data)



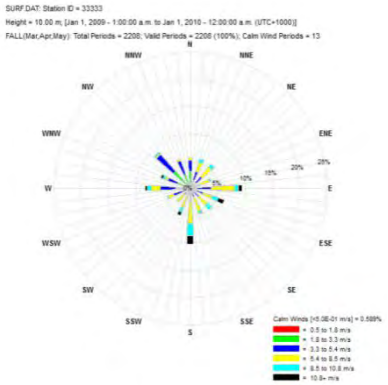
Annual – Sydney , 2009



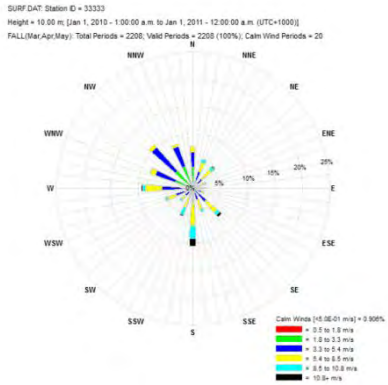
Annual – Sydney , 2010



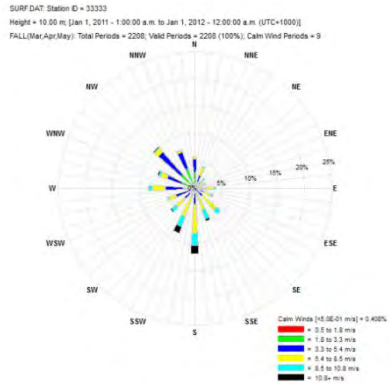
Annual – Sydney , 2011



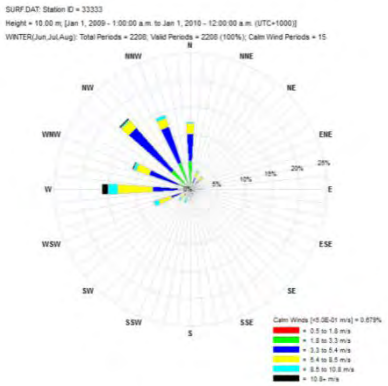
Autumn –Sydney , 2009



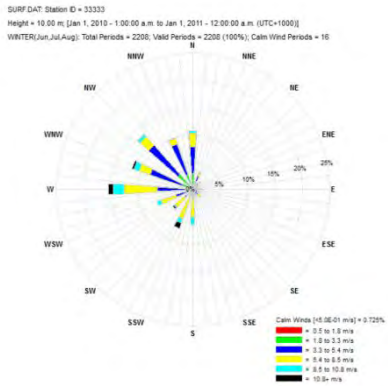
Autumn –Sydney , 2010



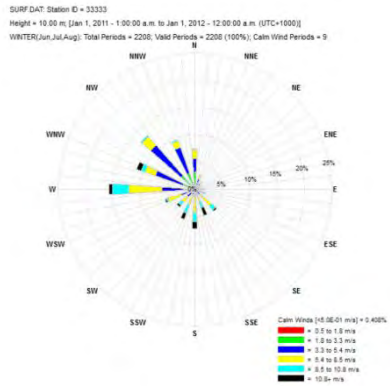
Autumn –Sydney , 2011



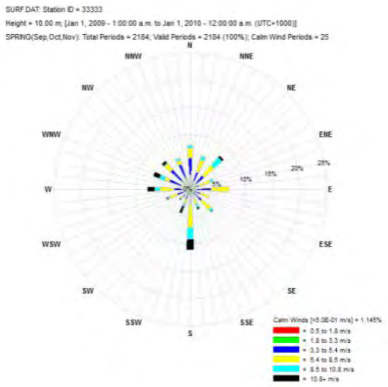
Winter – Sydney , 2009



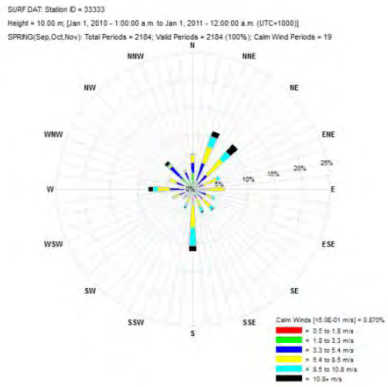
Winter – Sydney , 2010



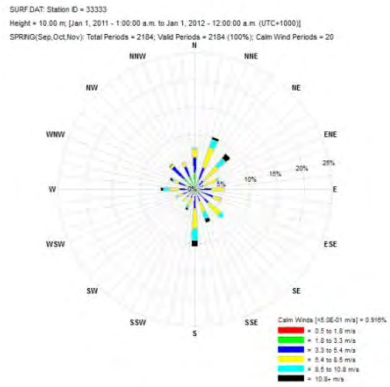
Winter – Sydney , 2011



Spring – Sydney , 2009



Spring – Sydney , 2010



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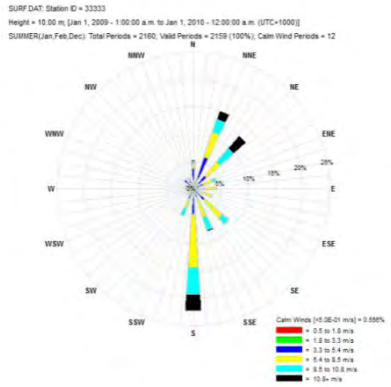

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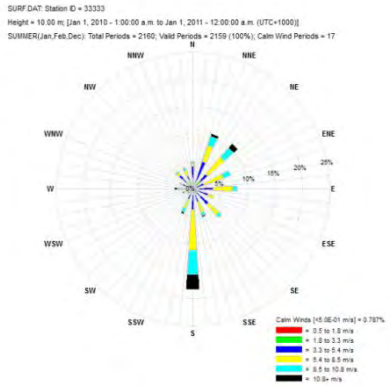

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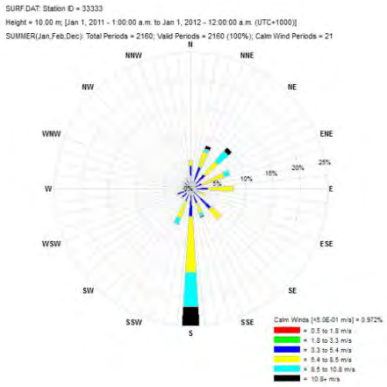

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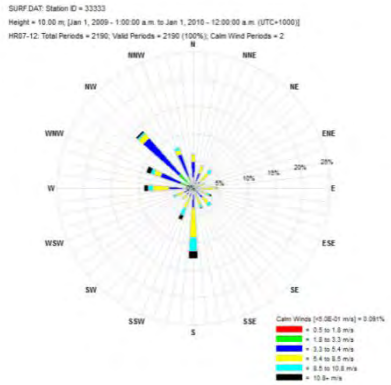
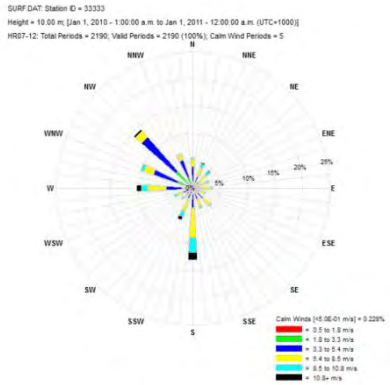
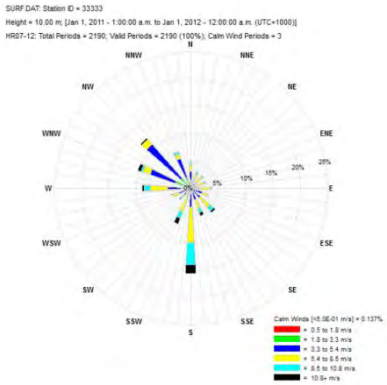


Morning (7am – 12pm) – Sydney, 2009



Morning (7am – 12pm) – Sydney, 2010



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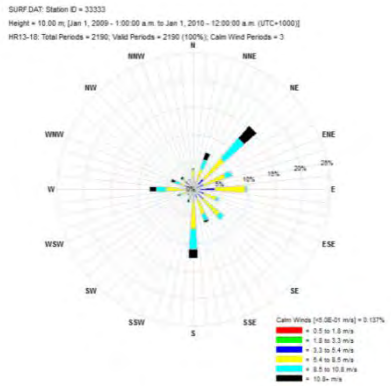
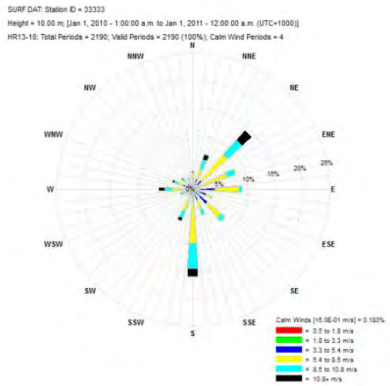
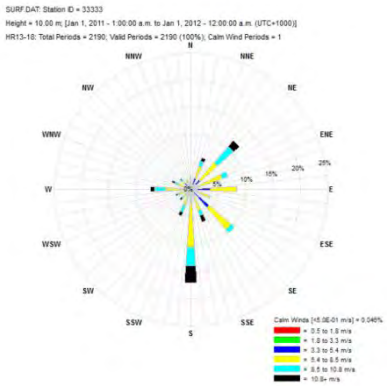


Afternoon (1pm – 6pm) – Sydney, 2009



Afternoon (1pm – 6pm) – Sydney, 2010



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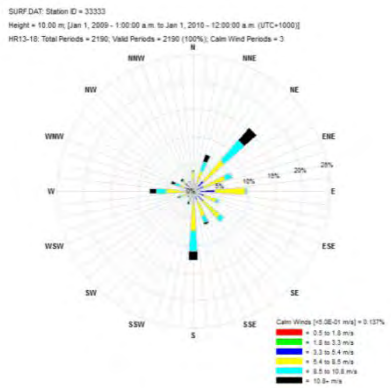
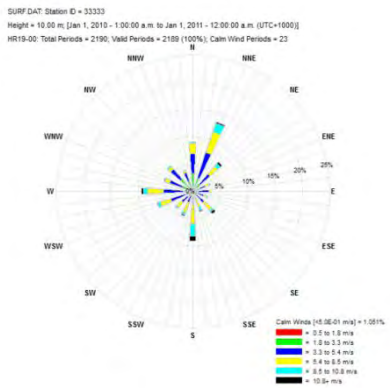
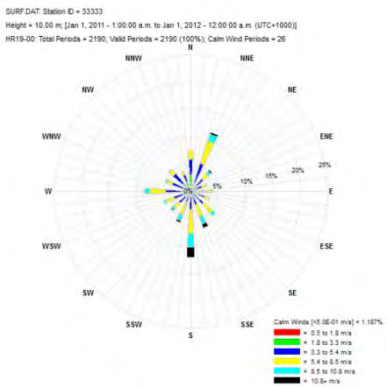


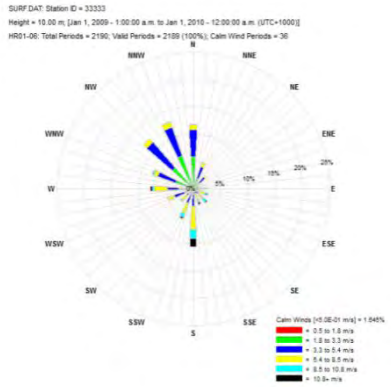
Evening (7pm – 12am) – Sydney, 2009



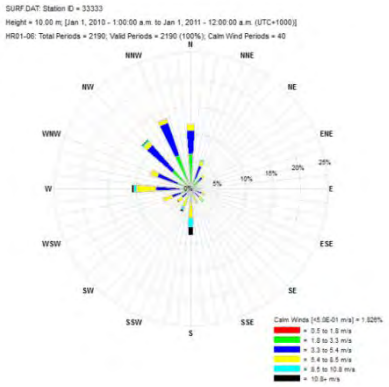
Evening (7pm – 12am) – Sydney, 2010



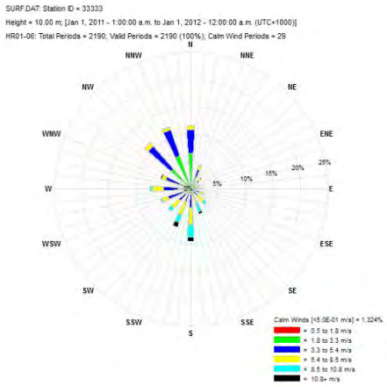
Evening (7pm – 12am) – Sydney, 2011



Night (1am – 6am) – Sydney, 2009



Night (1am – 6am) – Sydney, 2010



Night (1am – 6am) – Sydney, 2011

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Appendix G

Additional modelling results

Appendix G Additional modelling results

Design Analysis A

A summary of the dispersion modelling results under the theoretical maximum peak hour capacity of the project (design analysis A) for each ventilation outlet are presented in **Table G1**. Where applicable air quality criteria are predicted to be exceeded, these values are shown in bold. The 'project contribution' reflects the pollutant concentrations at receiver locations attributable to emissions from the ventilation outlets. The background data presented represent either the predicted road modelling concentrations (for road receivers) or the maximum background concentrations measured at Lindfield/Prospect for the associated time period (for receivers away from roads).

