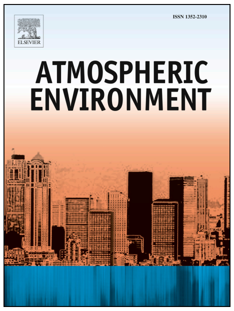

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In-vehicle nitrogen dioxide concentrations in road tunnels

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Abstract

There is a lack of knowledge regarding in-vehicle concentrations of nitrogen dioxide (NO_2) during transit through road tunnels in urban environments. Furthermore, previous studies have tended to involve a single vehicle and the range of in-vehicle NO_2 concentrations that vehicle occupants may be exposed to is not well defined. This study describes simultaneous measurements of in-vehicle and outside-vehicle NO_2 concentrations on a route through Sydney, Australia that included several major tunnels, minor tunnels and busy surface roads. Tests were conducted on nine passenger vehicles to assess how vehicle characteristics and ventilation settings affected in-vehicle NO_2 concentrations and the in-vehicle-to-outside vehicle (I/O) concentration ratio. NO_2 was measured directly using a cavity attenuated phase shift (CAPS) technique that gave a high temporal and spatial resolution. In the major tunnels, transit-average in-vehicle NO_2 concentrations were lower than outside-vehicle concentrations for all vehicles with cabin air recirculation either on or off. However, markedly lower I/O ratios were obtained with recirculation on (0.08 – 0.36), suggesting that vehicle occupants can significantly lower their exposure to NO_2 in tunnels by switching recirculation on. The highest mean I/O ratios for NO_2 were measured in older vehicles (0.35 – 0.36), which is attributed to older vehicles having higher air exchange rates. The results from this study can be used to inform the design and operation of future road tunnels and modelling of personal exposure to NO_2.

Keywords: nitrogen dioxide, in-vehicle, inside-to-outside ratio, air exchange rate, tunnel, air quality

1 Introduction

The presence of atmospheric nitric oxide (NO) and nitrogen dioxide (NO_2) - collectively known as oxides of nitrogen (NO_X) - impact on human health and the environment. Road transport is a major source of NO_X in urban areas; for instance, in 2008 motor vehicles contributed around 62% of anthropogenic NO_X emissions in Sydney, Australia's most populous city (~4.5 million) (NSW EPA, 2012). In road tunnels, NO_2 concentrations can be much higher than those on surface roads due to the lack of atmospheric dispersion. As the air in vehicle cabins is exchanged with the outside air, this can result in elevated NO_2 concentrations in vehicles (Chan and Chung, 2003; Yamada et al., 2016). There is concern that vehicle occupants could be exposed to elevated NO_2 concentrations in existing and future road tunnels.

Exposure to NO_2 is associated with direct, adverse effects on health, even after adjustment for the effects of other pollutants (WHO Regional Office Europe, 2013; US EPA 2015), and NO_2 is considered to be a more important pollutant than NO from a health perspective. The main health effects of short-term NO_2 exposure (<30 minutes) at concentrations that are representative of road tunnels (<500 ppb) include increased airway responsiveness, decreased lung function, and an increase in blood inflammation markers (Jalaludin, 2015); however, no health effects were identified effects at NO_2 concentrations <200 ppb. Since vehicle emissions are a major source of NO_2, vehicle occupants in urban environments are expected to be at the greatest risk to these effects (Dons et al., 2012). Despite this, measurements of NO_2 concentrations in vehicle cabins (herein referred to as 'in-vehicle') are limited as previous studies typically have measured other pollutants, such as carbon monoxide (e.g. Colwill and Hickman, 1980; Clifford et al., 1997; Chan et al., 2002), and particulate matter (e.g. Knibbs et al., 2010; Hudda et al., 2012; Goel and Kumar 2015).

