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Report

Road tunnels: reductions in nitrogen dioxide concentrations in-cabin using vehicle ventilation systems

NSW Roads and Maritime Services

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Pacific Environment Operations Pty Ltd: ABN 86 127 101 642

BRISBANE
Level 1, 59 Melbourne Street, South Brisbane Qld 4101
PO Box 3306, South Brisbane Qld 4101
Ph: +61 7 3004 6400
Fax: +61 7 3844 5858

Unit 1, 22 Varley Street
Yeerongpilly, Qld 4105
Ph: +61 7 3004 6460

ADELAIDE
35 Edward Street, Norwood SA 5067
PO Box 3187, Norwood SA 5067
Ph: +61 8 8332 0960
Fax: +61 7 3844 5858

SYDNEY
Suite 1, Level 1, 146 Arthur Street
North Sydney, NSW 2060
Ph: +61 2 9870 0900
Fax: +61 2 9870 0999

MELBOURNE
Level 10, 224 Queen Street
Melbourne Vic 3000
Ph: +61 3 9036 2637
Fax: +61 2 9870 0999

PERTH
Level 1, Suite 3
34 Queen Street, Perth WA 6000
Ph: +61 8 9481 4961
Fax: +61 2 9870 0999

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EXECUTIVE SUMMARY

Introduction

Pacific Environment was commissioned by NSW Roads and Maritime Services (RMS) to obtain primary data on typical in-vehicle NO_2 concentrations. The study involved the extensive measurement of in-vehicle and outside-vehicle NO_2 concentrations for a range of cars and driving conditions in Sydney, including major tunnels, minor tunnels and surface roads. The measurements were used to derive in-vehicle/outside-vehicle (I/O) concentration ratios for NO_2. In-vehicle NO_2 concentrations are dependent upon the volume of outside air delivered by the vehicle's ventilation system and leakage, which together determine the cabin air exchange rate (AER). The study also therefore involved both the measurement of AERs and the validation of a simple model for their estimation. This in turn allowed the in-vehicle NO_2 concentrations in Australian cars to be estimated based on vehicle manufacturer, year of manufacture, and vehicle cabin volume.

Objectives

The general objectives of the study were as follows:

- To quantify the AERs, in-vehicle NO_2 concentrations and outside-vehicle NO_2 concentrations for cars being driven through tunnels in Sydney. The vehicles reflected the types and ages of the current and likely future car fleet, and included some 'worst case' examples.
- To determine I/O ratios for NO_2.
- To understand the influence of vehicle ventilation settings and other parameters on in-vehicle NO_2 concentrations and the I/O ratio.
- To combine the results from a measurement campaign in Sydney with information from a literature review, and to develop a simple predictive model relating AERs, in-vehicle NO_2 concentrations and outside-vehicle NO_2 concentrations.

The study answered the following key questions:

- What are the ranges of outside-vehicle and in-vehicle NO_2 concentrations in tunnels and on surface roads in Sydney?
- How do elevated outside-vehicle NO_2 concentrations in tunnels affect in-vehicle NO_2 concentrations in tunnels, and can in-vehicle NO_2 concentrations and I/O ratios be reduced by utilising vehicle ventilation settings such as 'recirculation' mode?
- How do in-vehicle NO_2 concentrations and I/O ratios vary by vehicle for typical cars in the Sydney fleet?
- What are the best-case and worst case conditions for outside-vehicle and in-vehicle NO_2 concentrations in Sydney tunnels?
- What is the range of AERs for vehicles in the Sydney car fleet, and can AERs be predicted using a model?
- Can measured AERs be used to predict in-vehicle NO_2 concentrations and I/O ratios using a model?

Transit-average NO_2 concentrations in the tunnels were compared with a tunnel-average concentration level of 0.5 ppm (500 ppb).

Methodology

Nine different petrol cars were used in the experimental work. These cars were broadly representative of the Sydney fleet, and their characteristics covered the range of variables known to be important determinants of AERs and in-vehicle pollution. Each test vehicle was fitted with fast-response (one-second) analysers to measure the in-vehicle and outside-vehicle CO_2 and NO_2 concentrations, as well as equipment to monitor and record vehicle operation and position.

A driving route was selected to maximise the number of runs through the major Sydney tunnels. The route had a length of 30 km (one way), and a typical travel time of between 45 and 60 minutes. Each vehicle was tested over a two-day period. The first half-day was used to conduct AER measurements (using CO_2 as a tracer gas), and the remaining 1.5 days were used for NO_2 measurements. Given that multiple NO_2 measurements were made in each tunnel, a large amount of data was generated in the study. The total distance driven was more than 3,000 km.

Several vehicle ventilation modes were evaluated in the study. A key test condition was the air recirculation setting, as AERs can be significantly reduced with recirculation switched on. The purging effect of opening the vehicle windows following a transit through a tunnel, the use of air conditioning, and alternative fans speeds were also evaluated. The performance of the different vehicle types was also considered.

Summary and conclusions

The main findings of the study are summarised below.

Outside-vehicle NO_2 concentrations

1. On individual runs concentrations exceeded 500 ppb in the M5 East eastbound, M5 East westbound and the Lane Cove eastbound tunnels. NO_2 concentrations in these tunnels were less than 500 ppb for at least 75% of transits. The relatively high NO_2 concentrations in the M5 East tunnels are linked to the high traffic volume and high proportion of heavy vehicles. Transit-average outside-vehicle NO_2 concentrations in the minor tunnels were fairly similar, and the mean concentrations were all less than 300 ppb. However, even these relatively short tunnels can have elevated outside-vehicle NO_2 concentrations.

2. The outside-vehicle NO_2 concentrations for surface roads were generally less than 150 ppb.

Effects of air recirculation on in-vehicle NO_2 concentrations and I/O ratios

Major tunnels

3. With recirculation mode switched on, the transit-average in-vehicle NO_2 concentrations were less than 200 ppb for all major tunnels, despite transit-average outside-vehicle NO_2 concentrations exceeding 700 ppb in some tunnels. Transit-average I/O ratios for NO_2 were less than 0.6 in all major tunnels except the Sydney Harbour southbound tunnel. This is probably because the outside-vehicle concentrations in this tunnel were relatively low, and so the background NO_2 levels had a proportionally larger impact on the I/O ratio. Occasionally the I/O ratio was greater than one with recirculation on. This was due to the accumulation of NO_2 in the vehicle cabin.

4. With recirculation mode switched off, the transit-average in-vehicle NO_2 concentrations were generally less than 200 ppb in all major tunnels, except for the M5 East eastbound tunnel. The I/O ratios were relatively high in all tunnels due to the increased AER between the vehicle cabin and the tunnel.

Minor tunnels and surface roads

5. With recirculation mode switched on, the mean transit-average in-vehicle NO_2 concentrations in minor tunnels and on surface roads were less than 50 ppb. The I/O ratio ranged from 0.05 to 2.70.

6. With recirculation mode switched off, the mean transit-average in-vehicle NO_2 concentrations increased to 50-100 ppb. The I/O ratio ranged from 0.05 to 4.0.

7. The higher I/O ratios in minor tunnels and on surface roads compared with major tunnels are attributed to lower NO_2 concentrations in outside air and accumulated in-vehicle NO_2 during tunnel transit.

Effect of other vehicle ventilation settings on I/O ratios

8. For a given fan speed and recirculation setting, switching air conditioning systems on had little effect on the I/O ratio for NO_2.

9. Increasing the fan speed from 0% to 50% shifted the I/O ratio distribution towards significantly higher values. Further increasing the fan speed to 100% further increased the I/O ratios. This is attributed to the increased intake rate of outside-vehicle air with a high NO_2 concentration.

Switching recirculation mode on/off following tunnel entrance/exit

10. A test involved switching off recirculation mode at a tunnel entrance and switching recirculate on upon exiting the tunnel. With recirculate on, in-vehicle NO_2 concentrations remained higher than outside-vehicle concentrations for approximately 80 seconds after exiting the tunnel. There was no difference when recirculate was turned off after exiting the tunnel; in-vehicle NO_2 concentrations also remained higher than outside-vehicle concentrations for approximately 80 seconds.

Effects of opening windows following tunnel exit

11. Tests were carried out to examine the effects of opening the vehicle windows at the end of the study route (exit of M5 East westbound tunnel). NO_2 concentrations did not decrease as rapidly as outside-vehicle NO_2 concentrations following tunnel exit. However, the experimental set-up meant that not all windows could be opened, and in practice it is likely that opening the windows would lead to a faster decrease in the in-vehicle concentration.

I/O ratio for NO_2 by vehicle type

12. Transit-average I/O ratios ranged from 0.06 to 0.32 with recirculation on, and 0.28 to 0.76 with recirculation off. This shows that all vehicles, regardless of vehicle model/manufacturer, can maintain lower in-vehicle NO_2 concentrations compared to outside-vehicle NO_2 concentrations with recirculation on.

13. The best performing vehicles (all I/O ratios less than 0.20) with recirculate-on were a Holden Astra Wagon, Hyundai i30, Fiat Punto, and Toyota Corolla. The highest I/O ratios were measured in a Subaru Outback. The performance of the Holden Astra Wagon is also surprising, as current AER models assume that Australian vehicles are equal to American cars, which are expected to have the worst performance. This suggests that vehicles manufactured in Australia may perform better than current AER models assume.

Best-case and worst case conditions for outside-vehicle and in-vehicle NO_2

14. Best-case and worst-case conditions were examined by comparing a high performing vehicle with recirculation on (2014 Hyundai i30), and a low performing vehicle with recirculation off (2008 Holden Astra Wagon). For the Hyundai, despite outside-vehicle 1-second NO_2 reaching 1,000 ppb, in-vehicle NO_2 with recirculation on remained well below 200 ppb. This demonstrates the effectiveness of recirculation in well-sealed vehicles.

AER measurements and model performance

15. The AERs measured at 60 km/h with recirculation on were low, ranging from 3.6/h for the 2007 Subaru Outback to 14.3/h for the 2002 Audi A3. Increasing the speed from 60 km/h to 100 km/h had little effect on measured AERs with recirculation on. However, switching ventilation setting to recirculation off resulted in much higher AERs for most vehicles, which ranged from 10.2 – 61.7/h at 60 km/h. As expected, the highest AERs were generally measured with recirculation off at 100 km/h.

16. AERs were predicted for the test vehicles using a model. The predicted AERs were within the same order of magnitude as measured AERs with recirculate-on, but did not agree with measured AERs with recirculation off. This was probably due to differences in the strength of fan systems between different vehicles.

Use of AERs to predict in-vehicle NO_2 concentrations and I/O ratios

17. In-vehicle NO_2 concentrations were predicted using measured AERs and the model. Predicted concentrations using the model were found to be in good agreement with measured in-vehicle concentrations. However, the model slightly overestimated the in-vehicle NO_2 concentration, which may be a result of in-vehicle NO_2 deposition.

Recommendations

The results from this study can be used to inform the design and operation of future road tunnels in Australia. The M5 East Tunnel is presented as the worst-case condition in terms of NO_2 concentrations. However, despite the high outside-vehicle NO_2 concentrations in tunnels, the study shows that in-vehicle NO_2 concentrations can be significantly reduced with ventilation set to recirculate. It would be advisable to encourage vehicle operators to use air recirculation mode in Sydney tunnels.

GLOSSARY

Term	Definition
AER	Air exchange rate. This unit of measurement describes how many times each hour a volume of air equal to the volume of the space (e.g. within a vehicle) enters. The incoming air displaces (i.e. exchanges) an equivalent volume of in-cabin air.
CAPS	Cavity attenuated phase shift analyser. Used for measuring NO_2 concentrations.
CO_2	Carbon dioxide. A colourless and odourless gas arising, in part, from vehicle exhaust.
Outside-vehicle air	Air outside of the vehicle including tunnels and surface roads
GPS	Global Positioning System
I/O ratio	This refers to the ratio of the inside (i.e. within cabin) gas concentration and outside (i.e. outside-vehicle air) gas concentration
In-vehicle air	Air enclosed within the vehicle cabin
M5E	M5 East
NDIR	Non-dispersive infrared. Spectroscopic technique for CO_2 analysis.
NO_2	Nitrogen dioxide. A gaseous pollutant arising, in part, from vehicle exhaust.
OBD	On-board diagnostics
Parts per billion (ppb)	A measure of very dilute concentrations of substances. Just as per cent means out of a hundred, so parts per billion or ppb means out of a billion
Parts per million (ppm)	A measure of very dilute concentrations of substances. Just as per cent means out of a hundred, so parts per million or ppm means out of a million
PIARC	Permanent International Association of Road Congresses (World Road Association)
R^2	Coefficient of determination. The R^2 provides an indication of how well data fits to a statistical model.
Recirculation	Vehicle ventilation settings that prevents outdoor air intake and causes the recirculation of air already present within the cabin.
RMS	Roads and Maritime Services
SHT	Sydney Harbour Tunnel
UFP	Ultrafine particles
UK	United Kingdom
VKT	Vehicle kilometres travelled

CONTENTS

1 INTRODUCTION

1.1 Context

Several major road infrastructure developments are currently planned for Sydney. Tunnels feature prominently amongst these developments, notably in the NorthConnex (http://northconnex.com.au/) and WestConnex (http://www.westconnex.com.au/) projects. If it is approved, WestConnex will form the longest single network of road tunnels in Australia.

Air quality has historically been a factor that influences the acceptance of road tunnels by the Sydney community, particularly ambient (outdoor) air quality and the effects of tunnel ventilation outlets. However, given the likely lengths and traffic volumes of the planned tunnels for NorthConnex and WestConnex, the potential exposure of vehicle occupants to elevated levels of air pollutants within tunnels is increasingly being scrutinised.

Tunnel ventilation sizing (*i.e.* the demand for fresh air) to reduce in-tunnel pollutant concentrations to acceptable levels is determined according to World Road Association guidelines **(PIARC, 2012)**. The fresh air requirements have traditionally been based on the in-tunnel concentration of carbon monoxide (CO). In the past, most of the CO was emitted by petrol vehicles. However, following the introduction and refinement of engine management and exhaust after-treatment systems, CO emissions from petrol vehicles are now very low.

The reduction in CO emissions, and the increased market penetration of diesel vehicles in passenger car fleets, has meant that some countries - such as those in Europe - are considering the use of nitrogen dioxide (NO_2) concentrations for tunnel ventilation sizing. This emphasis on NO_2 in Europe is further supported by evidence of an increase in NO_2 emissions from diesel vehicles. Whilst the diesel share of the car fleet is much higher in European countries than in Australia, for the planned tunnels in Sydney it is likely that ventilation sizing will also be mainly dictated by in-tunnel NO_2 concentrations rather than in-tunnel CO concentrations or ambient air quality. However, there is little evidence in the literature relating to the application of in-tunnel NO_2 limits, other than general comments that the management of in-tunnel NO_2 will require the development of reliable monitoring methods and models. The actual exposure of vehicle occupants to NO_2 in tunnels, and the implications of this for tunnel ventilation design, has not been studied in detail. Whilst this is considered in some overseas guidance, such as the UK Design Manual for Roads and Bridges **(Highways Agency *et al.*, 1999)**, it is not explicitly addressed by PIARC or Australian guidance.

In response to the increasing concerns about tunnel-related air quality, the NSW Government has established the Advisory Committee on Tunnel Air Quality (ACTAQ). ACTAQ is chaired by the NSW Chief Scientist and Engineer, and includes representatives from several government departments. In its *Initial Report on Tunnel Air Quality*[a], the Committee advised that work should be undertaken to:

> *'...research, develop and make recommendations on in-tunnel NO_2 limits.'*

Appropriate in-tunnel NO_2 limits depend on the link between in-tunnel NO_2 levels and exposure of vehicle occupants. Therefore, ACTAQ has set up a Working Group to collate information on the air exchange rates (AERs) of passenger vehicles and the effectiveness of vehicle ventilation systems in reducing occupant exposure to NO_2 in road tunnels in Sydney.

The NSW Department of Planning and Environment has also referred to in-tunnel NO_2 limits regarding the planned NorthConnex tunnels **(NSW DPE, 2015)**:

[a] http://www.chiefscientist.nsw.gov.au/reports

"The Department considers that nitrogen dioxide (NO_2) is now the key pollutant of concern for in-tunnel air quality. While carbon monoxide has historically been the basis for in-tunnel criteria in NSW and internationally, improvements in modern vehicle technology mean that NorthConnex will comply with existing health based carbon monoxide standards. By contrast, vehicle emissions of NO_2 have fallen less quickly, and uptake of diesel vehicles (which produce more NO_2 than petrol based vehicles) has risen.

……..

"…..Accordingly, it is recommended that the Proponent's design criteria for NO_2 of 0.5 ppm (averaged over 15 minutes) be applied as an average across the tunnel under all operating conditions."

1.2 Background to the study

Pacific Environment was commissioned by NSW Roads and Maritime Services (RMS) to obtain primary data on in-vehicle NO_2 concentrations, and to compare these with values in the literature.

The study involved the measurement of in-vehicle and outside-vehicle NO_2 concentrations for a range of cars and driving conditions in Sydney, including tunnels and surface roads. The measurements were used to derive in-vehicle/outside (I/O) concentration ratios. In-vehicle NO_2 concentrations in tunnels are dependent upon the capacity of the vehicle's ventilation system to minimise the cabin air exchange rate (AER)[b]. The study also therefore involved the validation of a simple model for estimating AERs. The AER is dependent, in turn, upon on the vehicle ventilation settings, vehicle age (or model year), country of manufacture, vehicle speed and fan strength **(Knibbs *et al*., 2009; Knibbs *et al*., 2010**; **Hudda *et al*., 2012; Hudda *et al*., 2013)**. These factors were considered in the study design.

It is anticipated that the outcomes of the study will be used to inform the design and operation of future road tunnels in NSW.

1.3 Objectives

High NO_2 concentrations in tunnels are primarily a human health issue. The overall objective of the study was to develop a mechanism for determining whether proposed in-tunnel NO_2 limits would be achievable for the upcoming tunnel projects in Sydney, as currently designed. The study quantified the range of NO_2 concentrations in Sydney tunnels, and determined the effectiveness of vehicle ventilation settings at limiting in-vehicle NO_2 concentrations.

The general objectives of the study were as follows:

1. To quantify the AERs, in-vehicle NO_2 concentrations and outside-vehicle NO_2 concentrations for cars being driven through tunnels in Sydney. The vehicles reflected the types and ages of the current and likely future car fleet, and included some 'worst case' examples.
2. To determine I/O ratios for NO_2.
3. To understand the influence of vehicle ventilation settings and other parameters on in-vehicle NO_2 concentrations and the I/O ratio.
4. To combine the results from a measurement campaign in Sydney with information from a literature review, and to develop a simple predictive model relating AERs, in-vehicle NO_2 concentrations and outside-vehicle NO_2 concentrations.

[b] The AER in an enclosed space, such as a vehicle cabin, describes how many times each hour a volume of air equal to the volume of the space enters. The incoming air displaces (i.e. exchanges) an equivalent volume of in-cabin air.

The study answered the following key questions:

- What are the ranges of outside-vehicle and in-vehicle NO_2 concentrations in tunnels and on surface roads in Sydney?
- How do elevated outside-vehicle NO_2 concentrations in tunnels affect in-vehicle NO_2 concentrations in tunnels, and can in-vehicle NO_2 concentrations and I/O ratios be reduced by utilising vehicle ventilation settings such as 'recirculation' mode?
- How do in-vehicle NO_2 concentrations and I/O ratios vary by vehicle for typical cars in the Sydney fleet?
- What are the best-case and worst case conditions for outside-vehicle and in-vehicle NO_2 concentrations in Sydney tunnels?
- What is the range of AERs for vehicles in the Sydney car fleet, and can AERs be predicted using a model?
- Can measured AERs be used to predict in-vehicle NO_2 concentrations and I/O ratios using a model?

The study also provided a considerable amount of additional information that will inform the design and operation of future road tunnels, including:

- Pollutant NO_2 concentration profiles for tunnel air (outside concentration as a function of distance into the tunnel).
- Driving patterns in Sydney for both surface roads and tunnel roads.

2 METHODOLOGY

2.1 Overview

The methodology was designed to address the findings and recommendations of a literature review and gap analysis report that was undertaken at the start of the study (**Appendix A**). A simplified representation of the methodology is shown in **Figure 2-1**. The various steps are explained in the following Sections, with more detail being provided in **Appendix B**.