The values for PM_{10}, $PM_{2.5}$, NO_2 and CO represent the peak predicted concentrations from the project alone or the peak cumulative concentration (where relevant) across the modelling domain. The NO_2 results represent the conversion of the model NO_X predictions to NO_2 using the OLM as described in **Section 4.2.11.1**. **Figures G1** to **G12** show contour plots for the maximum predicted project contributions of PM_{10}, $PM_{2.5}$ and NO_2 for the relevant averaging periods. It should be noted that plots of cumulative concentrations are not provided.

As shown, the applicable air quality criteria are comfortably met, with the exception of cumulative 24 hour PM_{10} and $PM_{2.5}$ concentrations and annual $PM_{2.5}$. In the case of these pollutants, however, the following should be noted:

- For 24 hour PM_{10}, the contribution from the project is predicted to be very minor, with a maximum of 3.1 $\mu g/m^3$ attributable to the ventilation outlet emissions. This contribution represents six per cent of the applicable impact assessment criterion of 50 $\mu g/m^3$.
- For 24 hour $PM_{2.5}$, the maximum contribution from the project was predicted to be 3.0 $\mu g/m^3$, which is 12 per cent of the advisory reporting standard of 25 $\mu g/m^3$.
- For annual $PM_{2.5}$, the maximum contribution from the project was predicted to be 0.25 $\mu g/m^3$, which is three per cent of the advisory reporting standard of 8 $\mu g/m^3$.

The top ten concentrations ranked by cumulative concentration, project contribution and background concentration for PM_{10} and $PM_{2.5}$ are shown in **Tables G2** – **Table G5**. These results demonstrate that predicted exceedences of applicable assessment criteria for PM_{10} and $PM_{2.5}$ are the result of background air quality rather than contributions from the project.

The total VOC concentrations were speciated based on data published by the OEH (2012). Results are shown in **Table G6**. The predicted concentrations of individual VOC species were all well below the impact assessment criteria.

Predicted concentrations of CO and PAHs were well below the relevant impact assessment criteria. As such, no further analysis of these pollutants was undertaken.

As stated previously, the particulate emissions from vehicles primarily comprise the smaller fractions, such as PM_{10} and $PM_{2.5}$. As such, the estimated Total Suspended Particulates (TSP) emissions from vehicles essentially equate to PM_{10} emissions. The EPA has an annual criterion for TSP of 90 $\mu g/m^3$. The maximum annual average PM_{10} concentrations predicted by the modelling are well below this criterion. As a consequence, no adverse impacts from TSP are expected to result from the project.

Table G1 Predicted Pollutant Concentrations – Design Analysis A (µg/m^3)

Pollutant	Source	Averaging period	Predicted maximum concentrations (µg/m^3)		Impact assessment criteria (µg/m^3)
			Northern ventilation outlet	Southern ventilation outlet	
PM_{10}	Peak project contribution	24 hour maximum	2.2	3.1	-
		Annual average	0.2	0.3	-
	Peak cumulative concentration (project plus background)	24 hour maximum	**Cumulative concentrations shown in Table G2**		50
		Annual average	21.3	21.4	30
	Project contribution (% of criteria)	24 hour maximum	4 %	6 %	-
		Annual average	0.6 %	0.9 %	-
$PM_{2.5}$	Peak project contribution	24 hour maximum	2.1	3.0	-
		Annual average	0.16	0.25	-
	Peak cumulative concentration (project plus background)	24 hour maximum	**Cumulative concentrations shown in Table G3**		25
		Annual average	8.7	10.3	8
	Project contribution (% of criteria)	24 hour maximum	8 %	12 %	-
		Annual average	2 %	3 %	-
NO_2	Peak project contribution	1 hour maximum	114.8	98.2	-
		Annual average	2.5	2.4	-
	Peak cumulative concentration (project plus background)	1 hour maximum	182	167	246
		Annual average	39	43	62
	Project contribution (% of criteria)	1 hour maximum	47 %	40 %	-
		Annual average	4 %	4 %	-

Pollutant	Source	Averaging period	Predicted maximum concentrations (µg/m^3)		Impact assessment criteria (µg/m^3)
			Northern ventilation outlet	Southern ventilation outlet	
CO	Peak project contribution	1 hour maximum	179	167	-
		8 hour maximum	80	82	-
	Peak cumulative concentration (project plus background)	1 hour maximum	3,804	3,792	30,000
		8 hour maximum	2,682	2,684	10,000
	Project contribution (% of criteria)	1 hour maximum	0.6 %	0.6%	-
		8 hour maximum	0.8 %	0.8 %	-
Total VOC	Peak project contribution	1 hour 99.9%	7.4	9.0	29*
	Project contribution (% of criteria)	1 hour 99.9%	26 %	31 %	-
PAH	Peak project contribution	1 hour 99.9%	0.0015	0.0018	0.4
	Project contribution (% of criteria)	1 hour 99.9%	0.4 %	0.4 %	-

* as benzo(a)pyrene
** as benzene

Table G2 Predicted maximum PM_{10} concentrations ($\mu g/m^3$) sorted by cumulative concentrations and project contributions – 24 hour averaging period3

Outlet	Rank	Maximum cumulative concentration ($\mu g/m^3$)			Maximum project contribution ($\mu g/m^3$)		
		Cumulative concentration	Project contribution	Background contribution	Project contribution	Background contribution	Cumulative concentration
Northern ventilation outlet	1	222.0	0.4	221.6	2.2	20.2	22.4
	2	134.9	0.8	134.1	1.9	8.1	10.1
	3	92.9	1.2	91.7	1.9	19.6	21.4
	4	90.5	0.7	89.8	1.9	11.1	13.0
	5	61.6	1.5	60.1	1.8	19.2	21.0
	6	61.1	1.0	60.1	1.8	9.4	11.3
	7	56.6	0.6	56.0	1.8	18.5	20.3
	8	51.5	1.3	50.2	1.8	21.0	22.8
	9	50.6	0.5	50.1	1.8	11.9	13.7
	10	49.9	1.4	48.5	1.8	9.0	10.8
Southern ventilation outlet	1	222.1	0.5	221.6	3.1	11.1	14.2
	2	134.7	0.6	134.1	3.0	17.8	20.8
	3	92.8	1.1	91.7	2.9	7.8	10.7
	4	90.4	0.6	89.8	2.8	15.0	17.9
	5	61.9	0.8	61.1	2.8	22.3	25.0
	6	60.8	0.7	60.1	2.7	19.5	22.2
	7	56.9	0.9	56.0	2.6	8.9	11.5
	8	51.4	1.2	50.2	2.6	20.2	22.7
	9	50.6	0.5	50.1	2.5	13.3	15.8
	10	49.6	1.1	48.5	2.5	17.1	19.6

Table G3 Predicted maximum PM_{10} concentrations ($\mu g/m^3$) sorted by background – 24 hour averaging period –Design Analysis A

Rank	Maximum concentrations sorted by background ($\mu g/m^3$)					
	Northern ventilation outlet			Southern ventilation outlet		
	Background	Project	Cumulative	Background	Project	Cumulative
1	221.6	0.4	222.0	221.6	0.5	222.1
2	134.1	0.8	134.9	134.1	0.6	134.7
3	91.7	1.2	92.9	91.7	1.1	92.8
4	89.8	0.7	90.5	89.8	0.6	90.4
5	60.1	1.5	61.6	61.1	0.8	61.9
6	60.1	1.0	61.1	60.1	0.7	60.8
7	56.0	0.6	56.6	56.0	0.9	56.9
8	50.2	1.3	51.5	50.2	1.2	51.4
9	50.1	0.5	50.6	50.1	0.5	50.6
10	48.5	1.4	49.9	48.5	1.1	49.6

Table G4 Predicted maximum $PM_{2.5}$ concentrations ($\mu g/m^3$) sorted by cumulative concentrations and project contributions – 24 hour averaging period –Design analysis A

Outlet	Rank	Maximum cumulative concentration ($\mu g/m^3$)			Maximum project contribution ($\mu g/m^3$)		
		Cumulative concentration	Project contribution	Background contribution	Project contribution	Background contribution	Cumulative concentration
Northern ventilation outlet	1	77.9	0.4	77.6	2.1	7.1	9.2
	2	47.7	0.7	47.0	1.8	2.8	4.7
	3	33.2	1.2	32.1	1.8	6.8	8.6
	4	32.1	0.6	31.4	1.8	3.9	5.6
	5	22.0	0.9	21.0	1.7	6.7	8.5
	6	21.9	0.5	21.4	1.7	3.3	5.0
	7	20.2	0.6	19.6	1.7	6.5	8.2
	8	18.8	1.3	17.6	1.7	7.4	9.1
	9	18.3	1.3	17.0	1.7	4.2	5.9
	10	18.1	1.2	16.9	1.7	3.2	4.9
Southern ventilation outlet	1	78.0	0.4	77.6	3.0	3.9	6.9
	2	47.5	0.5	47.0	2.8	6.2	9.1
	3	33.2	1.1	32.1	2.7	5.4	8.1
	4	32.0	0.6	31.4	2.7	5.3	7.9
	5	22.1	0.8	21.4	2.6	7.8	10.4
	6	21.7	0.6	21.0	2.6	6.8	9.4
	7	20.4	0.8	19.6	2.5	3.1	5.6
	8	18.7	1.1	17.6	2.4	7.1	9.5
	9	18.2	0.0	18.2	2.4	4.6	7.1
	10	18.1	1.2	16.9	2.4	6.0	8.4

Table G5 Predicted maximum cumulative $PM_{2.5}$ concentrations ($\mu g/m^3$) sorted by background– 24 hour averaging period – Design analysis A

Rank	Design Analysis A					
	Northern ventilation outlet			Southern ventilation outlet		
	Background	Project	Cumulative	Background	Project	Cumulative
1	77.6	0.4	77.9	77.6	0.4	78.0
2	47.0	0.5	47.7	47.0	0.5	47.5
3	32.1	1.1	33.2	32.1	1.1	33.2
4	31.4	0.6	32.1	31.4	0.6	32.0
5	21.4	0.8	21.9	21.4	0.8	22.1
6	21.0	0.6	22.0	21.0	0.6	21.7
7	19.6	0.8	20.2	19.6	0.8	20.4
8	18.2	0.0	18.8	18.2	0.0	18.2
9	18.0	0.0	18.0	18.0	0.0	18.0
10	17.9	0.0	18.3	17.9	0.0	17.9