Exchange between in-vehicle air, and air in the outside environment (referred to here as 'outside-vehicle') occurs through leaks in the body (door seals, window cracks, etc.) and/or through the ventilation system. The vehicle air exchange rate (AER) describes how frequently the cabin air is replaced by an equivalent volume of outside air and depends on the size and distribution of air leakage sites (related to vehicle age or model year and country of manufacture), pressure differences induced by wind (changes in vehicle speed) and temperature, mechanical ventilation system settings, occupant behaviour and vehicle speed (Fletcher and Saunders, 1994; Knibbs et al., 2009; Knibbs et al., 2010; Hudda et al., 2011; Hudda et al., 2012). In older vehicles (manufactured pre-2000), pollutant concentrations were similar inside vehicles and in the outside air (Colwill and Hickman, 1980; Petersen and Allen, 1982; Rudolf, 1990; Chan et al., 1991; Koushki et al., 1992; Lawryk and Weisel, 1996; Clifford et al., 1997; Febo and Perrino, 1995). Recent advancements in vehicle design have resulted in modern vehicles being more airtight and having lower AERs and lower inside-to-outside (I/O) concentration ratios of pollutants (Pui et al., 2008; Knibbs et al., 2009). In addition, AERs are dependent on the vehicle manufacturer (or region of origin) as vehicles with a higher quality of manufacturing (e.g. Japanese or German vehicles) are expected to have lower AERs and lower I/O ratios (Hudda et al., 2012). There is a close correspondence between the AER and I/O ratios, e.g. ultrafine particles (Knibbs et al., 2010; Hudda et al., 2011).

Vehicle cabins generally have two ventilation settings: 1) recirculation (referred to here as ‘RC on’) where the outside air entry point is sealed (with varying degrees of efficiency) and cabin air is recirculated by a fan; and 2) outside air intake (referred to here as ‘RC off’) where air is sourced from outside the vehicle before being exhausted. In-vehicle pollutant concentrations can be minimised by switching RC on (Chan and Chung, 2003; Hudda et al., 2011; Knibbs et al., 2009; Yamada et al., 2016), and it may be desirable to minimise in-vehicle concentrations whilst travelling through congested traffic and/or tunnels. However, switching RC on could result in prolonged exposure to elevated in-vehicle concentrations after transitioning from a more polluted to a less polluted environment. The ventilation fan speed can also affect the AER (Knibbs et al., 2009). Knibbs et al. (2010) showed that higher fan speeds under RC on conditions decreased pollutant I/O ratios, which may suggest that pollutants are diluted by increased mixing of the in-vehicle air. In contrast, I/O ratios increased at higher fan speeds with air conditioning on, which is likely to be due to more (polluted) air being cycled into the vehicle cabin.

Although previous studies have shown that in-vehicle NO_2 concentrations can be minimised on surface roads and in road tunnels with RC on compared with RC off (Chan and Chung, 2003; Yamada et al., 2016), these studies only included one test vehicle. As passenger vehicle fleets comprise a wide range of vehicles (and AERs), the upper and lower bounds of potential NO_2 exposure for vehicle occupants remain unknown. Vehicles with low AERs may be desirable in environments with low NO_2 concentrations to minimise in-vehicle concentrations, suggesting occupants in older vehicles could be more at risk than those in modern vehicles. On the contrary, in-vehicle concentrations could remain high in modern vehicles with low AERs following transit to an environment with lower NO_2 concentrations, e.g. after exiting a road tunnel. Given that the time spent road on surface roads is typically much greater than time spent in road tunnels, occupants in modern vehicles could have a prolonged exposure to elevated in-vehicle NO_2 concentrations. This study aims to quantify the typical in-vehicle NO_2 concentrations for a range of typical passenger vehicles (n = 9) with simultaneous in-vehicle and outside-vehicle measurements. Vehicles were tested on a 30 km route through Sydney, Australia with several tunnels and busy surface roads to assess typical NO_2 concentrations that vehicle occupants may experience in the urban environment. Experiments were conducted with RC on and RC off to determine the reduction that can be achieved using vehicle ventilation settings.

2 Experimental work

2.1 Overview

In-vehicle and outside-vehicle carbon dioxide (CO_2) and NO_2 concentrations were simultaneously measured on a route through Sydney that included several major road tunnels, some minor tunnels and busy surface roads. CO_2 concentrations were measured with a view to calculating AERs. The work on AERs is not discussed further here.

During a two-month monitoring campaign between August and October of 2015, tests were conducted on multiple cars. The NO_2 measurements were used to assess how vehicle characteristics and ventilation settings affected in-vehicle NO_2 concentrations and the in-vehicle-to-outside vehicle (I/O) concentration ratio. Measurements were only taken during weekdays, and between 06:30 and 20:00.

NO_2 was determined using a direct measurement technique that gave a high temporal and spatial resolution. However, for simplicity of presentation the NO_2 results are presented mainly in terms ‘transit-average’ concentrations for tunnels and surface roads.

2.2 Monitoring equipment and procedures

2.2.1 Carbon dioxide

Previous studies have shown that in-vehicle CO_2 levels typically reach around 2,000 – 3,000 parts per million (ppm) with an outside-vehicle concentration of around 400 ppm (e.g. Fruin et al., 2011). 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, which employed a non-dispersive infrared detection technique. The Li-820 was pump driven, thus allowing a fast response time. It had a 1 ppm signal noise at 370 ppm CO_2, and a range of 0 – 20,000 ppm.