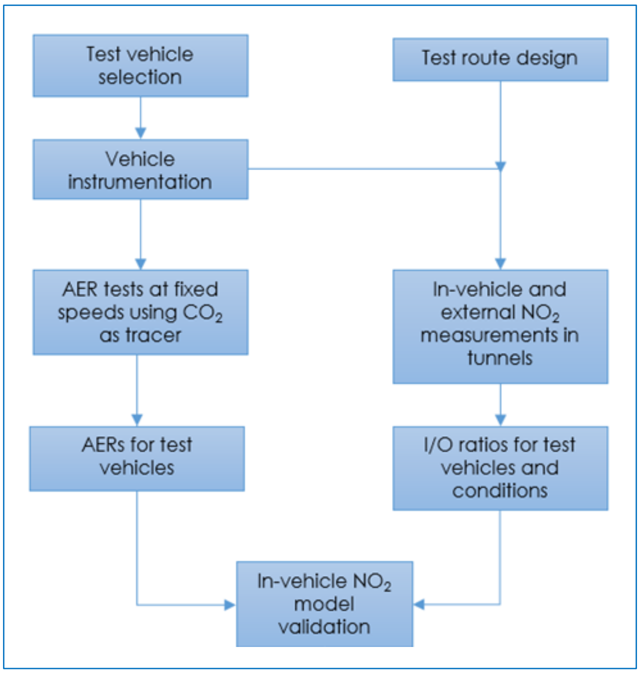


Figure 2-1: Overview of methodology

2.2 Selection of test vehicles

Nine different cars were used in the experimental work. The cars were selected to be broadly representative of the Sydney fleet, and covered the range of variables used in models for predicting AERs and in-vehicle pollution (*e.g.* manufacturer, odometer reading). The selection of vehicles was based on the following specific considerations (discussed in more detail in **Appendix C**):

- The likely composition of the car fleet in terms of fuel type, vehicle type, vehicle age and vehicle size in 2021[c]. The vehicle kilometres travelled (VKT) by vehicle type was also considered. This was to ensure that the vehicle models in the test programme would not be 'outliers' in the fleet.
- Car sales by vehicle model.
- The need to select vehicles that covered a reasonably wide range of AER model parameters, rather than focussing on a narrow range of characteristics. Several older vehicles were therefore included in the test programme as well as new ones, and vehicles from different manufacturers were used.

[c] The anticipated opening years for the NorthConnex and WestConnex M4 East projects are 2019 and 2021, respectively.

All the vehicles selected for monitoring were petrol cars, given that statistics from **ABS (2014)** show that petrol vehicles accounted for 80% of the total registered vehicle fleet (all types) in 2014. The information in NSW EPA's GMR emissions inventory also suggests a petrol/diesel split (by VKT) for passenger cars of approximately 80:20 in 2021. However, **Jones (2015)** provided evidence that only 8% of cars sold in NSW in 2014 were diesel cars. This contrasts with the inventory projection of 19% for 2014, and suggests that sales of diesel cars are growing more slowly than anticipated. The inclusion of a diesel car in the experimental work was considered. However, the issue of fuel type was not considered to be pertinent to the study, as emissions from the individual test vehicles would have been negligible compared with the emissions from the traffic in the tunnels.

The test vehicle matrix is shown in **Table 2-1**. For each age range the vehicles were classified based on the literature, into anticipated AER performance: 'best', 'intermediate' and 'worst' in terms of manufacture region. The specifications for the test vehicles are summarised in **Table 2-2**; the cabin volumes were calculated from the manufacturer specifications.

Table 2-1: Final test vehicle matrix

Expected AER performance by manufacturer region	Vehicle make and model by age band[a]		
	New (2011-2015 model years)	Intermediate (2006-2010 model years)	Old (pre-2006 model years)
Best (EU)	2014 BMW Prestige SUV (large)	2007 Fiat Punto (small)	2002 Audi A3 (medium)
Intermediate (JP/KO)	2014 Hyundai i30 (small)	2008 Toyota Corolla (medium)	2007 Subaru Outback (large)
Worst (US/AU)	2011 Holden Cruze (medium)	2008 Holden Astra Wagon (large)	2002 Ford Fiesta (small)

(a) Size class shown in brackets: small, medium, large.

Table 2-2: Vehicle specifications

Vehicle ID	Make and model	Year of manufacture	Engine size (litres)	Odometer reading (km)	Cabin volume (m^3)	Notes
V-01	Holden Astra	2008	1.8	80,000	10.2	
V-02	Ford Fiesta	2004	1.4	21,000	8.0	
V-03	BMW X3	2014	2.0	15,000	10.9	
V-04	Hyundai i30	2014	1.8	20,000	8.4	
V-05	Fiat Punto	2007	1.4	60,000	7.6	
V-06	Toyota Corolla	2007	1.8	75,000	8.4	
V-07	Subaru Outback	2007	2.5	139,000	11.1	
V-08	Audi A3	2002	1.8	35,000	8.2	Door seals visibly degraded
V-09	Holden Cruze	2011	1.8	37,790	6.1	

2.3 Vehicle instrumentation

2.3.1 Overview

Each test vehicle was equipped with the following instrumentation:

- Analysers to measure the in-vehicle and outside-vehicle CO_2 concentrations. CO_2 was the tracer gas used to determine AERs, with the vehicle occupants being the interior source.
- Analysers to measure the in-vehicle and outside-vehicle NO_2 concentration.
- Associated pumps, manifolds and sample lines.
- Equipment to monitor and record vehicle operation and position. This included an on-board diagnostics (OBD) scanning tool and software, and GPS for recording position (and speed where an OBD port was not available in the test car).
- Four 12V DC batteries.
- Inverters to convert the 12V DC power from the batteries to 240V AC power for the NO_2 analysers.
- A data logging computer.

A schematic diagram of the car set-up is shown in **Figure 2-2**, with a close-up diagram of the analysers shown in **Figure 2-3**. All instruments were powered by on-board batteries, and the instruments and batteries were installed in the boot of each test vehicle. The maximum sampling duration permitted by the batteries was determined prior to the field work, and back-up batteries were carried on-board to avoid loss of data. All instruments were synchronised to within one second prior to the sampling for each vehicle.

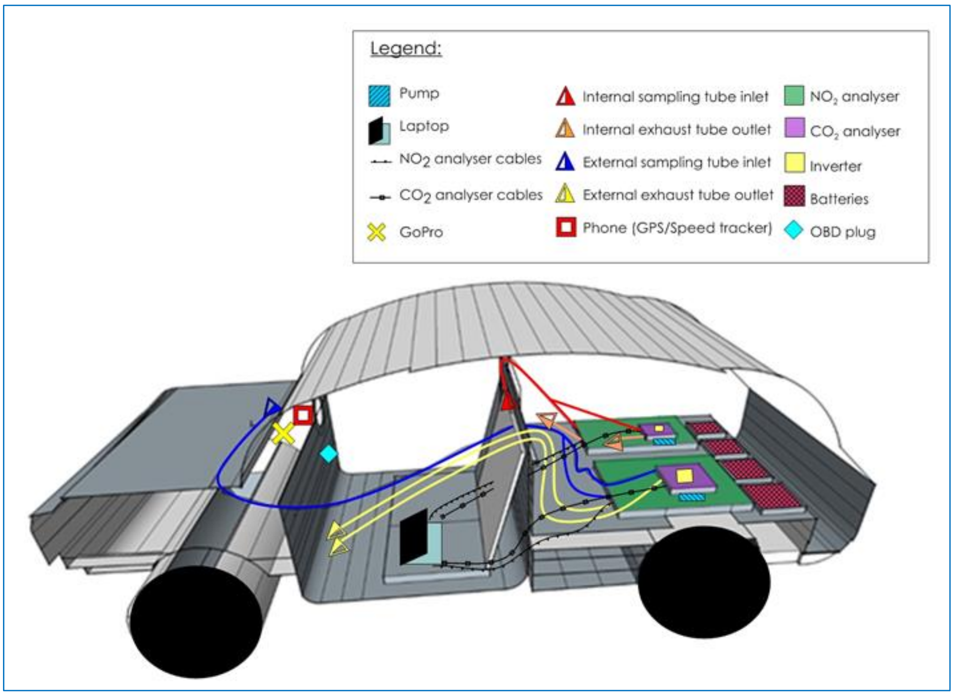


Figure 2-2: Diagram of car set-up

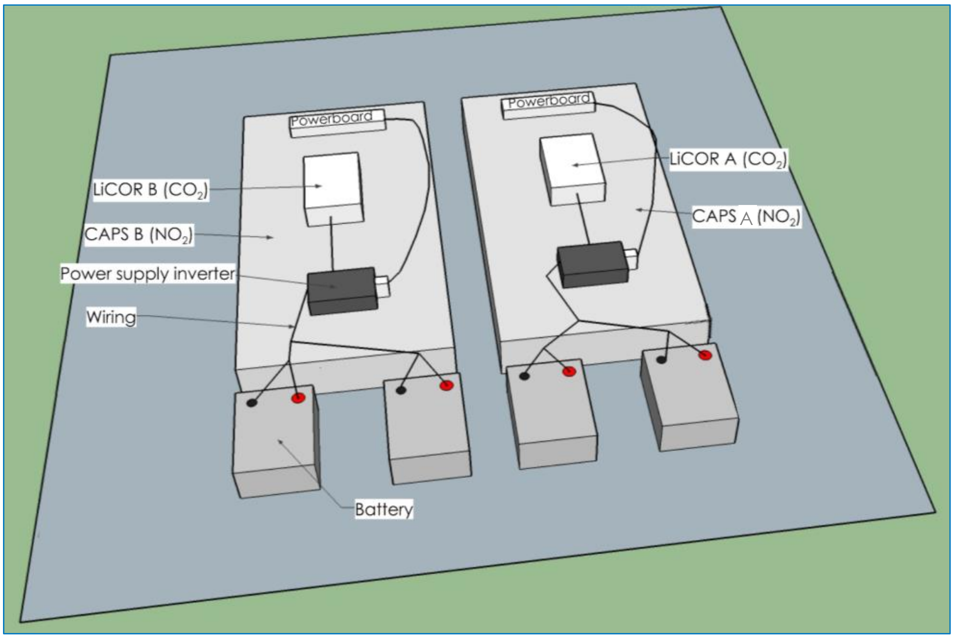


Figure 2-3: Close-up diagram of analyser set-up (A: in-vehicle and B; outside-vehicle)

Precautions were taken to minimise the influence of other potential errors and artefacts. For example, in-vehicle samples were collected close to the breathing zone of vehicle occupants for representativeness. All inlets/outlets for sample lines were well sealed. Foam padding was used to protect the equipment and dampen on-board vibration.

To complement the measurements a log sheet was completed for each trip. This included information such as adverse weather conditions (*e.g.* heavy rain, fog, gales) and unusual traffic conditions (*e.g.* breakdowns, accidents).

2.3.2 Carbon dioxide measurement

CO_2 measurements were undertaken to determine AERs for the test vehicles.

The specification, cost and practicality of various different instruments for measuring in-vehicle CO_2 concentrations were assessed (**Appendix B**).

Previous studies have shown that in-vehicle CO_2 levels typically reach around 2,000 – 3,000 ppm with an outside-vehicle concentration of around 400 ppm. Highly sensitive laboratory-grade instruments are generally not required for AER studies, and CO_2 can be successfully measured using portable instruments.

The instrument used to measure CO_2 in the study was the LI-COR Li-820. This instrument uses a non-dispersive infrared detection technique. The Li-820 is pump driven, thus allowing a fast response time. It has a 1 ppm signal noise at 370 ppm CO_2, and a range of 0 – 20,000 ppm. The unit is compact and has a lightweight design with low power (14 W) requirements, enabling mobility and easy deployment across multiple vehicles.

2.3.3 Nitrogen dioxide measurement

As with CO_2, various instruments for measuring NO_2 – ranging from low-cost, passive sensors to high-grade laboratory instruments – were considered in the literature review (**Appendix B**). The main considerations governing instrument selection for the study were measurement frequency, resolution and size (portability). For example, a passage through a four-kilometre long road tunnel at a speed of

80 km/h only takes three minutes. Sub-minute averaging periods and fast instrument response are therefore required to give an adequate temporal resolution in the measurements. The instrument resolution also needs to enable a clear differentiation between in-vehicle and in-tunnel NO_2 concentrations (*i.e.* measurement of ppb-level concentrations was required).

The instrument that was considered to be the most appropriate for the measurement of NO_2 in the study was the Aerodyne cavity attenuated phase shift (CAPS) analyser. This analyser provides a direct absorption measurement of NO_2 at a wavelength of 450 nm. Unlike chemiluminescence-based monitors, CAPS requires no conversion of NO to NO_2 and is not sensitive to the presence of other nitrogen-containing species. The Aerodyne instrument is capable of providing response times of up to 1 Hz with an NO_2 resolution of approximately 1 ppb and a linear response at concentrations up to several ppm. This measurement range was appropriate for the typical range of NO_2 concentrations in road tunnels.

Each test vehicle was equipped with two CAPS analysers, one to measure the in-vehicle NO_2 concentration and the other to measure the outside-vehicle NO_2 concentration. Measurements were made at one-second intervals. Daily baseline tests using a source of NO_2-free air were conducted. The CAPS analysers were battery powered (the power requirement of each unit was 100 W), enabling mobility and relatively straightforward deployment across multiple vehicles. The gas flow through each CAPS analyser was 0.85 litres per minute.

2.3.4 Vehicle operation and location tracking

The output from the on-board diagnostics (OBD) port of each vehicle was recorded using a scanning tool and software. There was a need to ensure that the selected test vehicles were capable of communicating according to one of the approved protocols (*e.g.* ISO 9141, J1850, KWP2000 or CAN). On-line data acquisition was achieved via a simple interface that was connected to the serial port of a standard PC having OBD-scanning software. Several vehicle operation parameters were recorded in real time (around 2 Hz). The most important parameter was vehicle speed, although other potentially useful information was collected, such as engine speed and engine load.

A GPS receiver (SpeedTrak) was also used to log the location, speed, bearing, trip distance and altitude of each vehicle. The OBD data and a manual record of vehicle location were used as back-up where the GPS signal was lost (*e.g.* inside tunnels).

2.4 Study route

2.4.1 Overview

A driving route was selected to maximise the number of runs through four main Sydney tunnels: Lane Cove tunnel, Sydney Harbour tunnel, Eastern Distributor tunnel and M5 East tunnel. This route is shown in **Figure 2-4**. The length of the route was 30 km (one way), and the typical travel time was between 45 and 60 minutes. The other major tunnel is Sydney, the Cross-City tunnel, was excluded from the route as its inclusion would have resulted in a significant detour.

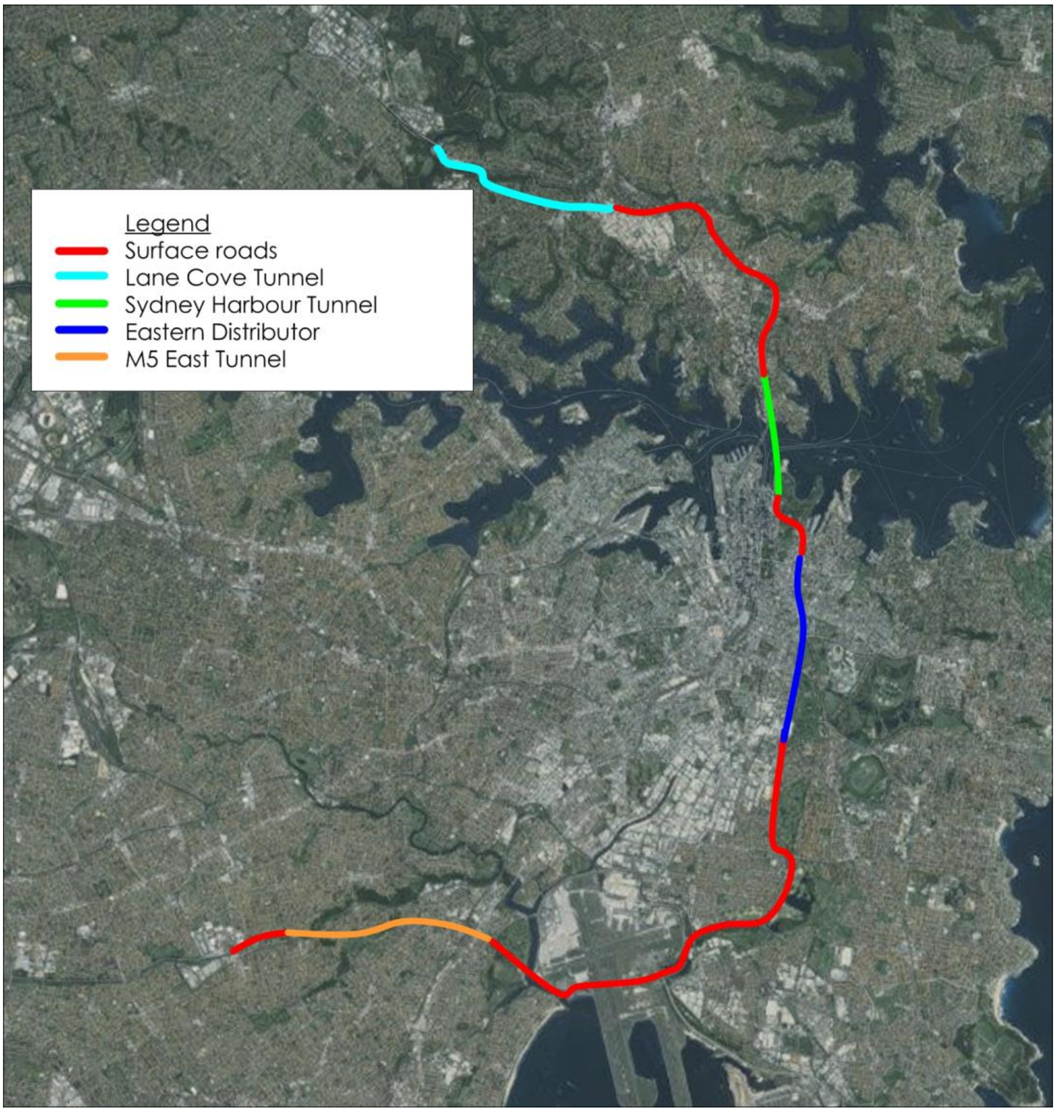


Figure 2-4: Monitoring route and road tunnels studied

2.4.2 Major tunnels

2.4.2.1 Lane Cove tunnel

The Lane Cove tunnel is 3.6 km in length. Approximately 1.4 km into the eastbound tunnel the number of lanes changes from two to three, with the additional lane continuing until approximately 2.8 km where it splits off at an exit ramp. The westbound tunnel changes from two to three lanes near the western main entrance, and remains as three lanes for the rest of the tunnel length.

The eastbound Lane Cove tunnel is predominantly uphill, with the westbound tunnel being predominantly downhill. The maximum gradient in both tunnels is approximately 4% (at the tunnel exits). The minimum tunnel gradient in the eastbound tunnel is -4.6%. This gradient occurs immediately at the entrance of the eastbound tunnel. The minimum tunnel gradient in the mainline westbound tunnel is -3.9%, and is also at the tunnel entrance.

Ventilation stacks are located at each of the main exit portals at Lane Cove West Industrial Park on Sirius Road (western end) and the Artarmon industrial area (eastern end) **(Transurban, 2015a)**. Around 120 large axial jet fans are also mounted in the tunnel ceilings to draw fresh air longitudinally through the tunnel from the entry points. The fresh air intake point for the Lane Cove Tunnel is located on Epping Road. Additional mid-tunnel exhaust points are turned on if there is significant traffic congestion.

2.4.2.2 Sydney Harbour tunnel

The Sydney Harbour tunnel is 2.3 km in length with two lanes in either direction. The tunnel entrances descend with a maximum gradient of 8% at the exit of the Sydney Harbour southbound tunnel and a minimum gradient of -8% at the Sydney Harbour northbound tunnel entrance.

The Sydney Harbour tunnel has a semi-transverse ventilation system, with air being expelled through a ventilation building located in the northern pylon of the Sydney Harbour Bridge. To maintain tunnel air quality, fresh air can be drawn into the tunnel through a duct located on the top, or in the case of the submerged portion of the tunnel, the sides of the tunnel **(Kuesel *et al.*, 1995)**.

2.4.2.3 Eastern Distributor

The Eastern Distributor tunnel comprises two 1.7 km tunnels (maximum width 24.5 m) running under Darlinghurst, East Sydney and Surry Hills, extending from near Cathedral Street, Woolloomooloo to Driver's Triangle at Moore Park beneath Fitzroy Street. The emissions from motor vehicles are released from the portals at each end of the tunnel, as well as from two ventilation stacks. The stack serving the Eastern Distributor northbound tunnel is located at Palmer Street, Woolloomooloo, and the stack serving the Eastern Distributor southbound tunnel is located on Flinders Street, Surry Hills.

2.4.2.4 M5 East

The M5 East tunnel comprises two 4 km tunnels with two lanes in either direction. Both tunnels dip at the entrance, after which they continue a relatively flat path for a large portion of the tunnel and then ascend to the main tunnel exits. The eastbound M5 East tunnel has two additional exit ramps. These include the Princes Highway exit (approximately 2.5 km into the tunnel), and the Marsh Street exit (approximately 3 km into the tunnel). The westbound M5 East tunnel has one exit ramp at Marsh Street.

The tunnel height for both tunnels is approximately 4.7 m, and there is a maximum road gradient of approximately 8.3%. This gradient is found at the entry of the westbound tunnel and the exit of the eastbound tunnel (*i.e*. at the eastern end of both tunnels).