Table G6 Predicted concentrations of speciated VOCs (µg/m^3) (project contribution) – Design Analysis A

Pollutant	Averaging Period	Predicted concentrations of speciated VOCs (µg/m^3)		Impact assessment criteria (µg/m^3)
		Northern ventilation outlet	Southern ventilation outlet	
Total VOCs	1 hour 99.9 %	7.4	9.0	-
1,3-butadiene	1 hour 99.9 %	0.07	0.08	40
Acetaldehyde	1 hour 99.9 %	0.16	0.19	42
Benzene	1 hour 99.9 %	0.24	0.30	29
Formaldehyde	1 hour 99.9 %	0.36	0.44	20
Xylenes	1 hour 99.9 %	0.34	0.41	190
Toluene	1 hour 99.9 %	0.41	0.50	360

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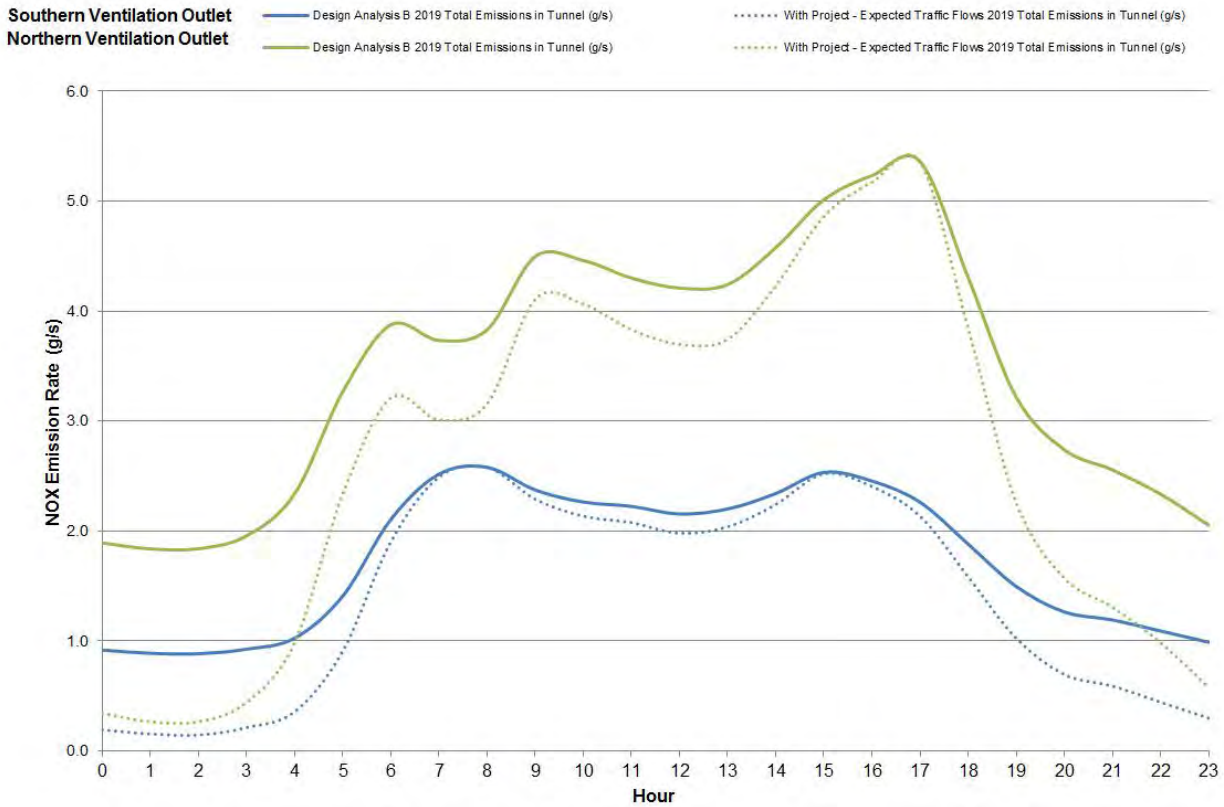
Design Analysis B

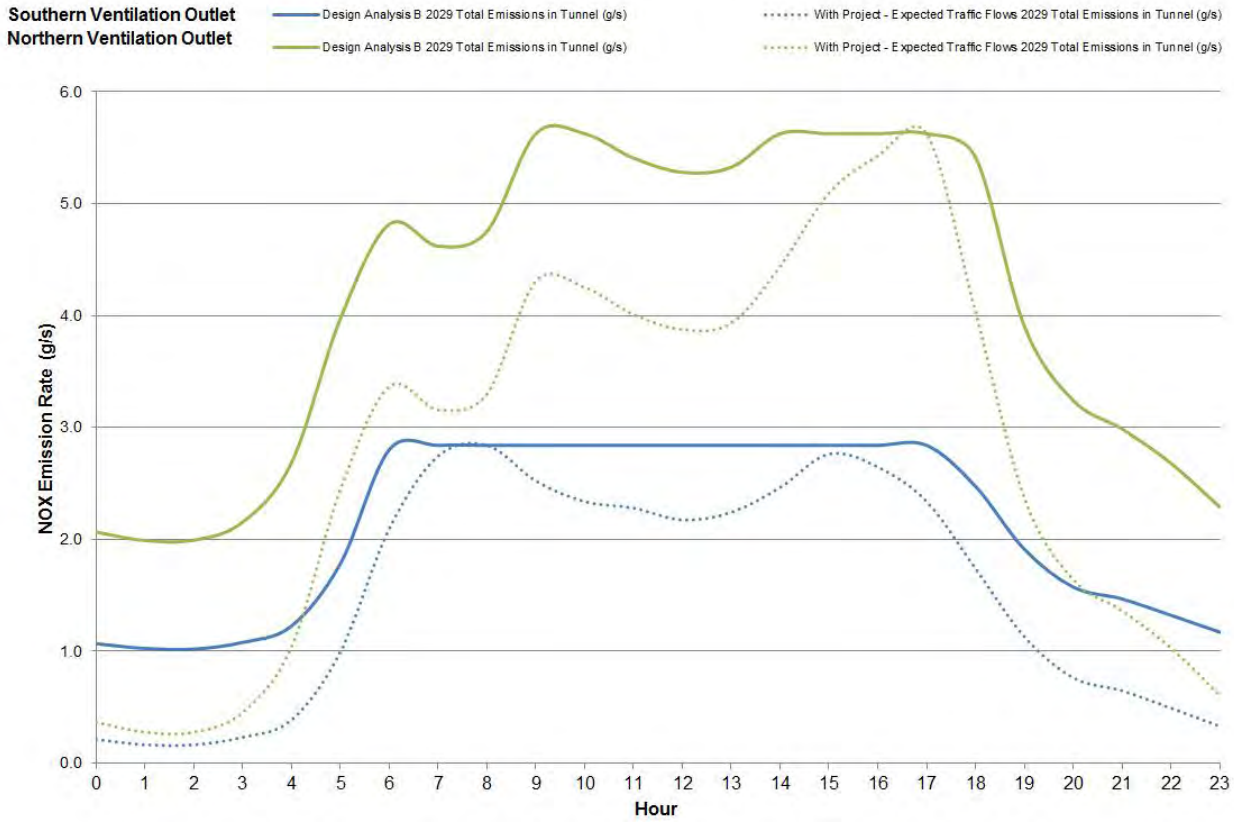
The purpose of design analysis B was to inform regulatory agencies of maximum emission concentrations from the project, which could then be used to develop licensing conditions for the project if it is approved. The Design analysis B emissions were based on those calculated for 'with project – expected traffic flows; (scenario 2a / 2b). The maximum concentrations calculated for each tunnel in 2019 and 2029 were used to develop the emission profiles for design analysis B (2019) and design analysis B (2029) respectively. For design analysis B, the maximum emission concentrations from the 'with project – expected traffic flows' 2019 and 2029 scenarios were assumed to be constant throughout each hour of the day. Those maximum emission concentrations were used to back-calculate emission rates using hourly varying volumetric flow rates, which were interpolated between the maximum and minimum flow rates from 'with project – expected traffic flows, 2019' (scenario 2a) based on predicted traffic flows.

The differences between the emission rates for the 'with project – expected traffic flows' and design analysis B are illustrated graphically in the following two figures. The solid lines show the indicative profile of the design analysis B emissions, while the dotted lines reflect the emissions calculated for 'with project – expected traffic flows'. As shown, the maxima between the two scenarios are consistent, while the other emissions vary hourly. The maximum emissions remain the same but, in effect, the other hourly emissions are shifted upwards, with the greatest differences apparent in the hours of low traffic flows. The ceiling and floor effects in the design analysis B emissions, illustrated by the shifted minima in both figures and the slight plateaus in the second figure, are a result of the application of the maximum and minimum flow rates.

The results of the dispersion modelling for design analysis B, which represented maximum / 99.9th percentile pollutant concentrations at receivers, are shown in the following table. The results represent project contributions. As expected, the predicted concentrations from design analysis B are higher than those predicted for 'with project – expected traffic flows'. The differences are, however, relatively minor.



Comparison of 'with project – expected traffic flows' and design analysis B emission profiles (2019 traffic data)



Comparison of 'with project – expected traffic flows' and design analysis B emission profiles (2029 traffic data)

Comparison of modelling results – of 'with project – expected traffic flows' and design analysis B

Pollutant	Averaging period	Predicted concentrations (µg/m^3)								Applicable air quality criteria (µg/m^3)
		With project – expected traffic flows, 2019 variable emission (Scenario 2a)		With project – expected traffic flows, 2019 constant emission (Design Analysis B)		With project – expected traffic flows, 2029 variable emission (Scenario 2a)		With project – expected traffic flows, 2029 constant emission (Design Analysis B)		
		North	South	North	South	North	South	North	South	
PM_{10}	24 hour maximum	1.0	1.4	1.6	3.1	1.4	2.1	2.2	4.2	50
	Annual average	0.09	0.11	0.1	0.1	0.11	0.13	0.2	0.2	30
$PM_{2.5}$	24 hour maximum	0.9	1.3	1.5	2.9	1.3	2.0	2.1	3.9	25
	Annual average	0.08	0.11	0.10	0.13	0.10	0.13	0.10	0.18	8
NO_2	1 hour maximum	68.9	61.8	85.2	64.9	74.6	65	96.4	65.6	246
	Annual average	1.4	1.2	1.7	1.4	1.7	1.4	2.1	1.9	62
CO	1 hour maximum	86.6	70.1	128.5	143.4	107.4	90.3	159.5	178.8	30,000
	8 hour maximum	32.4	33.1	44.5	77.6	54.2	57.9	72.6	108.4	10,000
Total VOCs	1 hour 99.9%	4.0	3.7	4.5	3.9	5.38	5.36	7.07	6.92	29
PAH	1 hour 99.9%	0.00074	0.00068	0.0008	0.0007	0.00089	0.00092	0.0012	0.0012	0.4

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Appendix H

Emission calculations

Appendix H Emission calculations

This appendix provides an outline of the methodology and data sources used to calculate the emissions inventory used in this air quality impact assessment. An example calculation based on carbon monoxide is provided at the end of the appendix to demonstrate how the emissions inventory was determined.

Operational traffic data emissions

Internationally-recognised vehicle emission factors prepared by the World Road Association (PIARC, 2012) were used for the assessment. These factors are based largely on European vehicle standards, incorporating pre-Euro engine classifications through to new Euro-6 classifications, together with the penetration of hybrid fuel and electric vehicles. The document, however, includes country-specific emissions based on respective fleet compositions for a number of other locations including Australia, which is a contributing member to the World Road Association.

The PIARC emissions dataset was developed and intended for *"ventilation design purposes and differs from emissions data used for environmental assessments, as a safety margin is added to take a certain proportion of high emitting vehicles into account."* (PIARC, 2012, p.7). As the PIARC emissions data were used for the calculation of all road links in the study (i.e. the tunnel emissions and surface road emissions), the use of these emission factors was considered to be an appropriate, if conservative, approach, particularly in the absence of more applicable emission factors[6].