2.2.2 Nitrogen dioxide

A transit through a four-kilometre long road tunnel at a speed of 80 km/h (optimal traffic flow) only takes three minutes. Sub-minute averaging periods and a fast instrument response were therefore required to give an adequate temporal resolution in the NO_2 measurements. The instrument resolution also needed to enable a clear differentiation between in-vehicle and in-tunnel concentrations. NO_2 was measured using two cavity attenuated phase shift (CAPS) analysers (Aerodyne) (Kebabian et al., 2008). The CAPS analyser was chosen for its ability to measure NO_2 with a high temporal resolution (frequency of 1 Hz), a high precision (resolution of 1 ppb), and across a wide concentration range (linear response up to several ppm). The measurement range was appropriate for road tunnels. Moreover, the CAPS analyser provided a direct absorption measurement of NO_2 at a wavelength of 450 nm. Unlike standard chemiluminescence analysers, CAPS requires no conversion of NO to NO_2 and is not sensitive to the presence of other nitrogen-containing species.

Each test vehicle was equipped with two CAPS analysers, one to measure the in-vehicle NO_2 concentrations and the other to measure the outside-vehicle NO_2 concentrations. The gas flow rate was 0.85 litres per minute. Precautions were taken to minimise the influence of potential errors and artefacts. For example, in-vehicle samples were collected close to the breathing zone of vehicle occupants. All inlets and outlets for sample lines were well sealed. Foam padding was used to protect the equipment and dampen on-board vibration.

Zero and single-point calibrations were conducted on the NO_2 instruments before and half-way through the measurement campaign. High-purity nitrogen (>99.99%) was used for NO_2 zero calibrations. The NO_2 span calibration gas had a concentration of 2,100 ± 210 ppb. As all span values were within 1% of the desired concentration for both NO_2 instruments, error in NO_2 measurements is estimated to be ±10% and measurements are reported to two significant figures. Baseline tests were carried out before each monitoring session to correct for any measurement drift. Baseline tests were also conducted with the doors and boot of each vehicle open in order for the in-vehicle air to equilibrate with the outside air and correct for any differences in instrument response. These tests were conducted at Blenheim Park, Sydney (33°47'46.155"S 151°8'7.955" E) to minimise influences from traffic 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.

2.2.3 Vehicle operation and location

During the experiments there were two vehicle occupants: a driver and a passenger to take notes and operate the monitoring equipment. The output from the on-board diagnostics (OBD) port of each vehicle was recorded using a scanning tool and 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). OBD measurements were not available in the majority of vehicles as many pre-2007 vehicles are not OBD-compliant.

2.3 Vehicle selection

Nine vehicles were included in the test programme to cover the likely performance range of the Sydney passenger car fleet in terms of in-vehicle pollution. The specifications of the test vehicles are given in Table 1. All the vehicles selected for monitoring were petrol cars, given that data from the Australian Bureau of Statistics (2014) show that petrol vehicles accounted for 80% of the total registered vehicle fleet (all types) in 2014. All vehicles were generally in good condition, although the oldest vehicle tested (V2, Audi A3) had visibly degraded door seals. The vehicles were classified in terms of age (model year) and size (based on cabin dimensions). The anticipated AER performance of each vehicle (associated with the region of manufacture) was also predicted using the model of Hudda et al. (2012).

Table 1: Test vehicle specifications

Code	Make and model	Model year	Engine size (litres)	Odometer reading (km)	Vehicle dimensions (m^3)	Age band[(a)]	Size band	Country of manufacture	Expected AER performance band
V1	Ford Fiesta	2004	1.4	21,000	4.0 x 2.0 x 1.4	Old	Small	US	Worst
V2	Audi A3	2002	1.8	35,000	4.2 x 1.8 x 1.4	Old	Medium	Germany	Best
V3	Subaru Outback	2007	2.5	139,000	4.7 x 2.0 x 1.5	Old	Large	Japan	Intermediate
V4	Fiat Punto	2007	1.4	60,000	4.0 x 1.7 x 1.5	Intermediate	Small	Italy	Best
V5	Toyota Corolla	2007	1.8	75,000	4.2 x 1.8 x 1.5	Intermediate	Medium	Japan	Intermediate
V6	Holden Astra	2008	1.8	80,000	4.5 x 2.0 x 1.5	Intermediate	Large	Australia	Worst
V7	Hyundai i30	2014	1.8	20,000	4.3 x 1.8 x 1.5	New	Small	Korea	Intermediate
V8	Holden Cruze	2011	1.8	37,790	4.6 x 1.8 x 1.5	New	Medium	Australia	Worst

V9	BMW X3	2014	2.0	15,000	4.7 x 1.9 x 1.7	New	Large	Germany	Best

(a) New: 2011-2015 model years, intermediate: 2006-2010 model years and old: pre-2006 model years.