The M5 East tunnel ventilation system, shown in **Figure 2-5**, has been designed to circulate tunnel air using a stack located approximately a third of the way along from the eastern end the tunnel. Tunnel air passes through the stack using fans, and is exhausted at Turrella. Fresh air is sucked in to dilute polluted tunnel air through an adjacent fresh air intake point which diverts fresh air to the eastbound and westbound tunnels.

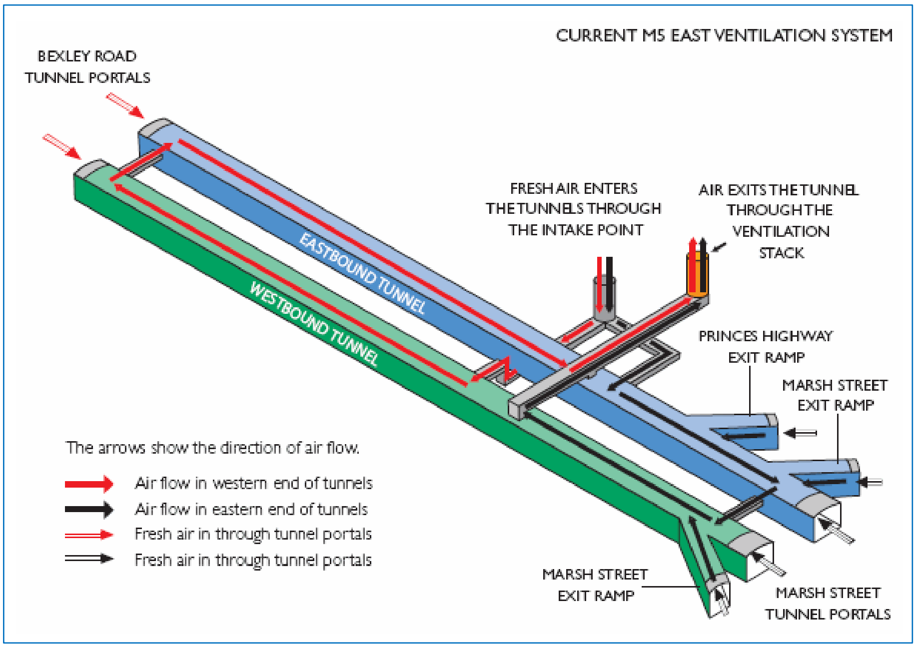


Figure 2-5: Ventilation system of the M5 East tunnel (RMS, 2015a)

2.4.2.5 Traffic volume

Traffic volumes for the major tunnels are shown in **Table 2-3**. The average number of vehicles per day is highest for the M5 East Tunnel, followed by the Lane Cove, Sydney Harbour and Eastern Distributor tunnels.

Table 2-3: Traffic volume and length summary for major tunnels

Tunnel	Average traffic volume (vehicles/day)
Lane Cove (eastbound)[a]	43,000[(a)]
Lane Cove (westbound)[a]	43,000[(a)]
Sydney Harbour (southbound)	42,000[(b)]
Sydney Harbour (northbound)	45,300[(b)]
Eastern Distributor (northbound)	27,500[(a)]
Eastern Distributor (southbound)	27,500[(a)]
M5 East (eastbound)	71,500[(a)]
M5 East (westbound)	71,500[(a)]

(a) Toll transactions per day from September quarter (**Transurban, 2015b**)
(b) Traffic counting data for 2015 from (**RMS, 2015b**)

2.4.3 Minor tunnels

The study route also included a number of shorter tunnels which were less than 600 m in length. These are summarised below.

2.4.3.1 Domain tunnel

The Domain tunnel starts near the Sydney Conservatorium of Music on the Eastern side of Circular Quay, and runs directly to the south entrance of the Sydney Harbour tunnel. The tunnel is approximately 350 m in length.

2.4.3.2 Airport tunnel

The Airport tunnel is located beneath Sydney Kingsford Smith Airport runways on General Holmes Drive, straight and is approximately 550 m in length.

2.4.3.3 Art Gallery tunnel

The Art Gallery tunnel to the north of the Art Gallery of NSW is a very short tunnel (150 m), and is located on the Cahill Expressway.

2.4.3.4 Cooks River tunnel

The Cooks River tunnel runs underneath a portion of the Cooks River and is approximately 550 m in length. The tunnel runs northwest to southeast at the eastern end of the M5 East Motorway.

2.4.4 Surface roads

The route includes a number of major surface roads (in order from north to south):

- M2 Hills Motorway
- M1 Motorway
- M1 Motorway-Eastern Distributor Motorway
- M1 Motorway-Southern Cross Drive
- M5 East Motorway

2.5 Measurement period

Each vehicle was tested over a two-day period. The first half-day was used to conduct the AER measurements, and the remaining 1.5 days were used for the NO_2 measurements. Given that multiple NO_2 measurements were made in each tunnel, a large amount of data was generated in the study.

Previous experience has shown that the cumulative number of measurement trips is less important than capturing the maximum variability in on-road conditions by sampling at different times of the day and night. Therefore, this aspect of the measurement campaign was prioritised over the total number of runs.

2.6 Ventilation settings

Several vehicle ventilation modes were evaluated in the study. A key test condition was the air recirculation setting, as AERs can be significantly reduced with recirculation switched on. The purging effect of opening the vehicle windows following a transit through a tunnel, the use of air conditioning, and alternative fans speeds were also evaluated.

The vehicle ventilation settings are summarised in **Table 2-4**. The emphasis was on testing the effects of air recirculation (settings MD1, MD2 and MD3, **Table 2-4**). Setting MD3 was included to investigate the effects of turning the ventilation system from ‘recirculation on’ to flow-through following tunnel transit. Settings MD4, MD5 and MD6 were used to investigate the effects of having air recirculation turned off under various fan speed settings (50%, 0% and 100% respectively). During an initial testing phase the effects of having constant ventilation settings during the entire multi-tunnel route were investigated, with the results being compared with those obtained when flushing the vehicle by opening the windows following a tunnel transit.

Table 2-4: Vehicle ventilation settings

Ventilation mode	Windows	Air recirculation	Air -conditioning	Fan speed (% of maximum)
MD1	Closed	On	On	50%
MD2		On	Off	50%
MD3		On/Off[(a)]	Off	50%
MD4		Off	Off	50%
MD5		Off	Off	0%
MD6		Off	Off	100%

(a) This investigated the effect of turning the ventilation system from 'recirculation on' to flow-through following tunnel transit.

2.7 Determination of vehicle AERs

The AER for a given vehicle depends on the size and distribution of air leakage sites, pressure differences induced by wind and temperature, mechanical system operation, and occupant behaviour. Air exchanges may be calculated from this information. However, some of the required parameters can be difficult to determine.

It was noted in the literature review that the best approach for quantifying AERs is to use a tracer gas to determine how much air enters a given space over time. Tracer gas testing permits the direct measurement of air exchanges. Various options are identified in *Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution* **(ASTM, 2006)**[d]. These options include the initial injection of a tracer gas into an air space, followed by a characterisation of the decay in concentration, and the constant injection of tracer gas to characterise the leakage rate.

Practical considerations regarding tracer gas selection are especially important in the dynamic and challenging in-cabin microenvironment. For this study CO_2 was adopted as the tracer gas. CO_2 is a useful tracer because of its ease of measurement using portable instruments and negligible toxicity at in-vehicle concentrations. Additionally, because vehicle occupants can be used as the source (through breathing) there is no requirement for transport and storage of tracer gases. The use of CO_2 as a tracer gas has been shown to be a fast, effective and low-cost method for performing AER measurements for diverse vehicle fleets.

The use of occupant-generated CO_2 is essentially a variation on the constant-injection technique (*i.e.* it is assumed that the CO_2 production rate from occupants is constant for sedentary activity). This approach was used by **Fruin *et al.* (2011).** For a given vehicle speed the AER was nearly constant and the CO_2 concentrations inside the vehicle eventually reached an equilibrium value of tracer from all in-vehicle sources.

For the AER tests the CO_2 generation rate of the occupants was determined by measuring the CO_2 increase with the car stationary and the ventilation set to recirculate with the fan at 50%. To determine the breathing rate, a simple linear regression model was applied whereby the CO_2 generation rate was equal to the gradient. For instance, the CO_2 generation rate for occupants in the 2011 Holden Cruze

(V-09) was 2.40 ppm/s or 8,600 ppm/hour (**Figure 2-6**), which is similar to values reported in **Fruin *et al.* (2011)**.

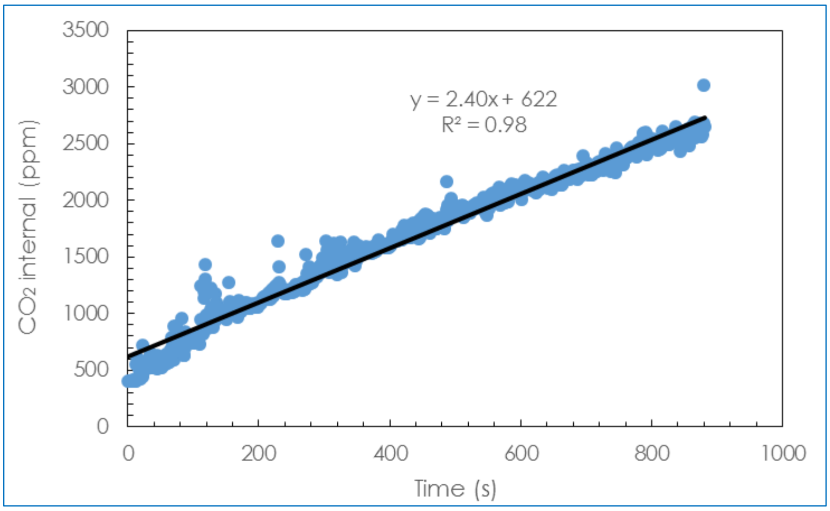


Figure 2-6: In-vehicle CO_2 generation rate for the 2011 Holden Cruze (V-09)

The AER tests were conducted under real-world traffic conditions, with each test vehicle being driven at different constant speeds. Nominal speeds of 60 km/h and 100 km/h were used, although the actual speed varied according to the test conditions at the time of measurement. Testing under real-world traffic conditions was seen as the most appropriate approach given the purpose of the AER test was to determine the validity of an existing AER model for cars in the Sydney fleet.

Low-traffic conditions were selected to enable steady-state conditions to be attained and to minimise changes in the outside-vehicle CO_2 concentration due to the presence of exhaust plumes from other vehicles. AERs were determined with windows closed, with the ventilation set to air recirculation, and with the fan set to either 50% or as close as possible to a mid-way setting. For a subset of tests AERs were also determined for stationary vehicles and other fan settings.

2.8 AER model

The model equation for air recirculation on (RC-on) is given as **(Hudda *et al.* 2012)**[e]**:**

$$\ln(AER) = 2.79 + (0.019 \times S) + [(0.015 \times age) + (3.3 \times 10^{-3} age^2)] + [(-0.023 \times V) + (6.6 \times 10^{-5} V^2)] + M.A.$$

Equation 1

where:

where:	age	is vehicle age[f] (in years)
	V	is vehicle cabin volume (in ft^3)
	S	is speed (in km h^{-1})
	$M.A.$	is the manufacturer adjustment (-0.71 for German vehicles, -0.39 for Japanese vehicles, and 0 for American/Australian manufactured vehicles)

Note that if the speed is zero a -0.51 factor should be added.

[e] This includes a corrigendum to the paper **(Hudda *et al.*, 2013)**.

[f] The predictors in the model include vehicle age but not model year (hence the former being more important than the latter).

The model equation for outdoor air intake (RC-off) is:

$$\ln(AER) = 4.20 + (0.048 \times S) + [(1.88 \times fan\ strength) + (0.92 \times fan\ strength^2)] + [(-0.073 \times V)]$$

Equation 2

Where *fan strength* refers to the fan setting as a fraction of the maximum (e.g. 4/4).

2.9 I/O ratio model

Most modelling of vehicle I/O ratios has focused on ultrafine particles (UFPs). However, the generic mass-balance models that have been used successfully to predict in-vehicle concentrations of UFPs can also be applied to NO_2. A standard mass-balance model developed by **Knibbs *et al.* (2010)** for predicting in-cabin UFP concentrations on the basis of on-road concentrations has been adapted to predict NO_2 with some minor modifications.

The mass balance approach has been employed in indoor air quality modelling for many years. **Knibbs *et al.* (2010)** successfully adapted an indoor model to predict in-vehicle UFP concentrations during trips through the M5 East Tunnel in Sydney, and this approach is therefore also suitable for modelling NO_2. This model is given as:

$$\begin{aligned} C(t) = {} & \frac{C_{O/A}[Q_{O/A} \cdot (1 - \varepsilon_{S/A}) + Q_{INF}] + G}{Q_{O/A} + Q_{EXF} + Q_{R/A} \cdot \varepsilon_{S/A}} \\ & \times \left[1 - \exp\left(-\frac{Q_{O/A} + Q_{EXF} + Q_{R/A} \cdot \varepsilon_{S/A}}{V} t\right)\right] \\ & + C_0 \cdot \exp\left(-\frac{Q_{O/A} + Q_{EXF} + Q_{R/A} \cdot \varepsilon_{S/A}}{V} t\right) \end{aligned}$$

Equation 3

Where:

- $C(t)$ is the particle concentration at time (t) (p cm^{-3})
- $C_{O/A}$ is the particle concentration in outdoor air (p cm^{-3})
- $Q_{O/A}$, Q_{INF}, Q_{EXF} and $Q_{R/A}$ are the flow rates of outdoor, infiltration, exfiltration and return air, respectively ($m^3\ s^{-1}$)
- $\varepsilon_{S/A}$ is the supply air filtration efficiency of an air-handling system (-)
- G is the generation rate of particles due to the occupants (p s^{-1})
- V is the volume of the space (m^3)
- t is the time (s)

2.10 Quality assurance and quality control

Zero and single-point calibrations were conducted on all CO_2 and NO_2 instruments before the measurement campaign and half-way through the measurement campaign prior to the testing of the seventh vehicle. High-purity nitrogen (>99.99%) was used for NO_2 and CO_2 zero calibrations. For span calibrations the concentrations were 2.1 ± 0.21 ppm for NO_2 and 3000 ± 30 ppm for CO_2. All span values were within 1% of the desired concentrations for all CO_2 and NO_2 instruments.

The CAPS analysers used for measuring NO_2 were liable to measurement drift. Baseline tests were carried out before each monitoring session to correct for the measurement drift. Baseline tests were also conducted with the doors and boot of each vehicle open in order for the NO_2 analysers to sample outside air and correct for any differences in instrument response. These tests were conducted at

Blenheim Park (33°47'46.155"S 151°8'7.955" E) to minimise influence from vehicle NO_2 emissions. The average NO_2 concentration at Blenheim Park after instrument calibration was 15 ppb. This value was subtracted from the baseline NO_2 concentrations to determine a concentration offset for each NO_2 instrument during each measurement session. These offsets are given in **Table 2-5**.

Table 2-5 NO_2 offset values determined from baseline tests

Session ID	Date	Instrument A offset (ppb)	Instrument B offset (ppb)
1	24-Aug-15	11	20
2	26-Aug-15	22	20
3	27-Aug-15	22	20
4	31-Aug-15	34	19
5	01-Sep-15	34	19
6	01-Sep-15	45	19
7	02-Sep-15	45	19
10	03-Sep-15	75	27
11	04-Sep-15	75	27
12	07-Sep-15	84	27
13	08-Sep-15	86	26
14	08-Sep-15	87	26
15	09-Sep-15	92	24
16	11-Sep-15	94	24
17	14-Sep-15	94	24
18	15-Sep-15	95	23
19	15-Sep-15	97	23
20	16-Sep-15	98	22
21	16-Sep-15	103	21
22	17-Sep-15	-19	10
23	18-Sep-15	-19	10
24	28-Sep-15	-19	10
25	29-Sep-15	-19	10
26	30-Sep-15	-19	10
27	01-Oct-15	-19	10

3 RESULTS AND DISCUSSION

3.1 Overview

This Chapter addresses the key questions identified in **Section 1.3**. It firstly outlines the range of outside-vehicle and in-vehicle NO_2 concentrations in tunnels and on surface roads in Sydney. Following this, the factors affecting in-vehicle NO_2 concentrations, such as vehicle manufacturer/model and vehicle ventilation setting, are discussed. As in-vehicle NO_2 concentrations were dependent upon outside-vehicle NO_2 concentrations, and these were not constant for each vehicle/ventilation setting, the vehicle/ventilation settings were also examined in terms of the I/O ratio. Based on the results the best-case and worst-case conditions for in-vehicle NO_2 concentrations were identified. The final Section of the Chapter examines the measured AERs to examine the range of values for typical vehicles in the Sydney car fleet. The measured AERs are also compared with predicted AERs to assess the model developed by **Hudda *et al.* (2012)**. In addition, the measured AERs and measured I/O ratios are compared, as these two parameters are closely related. Finally, the in-vehicle NO_2 concentrations predicted using the model from **Knibbs *et al.* (2010)** are assessed through comparison with the results from the monitoring campaign.

The data for each individual run of the measurement campaign are shown graphically in **Appendix F**.

3.2 Trip summary

The numbers of passes conducted for each vehicle for each tunnel and travel direction are shown in **Table 3-1**. In total, 59 complete runs of the study route were completed, which equated to a total distance driven of more than 1,750 km. Between 59 and 68 runs were completed in each individual tunnel, and the total number of passes through all tunnels was 495. As the number of runs was split fairly evenly across all tunnels, the results are not expected to be biased towards any particular tunnel or travel direction. Between 29 and 90 runs were conducted for each test vehicle, and there was an average of 55 runs per vehicle. No systematic bias in the results is expected to have resulted from this.

Table 3-1: Number of passes through each tunnel and direction

Vehicle (model year)	Number of passes by tunnel and direction[a]								
	Eastern Distributor		Lane Cove		M5 East		Sydney Harbour		
	NB	SB	EB	WB	EB	WB	NB	SB	Total
V-01: Holden Astra Wagon (2008)	8	7	8	7	7	7	7	8	**59**
V-02: Ford Fiesta (2002)	6	6	7	7	6	6	6	6	**50**
V-03: BMW X3 (2014)	4	3	4	4	4	4	4	4	**31**
V-04: Hyundai i30 (2014)	6	6	6	8	6	6	6	6	**50**
V-05: Fiat Punto (2002)	7	7	7	6	7	7	7	7	**55**
V-06: Toyota Corolla (2008)	8	8	10	8	8	8	8	8	**66**
V-07: Subaru Outback (2007)	4	3	4	4	4	3	4	3	**29**
V-08: Audi A3 (2002)	8	8	10	8	8	8	8	7	**65**
V-09: Holden Cruze (2011)	11	11	12	11	12	11	11	11	**90**
All vehicles	**62**	**59**	**68**	**63**	**62**	**60**	**61**	**60**	**495**

(a) NB = northbound, SB = southbound, EB= eastbound, WB = westbound

Figure 3-1 shows the percentage of runs conducted by time of day. The majority of runs (70%) were conducted during the Inter-peak period (09:00 – 16:30), which was due to this period covering the most daytime hours and the reduced congestion allowing for a greater number of runs. The percentage of runs conducted during the Peak AM (06:00 – 09:00) and Peak PM (16:30 – 19:00) periods were 10% and 15%, respectively. A small amount of runs were conducted during the Evening period (19:00 – 20:00).

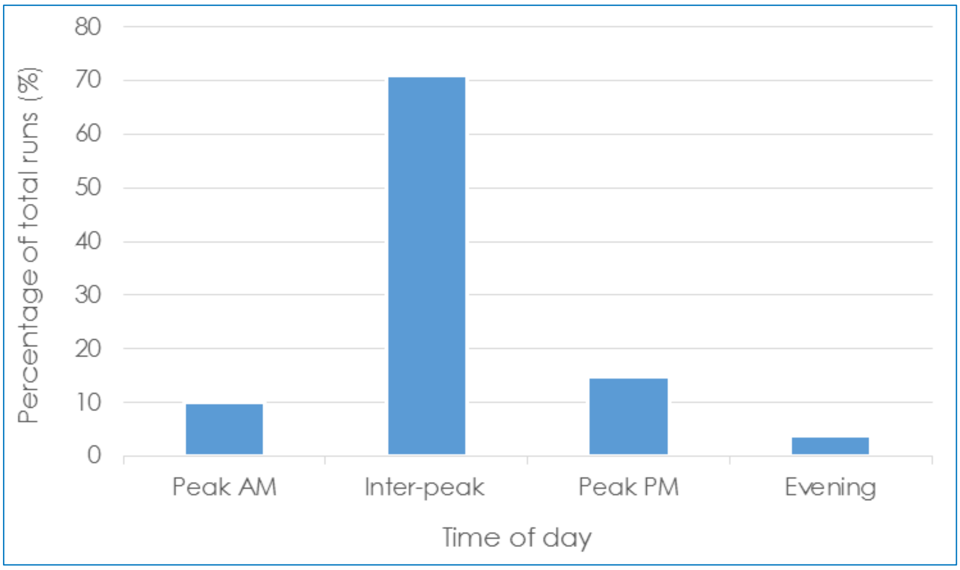


Figure 3-1: Percentage of runs by time of day (Peak AM: 06:00 – 09:00, Inter-peak: 09:00 – 16:30, Peak PM: 16:30 – 19:00, Evening: 19:00 – 20:00).