PIARC (2012) provides emissions data for the year 2010 for fine particulate matter (PM_{10}) (with opacity a proxy for PM_{10}), carbon monoxide and oxides of nitrogen for passenger car, light duty vehicle (LDV; < 3.5 tonnes) and heavy duty vehicle (HDV; > 3.5 tonnes) classifications. The effects of varying vehicle speeds (0 - 130 km/h) and road gradients (-6 per cent to 6 per cent) on engine load and resultant emissions are also taken into account within the emissions data. Non-exhaust related particulate emissions ($PM_{2.5}$), based on brake wear and the re-suspension of particulates from road surfaces, are also provided.

Adjustment factors provided within PIARC (2012) were used to forecast emissions for the proposed opening year of 2019 and the design year of 2029. These adjustment factors are based upon agreed assumptions on the expected continuous improvement in engine technologies, the phase-out of older, less efficient cars, and the gradual tightening of emissions legislation expected to occur between 2010 and 2020. No adjustment forecasts are provided past the year 2020; the 2020 emission data were, therefore, used to represent 2029 emissions in this assessment. This is considered to be a conservative approach due to the expected continual improvements in vehicle emissions over time and the phase out of older cars, which, subsequently, may result in an overestimation of 2029 emissions and resultant ground level pollutant concentrations.

The current Australian fleet distribution relating to the number of diesel-powered passenger vehicles and the fleet mix (proportion of LDV to HDV) data were obtained from the motor vehicle census prepared by the Australian Bureau of Statistics (ABS, 2013). Diesel-engine passenger cars were shown to make up approximately eight per cent of the current Australian fleet; this value was used in the emission calculations. The infiltration of diesel-powered passenger cars into the Australian market and fleet mix since 2008 has risen by over 100 per cent. While the use of diesel-powered vehicles is likely to continue to increase in future years, no reliable data was available regarding future trends and as such the assumption relating to eight percent of the vehicle fleet being diesel was made for this assessment. The current known petrol to diesel ratio (ABS, 2013) was, therefore, used for both 2019 and 2029.

Additional relevant road vehicle emissions not contained within PIARC (2012) (that is, exhaust-related $PM_{2.5}$, total volatile organic compounds (VOCs) and total polycyclic aromatic hydrocarbons (PAHs)) were sourced from the National Pollutant Inventory (DEWHA, 2008). Total suspended particulates were not included in the modelling as explicit emissions factors were not available from NPI or PIARC.

[6] The recently developed database and calculation tool, COPERT Australia, was reviewed as part of the assessment process. While the software was designed specifically for road transport emission inventories across Australia, discussions with the developer determined that, due to a lack of a valid fleet mix model to allow the calculation of fleet emissions, it was not considered suitable for use in project-related road source dispersion modelling.

Surface roads emissions

Forecast vehicle numbers for the surface roads potentially affected by the project were provided based on the strategic traffic model and traffic survey counts at key locations, undertaken as part of the project (refer to technical working paper: traffic and transport (AECOM, 2014)). These data consisted of the number of passenger cars, LDVs and HDVs. Turning movements at each of the road junctions on the network were also provided for the morning and afternoon peak periods, which were then factored by AECOM transport consultants to calculate 24 hour Annual Average Weekday Traffic (AAWT) flows for use in the air quality assessment.

The use of 24 hour AAWT data was considered to be a conservative approach in the assessment, rather than the use of 24 hour Annual Average Daily Traffic (AADT), as AAWT data only take into account the weekday traffic volumes, which are typically busier than weekend traffic volumes.

Surface roads traffic emissions

The CALRoads modelling package (version 6.2.0), using the CAL3QHCR line source dispersion model, was used for the prediction of pollutant concentrations from road vehicles. The model requires roads to be split into a series of 'links', which represent sections where traffic conditions are reasonably homogenous in regard to vehicle flow, vehicle fleet mix, average speed and road gradient.

A network of spatially correct road 'links' were, therefore, entered into the model, for the roads within the assessment study area considered to be affected by the project. This was based on the existing road layout and design proposals, for both with and without the project in place.

Speed limits and congestion advice on the road network were provided by AECOM transport consultants. Vehicle speeds at junctions were adjusted based on professional judgement. Between 300 – 400 road 'links' were entered into the model for each scenario to comprehensively represent the variable sections of road across the network in terms of vehicle emissions.

All roads modelled within the surface network were taken as being at 0 per cent grade (that is, flat), with the exception of the M1 Pacific Motorway and Hills M2 Motorway exit and entry ramps and the project portal entry and exit ramps.

Predicted emissions for the surface roads were calculated using the methodology (for the pollutants of concern) discussed in **Section 5** and entered into the model as grams per vehicle-mile, as required for the dispersion model.

Tunnel outlet ventilation emissions

Total traffic data emissions

Traffic data counts

Tunnel traffic data for 'with project – expected traffic flows, 2019' (Scenario 2a) and 'with project – expected traffic flows, 2029' (Scenario 2b) were obtained from strategic transport model.

For design analysis A, both northbound and southbound traffic, hourly traffic data were scaled from the 2019 hourly traffic data profiles using :

Equation 1

$$VPH_h^{Max} = VPH_h^{2019} \times \frac{4000}{VPH_{Max}^{2019}}$$

where:

VPH_h^{Max} = Maximum vehicles per hour for a given hour

VPH_h^{2019} = Vehicles per hour for 2019 for a given hour

VPH_{Max}^{2019} = Vehicles per hour for 2019 during peak hour

In-tunnel traffic vehicle emissions

As stated previously, the proposed project consists of two two-lane tunnels – one to carry southbound vehicles, and one to carry northbound vehicles. The number of vehicles within the proposed tunnels would vary throughout a 24-hour period and, subsequently, the level of pollutant emissions associated with vehicle movements would vary. Forecast hourly mainline vehicle numbers, heavy vehicle percentages and vehicle speeds for each tunnel were provided to AECOM for the opening year of the tunnel and 10 years after opening (2019 and 2029, respectively) for both southbound and northbound tunnels.

Predicted pollutant emissions from vehicles within the tunnel were calculated based on the methodology outlined in Section A1, taking into account the number of vehicles each hour, the speed and the fleet composition. The vertical design alignment of the tunnel was also taken into account, and each tunnel was split into a series of homogenous sections to calculate the differing emissions resulting from gradient changes along the lengths of the tunnels. Gradient data for the emission calculations were obtained from the design documents.

The assessment was conducted assuming zero emissions from the tunnel portals; that is, all vehicle emissions were assumed to be force vented via the tunnel ventilation outlets at the end of each tunnel. As such, the total tunnel emissions were calculated based on the sum of each section's emissions, factoring in the length of each section, the time taken for vehicles in the tunnel to pass through each section, the density of vehicles in the tunnel and the respective gradients. Hourly emission rates in grams per second were generated for the identified pollutants of concern for each individual tunnel for the expected traffic flows in the assessment years 2019 and 2029. The calculated emission rates used in the modelling assessment for the two tunnels are detailed at the end of this section.

Volumetric flow rates

Hourly volumetric flow rates (VFRs) were provided by for all scenarios modelled in this assessment. Volumetric flow rates were initially calculated for each hourly predicted traffic flow rates. This volumetric flow rate was then assigned to one of the "VSO Running Levels", which defined the conditions under which the ventilation stations will be operated. The running level above the predicted volumetric flow rate was adopted for each hour. Rates were based on a minimum VFR of 300 Nm^3/s and a maximum design capacity of 700 Nm^3/s (four fans operating at a maximum capacity of 175 Nm^3/s each). Settings provided to AECOM are shown in the following table.

Variable flow rates and velocities

Ventilation outlet airflow (m^3/s)	VSO running level	Ventilation outlet partition 1 status (29 m^2)	Ventilation outlet partition 2 status (17 m^2)	Ventilation outlet velocity (m/s)
700	6	Open	Open	15.2
620	5	Open	Open	13.5
540	4	Open	Closed	18.6
460	3	Open	Closed	15.9
380	2	Open	Closed	13.1
300	1	Closed	Open	17.6

Hourly variable outlet velocity and temperature

In order to estimate the likely temperature of the ventilation outlet emissions from the project, outlet temperature data measured at the Lane Cove tunnel were analysed. As the Lane Cove Tunnel is located in a different area of Sydney in relation to the project, the actual temperatures measured at this facility were not considered appropriate for use. Instead, the differences between the outlet emission temperatures and the ambient temperatures were determined for every hour of the meteorological modelling period (2009 – 2011). The average temperature variations for each hour of each season were then calculated (for example, the average variation between ambient and outlet emission temperatures at 1 am between December 1 and February 28 for each year was calculated, then 2 am, 3 am , 4 am and so on for each hour of the day and for each season). The hourly seasonal average temperature differences were then applied to the temperature data predicted for the project's ambient environment to calculate the estimated temperatures of emissions from the ventilation outlets.

The project would be serviced by ventilation systems, the operating parameters of which would vary depending on traffic flows. As such, the volume of air to be extracted from the tunnels would vary each hour and, therefore, the number of fans and the output of the fans would vary on an hourly basis, resulting in hourly-varying outlet emission velocities and flow rates. In order to accommodate this variation, the ventilation outlets would be partitioned so that portions of the ventilation outlets can be closed off when traffic flows are low in order to maintain good plume dispersion. This would result in time-varying ventilation outlet diameters. The CALPUFF model does not provide the functionality to enter time-varying outlet diameters. In order to accurately model the outlet emissions, each ventilation outlet was, therefore, modelled as three separate concentric outlets to allow for the operation of the different segments to be incorporated into the model.

The ventilation areas and settings the systems were designed for were provided by Roads and Maritime. Details are provided below.

Maximum outlet concentrations

Outlet concentrations

In-tunnel traffic vehicle emissions calculated using the methodology described above and the hourly-varying VFR profiles for each outlet were used to calculate the hourly-varying pollutant emission concentrations using .

Equation 2

$$C_h^s = {E_{h_i}^s}/{VFR_h^s}$$

where:

C_h^s = *Outlet concentration for a given scenario (s) at a given hour (h) in (g/Nm^3)*

$E_{h_i}^s$ = *Emission rate for pollutant 'i' for a given scenario (s) at a given hour (h) in (g/s)*

VFR_h^s = *Volumetric flow rate for scenario being examined for a given hour (Nm^3/s)*

Worst case emission concentrations

The diurnal outlet concentration profile was examined to determine the maximum outlet concentration for 'with project – expected traffic flows' for 2019 and 2029 (scenarios 2a and 2b). This value was used to identify the likely worst case scenario and provide guidance to the EPA for determining the conditions of consent for the project. The maximum outlet concentration was then used to calculate the worst case emission concentrations for the project by applying the maximum outlet concentration to the VFR profiles as calculated using the equations above.

Emission rates calculated using the maximum outlet concentrations and the calculated volumetric flow rates were then incorporated into the model to predict ground level concentrations using .

Equation 3

$$ME_{h_i}^{s} = C_{Max}^{s} \times VFR_{h}^{s}$$

Where:

C_{Max}^{s} = Maximum outlet concentration for a given scenario (s) in (g/Nm^3)

$ME_{h_i}^{s}$ = Emission rate for pollutant 'i' for a given scenario (s) at a given hour (h) in (g/s) using the maximum outlet concentration.

VFR_{h}^{s} = Volumetric flow rate for scenario being examined for a given hour (Nm^3/s)

Summary of ventilation outlet input parameters

The following tables provide a description of the assumptions made for the north and south outlet input parameters respectively including reference sources.