Table 3-2 shows the average speed, average transit time, and maximum transit time for each tunnel based on the monitoring data. The average speed in all tunnels ranged from 35 to 73 km/h. The tunnels with the lowest average speeds were the M5 East westbound and the Eastern Distributor southbound, which had average speeds of 35 and 42 km/h, respectively. The tunnels with the highest average speeds were the Lane Cove westbound and eastbound tunnels. The transit times in the tunnels ranged from 96 to 459 seconds. The longest transit times were in the M5 East tunnel, which is attributed to its greater length and traffic congestion.

Table 3-2: Average speed and transit time of tunnel trips

Tunnel	Average speed (km/h)	Average transit time (s)	Maximum transit time (s)
Eastern Distributor: Northbound	65	96	328
Eastern Distributor: Southbound	42	180	449
Lane Cove: Eastbound	66	203	519
Lane Cove: Westbound	73	179	242
M5 East: Eastbound	56	277	1339
M5 East: Westbound	35	459	756
Sydney Harbour: Northbound	61	139	240
Sydney Harbour: Southbound	57	175	660

3.3 What are the outside-vehicle and in-vehicle NO_2 concentrations in tunnels and on surface roads?

3.3.1 Outside-vehicle NO_2 measurements

An example of typical 1-second outside-vehicle NO_2 concentrations in tunnels is shown in **Figure 3-2**. This Figure shows a southbound trip from the Lane Cove tunnel to the end of the westbound M5 East tunnel. It can be seen that outside-vehicle NO_2 concentrations were generally higher in the Lane Cove tunnel, Eastern Distributor tunnel and M5 East tunnel than on surface roads. Elevated outside-vehicle NO_2 concentrations were also observed in some shorter or naturally ventilated tunnels, such as the Domain tunnel.

Outside-vehicle NO_2 concentrations increased with the distance travelled into each tunnel, unless there was an influence of a tunnel ventilation point. An example profile for the outside-vehicle NO_2 concentration is given for the westbound M5 East tunnel in **Figure 3-3**. Concentrations increased steadily from around 50 ppb at the entrance of the tunnel to around 500 ppb approximately 1 km into the tunnel, where concentrations decreased rapidly to around 200 ppb. This reflects the M5 East tunnel's ventilation system, which recirculates tunnel air to a stack located approximately a third of the way into the westbound tunnel (**Figure 2-5**). Following the stack, outside-vehicle NO_2 concentrations increased relatively steadily to a maximum of around 1,000 ppb, and then decreased rapidly to less than 200 ppb following exit of the tunnel. A similar effect was observed for the eastbound M5 East tunnel at the ventilation point approximately 1 km from the eastern exit (**Figure 3-4**).

In the Lane Cove tunnel the outside-vehicle NO_2 concentration increased consistently from the tunnel entrance to the tunnel exit (**Figure 3-5**). The steady increase in NO_2 concentration is attributable to the longitudinal in-tunnel ventilation system. The concentration profile is also a function of the tunnel gradient, which is uphill from about 1.3 km into the eastbound tunnel.

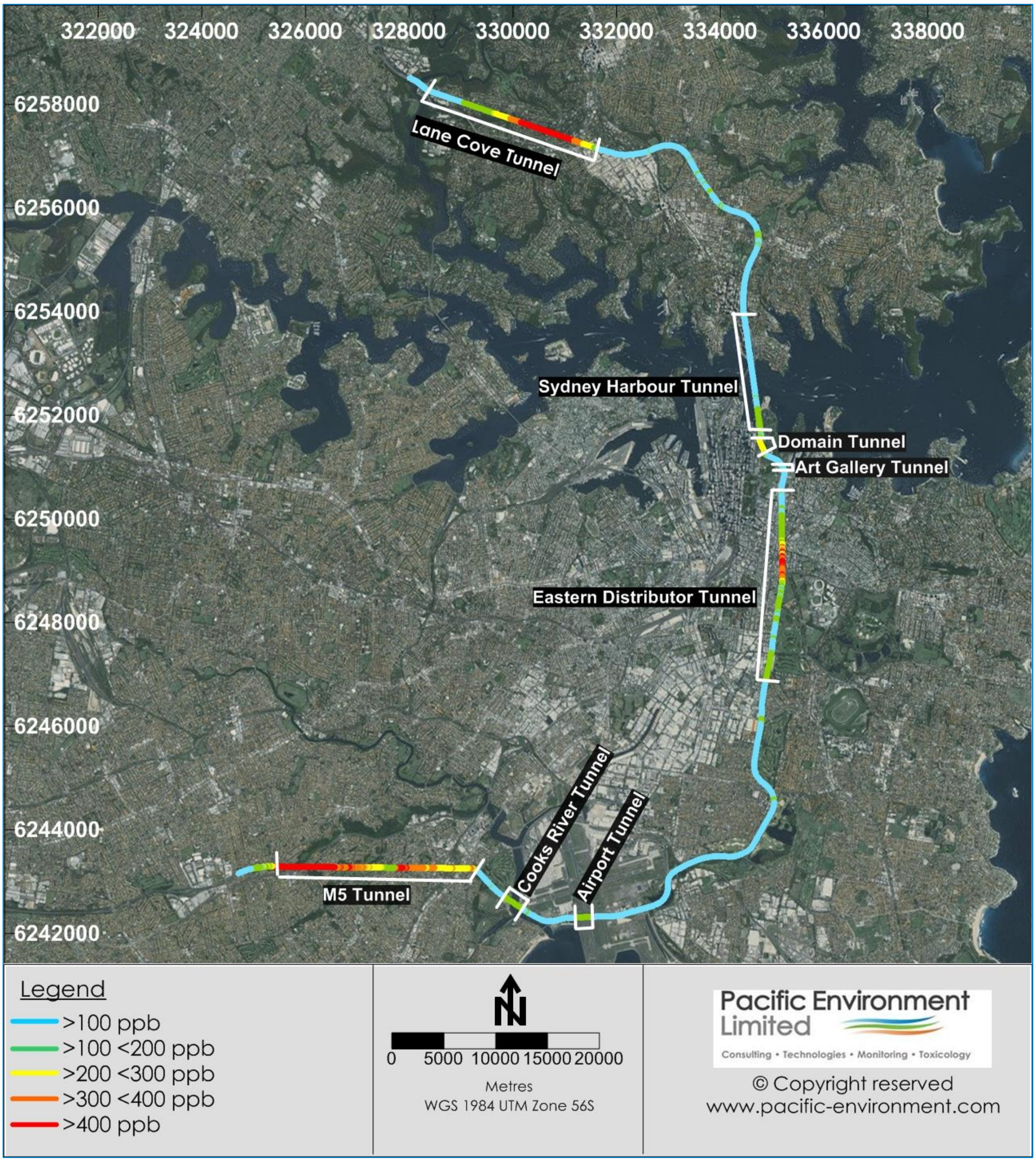


Figure 3-2: Example of outside-vehicle NO_2 concentrations along the study route (southbound route 26/08/15 7:55am – 8:40am)

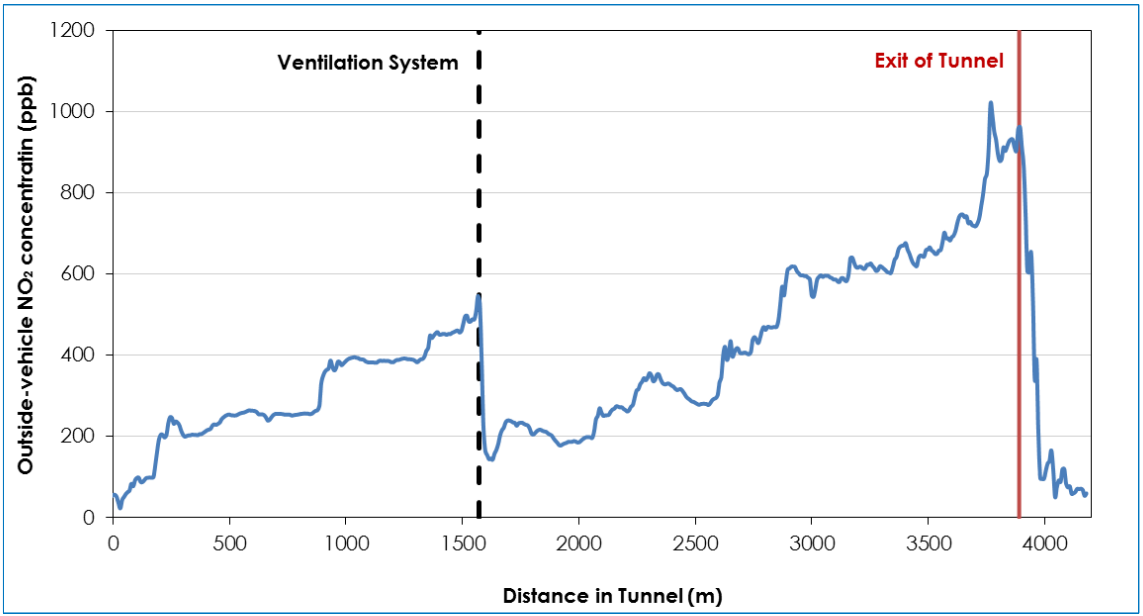


Figure 3-3: Example of 1-second outside-vehicle NO_2 concentrations (westbound M5 East tunnel)

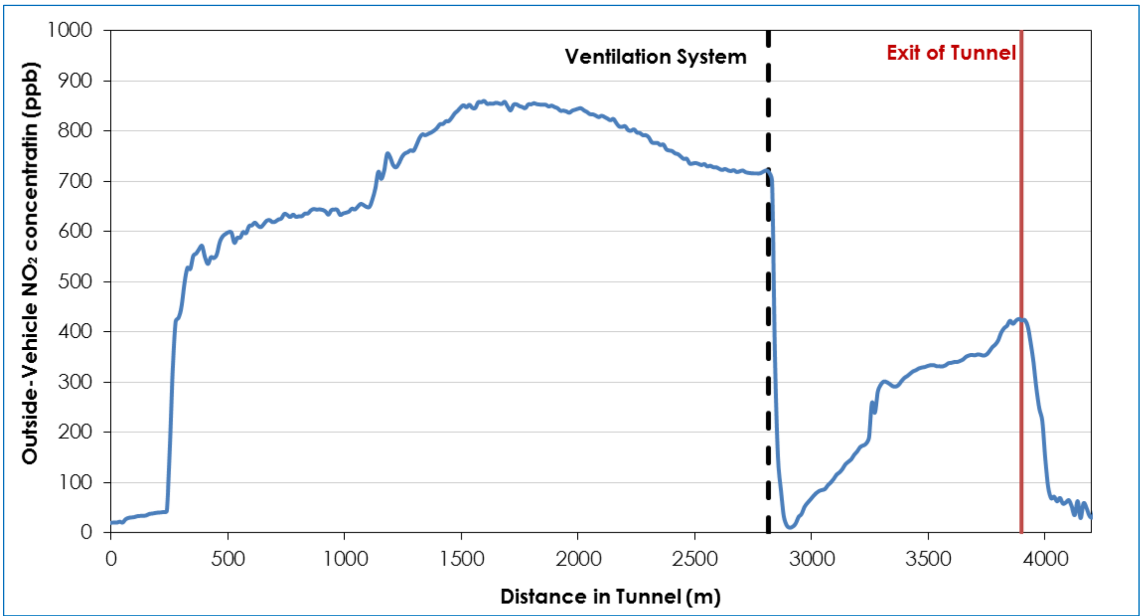


Figure 3-4: Example of 1-second outside-vehicle NO_2 concentrations (eastbound M5 East tunnel)

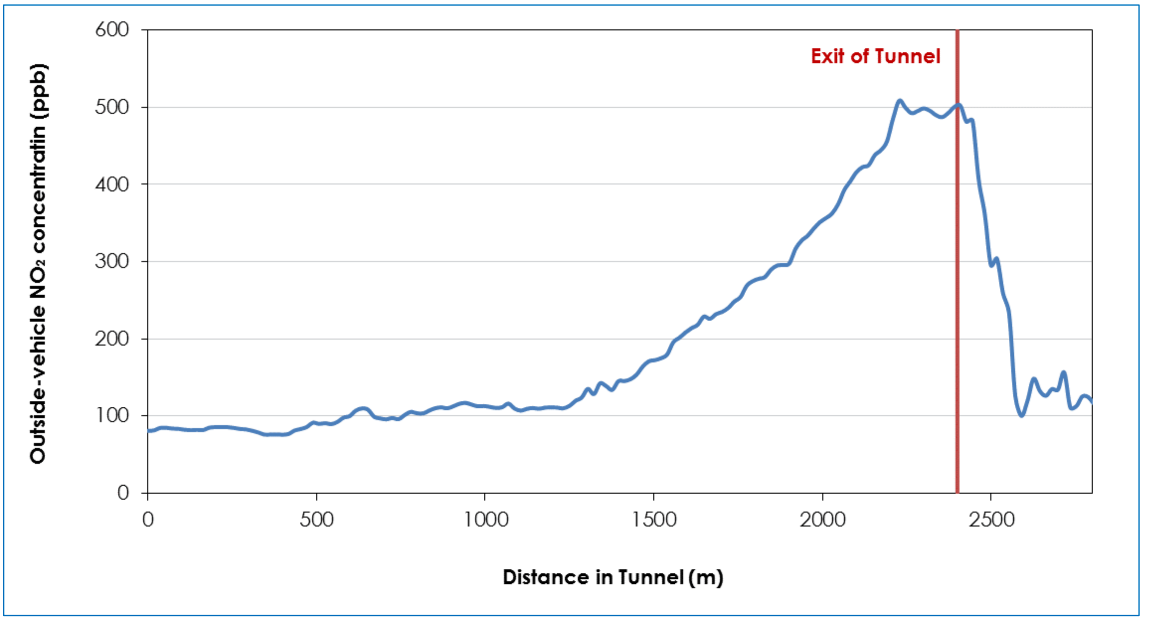


Figure 3-5: Example of 1-second outside-vehicle NO_2 concentrations (eastbound Lane Cove tunnel).

3.3.2 Transit-average outside-vehicle NO_2 concentrations

A summary of the mean transit-average outside-vehicle NO_2 concentrations is shown in **Table 3-3**.

Table 3-3: Mean transit-average outside-vehicle NO_2 concentrations for major tunnels

Tunnel	Mean transit-average outside-vehicle NO_2 concentration (ppb)
Lane Cove eastbound	276
Lane Cove westbound	124
Eastern Distributor northbound	120
Eastern Distributor southbound	181
Sydney Harbour northbound	153
Sydney Harbour southbound	97
M5 East eastbound	453
M5 East westbound	371
All tunnels	266

Box-and-whisker plots showing transit-average outside-vehicle NO_2 concentrations in the major tunnels are shown in **Figure 3-6**, with a tunnel-average level of 500 ppb shown as a red line. The centre line of each box-and-whisker plot indicates the median value of all data points. The lower and upper ends of the box indicate the first and third quartiles respectively, and the difference between these (the blue box) is the interquartile range (within which 50% of all data points lie). The top and bottom 'whiskers' indicate the minimum and maximum values.

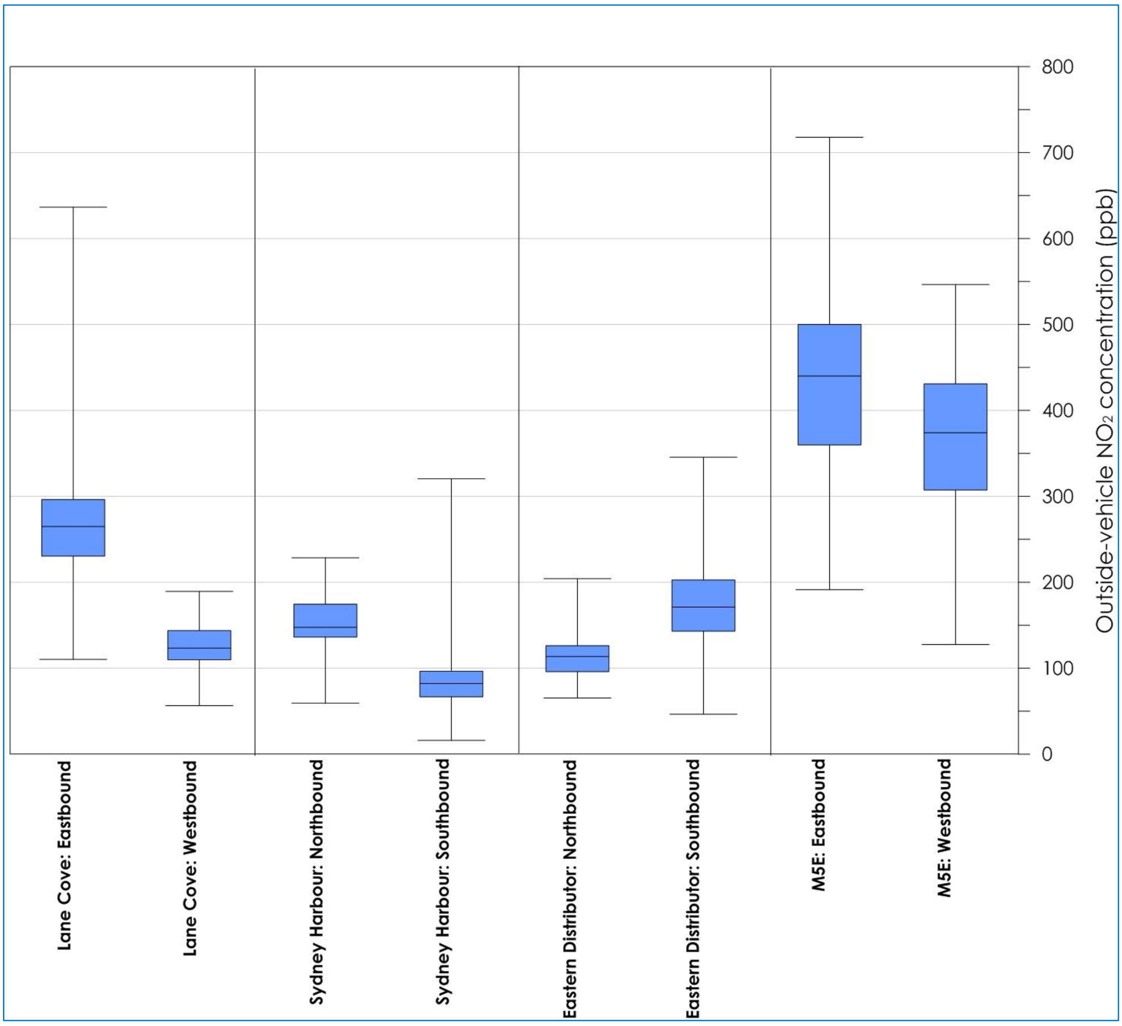


Figure 3-6: Outside-vehicle NO_2 concentrations averaged by tunnel transit time

There was an even distribution of measurements by time of day for each tunnel (a Figure is provided in **Appendix E** to show the number of measurements during each hour of the day), and the data were not considered to be biased.

The mean transit-average outside-vehicle NO_2 concentrations ranged from 97 ppb to 403 ppb for the Eastern Distributor, Lane Cove, M5 East, and Sydney Harbour tunnels. The NO_2 concentrations at the tunnel exits are almost twice the tunnel average values (**Figure 3-3, Figure 3-4,** and **Figure 3-5**).

Concentrations exceeded 500 ppb in the M5 East eastbound, M5 East westbound and the Lane Cove eastbound tunnels, which had maximum transit-average outside-vehicle NO_2 concentrations of 718 ppb, 546 ppb, and 637 ppb respectively. High NO_2 concentrations in the Lane Cove eastbound tunnel may be due to this tunnel being predominantly uphill, whereas the gradient is predominantly downhill in the westbound direction. Steeper gradients lead to increased vehicle fuel consumption and increased NO_2 emissions. The high NO_2 concentrations in the M5 East tunnels are attributed to the high traffic volume and high proportion of heavy vehicles (**Table 2-3**). An average of 143,000 vehicles per day passed through the M5 East tunnels, which is almost 40% more traffic than in other major tunnels.

NO2 concentrations in these tunnels were less than 500 ppb for at least 75% of transits, as the third quartiles (middle value between the median and the highest value of the data set) were all less than 500 ppb.

Lower in-vehicle NO_2 concentrations in the Eastern Distributor and Sydney Harbour tunnels are attributed to these tunnels being the shortest, and carrying the lowest traffic volumes (**Table 2-3**).