Northern ventilation outlet input parameters

Parameter	Value	Reference	Comments and assumptions
Outlet location	325,359 m E, 6,268,211 m S (MGA 56)	F3M2-5000-DR-UD-547	Estimated from plan.
Outlet height	15 metres	F3M2-5000-DR-UD-550	Outlet 15 metres above adjacent land taken from plan.
Outlet diameter	Hourly variable	F3M2-440-DR-US-0106	Based on maximum outlet opening area of 46 m^2.
Outlet temperature	Hourly variable	CALMET.DAT files	Hourly temperature data assumed to be equal to ambient temperature with a correction. Temperature data were extracted from CALMET outputs at 325,060 m E, 6,267,858 m S (MGA 56). Ventilation outlet temperature differentials were added to outlet parameters to better replicate the expected hotter air leaving the ventilation outlets than the ambient air conditions.
Outlet velocity	Hourly variable	Not applicable	Hourly velocity was calculated based on the hourly volumetric flow rates corrected for the expected ventilation outlet temperatures.
Building wakes[1]	Variable	F3M2-5000-DR-UD-547 F3M2-5000-DR-UD-550 F3M2-5000-DR-UD-555 F3M2-5000-DR-UD-556	Building dimensions from the sub-station, northern ventilation station (VS07) and deluge tanks were estimated from plans and input into the BPIP to estimate building wake effects on the northern outlet

[1] Note that building heights were modified to a maximum of 7 metres above surrounding land height for the modelling. This is different to the information provided in the engineering drawing and was adopted after consultation with Transurban.

Southern ventilation outlet input parameters

Parameter	Value	Reference	Comments and assumptions
Outlet location	319,233 m E, 6,262,984 m S (MGA 56)	F3M2-5000-DR-UD-0516	Estimated from plan.
Outlet height	15 m	F3M2-5000-DR-SK-UD-0525	Outlet 15 metres above adjacent land taken from plan
Outlet diameter	7.90 m	F3M2-440-DR-US-0100.	Based on outlet opening area of 46 m^2.
Outlet temperature	Hourly variable	CALMET.DAT Files	Hourly temperature data assumed to be equal to ambient temperature with a correction. Temperature data were extracted from CALMET output at 319.244 m E, 6,262,993 m S (MGA 56). Ventilation outlet temperature differentials were added to outlet parameters to better replicate the expected hotter air leaving the ventilation outlets than the ambient air conditions.
Outlet velocity	Hourly variable	Not applicable	Hourly velocities were calculated based on the hourly volumetric flow rates.
Building wakes[1]	Variable	F3M2-5000-DR-UD-0516 F3M2-5000-DR-SK-UD-0510 F3M2-5000-DR-SK-UD-0508 F3M2-5000-DR-UD-DU-0513 F3M2-5000-DR-SK-UD-0525	Building dimensions from the southern ventilation station (VS01), water tank, covered service yard, workshop and Motorway Control Centre (MCC) were estimated from plans and input into the BPIP to estimate building wake effects on the southern outlet. Building parameters used to calculate building wakes are presented in the following table.

[1] Note that building heights were modified to a maximum of 7metres above surrounding land height for the modelling. This is different to the information provided in the engineering drawing and was adopted after consultation with Transurban.

Building parameters used to calculate building wakes are presented in the following table.

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Building parameters used to calculate building wakes

ID	Description	Tier	Tier height (metres)	Diameter (metres)	Coordinates (MGA 56)							
					X1	Y1	X2	Y2	X3	Y3	X4	Y4
1	Deluge Tank 1	1	6.0	12	325,339	6,268,237						
2	Deluge Tank 2	1	6.0	12	325,356	6,268,235						
3	Northern ventilation facility	1	7.0		325,352	6,268,217	325,369	6,268,208	325,345	6,268,163	325,328	6,268,172
		2	15.0		325,355	6,268,215	325,353	6,268,210	325,362	6,268,206	325,364	6,268,211
4	North substation	1	4.5		325,328	6,268,168	325,311	6,268,135	325,318	6,268,131	325,336	6,268,164
5	Southern ventilation facility	1	6.0		319,206	6,263,028	319,196	6,263,026	319,198	6,263,016	319,208	6,263,018
		2	6.0		319,201	6,263,016	319,205	6,262,992	319,213	6,262,994	319,208	6,263,018
		3	6.0		319,213	6,262,994	319,202	6,262,992	319,205	6,262,981	319,215	6,262,983
		4	13.2		319,244	6,263,041	319,205	6,263,034	319,216	6,262,978	319,255	6,262,985
		5	18.0		319,227	6,262,985	319,238	6,262,988	319,240	6,262,981	319,228	6,262,979
		6	20.4		319,232	6,262,980	319,232	6,262,979	319,239	6,262,981	319,239	6,262,981
6	Covered service yard	1	8.7		319,192	6,263,095	319,200	6,263,055	319,225	6,263,060	319,217	6,263,100
7	Workshop	1	8.4		319,183	6,263,187	319,172	6,263,185	319,185	6,263,115	319,196	6,263,117
		2	8.4		319,205	6,263,118	319,194	6,263,175	319,185	6,263,174	319,196	6,263,117
8	Motorway control centre	1	11.5		319,127	6,263,370	319,139	6,263,306	319,169	6,263,312	319,156	6,263,376
9	Water tank	1	7.6	9	319,230	6,263,045	319,230	6,263,045	319,230	6,263,045	319,230	6,263,045

Emission rates

'With project – expected traffic flows'

Tunnel outlet emission rates (g/s) – 'With project – expected traffic flows, 2019' (Scenario 2a)

Northbound							Southbound						
Hour	Calculated total emissions in tunnel (g/s)						Hour	Calculated total emissions in tunnel (g/s)					
	CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs		CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs
1	0.248	0.344	0.044	0.042	0.025	0.000005	1	0.177	0.194	0.030	0.028	0.0176	0.000003
2	0.190	0.266	0.034	0.032	0.019	0.000004	2	0.139	0.153	0.024	0.022	0.0138	0.000003
3	0.193	0.266	0.034	0.032	0.019	0.000004	3	0.134	0.146	0.022	0.021	0.0133	0.000002
4	0.316	0.438	0.056	0.053	0.031	0.000006	4	0.187	0.210	0.032	0.031	0.0187	0.000003
5	0.720	0.988	0.126	0.120	0.071	0.000013	5	0.317	0.355	0.055	0.052	0.0318	0.000006
6	1.696	2.336	0.299	0.284	0.168	0.000031	6	0.813	0.904	0.139	0.132	0.0812	0.000015
7	2.336	3.214	0.411	0.390	0.232	0.000042	7	1.717	1.905	0.293	0.278	0.1714	0.000032
8	2.187	3.010	0.385	0.366	0.217	0.000040	8	2.252	2.494	0.384	0.365	0.2247	0.000042
9	2.289	3.151	0.403	0.383	0.227	0.000041	9	2.331	2.583	0.397	0.378	0.2327	0.000043
10	2.991	4.108	0.525	0.499	0.296	0.000054	10	2.064	2.292	0.353	0.335	0.2061	0.000038
11	2.952	4.061	0.519	0.493	0.293	0.000053	11	1.922	2.131	0.328	0.311	0.1918	0.000036
12	2.785	3.826	0.489	0.465	0.276	0.000050	12	1.872	2.074	0.319	0.303	0.1868	0.000035
13	2.688	3.700	0.473	0.449	0.267	0.000049	13	1.781	1.977	0.304	0.289	0.1779	0.000033
14	2.722	3.747	0.479	0.455	0.270	0.000049	14	1.840	2.042	0.314	0.298	0.1837	0.000034
15	3.074	4.233	0.541	0.514	0.305	0.000056	15	2.022	2.244	0.345	0.328	0.2019	0.000037
16	3.534	4.860	0.621	0.590	0.350	0.000064	16	2.272	2.518	0.387	0.368	0.2268	0.000042
17	3.766	5.175	0.661	0.628	0.373	0.000068	17	2.170	2.405	0.370	0.352	0.2166	0.000040
18	3.899	5.362	0.685	0.651	0.387	0.000071	18	1.920	2.131	0.328	0.311	0.1917	0.000036

Northbound							Southbound						
Hour	Calculated total emissions in tunnel (g/s)						Hour	Calculated total emissions in tunnel (g/s)					
	CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs		CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs
19	2.790	3.841	0.491	0.466	0.277	0.000051	19	1.426	1.582	0.243	0.231	0.1423	0.000026
20	1.644	2.258	0.289	0.274	0.163	0.000030	20	0.926	1.025	0.158	0.150	0.0924	0.000017
21	1.141	1.568	0.200	0.190	0.113	0.000021	21	0.626	0.694	0.107	0.101	0.0625	0.000012
22	0.947	1.302	0.166	0.158	0.094	0.000017	22	0.533	0.589	0.091	0.086	0.0531	0.000010
23	0.715	0.987	0.126	0.120	0.071	0.000013	23	0.403	0.444	0.068	0.065	0.0401	0.000007
24	0.417	0.579	0.074	0.070	0.042	0.000008	24	0.269	0.299	0.046	0.044	0.0268	0.000005

Tunnel outlet emission rates (g/s) – 'With project – expected traffic flows, 2029' (Scenario 2b)

Northbound							Southbound						
Hour	Calculated total emissions in tunnel (g/s)						Hour	Calculated total emissions in tunnel (g/s)					
	CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs		CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs
1	0.307	0.373	0.047	0.044	0.029	0.000005	1	0.220	0.213	0.032	0.030	0.021	0.000004
2	0.236	0.288	0.036	0.034	0.023	0.000004	2	0.172	0.169	0.025	0.024	0.017	0.000003
3	0.240	0.288	0.036	0.034	0.023	0.000004	3	0.166	0.160	0.024	0.023	0.016	0.000003
4	0.392	0.475	0.059	0.056	0.037	0.000006	4	0.233	0.230	0.035	0.033	0.022	0.000004
5	0.894	1.070	0.134	0.127	0.085	0.000014	5	0.394	0.389	0.059	0.056	0.038	0.000006
6	2.105	2.529	0.316	0.301	0.201	0.000033	6	1.010	0.993	0.149	0.142	0.097	0.000016
7	2.898	3.480	0.435	0.413	0.276	0.000046	7	2.133	2.092	0.314	0.299	0.205	0.000035
8	2.714	3.259	0.408	0.387	0.259	0.000043	8	2.797	2.740	0.412	0.391	0.269	0.000046
9	2.840	3.411	0.427	0.405	0.271	0.000045	9	2.896	2.837	0.426	0.405	0.278	0.000047
10	3.712	4.448	0.556	0.528	0.353	0.000059	10	2.564	2.517	0.378	0.359	0.246	0.000042
11	3.663	4.396	0.550	0.522	0.349	0.000058	11	2.388	2.341	0.352	0.334	0.229	0.000039

Northbound							Southbound						
Hour	Calculated total emissions in tunnel (g/s)						Hour	Calculated total emissions in tunnel (g/s)					
	CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs		CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs
12	3.456	4.143	0.518	0.492	0.329	0.000055	12	2.325	2.279	0.342	0.325	0.223	0.000038
13	3.335	4.006	0.501	0.476	0.318	0.000053	13	2.213	2.172	0.326	0.310	0.213	0.000036
14	3.377	4.056	0.507	0.482	0.322	0.000053	14	2.286	2.243	0.337	0.320	0.220	0.000037
15	3.815	4.582	0.573	0.545	0.363	0.000060	15	2.512	2.464	0.370	0.352	0.241	0.000041
16	4.385	5.262	0.658	0.625	0.418	0.000069	16	2.823	2.766	0.416	0.395	0.271	0.000046
17	4.673	5.603	0.701	0.666	0.445	0.000074	17	2.696	2.642	0.397	0.377	0.259	0.000044
18	4.838	5.805	0.726	0.690	0.461	0.000076	18	2.385	2.340	0.352	0.334	0.229	0.000039
19	3.462	4.158	0.520	0.494	0.330	0.000055	19	1.771	1.737	0.261	0.248	0.170	0.000029
20	2.040	2.445	0.306	0.290	0.194	0.000032	20	1.151	1.126	0.169	0.161	0.111	0.000019
21	1.415	1.698	0.212	0.202	0.135	0.000022	21	0.778	0.762	0.115	0.109	0.075	0.000013
22	1.176	1.409	0.176	0.167	0.112	0.000019	22	0.662	0.647	0.097	0.092	0.064	0.000011
23	0.887	1.069	0.134	0.127	0.085	0.000014	23	0.500	0.488	0.073	0.070	0.048	0.000008
24	0.518	0.627	0.078	0.075	0.049	0.000008	24	0.334	0.328	0.049	0.047	0.032	0.000005