Transit-average outside-vehicle NO_2 concentrations in minor tunnels and surface roads were calculated for comparison with the longer major tunnels (**Figure 3-7**). Outside-vehicle NO_2 concentrations were fairly similar in the minor tunnels, and mean concentrations were all less than 300 ppb. These data show that even relatively short tunnels (less than 500 m in length) can have elevated outside-vehicle NO_2 concentrations. The lowest outside-vehicle NO_2 concentrations were measured on surface roads, which were generally less than 150 ppb.

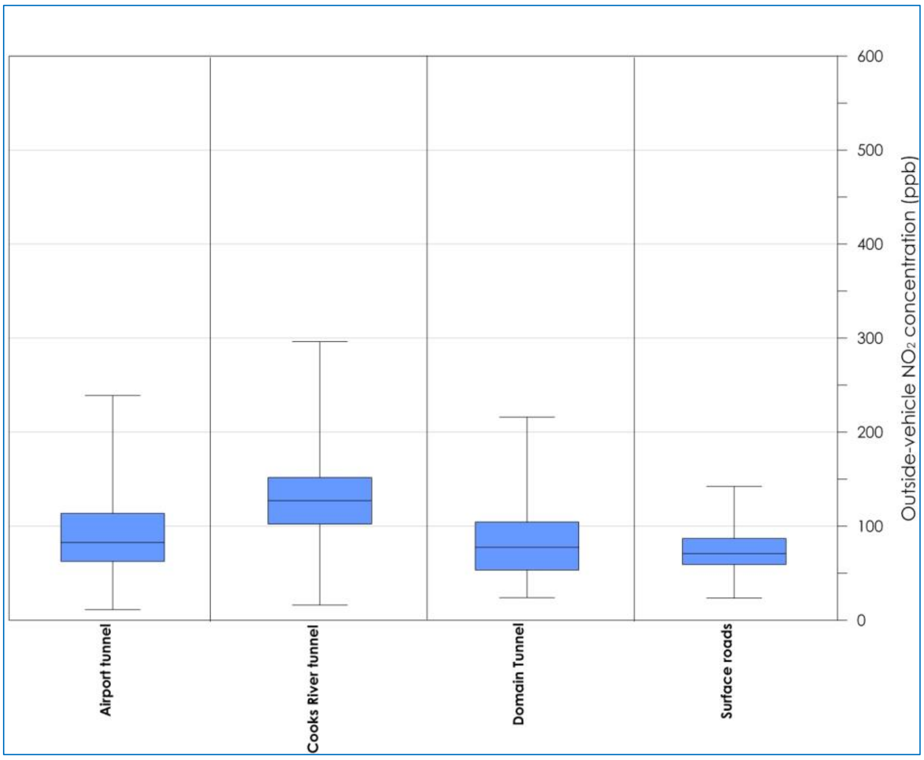


Figure 3-7: Box-and-whisker plots of transit-average outside-vehicle NO_2 concentrations for minor tunnels and surface roads

3.3.3 Relationship between outside-vehicle CO_2 and NO_2 concentrations

Outside-vehicle CO_2 and outside-vehicle NO_2 concentrations are shown for each tunnel in **Figure 3-8**, and for all major tunnels combined in **Figure 3-9**, with a linear regression model fitted to each set of data. These analyses were carried out to compare the NO_2 emissions per unit of fuel in different tunnels.

There was a fairly strong positive linear relationship between the outside-vehicle CO_2 and NO_2 concentrations in each tunnel. This is because CO_2 and NO_2 are both emitted by road vehicles. The positive intercept at just over 400 ppm CO_2 reflects the background concentration of CO_2 in ambient air. There was some variation between tunnels in the slope of the regression line, suggesting that the NO_2 emission per unit of fuel consumed was slightly different in each tunnel (although the values for the Lane Cove tunnel and Eastern Distributor tunnel were similar). The lowest slope (*i.e.* the highest NO_2:CO_2 ratio) was obtained for the M5 East tunnel, probably due to its relatively high proportion of diesel trucks.

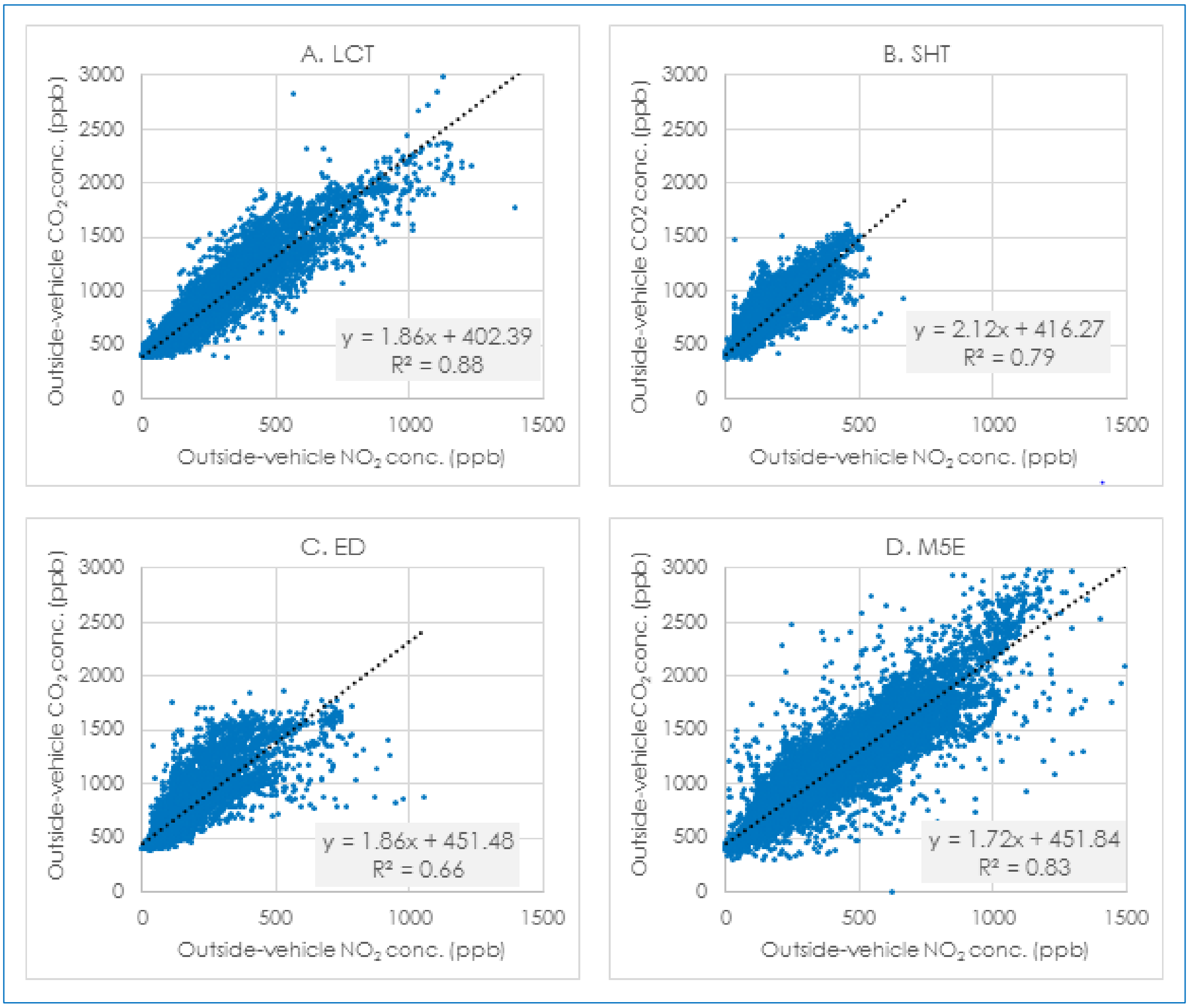


Figure 3-8: 1-average-outside-vehicle CO_2 vs 1-second outside-vehicle NO_2 concentrations for the A) Lane Cove tunnel, B) Sydney Harbour tunnel, C) Eastern Distributor tunnel, D) M5 East tunnel

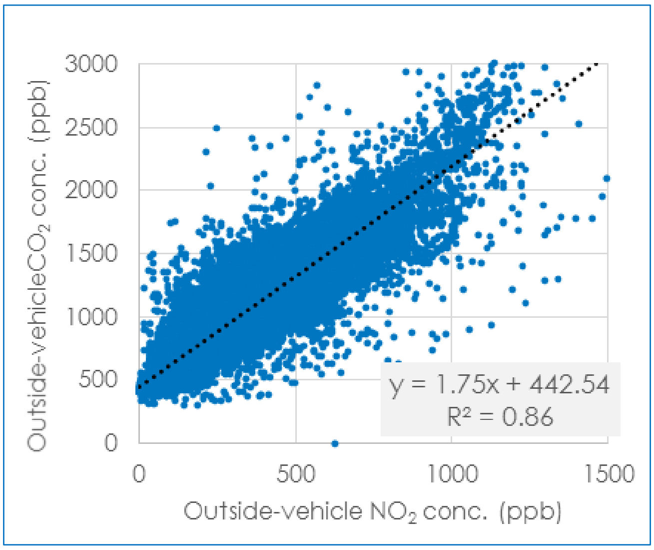


Figure 3-9: Outside-vehicle CO_2 vs outside-vehicle NO_2 for all major tunnels combined

3.4 What are the effects of air recirculation mode?

3.4.1 Example profiles

Typical examples of the I/O ratio and outside-vehicle NO_2 concentration profiles in the major tunnels are shown in **Figure 3-10** with recirculation on, and in **Figure 3-11** with recirculation off. With recirculation on, the I/O ratio remains low as it is relatively unaffected by the outside-vehicle NO_2 concentrations due to the low air exchange rate between air in the vehicle cabin and tunnel. However, with recirculation off there is strong inverse relationship between outside-vehicle NO_2 concentrations and the I/O ratio. This demonstrates that in-vehicle NO_2 concentrations are more strongly affected by outside-vehicle NO_2 concentrations with recirculation off.

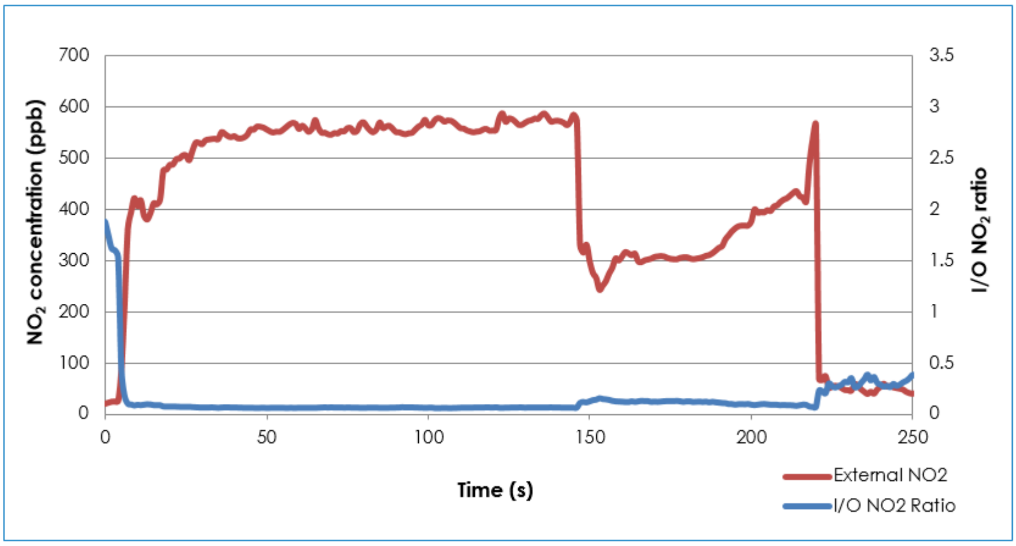


Figure 3-10: I/O ratio and outside-vehicle NO_2 concentration for the Toyota Corolla travelling through the M5 East tunnel with recirculation on, air conditioning off and a fan speed 50%

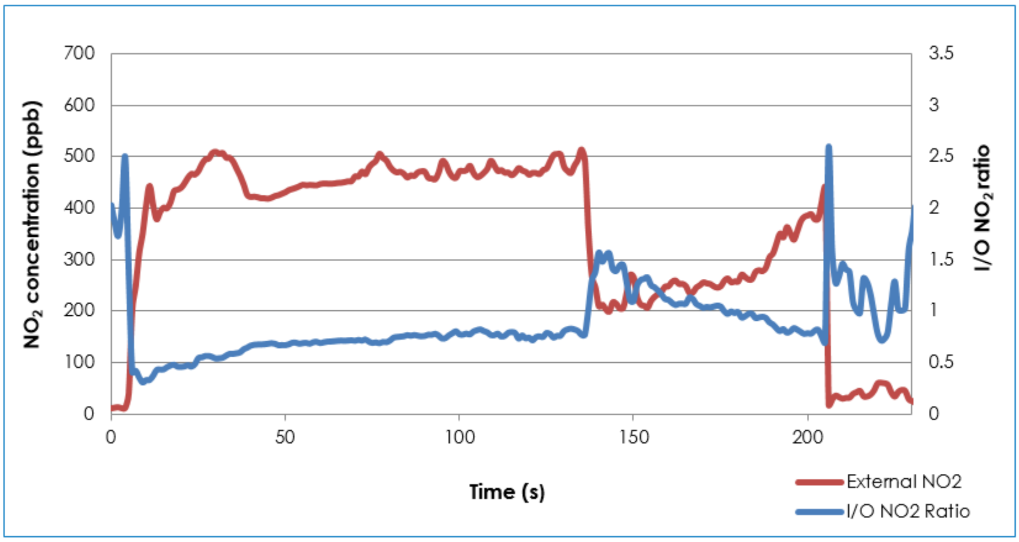


Figure 3-11: I/O ratio and outside-vehicle NO_2 concentration for the Toyota Corolla through the M5 East tunnel with recirculation off, air conditioning off and 50% fan speed

Box-and-whisker plots showing transit-average in-vehicle NO_2 concentrations in the major tunnels with recirculation on (modes MD1 and MD2) are shown in **Figure 3-12**, and with recirculation off (MD4, and MD5) in **Figure 3-13**. Transit-average in-vehicle NO_2 concentrations were less than 200 ppb for all tunnels with recirculation on (**Figure 3-12**), despite transit-average outside-vehicle NO_2 concentrations exceeding 700 ppb in some tunnels. Transit-average in-vehicle NO_2 concentrations were generally less than 200 ppb in all tunnels with recirculation off, except for the M5 East eastbound tunnel.

Transit-average I/O ratios for NO_2 in the major tunnels are shown in **Figure 3-14** (recirculation on) and **Figure 3-15** (recirculation off). I/O ratios with recirculation on were less than 0.6 in all tunnels except the Sydney Harbour southbound tunnel. This is probably because the outside-vehicle concentrations in this tunnel were the lowest (**Figure 3-6**), and the background NO_2 levels in had a proportionally larger impact on the I/O ratio. In some cases the I/O ratios were greater than one with recirculation on. This is attributed to the accumulation of NO_2 in the vehicle cabin. With recirculation off, I/O ratios were relatively high in all tunnels due to the increased exchange rate between air in the vehicle cabin and the tunnel.

Box-and-whisker plots showing transit-average in-vehicle NO_2 concentrations with recirculation on in minor tunnels and surface roads are given in **Figure 3-16**, and with recirculation off in **Figure 3-17**. These plots include data from all test vehicles. Mean transit-average in-vehicle NO_2 concentrations were less than 50 ppb with recirculation on and increased to 50-100 ppb with recirculation off. An in-vehicle concentration of 200 ppb was only exceeded in the Cooks River tunnel, both with recirculation on and recirculation off. However, the box plots show that the third quartiles (the number at which 75% of the data lies below) for each dataset were well below this value.

Box-and-whisker plots showing transit-average NO_2 I/O ratios with recirculation on and off for minor tunnels and surface roads are given in **Figure 3-18**, and **Figure 3-19**. These plots include data from all test vehicles. The I/O ratios for surface roads and minor tunnels with recirculation on ranged from 0.05 to 2.70, and 0.05 to 4.0 with recirculation off. Higher I/O ratios in minor tunnels and on surface roads compared to major tunnels are attributed to lower NO_2 concentrations in outside air and accumulated in-vehicle NO_2 during tunnel transit.

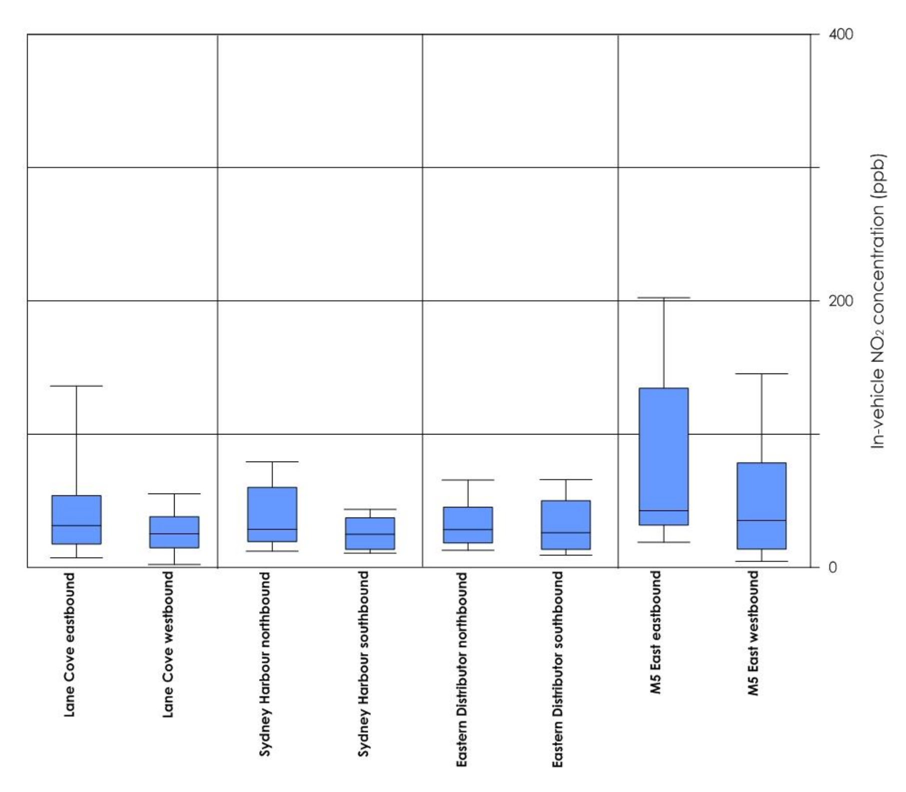


Figure 3-12: Box-and-whisker plots of transit-average in-vehicle NO_2 concentrations in major tunnels with recirculation on

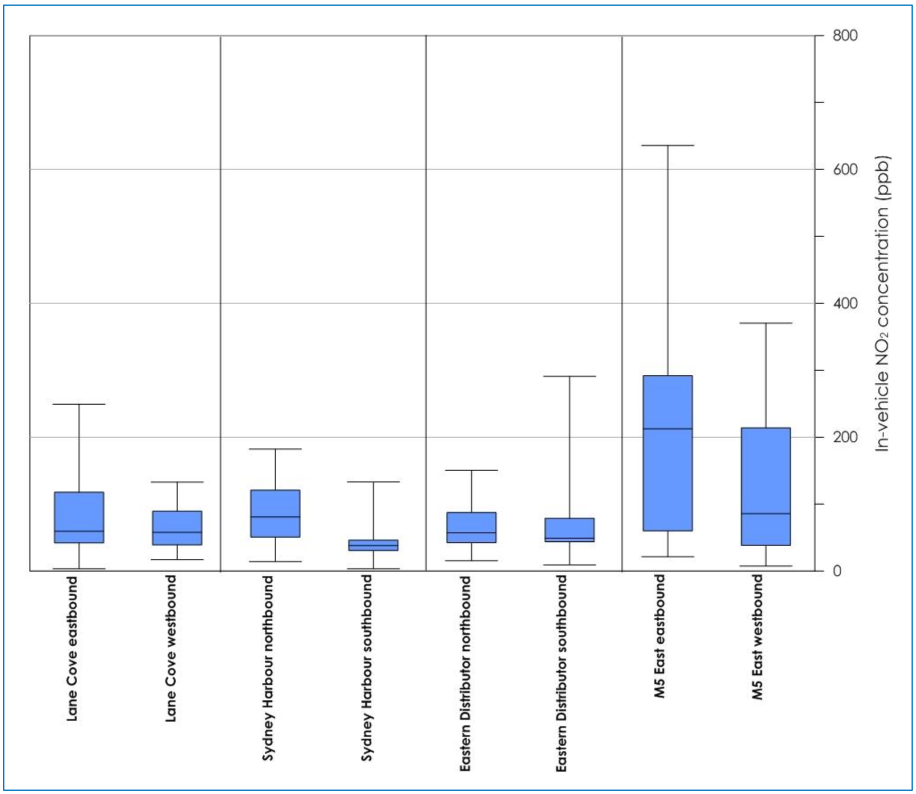


Figure 3-13: Box-and-whisker plots of transit-average in-vehicle NO_2 concentrations in major tunnels with recirculation off