Design Analysis A

Emission rates (g/s) from scaled vehicle numbers (Design analysis A) (2019)

Northbound							Southbound						
Hour	Calculated total emissions in tunnel (g/s)						Hour	Calculated total emissions in tunnel (g/s)					
	CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs		CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs
1	0.51	0.71	0.04	0.0394	0.0511	0.000009	1	0.397	0.435	0.040	0.0382	0.039	0.000007
2	0.39	0.55	0.03	0.0304	0.0393	0.000007	2	0.311	0.344	0.032	0.0301	0.031	0.000006
3	0.40	0.55	0.03	0.0305	0.0397	0.000007	3	0.300	0.327	0.030	0.0287	0.030	0.000005
4	0.65	0.91	0.05	0.0501	0.0650	0.000012	4	0.420	0.470	0.043	0.0410	0.042	0.000008
5	1.49	2.05	0.12	0.1133	0.1479	0.000027	5	0.711	0.795	0.073	0.0694	0.071	0.000013
6	3.51	4.84	0.28	0.2676	0.3486	0.000064	6	1.824	2.026	0.187	0.1771	0.182	0.000034
7	4.84	6.66	0.39	0.3683	0.4799	0.000088	7	3.850	4.270	0.395	0.3734	0.384	0.000071
8	4.53	6.24	0.36	0.3449	0.4494	0.000082	8	5.348	5.828	0.544	0.5146	0.551	0.000109
9	4.74	6.53	0.38	0.3611	0.4703	0.000086	9	5.538	6.036	0.564	0.5329	0.571	0.000113
10	6.20	8.51	0.50	0.4710	0.6142	0.000112	10	4.903	5.355	0.500	0.4725	0.506	0.000100
11	6.12	8.41	0.49	0.4654	0.6064	0.000111	11	4.309	4.777	0.442	0.4178	0.430	0.000080
12	5.77	7.93	0.46	0.4386	0.5719	0.000104	12	4.196	4.650	0.430	0.4068	0.419	0.000078
13	5.57	7.67	0.45	0.4240	0.5523	0.000101	13	3.993	4.432	0.410	0.3876	0.399	0.000074
14	5.64	7.76	0.45	0.4293	0.5593	0.000102	14	4.126	4.577	0.424	0.4003	0.412	0.000076
15	6.37	8.77	0.51	0.4850	0.6317	0.000115	15	4.804	5.242	0.489	0.4627	0.495	0.000098
16	6.63	9.88	0.60	0.5713	0.6940	0.000142	16	5.398	5.884	0.550	0.5195	0.556	0.000110
17	7.06	10.52	0.64	0.6084	0.7393	0.000151	17	5.154	5.620	0.525	0.4962	0.531	0.000105
18	7.31	10.90	0.67	0.6303	0.7657	0.000157	18	4.305	4.776	0.442	0.4177	0.430	0.000080
19	5.78	7.96	0.47	0.4401	0.5733	0.000105	19	3.196	3.546	0.328	0.3101	0.319	0.000059

Northbound							Southbound						
Hour	Calculated total emissions in tunnel (g/s)						Hour	Calculated total emissions in tunnel (g/s)					
	CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs		CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	PAHs
20	3.41	4.68	0.27	0.2589	0.3376	0.000062	20	2.077	2.299	0.213	0.2011	0.207	0.000038
21	2.36	3.25	0.19	0.1797	0.2343	0.000043	21	1.404	1.556	0.144	0.1361	0.140	0.000026
22	1.96	2.70	0.16	0.1492	0.1946	0.000036	22	1.194	1.321	0.122	0.1156	0.119	0.000022
23	1.48	2.05	0.12	0.1130	0.1471	0.000027	23	0.902	0.996	0.092	0.0872	0.090	0.000017
24	0.86	1.20	0.07	0.0663	0.0860	0.000016	24	0.603	0.669	0.062	0.0585	0.060	0.000011

Design analysis B – expected traffic flows with maximum emission concentrations

Tunnel outlet emission rates (g/s) – Design analysis B (2019)

Northbound							Southbound						
Hour	Calculated total emissions in tunnel (g/s)						Hour	Calculated total emissions in tunnel (g/s)					
	CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	TPAHs		CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	TPAHs
1	1.89	2.59	0.15	0.14	0.187	0.000034	1	1.13	1.25	0.12	0.1093	0.113	0.000021
2	1.89	2.59	0.15	0.14	0.187	0.000034	2	1.13	1.25	0.12	0.1093	0.113	0.000021
3	1.89	2.59	0.15	0.14	0.187	0.000034	3	1.13	1.25	0.12	0.1093	0.113	0.000021
4	1.89	2.59	0.15	0.14	0.187	0.000034	4	1.13	1.25	0.12	0.1093	0.113	0.000021
5	2.39	3.29	0.19	0.18	0.237	0.000043	5	1.43	1.58	0.15	0.1385	0.143	0.000026
6	2.89	3.98	0.23	0.22	0.287	0.000052	6	1.73	1.92	0.18	0.1677	0.173	0.000032
7	3.40	4.67	0.27	0.26	0.337	0.000061	7	2.03	2.25	0.21	0.1968	0.203	0.000038
8	3.40	4.67	0.27	0.26	0.337	0.000061	8	2.33	2.58	0.24	0.2260	0.233	0.000043
9	3.40	4.67	0.27	0.26	0.337	0.000061	9	2.33	2.58	0.24	0.2260	0.233	0.000043
10	3.40	4.67	0.27	0.26	0.337	0.000061	10	2.33	2.58	0.24	0.2260	0.233	0.000043
11	3.40	4.67	0.27	0.26	0.337	0.000061	11	2.03	2.25	0.21	0.1968	0.203	0.000038
12	3.40	4.67	0.27	0.26	0.337	0.000061	12	2.03	2.25	0.21	0.1968	0.203	0.000038
13	3.40	4.67	0.27	0.26	0.337	0.000061	13	2.03	2.25	0.21	0.1968	0.203	0.000038
14	3.40	4.67	0.27	0.26	0.337	0.000061	14	2.03	2.25	0.21	0.1968	0.203	0.000038
15	3.40	4.67	0.27	0.26	0.337	0.000061	15	2.33	2.58	0.24	0.2260	0.233	0.000043
16	3.90	5.36	0.31	0.30	0.387	0.000071	16	2.33	2.58	0.24	0.2260	0.233	0.000043
17	3.90	5.36	0.31	0.30	0.387	0.000071	17	2.33	2.58	0.24	0.2260	0.233	0.000043
18	3.90	5.36	0.31	0.30	0.387	0.000071	18	2.03	2.25	0.21	0.1968	0.203	0.000038
19	3.40	4.67	0.27	0.26	0.337	0.000061	19	2.03	2.25	0.21	0.1968	0.203	0.000038

Northbound							Southbound						
Hour	Calculated total emissions in tunnel (g/s)						Hour	Calculated total emissions in tunnel (g/s)					
	CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	TPAHs		CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	TPAHs
20	2.89	3.98	0.23	0.22	0.287	0.000052	20	1.73	1.92	0.18	0.1677	0.173	0.000032
21	2.89	3.98	0.23	0.22	0.287	0.000052	21	1.73	1.92	0.18	0.1677	0.173	0.000032
22	2.39	3.29	0.19	0.18	0.237	0.000043	22	1.43	1.58	0.15	0.1385	0.143	0.000026
23	2.39	3.29	0.19	0.18	0.237	0.000043	23	1.43	1.58	0.15	0.1385	0.143	0.000026
24	2.39	3.29	0.19	0.18	0.237	0.000043	24	1.43	1.58	0.15	0.1385	0.143	0.000026

Tunnel outlet emission rates – Design analysis B (2029)

Northbound							Southbound						
Hour	Calculated total emissions in tunnel (g/s)						Hour	Calculated total emissions in tunnel (g/s)					
	CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	TPAHs		CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	TPAHs
1	2.34	2.81	0.18	0.17	0.223	0.000037	1	1.40	1.37	0.14	0.13	0.135	0.000023
2	2.34	2.81	0.18	0.17	0.223	0.000037	2	1.40	1.37	0.14	0.13	0.135	0.000023
3	2.34	2.81	0.18	0.17	0.223	0.000037	3	1.40	1.37	0.14	0.13	0.135	0.000023
4	2.97	3.56	0.22	0.21	0.282	0.000047	4	1.40	1.37	0.14	0.13	0.135	0.000023
5	2.97	3.56	0.22	0.21	0.282	0.000047	5	1.78	1.74	0.17	0.16	0.170	0.000029
6	4.21	5.06	0.32	0.30	0.401	0.000067	6	2.15	2.11	0.21	0.20	0.206	0.000035
7	4.21	5.06	0.32	0.30	0.401	0.000067	7	2.90	2.84	0.29	0.27	0.278	0.000047
8	4.21	5.06	0.32	0.30	0.401	0.000067	8	2.90	2.84	0.29	0.27	0.278	0.000047
9	4.21	5.06	0.32	0.30	0.401	0.000067	9	2.90	2.84	0.29	0.27	0.278	0.000047
10	4.84	5.81	0.36	0.34	0.461	0.000076	10	2.90	2.84	0.29	0.27	0.278	0.000047
11	4.84	5.81	0.36	0.34	0.461	0.000076	11	2.90	2.84	0.29	0.27	0.278	0.000047
12	4.84	5.81	0.36	0.34	0.461	0.000076	12	2.90	2.84	0.29	0.27	0.278	0.000047
13	4.84	5.81	0.36	0.34	0.461	0.000076	13	2.90	2.84	0.29	0.27	0.278	0.000047
14	4.84	5.81	0.36	0.34	0.461	0.000076	14	2.90	2.84	0.29	0.27	0.278	0.000047
15	4.84	5.81	0.36	0.34	0.461	0.000076	15	2.90	2.84	0.29	0.27	0.278	0.000047
16	4.84	5.81	0.36	0.34	0.461	0.000076	16	2.90	2.84	0.29	0.27	0.278	0.000047
17	4.84	5.81	0.36	0.34	0.461	0.000076	17	2.90	2.84	0.29	0.27	0.278	0.000047
18	4.84	5.81	0.36	0.34	0.461	0.000076	18	2.90	2.84	0.29	0.27	0.278	0.000047
19	4.84	5.81	0.36	0.34	0.461	0.000076	19	2.52	2.47	0.25	0.23	0.242	0.000041
20	4.21	5.06	0.32	0.30	0.401	0.000067	20	2.15	2.11	0.21	0.20	0.206	0.000035

Northbound							Southbound						
Hour	Calculated total emissions in tunnel (g/s)						Hour	Calculated total emissions in tunnel (g/s)					
	CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	TPAHs		CO	NOx	PM_{10}	$PM_{2.5}$	TVOCs	TPAHs
21	3.59	4.31	0.27	0.26	0.342	0.000057	21	2.15	2.11	0.21	0.20	0.206	0.000035
22	3.59	4.31	0.27	0.26	0.342	0.000057	22	2.15	2.11	0.21	0.20	0.206	0.000035
23	2.97	3.56	0.22	0.21	0.282	0.000047	23	1.78	1.74	0.17	0.16	0.170	0.000029
24	2.97	3.56	0.22	0.21	0.282	0.000047	24	1.78	1.74	0.17	0.16	0.170	0.000029

Example calculation – carbon monoxide

The emissions data for the project were compiled based on the expected diurnal traffic volumes, vehicle fleet mix, fleet emissions profile (based on year of emission) and tunnel characteristics (length, grade capacity etc.).