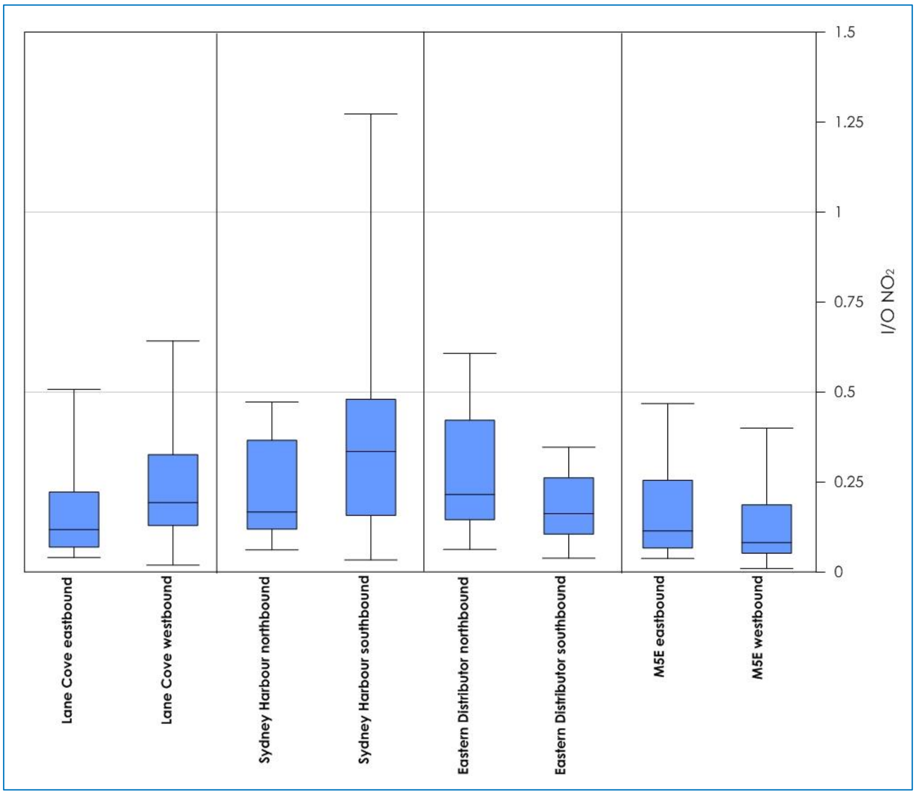


Figure 3-14: Transit-average I/O ratios for major tunnels with recirculation on

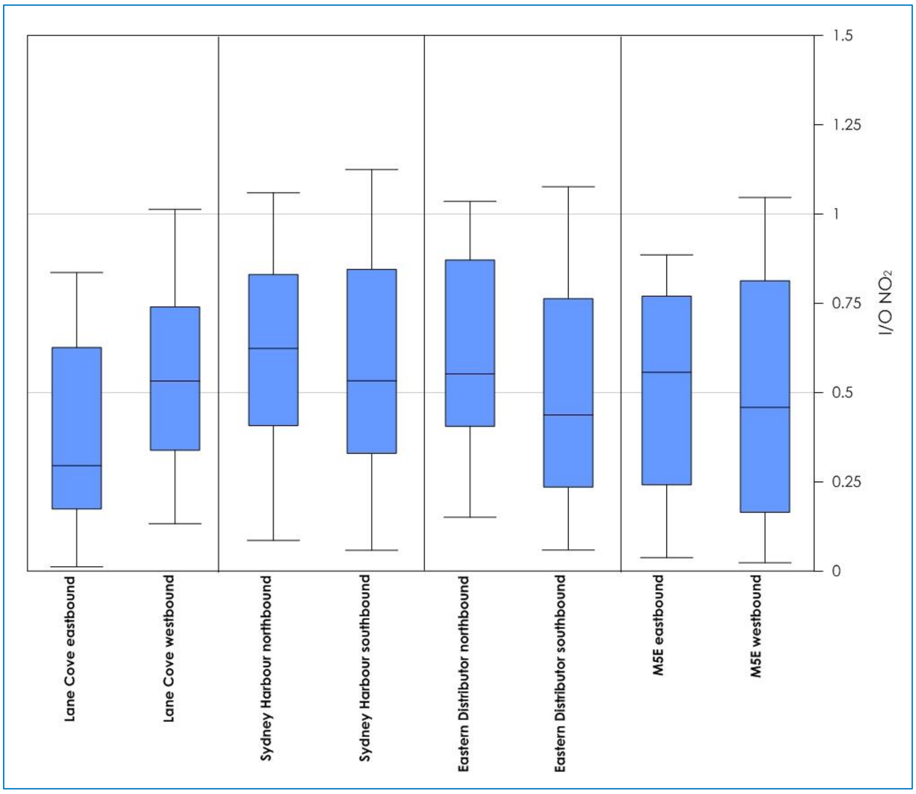


Figure 3-15: Transit-average I/O ratios for major tunnels with recirculation off

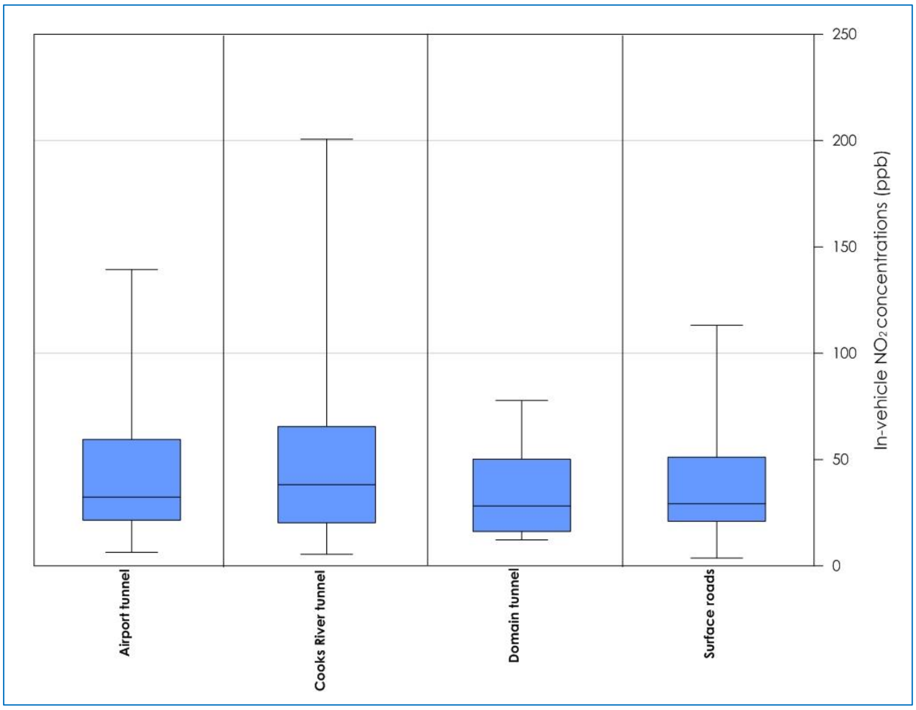


Figure 3-16: In-vehicle NO_2 concentrations for minor roads with recirculation on

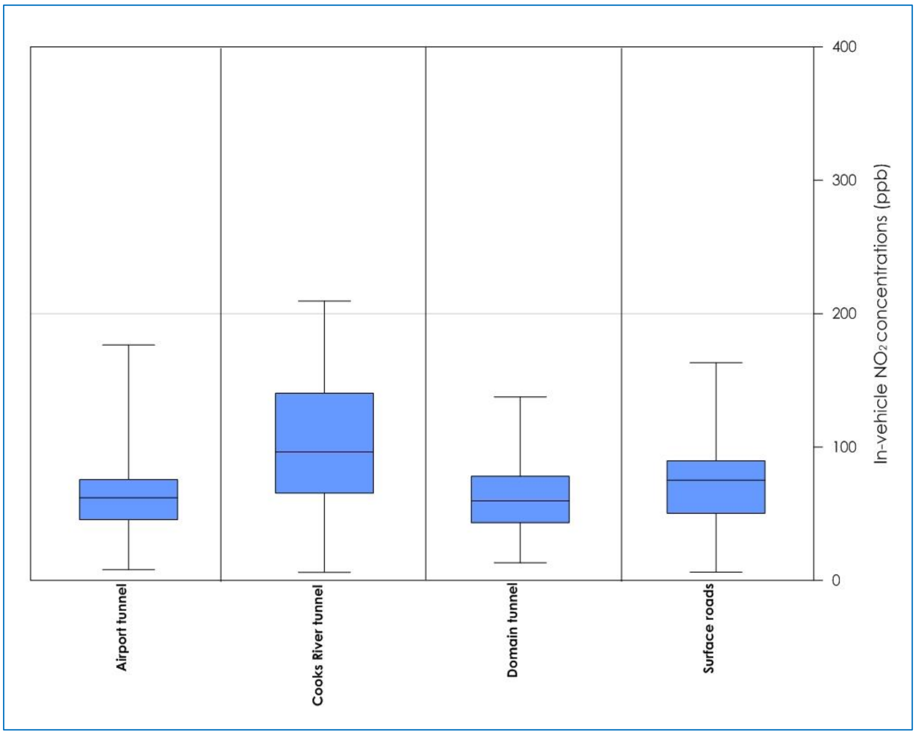


Figure 3-17: In-vehicle NO_2 concentrations for minor roads with recirculation off

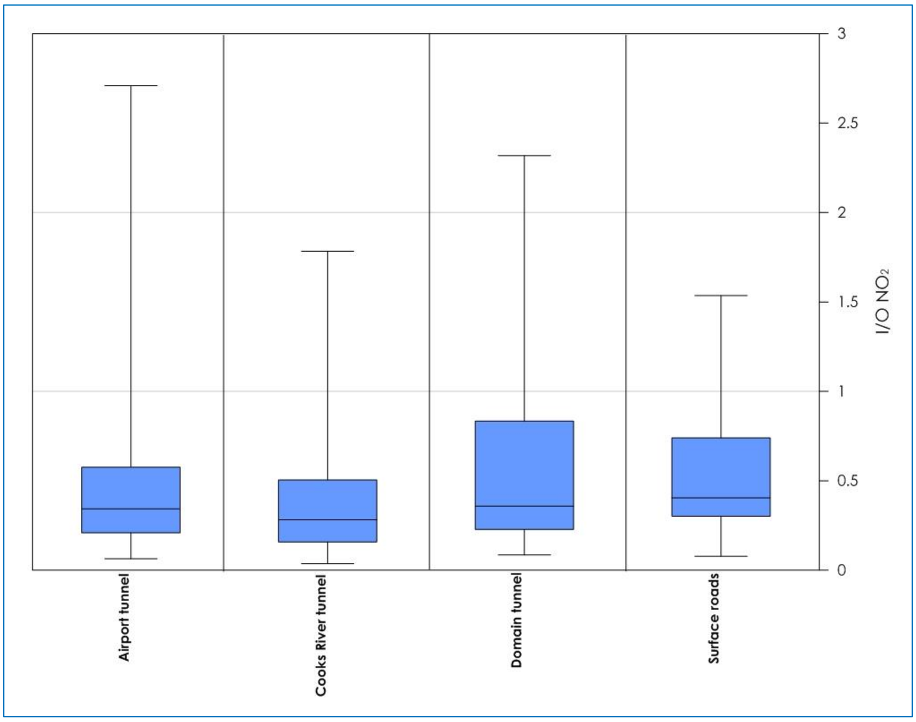


Figure 3-18: I/O NO_2 ratios for minor tunnels and surface roads with recirculation on

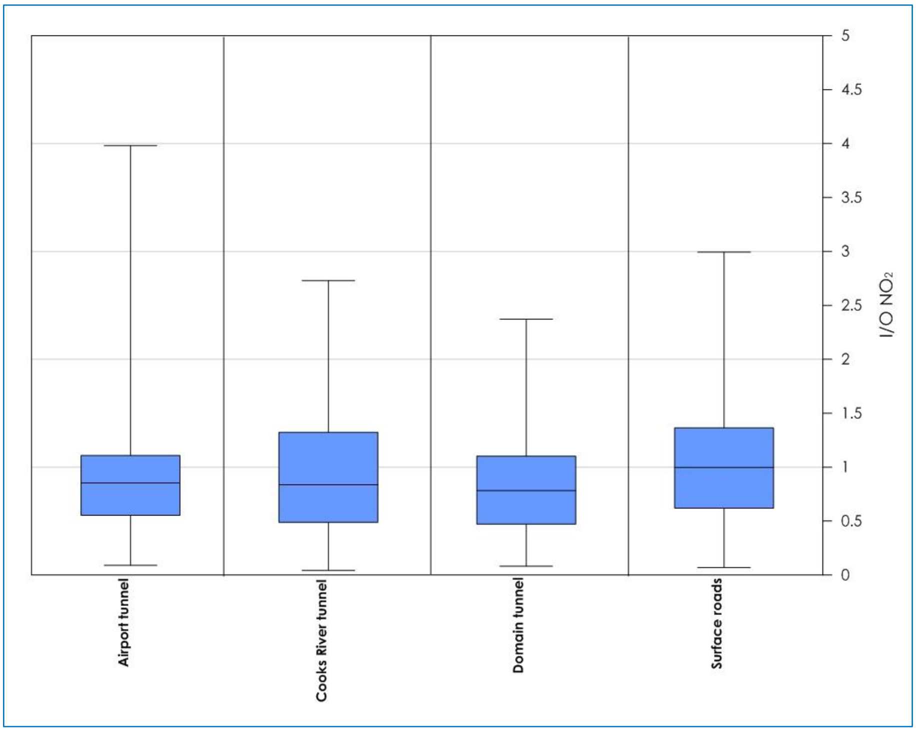


Figure 3-19: I/O NO_2 ratios for minor tunnels and surface roads with recirculation off

3.4.2 Effect of other vehicle ventilation settings on I/O ratios

To examine the effect of other vehicle ventilation settings on I/O ratios, a frequency distribution was constructed for each setting. The resulting distributions are shown in **Figure 3-20**. In-vehicle NO_2 concentrations were not used, as these are dependent upon outside-vehicle NO_2 concentrations.

The effects of air conditioning on I/O ratios was compared for ventilation settings MD1 and MD2, with the fan speed and recirculation settings being held constant. The median I/O ratios were similar with air conditioning on and off (0.16 and 0.17, respectively). This is expected, as air conditioning systems do not affect gases.

Increasing the fan speed from 0% (MD5) to 50% (MD4) shifted the distribution towards significantly higher I/O ratios. Further increasing the fan speed to 100% (MD6) further increased the I/O ratios and shifted the median to 0.83. This is attributed to the increased intake rate of outside-vehicle air at higher fan speeds, which results in the increased intake of air with a high NO_2 concentration.

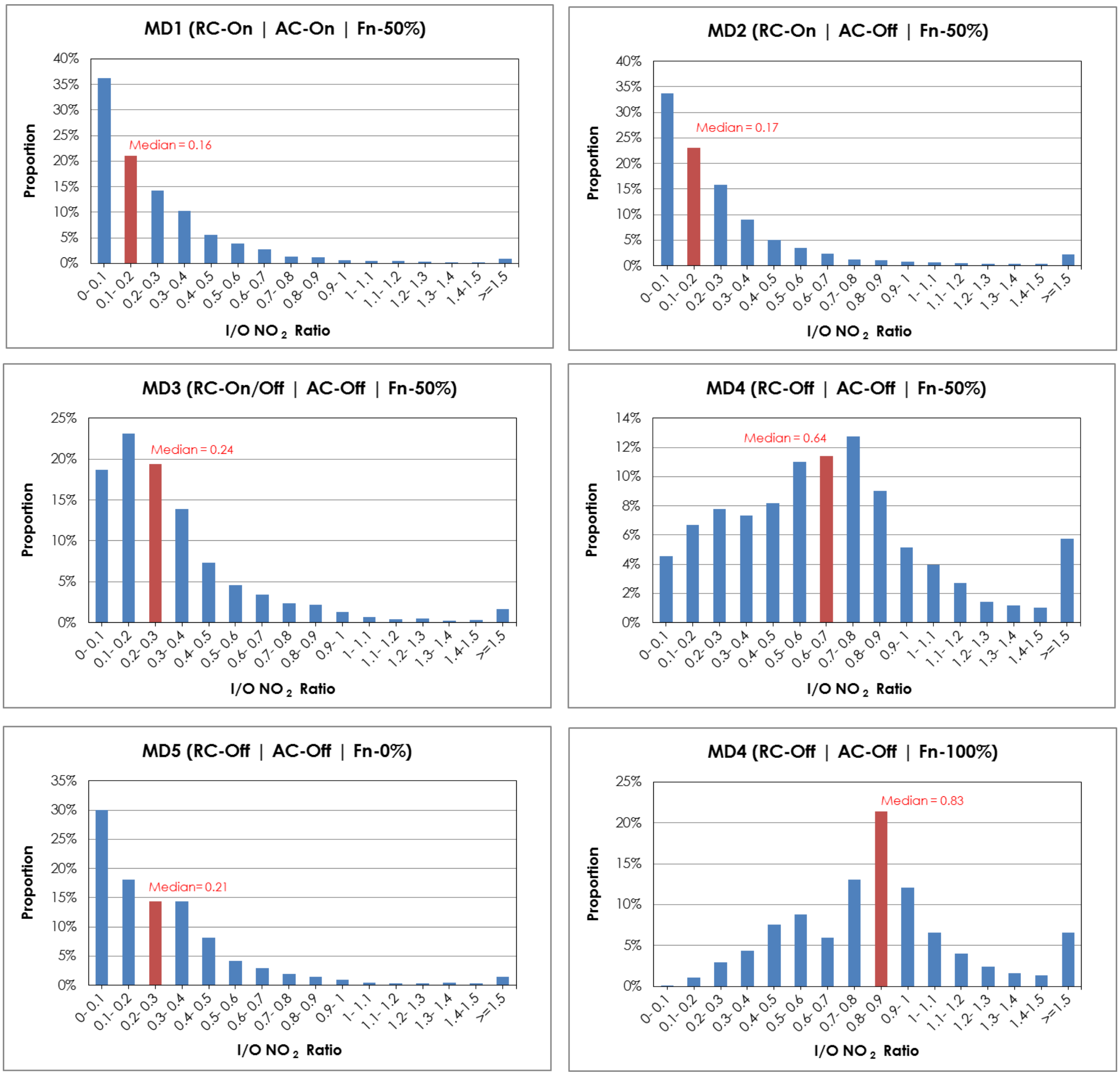


Figure 3-20: Frequency distribution of 1-second NO_2 I/O ratios for each ventilation setting including all vehicles and tunnels

3.4.3 Switching recirculate on/off following tunnel entrance/exit

With the recirculate mode switched on, it is possible that NO_2 could accumulate during a tunnel transit and then remain in the vehicle following exit from the tunnel. As outside-vehicle NO_2 concentrations are lower on surface roads, this could result in higher in-vehicle NO_2 concentrations compared with outside-vehicle concentrations. Therefore, one ventilation setting involved switching off recirculation at the tunnel entrance and switching recirculate on upon exit of the tunnel (MD3). Examples of this are shown for the Audi A3 in **Figure 3-21** and **Figure 3-22**. With recirculate on (MD1), in-vehicle NO_2 concentrations remained higher than outside-vehicle concentrations for approximately 80 seconds after exiting the tunnel (**Figure 3-21**). There was no difference when recirculate was turned off after exiting the tunnel (MD3), as in-vehicle NO_2 concentrations also remained higher than outside-vehicle concentrations for approximately 80 seconds (**Figure 3-22**).