An example of an emissions calculation (using carbon monoxide) is provided below to explain how the emissions were calculated and to define the sources of the data.

The emission factors used in this assessment were sourced from PIARC (2012), which provides different emission factors for different vehicle speeds and road gradients (slopes). The PIARC (2012) emissions data for carbon monoxide for passenger cars, light diesel vehicles and heavy vehicles are shown in the following tables.

Base emission factors for carbon monoxide – Passenger cars (gasoline) (Table 29 of PIARC, 2012)

Passenger car – gasoline CO (g/h) 2010							
	Gradient %						
v (km/h)	-6	-4	-2	0	2	4	6
0	38.9	38.9	38.9	38.9	38.9	38.9	38.9
10	45.3	48.5	52.4	56.3	61.9	68.1	80.3
20	51.6	58.2	66	73.7	84.8	97.3	121.7
30	51.7	61.4	73.4	88.3	106.1	126.2	166.7
40	51.4	64.4	81.8	106.1	136.1	177.3	227.3
50	50.3	66.1	88.9	120.8	164.6	228	307
60	48.8	66.5	93.9	132.8	191.4	274.1	408.6
70	47.4	66.1	96.9	145.2	221.8	326.7	532.1
80	46.7	65.9	99.7	161	262.8	408.1	677.6
90	47.5	67.4	105	181.6	318.4	543.9	849
100	50.1	72.2	115.9	207.5	396	753.9	1049.5
110	54.7	81.5	135.2	240	501.1	1040	1307
120	60.7	96.1	163.8	284.7	643.9	1302.3	1679.9
130	67.1	115.6	199.3	356.2	843.7	1589.2	2163.5

Base emission factors for carbon monoxide – Passenger cars (diesel) (Table 31 of PIARC, 2012)

Passenger car – Diesel CO (g/h) 2010							
	Gradient %						
v (km/h)	-6	-4	-2	0	2	4	6
0	3.3	3.3	3.3	3.3	3.3	3.3	3.3
10	9.6	9.6	9.6	10.3	10.9	11.4	12.9
20	9.6	9.6	9.8	11	11.9	11.2	12.9
30	9.6	9.6	10.1	11.6	11.2	13.3	12.9
40	9.6	9.6	10.1	12	12.4	13.3	9.8
50	9.6	9.6	10	11.5	13.7	10.8	8.1
60	9.6	9.6	10.2	11.2	13.2	8.8	7.5
70	9.6	9.6	10.7	12.4	10.7	7.3	8.5
80	9.6	9.6	11.4	12.2	8.8	7.9	9.5
90	9.6	9.6	11.5	12.3	7.4	8.8	10.5
100	9.6	9.6	11.5	9.8	7.8	9.8	11.6
110	9.6	9.6	11.7	7.9	8.8	10.9	12.8
120	9.6	10.5	11.7	7.6	9.9	12.1	14.1
130	9.6	11	11	10	11.1	13.3	15.4

Base emission factors for carbon monoxide – Light delivery vehicles (diesel/gasoline) (Table 37 of PIARC, 2012)

Light delivery vehicles (diesel/gasoline) – CO (g/h) 2010							
	Gradient %						
v (km/h)	-6	-4	-2	0	2	4	6
0	10.7	10.7	10.7	10.7	10.7	10.7	10.7
10	34.8	34.8	35.8	73.8	100.3	124.5	126
20	34.8	34.8	53.3	108.4	96.9	53.9	63.1
30	34.8	34.8	70.6	116	51.1	78.4	145.2
40	34.8	34.8	85.9	72.8	66.2	148.6	274.5
50	34.8	34.8	92.5	54.8	105.8	239	439.6
60	34.8	34.8	115	56.5	179.4	393.2	616.9
70	34.8	34.8	120	102.9	299.8	567.8	831.4
80	34.8	34.8	130	181.4	474.8	758.9	1089.6
90	34.8	76.8	140	304.8	637.6	988.4	1393.1
100	34.8	105.1	153.4	498.6	858.7	1286.6	1775.3
110	34.8	119.9	300.8	698.6	1138	1651.9	2233.2
120	58.1	128.3	520.5	957.2	1485.2	2094.2	2394
130	86.3	293.6	755.5	1284.5	1910.5	2194.8	2592

Base emission factors for carbon monoxide – Heavy delivery vehicles (diesel) (Table 41 of PIARC, 2012)

Heavy delivery vehicles (diesel) – CO (g/h) 2010							
	Gradient %						
v (km/h)	-6	-4	-2	0	2	4	6
0	38.6	38.6	38.6	38.6	38.6	38.6	38.6
10	30.4	35	52.3	63.6	69.5	75.2	81.7
20	21.9	31.4	55	67.6	76	90.2	105.1
30	20	32.3	60.2	71.6	85.8	109.7	131.2
40	18.2	29.6	62.1	75.4	97.9	129.4	156.3
50	18.2	27.2	60.6	78.3	112.3	147.8	183.9
60	18.2	23.5	56.2	82.1	127	167.4	212.1
70	18.2	19.4	51.6	88.3	140.5	188.6	242.1
80	18.2	20.3	56.9	98.9	156.3	212.2	274.5
90	18.2	22.3	62.7	113.3	173.1	236	306.8
100	18.2	26.5	71.8	129.5	190.1	260	339
110	18.2	30.3	80.6	143.5	206.2	283.7	371
120	18.5	44.4	91.5	154	222.5	307.1	402.7
130	21.1	50.9	105.3	163.3	238.5	330.4	434.8

As noted in the above tables, these data are for 2010 vehicle emissions. To account for changes in emission profiles with time, PIARC (2012) provide future years influencing factors to allow for scaling of the emissions. The following table outlines the PIARC (2012) influencing factors for future years.

Influencing factor for years different to 2010 (base year) (Table 34 of PIARC, 2012)

Influencing factor	CO	
Passenger Cars	**Gasoline**	**Diesel**
2010	*1*	*1*
2011	0.92	0.93
2012	0.84	0.87
2013	0.75	0.80
2014	0.67	0.74
2015	*0.59*	*0.67*
2016	0.56	0.62
2017	0.52	0.57
2018	0.49	0.53
2019	*0.45*	*0.48*
2020	*0.42*	*0.43*
2025/2030	*n/a*	*n/a*
Factors between 2010 and 2015 and factors between 2015 and 2020 were linearly interpolated from the charts provided in PIARC (2012).		

Given that the PIARC tables do not extend beyond 2020, the influencing factor for 2029 was assumed to be the same as 2020. This is a conservative assumption, as emission standards are expected to continue to drive emissions lower between 2020 and 2029. For this example calculation, however, the 2019 influencing factors were used.

The resultant emissions following the application of the 2019 influencing factors are shown in the following tables for passenger cars, light diesel vehicles and heavy vehicles.

Adjusted factors for carbon monoxide – Passenger cars (gasoline)

Passenger car – gasoline CO (g/h) 2019							
	Gradient %						
v (km/h)	**-6**	**-4**	**-2**	**0**	**2**	**4**	**6**
0	17.7	17.7	17.7	17.7	17.7	17.7	17.7
10	20.6	22.0	23.8	25.6	28.1	30.9	36.5
20	23.4	26.4	30.0	33.5	38.5	44.2	55.3
30	23.5	27.9	33.3	40.1	48.2	57.3	75.7
40	23.3	29.2	37.1	48.2	61.8	80.5	103.2
50	22.8	30.0	40.4	54.8	74.7	103.5	139.4
60	22.2	30.2	42.6	60.3	86.9	124.4	185.5
70	21.5	30.0	44.0	65.9	100.7	148.3	241.6
80	21.2	29.9	45.3	73.1	119.3	185.3	307.6
90	21.6	30.6	47.7	82.4	144.6	246.9	385.4
100	22.7	32.8	52.6	94.2	179.8	342.3	476.5
110	24.8	37.0	61.4	109.0	227.5	472.2	593.4
120	27.6	43.6	74.4	129.3	292.3	591.2	762.7
130	30.5	52.5	90.5	161.7	383.0	721.5	982.2

Adjusted factors for carbon monoxide – Passenger cars (diesel)

Passenger car – Diesel CO (g/h) 2019							
	Gradient %						
v (km/h)	-6	-4	-2	0	2	4	6
0	1.58	1.58	1.58	1.58	1.58	1.58	1.58
10	4.59	4.59	4.59	4.92	5.21	5.45	6.17
20	4.59	4.59	4.68	5.26	5.69	5.35	6.17
30	4.59	4.59	4.83	5.54	5.35	6.36	6.17
40	4.59	4.59	4.83	5.74	5.93	6.36	4.68
50	4.59	4.59	4.78	5.50	6.55	5.16	3.87
60	4.59	4.59	4.88	5.35	6.31	4.21	3.59
70	4.59	4.59	5.11	5.93	5.11	3.49	4.06
80	4.59	4.59	5.45	5.83	4.21	3.78	4.54
90	4.59	4.59	5.50	5.88	3.54	4.21	5.02
100	4.59	4.59	5.50	4.68	3.73	4.68	5.54
110	4.59	4.59	5.59	3.78	4.21	5.21	6.12
120	4.59	5.02	5.59	3.63	4.73	5.78	6.74
130	4.59	5.26	5.26	4.78	5.31	6.36	7.36

Adjusted factors for carbon monoxide – Light delivery vehicles (diesel/gasoline)

Light delivery vehicles (diesel/gasoline) – CO (g/h) 2019							
	Gradient %						
v (km/h)	-6	-4	-2	0	2	4	6
0	5.8	5.8	5.8	5.8	5.8	5.8	5.8
10	19.0	19.0	19.5	40.3	54.8	68.0	68.8
20	19.0	19.0	29.1	59.2	52.9	29.4	34.5
30	19.0	19.0	38.5	63.3	27.9	42.8	79.3
40	19.0	19.0	46.9	39.7	36.1	81.1	149.9
50	19.0	19.0	50.5	29.9	57.8	130.5	240.0
60	19.0	19.0	62.8	30.8	98.0	214.7	336.8
70	19.0	19.0	65.5	56.2	163.7	310.0	453.9
80	19.0	19.0	71.0	99.0	259.2	414.4	594.9
90	19.0	41.9	76.4	166.4	348.1	539.7	760.6
100	19.0	57.4	83.8	272.2	468.9	702.5	969.3
110	19.0	65.5	164.2	381.4	621.3	901.9	1219.3
120	31.7	70.1	284.2	522.6	810.9	1143.4	1307.1
130	47.1	160.3	412.5	701.3	1043.1	1198.4	1415.2

Adjusted factors for carbon monoxide – Heavy delivery vehicles (diesel)

Heavy delivery vehicles (diesel) – CO (g/h) 2019							
	Gradient %						
v (km/h)	-6	-4	-2	0	2	4	6
0	21.08	21.08	21.08	21.08	21.08	21.08	21.08
10	16.60	19.11	28.56	34.73	37.95	41.06	44.61
20	11.96	17.14	30.03	36.91	41.50	49.25	57.38
30	10.92	17.64	32.87	39.09	46.85	59.90	71.64
40	9.94	16.16	33.91	41.17	53.45	70.65	85.34
50	9.94	14.85	33.09	42.75	61.32	80.70	100.41
60	9.94	12.83	30.69	44.83	69.34	91.40	115.81
70	9.94	10.59	28.17	48.21	76.71	102.98	132.19
80	9.94	11.08	31.07	54.00	85.34	115.86	149.88
90	9.94	12.18	34.23	61.86	94.51	128.86	167.51
100	9.94	14.47	39.20	70.71	103.79	141.96	185.09
110	9.94	16.54	44.01	78.35	112.59	154.90	202.57
120	10.10	24.24	49.96	84.08	121.49	167.68	219.87
130	11.52	27.79	57.49	89.16	130.22	180.40	237.40

The numbers provided in the tables above were used with the ratio of petrol to diesel vehicles (eight per cent diesel vehicles and 92 per cent petrol vehicles) and the proportion of light duty vehicles to passenger vehicles (16 per cent light duty vehicles to 84 per cent passenger vehicles) to calculate a fleet-weighted emission factor table for passenger and light duty vehicles. The final emission factors were calculated as shown in the following tables.