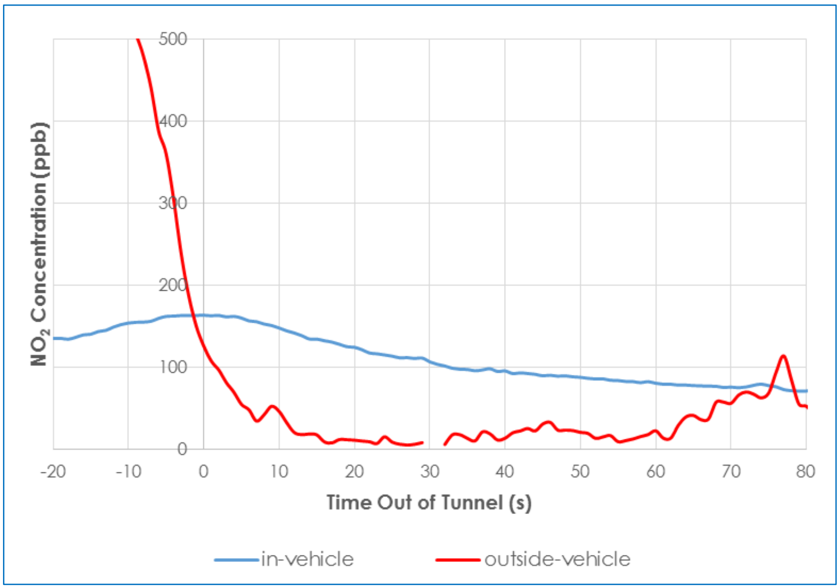


Figure 3-21: In-vehicle NO_2 concentrations following exit of the Lane Cove eastbound tunnel in the Audi A3 with recirculation on, A/C On, and fan speed 50%

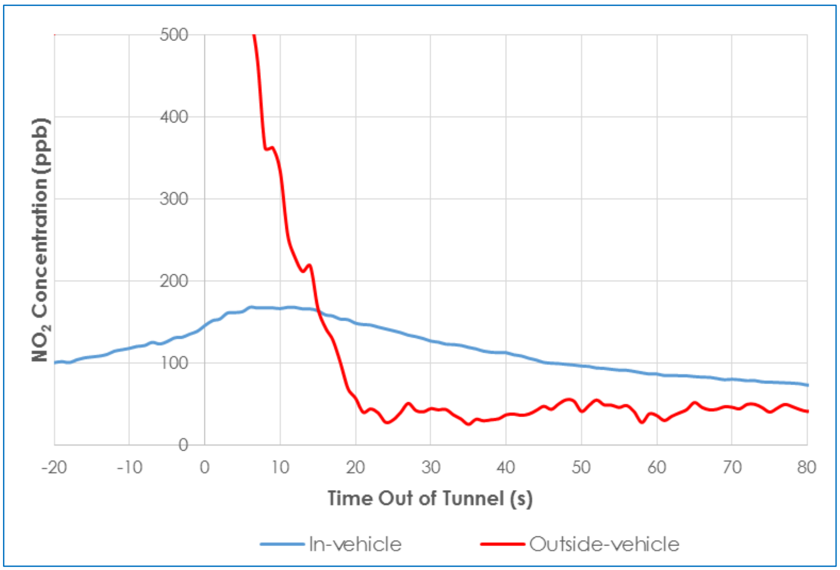


Figure 3-22: In-vehicle NO_2 concentrations following exit of the Lane Cove eastbound tunnel in the Audi A3 with recirculation off, A/C On, and fan speed 50%

3.4.4 Effects of opening windows following tunnel exit

Tests were carried out to examine the effects of opening the vehicle windows at the end of the study route (M5 East westbound tunnel). It should be noted that it was not possible to open the front passenger window due to the fact that it was being used to hold the gas sampling lines. This meant that the exchange of air between the vehicle cabin and the exterior was somewhat restricted. **Figure 3-23** shows an example of the in-vehicle and outside-vehicle NO_2 concentrations when the windows were left closed. The example shown is for the Audi A3 (V-08) with recirculation mode switched on. For this condition the in-vehicle NO_2 concentration decreased by only 38% (from 210 ppb to 130 ppb) during the 80-second period after exiting the tunnel, despite the outside-vehicle NO_2 concentration decreasing from 500 ppb to 50 ppb in around 10 seconds. This was reasonable considering the low AER with recirculation switched on. **Figure 3-24** shows the data for a run with the windows opened at the tunnel exit. In-vehicle NO_2 concentrations did not decrease as rapidly as outside-vehicle NO_2 concentrations following tunnel exit.

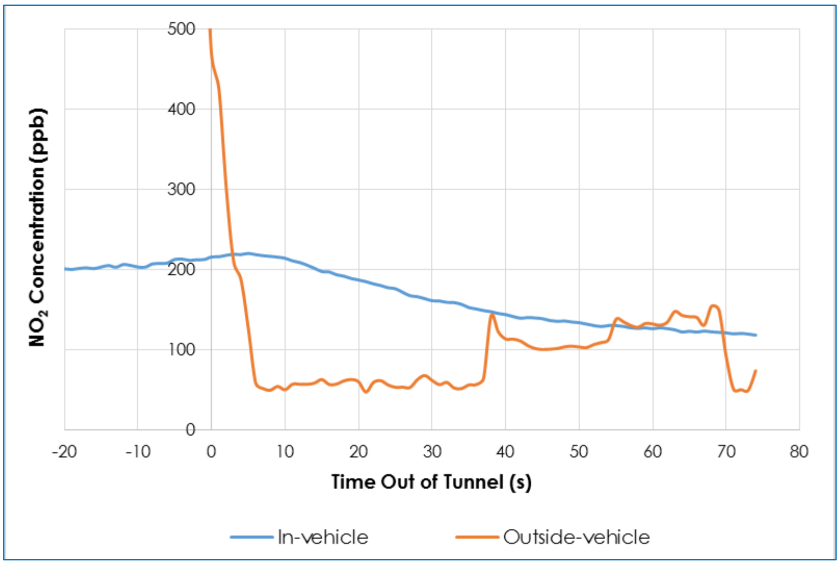


Figure 3-23: Effect of no window opening after tunnel exit. Audi A3, MD1 (Recirculate On, A/C On, Fan 50%), eastbound M5 East tunnel

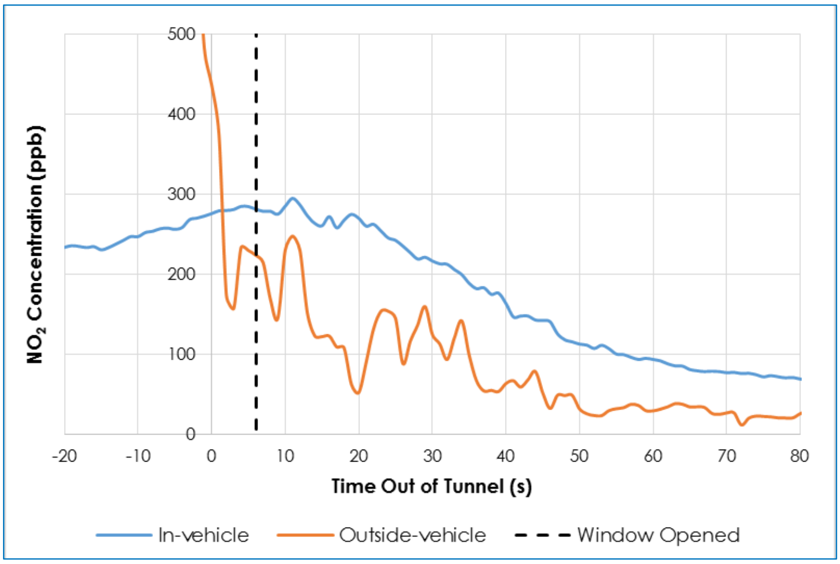


Figure 3-24: Effect of window opening after tunnel exit. Audi A3, MD1 (Recirculate On, A/C On, Fan 50%), westbound M5 East tunnel

3.5 How do in-vehicle NO_2 concentrations and I/O ratios vary by vehicle?

Transit-average I/O ratios were used to assess the range of I/O ratios for typical vehicles in the Sydney car fleet. The in-vehicle NO_2 concentration was not used to assess vehicle performance as this is a dependent variable that is linked to the outside-vehicle concentration with recirculation on or off. As vehicle performance is also controlled by the vehicle ventilation settings, this was assessed with recirculation on and recirculation off.

A summary of mean I/O ratios with recirculation on and off is shown in **Table 3-4** for each vehicle. Transit-average I/O ratios for each test vehicle with recirculation on and off are shown in **Figure 3-25** and **Figure 3-26** respectively. These plots only include NO_2 concentrations measured in the major tunnels.

Table 3-4: Transit-average I/O ratios for each test vehicle in major tunnels

Vehicle	I/O ratio for NO_2	
	Recirculation on	Recirculation off
V-01: Holden Astra Wagon (2008)	0.12	0.63
V-02: Ford Fiesta (2002)	0.23	0.59
V-03: BMW X3 (2014)	0.28	0.33
V-04: Hyundai i30 (2014)	0.06	0.56
V-05: Fiat Punto (2007)	0.14	0.76
V-06: Toyota Corolla (2008)	0.08	0.52
V-07: Subaru Outback (2007)	0.23	0.71
V-08: Audi A3 (2002)	0.32	0.28
V-09: Holden Cruze (2011)	0.21	0.30

Transit-average I/O ratios ranged from 0.06 to 0.32 with recirculation on, and 0.28 to 0.76 with recirculation off. This shows that all vehicles, regardless of vehicle model/manufacturer, can maintain lower in-vehicle NO_2 concentrations compared to outside-vehicle NO_2 concentrations with recirculation on.

The best performing vehicles (all I/O ratios less than 0.20) with recirculate-on were the Holden Astra Wagon (V-01), Hyundai i30 (V-04), Fiat Punto (V-05), and Toyota Corolla (V-06).

Results from the 2002 Audi A3 appear to be anomalous as the I/O ratios were higher with recirculation on than with recirculation off. I/O ratios are expected to be lower with recirculation on due to the lower exchange rate between outside-vehicle and in-vehicle air.

The performance of the Holden Astra Wagon (V-01) is also surprising, as current AER models **(***e.g.* **Hudda *et al.*, 2012)** assume that Australian vehicles are equal to American cars, which are expected to have the worst performance. This suggests that vehicles manufactured in Australia may perform better than current models predict.

The highest I/O ratios were measured for the Subaru Outback (V-07).

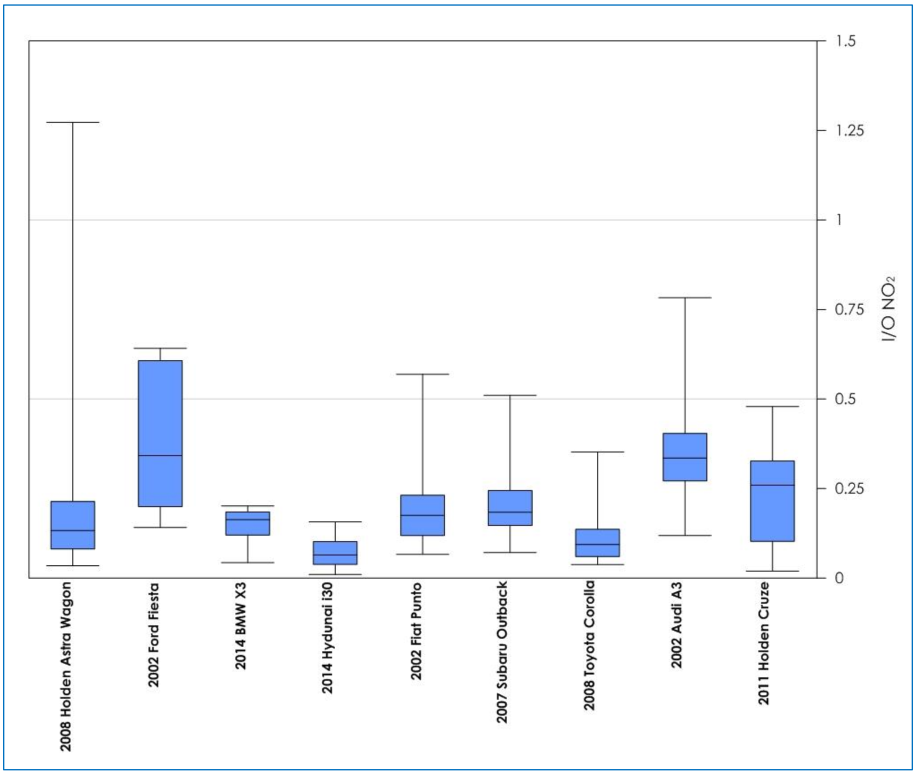


Figure 3-25: Transit-average I/O ratios for each test vehicle with recirculation on in major tunnels

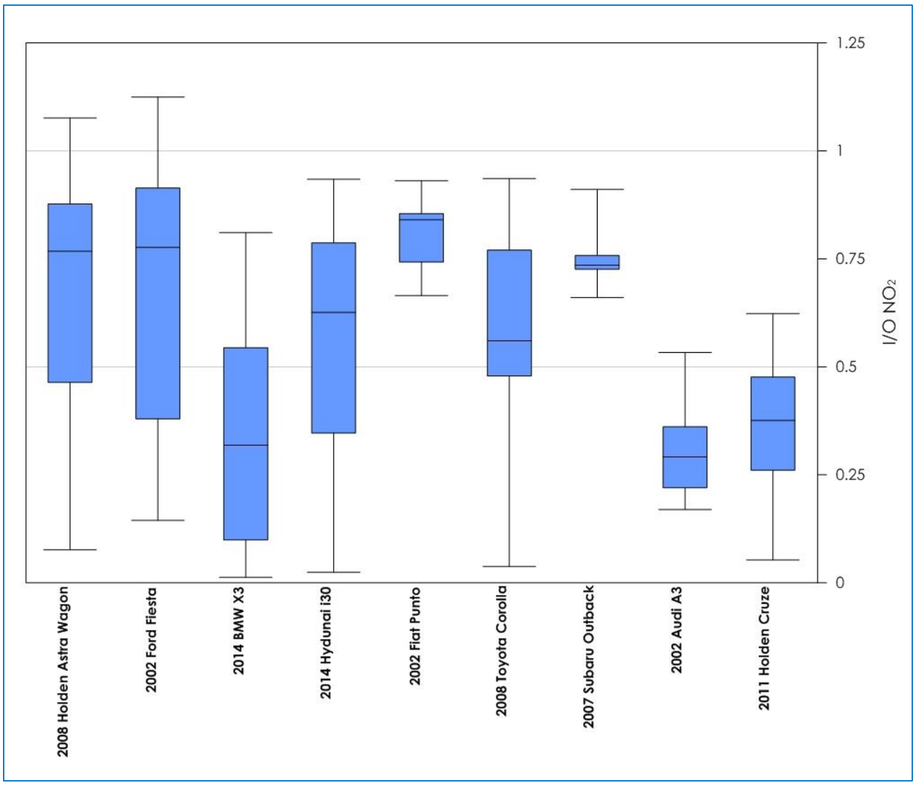


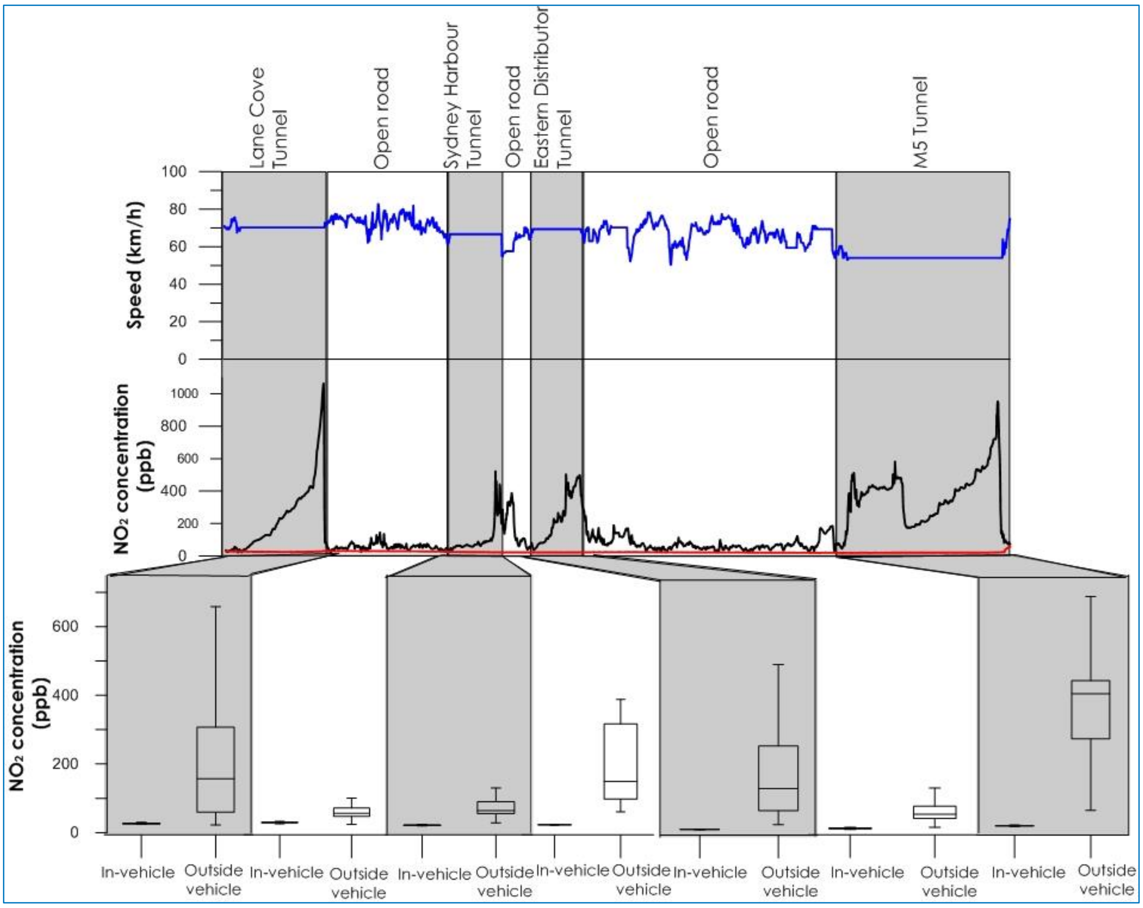
Figure 3-26: Transit-average I/O ratios for each test vehicle with recirculation off in major tunnels

3.6 What are the best and worst case conditions for outside-vehicle and in-vehicle NO_2 concentrations in Sydney tunnels?

In-vehicle NO_2 concentrations were mainly influenced by the vehicle ventilation settings for a given outside-vehicle concentration. Best-case and worst case conditions along the study were examined by comparing a high performing vehicle with recirculation on (2014 Hyundai i30, V-04), and a low performing vehicle with recirculation off (2008 Holden Astra Wagon, V-01). These selections are consistent with the AER model from **Hudda *et al.* (2012)**, which predicts that a new/Korean-manufactured vehicle will perform better than an older/Australian vehicle.

An example run for the Hyundai i30 (V-04) using MD1 from the start of the Lane Cove tunnel to the end of the M5 East tunnel is shown in **Figure 3-27**. This run was conducted during the inter-peak traffic period at midday between 11:40 and 12:15.

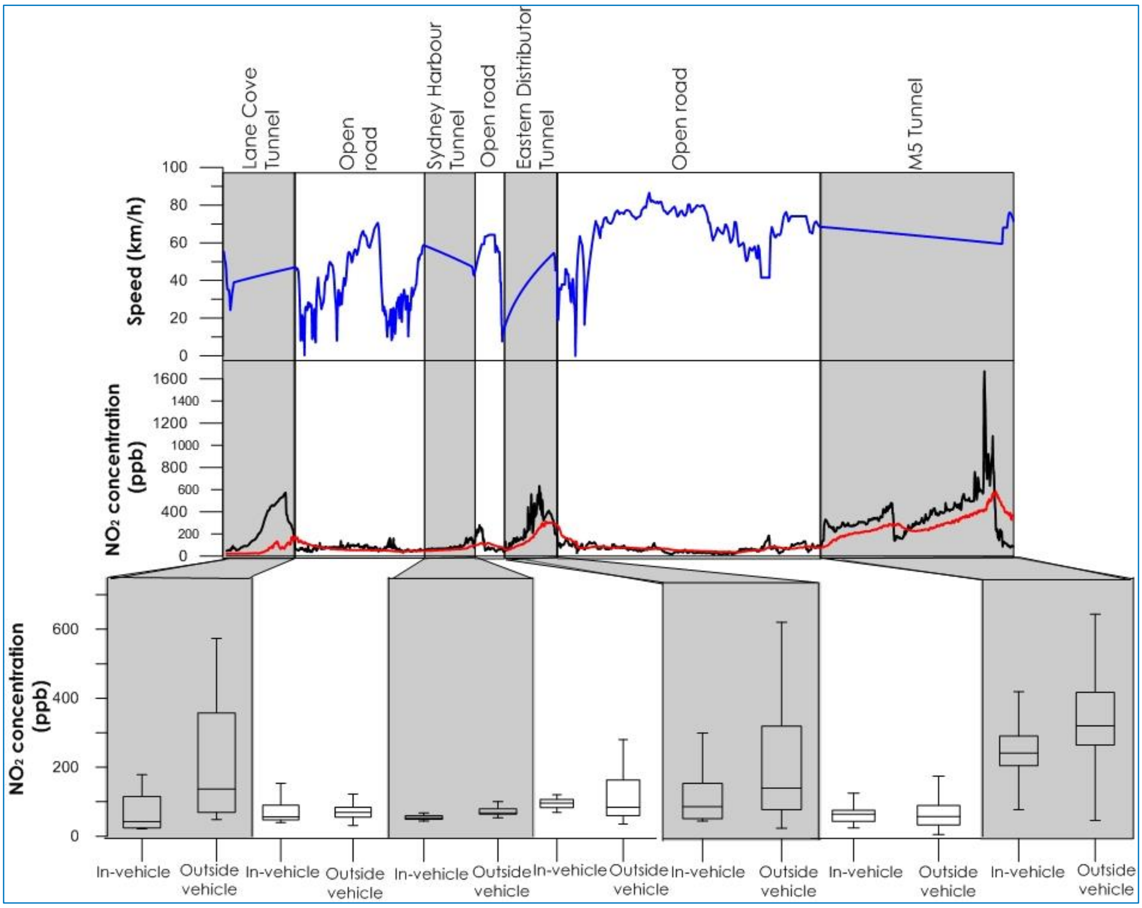
Despite outside-vehicle 1-second NO_2 concentrations reaching almost 1,000 ppb, in-vehicle 1-second NO_2 concentrations in the 2014 Hyundai i30 with recirculation on did not increase and remained well below 200 ppb. This demonstrates that the recirculation setting maintains low in-vehicle NO_2 concentrations in better performing vehicles.