Final base factors for carbon monoxide – Passenger cars and delivery vehicles (diesel/gasoline)

CO (g/h) 2019							
	Gradient %						
v (km/h)	-6	-4	-2	0	2	4	6
0	14.6	14.6	14.6	14.6	14.6	14.6	14.6
10	19.3	20.4	21.8	26.6	31.0	35.4	39.8
20	21.4	23.8	28.2	35.9	38.7	39.2	48.6
30	21.5	24.9	32.3	41.7	42.0	51.5	71.7
40	21.4	25.9	36.6	44.0	53.9	75.7	104.4
50	21.0	26.5	39.7	47.5	67.4	101.5	147.1
60	20.5	26.6	43.5	51.8	83.4	131.5	198.6
70	20.0	26.5	45.0	60.3	104.8	165.6	261.1
80	19.7	26.4	46.9	73.0	134.9	211.3	335.2
90	20.0	30.8	49.7	91.3	169.0	279.4	422.5
100	20.9	35.0	54.7	117.8	216.1	379.7	527.0
110	22.5	39.6	74.7	147.2	278.0	512.5	658.3
120	26.7	45.5	104.6	186.1	359.3	644.1	803.0
130	31.5	67.2	138.2	240.8	467.5	753.3	989.6

The following parameters were then assumed for illustrative purposes:

- Project (tunnel) link distance of 0.367 kilometres.
- Tunnel link gradient of -4.
- Two traffic lanes.
- Traffic flow of 100 vehicles per hour.
- A constant vehicle speed of 80 kilometres per hour for the link.
- Heavy vehicle percentage of 28 per cent.

Using the assumed parameters above and the calculated emission factors, the vehicle carbon monoxide emissions were then calculated to be:

- PC and LDV combined EF of 26.4 grams per hour = 0.0073 (grams per second per vehicle (g/s/vehicle)).
- HDV combined EF of 11.08 grams per hour = 0.0031 g/s/vehicle.

For a heavy vehicle fleet fraction of 28 per cent, the final combined vehicle emission factor was calculated to be 0.0062 g/s/vehicle.

In order to calculate a final mass emission rate from that section of the tunnel, the number of vehicles per second in the road tunnel was first calculated as follows::

$$Vehicles\ in\ tunnel\ section = \frac{VPH}{3600} \times \text{[(Time to travel 1km) x (Length of Tunnel Section)]}$$

For the assumed data, the vehicles in tunnel section = 100/3600 x [(45 x 0.367) = 0.46 vehicles per second per section.

Using the calculated final combined vehicle emission factor of 0.0062 g/s/vehicle, the final mass emission rate for carbon monoxide for this section of the tunnel was calculated to be 0.0028 g/s.

Mass emission rates were calculated for each hour of day for each tunnel link for carbon monoxide, PM_{10} and nitrogen dioxide in a similar manner to that outlined above. The sum of all of the individual pollutant link data was assumed to be the mass emission rate emitted from the tunnel ventilation outlet.

Emission factors for the other pollutants considered in the assessment, namely $PM_{2.5}$, total VOCs and PAHs, were not included in PIARC (2012). The emission factors published in the National Pollutant Inventory (NPI) (DEWHA, 2008) were used to estimate emissions of these pollutants. The NPI provides emission factors for a variety of different vehicle types and fuels. The ratios of PM_{10} to $PM_{2.5}$ emissions were calculated for the various vehicle types assessed. The ratios for cars and LDVs were averaged to provide an average ratio of $PM_{2.5}$ to PM_{10} for non-HDVs (0.93); this ratio was then multiplied by the PM_{10} emissions calculated using the PIARC emission factors to estimate $PM_{2.5}$ emission rates. As such, $PM_{2.5}$ emissions were calculated as 93 per cent of PM_{10} emissions for non-HDVs. A similar process was followed for HDVs, where the ratio of $PM_{2.5}$ to PM_{10} was calculated to be 0.95.

Emissions of VOCs and PAHs were similarly calculated using the carbon monoxide emission rates. The ratios of NPI emission factors for these pollutants and carbon monoxide were firstly calculated. The carbon monoxide emission rates calculated from the PIARC carbon monoxide emission factors were then multiplied by the calculated ratios to estimate emission rates of VOCs and PAHs.

Appendix I

NO_x to NO_2 conversion

Appendix I NO_x to NO_2 conversion

One of the challenges of modelling NOx emissions is determining the amount of NO_2 at a receiver, due to uncertainties in the conversion rates. Early studies (Hegg et al., 1977) showed that the rate of oxidation is controlled by the rate of plume mixing rather than by gas reaction kinetics. Ozone is usually the chemical that is responsible for most of the oxidation, but other reactive atmospheric gases can also oxidise NO.

Several methods were proposed for evaluating the amount of NO_2 that is formed from NO. These include:

1) Total conversion;
2) The Ambient Ratio Method (ARM) (0.75 is the US default value) when no measured nearby NOx/NO_2 ratios are available;
3) Ozone Limiting Method (OLM);
4) Jansenn's equations (which assume approximately 10 per cent of all NOx is NO_2) – used in Australia and New Zealand; and
5) Plume Volume Molar Ratio method.

All of these methods are referenced in the Federal Guideline on Air Quality Models (GAQM) and DEC (2005).

NO_x to NO_2 conversion in NSW

In NSW, the oxidation of NO to NO_2 is assessed by three methods (Method 1, the most simple, to Method 3, the most complex). Method 1, which assumes 100 per cent conversion of NO to NO2, can be used in one of two ways. A Level 1 assessment uses maximum predicted NO_X concentrations (assuming NOx = NO_2) and maximum ambient NO_2 concentrations to determine a cumulative NO_2 concentration. If the facility fails to meet the NO_2 impact assessment criteria, a Level 2 assessment is conducted, which again assumes 100 per cent conversion but with contemporaneous assessment of model predictions and ambient concentrations.

Method 2 is the OLM, where NO to NO_2 conversion is limited by the amount of ozone available. The OLM uses a simple approach to the reaction chemistry; it assumes that O_3 and NO react to form NO_2 in proportion to their ground level concentrations. That is, for each hour,

- if $O_3 < NO_{plume}$,
  - $NO_{2\ plume} = NO_{2\ initial} + O_3$, and if
- $O_3 \geq NO_{plume}$, $NO_{2\ plume} = NO_{x\ plume}$

Method 3 uses an empirical relationship to convert NO to NO_2 based on the equation developed by Janssen et al. (1988). The conversion is based on the distance of the receiver downwind from the source, and can be used with various levels of refinement (i.e. using maxima or contemporaneous data).

NO_x to NO_2 assessment in the United States

In the United States, the first level recommended technique in the Guideline on Air Quality Models (GAQM) is to assume the total conversion of NO to NO_2. This is the same first tier level as DEC (2005). It is a conservative, first-level technique, which may lead to unnecessary control in areas where the predicted impacts are close to ambient air quality criteria.

The Ambient Ratio Method (ARM) is the second-level technique recommended in the GAQM. The ARM is defined as the ratio of the average NO_2 and NOx ambient concentrations measured at a representative site. It uses local monitoring or a default 75 per cent ratio to find the ambient equilibrium NO_2/NOx ratio (annual average). Theoretically, equilibrium occurs when the rate of NO_2 formation equals the rate of dissociation of NO_2 by sunlight. Chu and Meyer (1991), who developed this technique, recommended that this monitoring be performed far away so that true equilibrium would occur. Unfortunately, ambient monitoring is usually insufficient for determining this ratio because ambient concentrations are frequently below the minimum monitoring threshold for NOx (20 ppb). Further, if the monitoring is performed too close to an existing source, the ARM's assumption of equilibrium is violated and the monitoring results are not applicable to receivers further downwind.

The third-level tier is the OLM (stated above) and a Plume Volume Molar Ratio method (PVMRM). The PVMRM method better simulates the NO to NO_2 conversion chemistry during plume expansion and is particularly well suited for the receivers located close to sources where maximum modelled NO concentrations are usually

predicted. The PVMRM method follows the chemistry of the main forward reaction of NO with O_3 as it occurs during expansion of a plume segment travelling downwind:

$NO + O_3 \rightarrow NO_2 + O_2$

This is accomplished by computing the number of moles of NOx and O_3 that are contained within a plume segment as it reaches a receiver. Although the PVMRM follows the same chemical reactions as those used in the OLM, it uses both plume size and O_3 concentration to derive the amount of O_3 available for the reaction. NOx moles are determined by emission rate and travel time through the plume segment. The number of O_3 moles is determined by the size of the plume segment and the measured background O_3 concentration. This plume segment always contains the same amount of primary NOx emissions as it travels downwind. The amount of O_3 available for reaction, however, increases as the plume segment enlarges downwind. The last approach, which is not yet included in any US Guideline criteria, is based on an empirical approach of some 3,000 co-located NOx and NO_2 monitors in Europe. The approach uses a scaled approach to NOx bins of concentration levels. This method was developed by the Atmospheric Studies Group and is included in the US EPA guideline model CALPOST. It has been used on a case-by-case basis when all other methods fail.

Concerns with and likely conservatism of the OLM

The OLM employed by the EPA (DEC, 2005) was taken from the US EPA OLM, originally developed by Cole and Summerhays (1979) and Tikvart (1996). The method assumes that all the available ozone in the atmosphere will react with NO in the plume until either all the O_3 or all the NO is used up. The approach is known to be conservative. Some of the reasons for its lack of robustness and conservatism are listed below:

- The OLM approach assumes that the atmospheric reaction is instant, whereas in reality the reaction takes place over a number of hours.
- The actual reactions of NO to NO_2 occur in proportion to the moles of each reactant rather than in proportion to the concentration assumed by the OLM. At constant volume, 1 ppm of a gas is proportional to 1 mole of a gas. This assumption is not valid in the open atmosphere, as there is virtually unlimited amount of O_3 available for reaction. As plumes expand downwind, more O_3 is available for reaction, and even lower concentrations of O_3 can react with NO in the plume.
- The OLM is further complicated as some of the NOx is already converted to NO_2 upstream in the plume before it reaches the receiver.
- Studies have shown that the NOx emission rates are extremely important with respect to the rate of conversion to NO_2. The size of the plume is not affected by the NOx emission rate, which means that there is the same amount of O_3 available for chemical conversion regardless of the NOx emission rate. Larger NOx emission rates lead to lower predicted ratios of NO_2/NOx. Maximum impacts that occur at receivers located further away have high predicted NO_2/NOx ratios. Further emissions emitted into stable (narrow) plumes will have less conversion to NO_2 compared to those emissions emitted into less stable (wider) plumes. The OLM does not take the NOx emission rate or plume size into consideration.
- The OLM can only be used on one plume at a time. The US EPA states that the OLM should be used with a 'plume-by-plume' approach. This is a big limitation to a facility with lots of different plumes. The OLM will therefore be very conservative for close in NO_2 impacts for large multi plume sources. The OLM may not be conservative for single plumes downwind, where low concentrations of O_3 can still react with the plume.

The OLM is expected to be conservative during daylight hours when the photochemical equilibrium reverses the oxidation of NO by O_3. It is also expected to be conservative during stable and night conditions when both NO_2 and O_3 are removed by reaction with vegetation and other surfaces.

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CONSUMER

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