Note: The centrelines of the box plots indicate the median value. The lower end of the box indicates the lower quartile and the upper end of the box indicates the upper quartile. The top and bottom error bars indicate the minimum and maximum of the non-outlier values. The red line indicates in-vehicle NO_2 concentration time-series, black line indicates outside-vehicle (external) NO_2 concentration time-series.

Figure 3-27: Example profile of vehicle speed, outside-vehicle NO_2 and in-vehicle NO_2 vs distance - High performance vehicle/mode (Hyundai i30 and mode MD1; 03/09/15 11:40am-12:15pm)

An example run in the 2008 Holden Astra Wagon with recirculation off is shown in **Figure 3-28**. The run was conducted in the peak AM traffic period. In-vehicle 1-second NO_2 concentrations in the 2008 Holden Astra Wagon (V-01) exceeded 200 ppb as outside-vehicle NO_2 concentrations exceeded 1,000 ppb. With recirculation off, the air exchange rate between the cabin and tunnel air is high and results in elevated in-vehicle NO_2 concentrations. A slight delay and smoothing of in-vehicle NO_2 concentrations compared to outside-vehicle NO_2 concentration is attributed to the incremental introduction of outside air and mixing with air already inside the vehicle cabin. Therefore, in-vehicle NO_2 concentrations were temporarily higher than outside-vehicle immediately after exiting most tunnels during this run.



Note: The centrelines of the box plots indicate the median value. The lower end of the box indicates the lower quartile and the upper end of the box indicates the upper quartile. The top and bottom error bars indicate the minimum and maximum of the non-outlier values. The red line indicates in-vehicle NO_2 concentration time-series, black line indicates outside-vehicle (external) NO_2 concentration time-series.

Figure 3-28: Example profile of vehicle speed, outside-vehicle NO_2 and in-vehicle NO_2 vs distance - Low performance vehicle/mode (2008 Holden Astra Wagon and mode MD4; 26/08/15 7:55am-8:35am)

3.7 What is the range of AERs for vehicles in the Sydney car fleet and can these be predicted using existing models?

3.7.1 Air exchange rate model

AERs were calculated for typical vehicles in the Sydney car fleet to evaluate model predictions of I/O ratios. These models predict I/O ratios by using measured outside-vehicle NO_2 concentrations and predicted in-vehicle NO_2 concentrations based on the vehicle AER, speed and ventilation setting. As AER can also be predicted by models based on vehicle characteristics, predicted AERs were first compared with measured AERs.

Table 3-5 shows the measured AERs for each vehicle at speeds of 60 km/h and 100 km/h, and with recirculation on and off at each speed. Between three and six repeat AER experiments were conducted for each combination, and these indicated that the variability for each measurement was around ±6%.

Table 3-5: Measured vehicle air exchange rates for ventilation settings MD2 (RC-on) and MD4 (RC-off).

Vehicle	Vehicle speed (km/h)	Mode	$AER_{measured}$ (/h)	Number of experiments	Relative standard deviation (%)[a]	$AER_{predicted}$[a] (/h)	Difference (%)
2008 Holden Astra	60	RC on	7	1	-	57	88
	100		10	1	-	66	7
	60	RC off	62	1	-	21	52
	100		105	1	-	25	-320
2014 BMW X3	60	RC on	8	1	-	42	81
	100		11	1	-	67	84
	60	RC off	16	1	-	17	7
	100		50	2	3	21	-135
2014 Hyundai i30	60	RC on	4	2	7	8	47
	100		14	1	-	13	-2
	60	RC off	57	1	-	33	-74
	100		63	1	-	39	-59
2007 Fiat Punto	60	RC on	6	1	-	5	-3
	100		7	1	-	6	-22
	60	RC off	39	1	-	41	4
	100		55	1	-	49	-11
2007 Toyota Corolla	60	RC on	4	2	13	12	66
	100		5	1	-	12	59
	60	RC off	51	1	-	33	-55
	100		45	1	-	39	-15
2007 Subaru Outback	60	RC on	4	1	-	99	96
	100		4	1	-	104	96
	60	RC off	36	1	-	16	-123
	100		58	1	-	20	-193
2002 Audi A3	60	RC on	14	2	4	11	-27
	100		13	1	-	6	-119
	60	RC off	10	1	-	35	71
	100		19	2	5	42	52
2011 Holden Cruze	60	RC on	3		-	6	46
	100		8	1	-	8	0
	60	RC off	11	1	-	60	82
	100		26	1	-	73	64

[a]Calculated using the model from Hudda *et al*., (2012)

The AERs measured at 60 km/h with recirculation on were low, ranging from 3.6/h for the 2007 Subaru Outback to 14.3/h for the 2002 Audi A3. Increasing the speed from 60 km/h to 100 km/h had little effect on measured AERs with recirculation on. However, switching ventilation setting to recirculation off resulted in much higher AERs for most vehicles, which ranged from 10.2 – 61.7/h at 60 km/h. As expected, the highest AERs were generally measured with recirculation off at 100 km/h.

Results for the 2002 Audi A3 appear to be anomalous as the AER decreased slightly from 14.3/h to 10.2/h upon switching from recirculation on to recirculation off, and the AER decreased with increasing speed from 14.3 /h to 12.9 /h for the 100 km/h test with recirculation on.

AERs were predicted using **Equation 1** and **Equation 2** from **Hudda *et al.* (2012)** for recirculation on and recirculation off, respectively. The predicted AERs with recirculation switched on were generally not consistent with measured AERs as large differences were observed between measured and predicted AERs. This is likely due to the limited number of experiments conducted to determine the AER of each vehicle in our results, and limitations in the regression models used to predict AERs.

A linear regression plot of measured I/O ratios vs measured AERs is shown in **Figure 3-29**. The measured I/O ratios were reasonably well correlated with the measured AERs, with the regression model explaining 64% of the total variation.

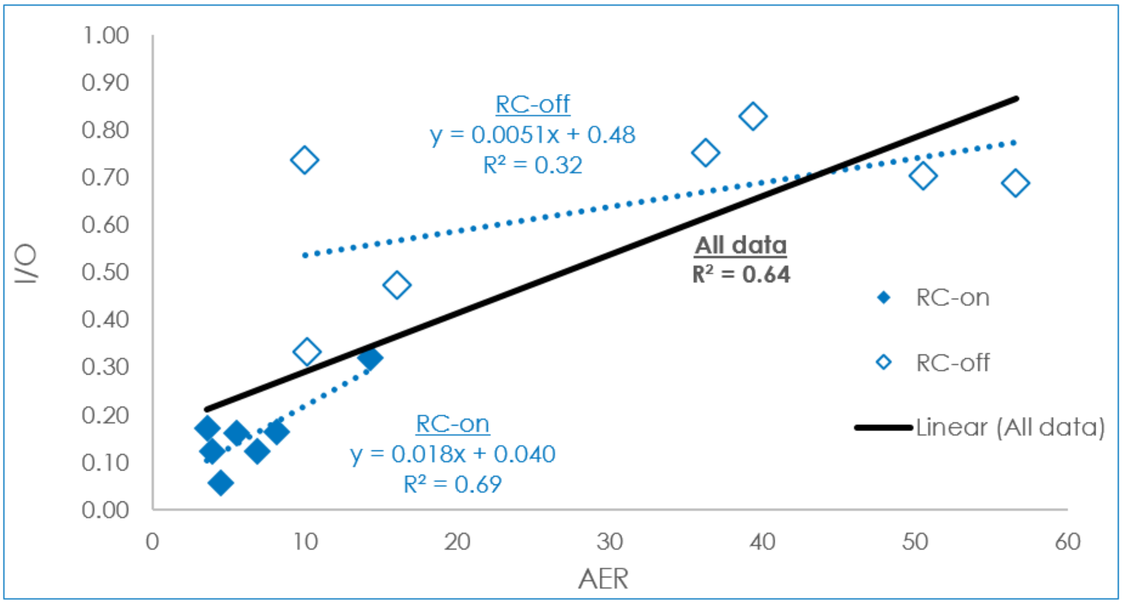


Figure 3-29: Measured AER and inside-to-outside (I/O) ratios for the test vehicles with recirculate-on (RC-on) and recirculate-off (RC-off)

3.8 Can measured AERs be used to predict in-vehicle NO_2 concentrations and I/O ratios?

In-vehicle NO_2 concentrations were predicted by inputting measured AERs into **Equation 3** for a typical run in the Lane Cove tunnel using the 2014 Hyundai i30 with RC-on (**Figure 3-30**).

In the tunnel, the outside-vehicle NO_2 concentration increased from 30 to 700 ppb and the predicted in-vehicle NO_2 concentration increased from 30 to 90 ppb; however, the measured in-vehicle NO_2 concentration remained constant at around 30 ppb. The I/O model may therefore over-predict in-vehicle NO_2 concentrations, which could be due in part to in-vehicle NO_2 deposition on surfaces, given the high surface-to-volume ratio of car cabins. There is little information in the literature on the rate of NO_2 deposition in passenger vehicles.

Predicted in-vehicle NO_2 concentrations and outside-vehicle NO_2 concentrations from **Figure 3-30** were then used to calculate corresponding I/O ratios (**Figure 3-31**). Predicted I/O ratios showed good agreement for the tunnel.

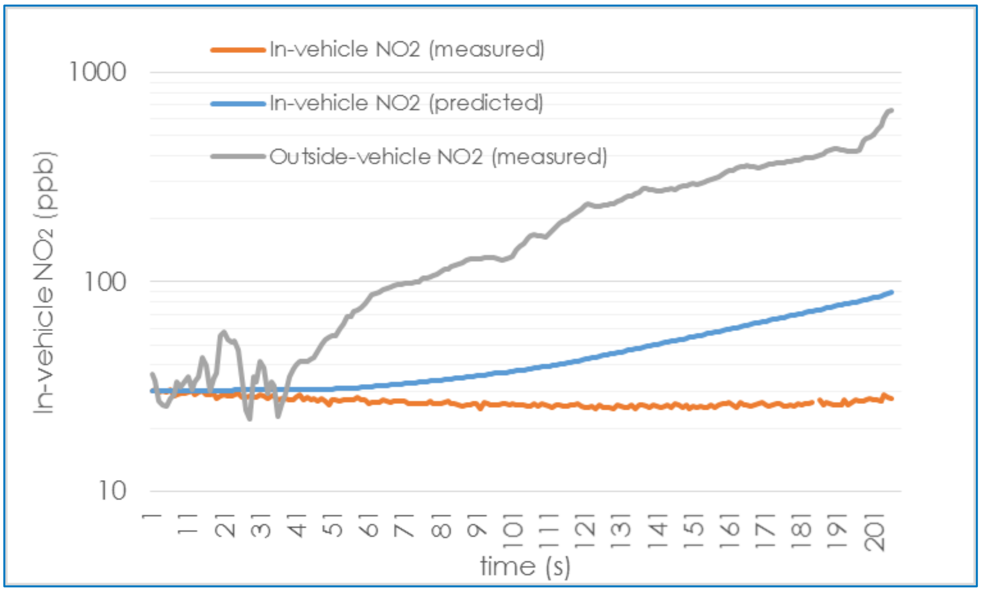


Figure 3-30 Measured in-vehicle NO_2 and outside-vehicle NO_2 concentrations shown with predicted in-vehicle NO_2 concentrations for a typical tunnel run with recirculation on

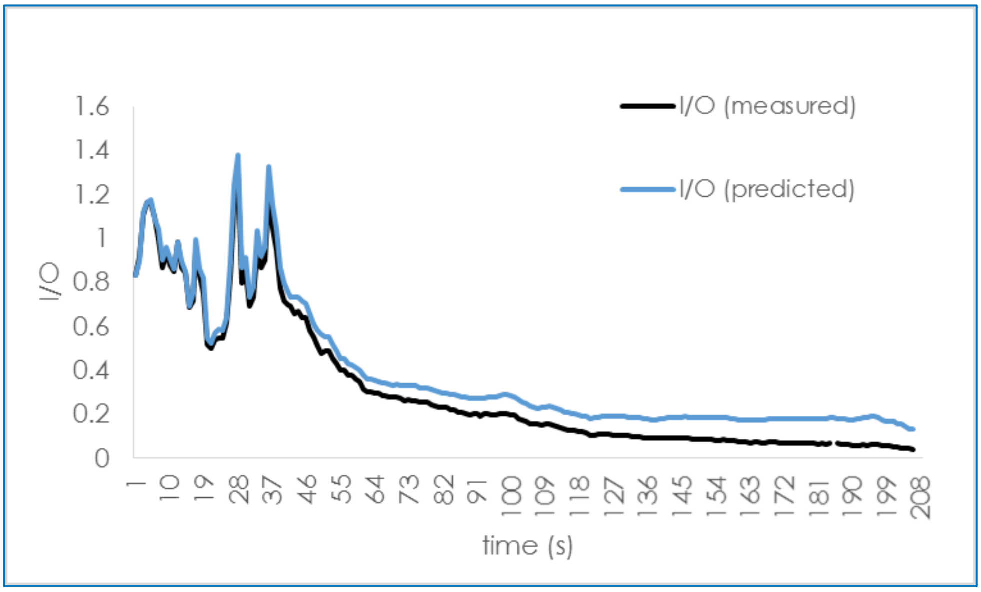


Figure 3-31 Measured and predicted inside-to-outside (I/O) ratios for NO_2 typical tunnel run with recirculation on

4 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary and conclusions

Outside-vehicle NO_2 concentrations

Major tunnels

1. On individual runs concentrations exceeded 500 ppb in the M5 East eastbound, M5 East westbound and the Lane Cove eastbound tunnels. These tunnels had maximum transit-average outside-vehicle NO_2 concentrations of 718 ppb, 546 ppb, and 637 ppb respectively. NO_2 concentrations in these tunnels were less than 500 ppb for at least 75% of transits The relatively high NO_2 concentrations in the M5 East tunnels are linked to the high traffic volume and high proportion of heavy vehicles The relatively high NO_2 concentrations in the M5 East tunnels are linked to the high traffic volume and high proportion of heavy vehicles.

Minor tunnels and surface roads

2. Transit-average outside-vehicle NO_2 concentrations were similar between the minor tunnels, and relatively low; the mean concentrations were all less than 300 ppb. However, the data show that even relatively short tunnels (less than 500 m in length) can have elevated outside-vehicle NO_2 concentrations.

Surface roads

3. The outside-vehicle NO_2 concentrations for surface roads were generally less than 150 ppb.

Effects of air recirculation on in-vehicle NO_2 concentrations and I/O ratios

Major tunnels

4. With recirculation mode switched on, the transit-average in-vehicle NO_2 concentrations were less than 200 ppb for all major tunnels, despite transit-average outside-vehicle NO_2 concentrations exceeding 700 ppb in some tunnels. Transit-average I/O ratios for NO_2 were less than 0.6 in all major tunnels except the Sydney Harbour southbound tunnel. This is probably because the outside-vehicle concentrations in this tunnel were relatively low, and so the background NO_2 levels in had a proportionally larger impact on the I/O ratio. Occasionally the I/O ratio was greater than one with recirculation on. This was due to the accumulation of NO_2 in the vehicle cabin.

5. With recirculation mode switched off, the transit-average in-vehicle NO_2 concentrations were generally less than 200 ppb in all major tunnels, except for the M5 East eastbound tunnel. The I/O ratios were relatively high in all tunnels due to the increased AER between the vehicle cabin and the tunnel.

Minor tunnels and surface roads

6. With recirculation mode switched on, the mean transit-average in-vehicle NO_2 concentrations in minor tunnels and on surface roads were less than 50 ppb. The I/O ratio ranged from 0.05 to 2.70.

7. With recirculation mode switched off, the mean transit-average in-vehicle NO_2 concentrations increased to 50-100 ppb. The I/O ratio ranged from 0.05 to 4.0.

8. The higher I/O ratios in minor tunnels and on surface roads compared with major tunnels are attributed to lower NO_2 concentrations in outside air and accumulated in-vehicle NO_2 during tunnel transit.

Effect of other vehicle ventilation settings on I/O ratios

9. For a given fan speed and recirculation setting, switching air conditioning systems on had little effect on the I/O ratio for NO_2.

10. Increasing the fan speed from 0% to 50% shifted the I/O ratio distribution towards significantly higher values. Further increasing the fan speed to 100% further increased the I/O ratios. This is attributed to the increased intake rate of outside-vehicle air with a high NO_2 concentration.

Switching recirculation mode on/off following tunnel entrance/exit

11. A test involved switching off recirculation mode at a tunnel entrance and switching recirculate on upon exiting the tunnel. With recirculate on, in-vehicle NO_2 concentrations remained higher than outside-vehicle concentrations for approximately 80 seconds after exiting the tunnel. There was no difference when recirculate was turned off after exiting the tunnel; in-vehicle NO_2 concentrations also remained higher than outside-vehicle concentrations for approximately 80 seconds.

Effects of opening windows following tunnel exit

12. Tests were carried out to examine the effects of opening the vehicle windows at the end of the study route (exit of M5 East westbound tunnel). NO_2 concentrations did not decrease as rapidly as outside-vehicle NO_2 concentrations following tunnel exit. However, the experimental set-up meant that not all windows could be opened, and in practice it is likely that opening the windows would lead to a faster decrease in the in-vehicle concentration.

I/O ratio for NO_2 by vehicle type

13. Transit-average I/O ratios ranged from 0.06 to 0.32 with recirculation on, and 0.28 to 0.76 with recirculation off. This shows that all vehicles, regardless of vehicle model/manufacturer, can maintain lower in-vehicle NO_2 concentrations compared to outside-vehicle NO_2 concentrations with recirculation on.

14. The best performing vehicles (all I/O ratios less than 0.20) with recirculate-on were the Holden Astra Wagon (V-01), Hyundai i30 (V-04), Fiat Punto (V-05), and Toyota Corolla (V-06). The highest I/O ratios were measured in the Subaru Outback (V-07). The performance of the Holden Astra Wagon (V-01) is also surprising, as current AER models assume that Australian vehicles are equal to American cars, which are expected to have the worst performance. This suggests that vehicles manufactured in Australia may perform better than current AER models assume.

Best-case and worst case conditions for outside-vehicle and in-vehicle NO_2

15. Best-case and worst-case conditions were examined by comparing a high performing vehicle with recirculation on (2014 Hyundai i30, V-04), and a low performing vehicle with recirculation off (2008 Holden Astra Wagon, V-01). For the Hyundai, despite outside-vehicle 1-second NO_2 reaching 1,000 ppb, in-vehicle NO_2 with recirculation on remained well below 200 ppb. This demonstrates the effectiveness of recirculation in well-sealed vehicles. In the case of the Holden Astra Wagon with recirculation off, in-vehicle NO_2 exceeded 200 ppb when outside-vehicle NO_2 exceeded 1,000 ppb.

AER measurements and model performance

16. AERs were measured on surface roads. The AERs measured at 60 km/h with recirculation on were low, ranging from 3.6/h for the 2007 Subaru Outback to 14.3/h for the 2002 Audi A3. Increasing the speed from 60 km/h to 100 km/h had little effect on measured AERs with recirculation on. However, switching ventilation setting to recirculation off resulted in much higher AERs for most vehicles, which ranged from 10.2 – 61.7/h at 60 km/h. As expected, the highest AERs were generally measured with recirculation off at 100 km/h.

17. AERs were predicted for the test vehicles using the model from **Hudda *et al.* (2012)**. The predicted AERs were within the same order of magnitude as measured AERs with recirculate-on, but did not agree with measured AERs with recirculation off. This was probably due to differences in the strength of fan systems between different vehicles.

Use of AERs to predict in-vehicle NO_2 concentrations and I/O ratios

18. In-vehicle NO_2 concentrations were predicted using measured AERs and the model. Predicted concentrations using the model were found to be in good agreement with measured in-vehicle concentrations. However, the model slightly overestimated the in-vehicle NO_2 concentration, which may be a result of in-vehicle NO_2 deposition.

4.2 Recommendations

The results from this study can be used to inform the design and operation of future road tunnels in Australia. The M5 East Tunnel is presented as the worst-case condition in terms of NO_2 concentrations. However, despite the high outside-vehicle NO_2 concentrations in tunnels, the study shows that in-vehicle NO_2 concentrations can be significantly reduced with ventilation set to recirculate. It would be advisable to encourage vehicle operators to use air recirculation mode in Sydney tunnels.

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