2.4 Ventilation settings

Several vehicle ventilation modes were evaluated in the study (Table 2). 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. Mode M3 investigated the effects of turning the ventilation system from RC on to RC off following tunnel transit. Modes M4, M5 and M6 investigated the effect of having air RC 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: Vehicle ventilation settings

Ventilation mode	Air recirculation (RC)	Air -conditioning	Fan speed (% of maximum)
M1	On	On	50%
M2	On	Off	50%
M3	On/off [(a)]	Off	50%
M4	Off	Off	50%
M5	Off	Off	0%
M6	Off	Off	100%

(a) This investigated the effect of turning the ventilation system from RC on to RC off following tunnel transit.

2.5 Study route

A driving route was selected to maximise the number of runs through four major Sydney tunnels: Lane Cove tunnel, Sydney Harbour tunnel, Eastern Distributor tunnel and M5 East tunnel (Figure 1). The length of the route was 30 km (one way), and the typical travel time was between 45 and 60 minutes.

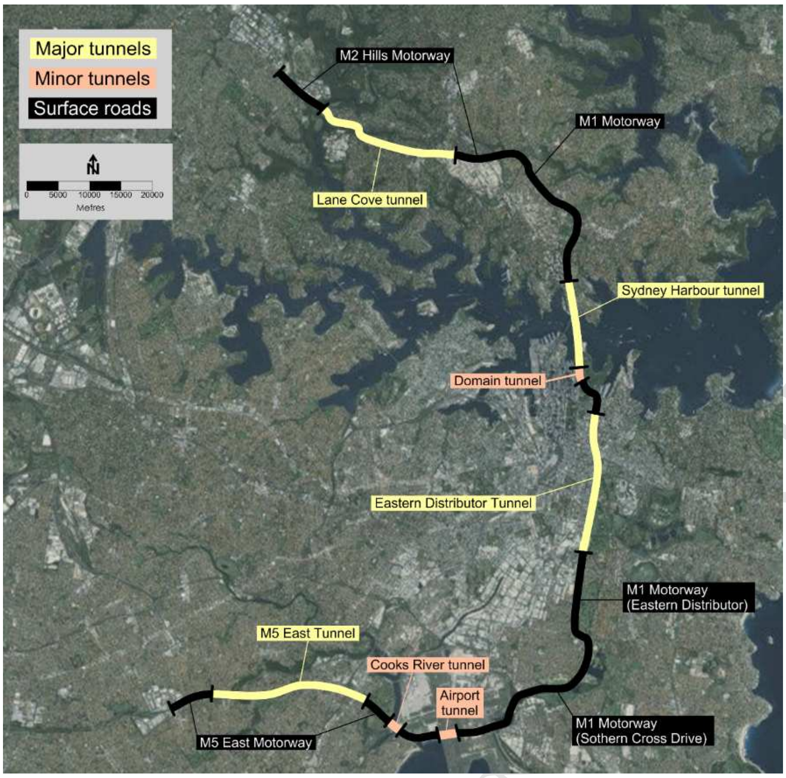


Figure 1: Study route and road sections

2.5.1 Major tunnels

The Lane Cove tunnel connects the M2 Motorway at North Ryde in the east with the Gore Hill Freeway at Artarmon in the west. The eastbound (EB) tunnel is predominantly uphill, and the westbound (WB) tunnel is predominantly downhill. The tunnel has a longitudinal ventilation system, with a stack at each end.

The Sydney Harbour tunnel connects the north of Sydney Harbour to the south. The northbound (NB) and southbound (SB) tunnels have a semi-transverse ventilation system, with the tunnel air being expelled through the northern pylon of Sydney Harbour Bridge.

The Eastern Distributor tunnel links the Sydney central business district with Sydney Airport. The tunnel features a 1.7 km double-deck section to enable three lanes of traffic in each direction within the existing road corridor. At the time of construction the tunnel was one of the widest in the world, and it has a large cross-sectional area. Emissions are released from the portals at each end of the tunnel, as well as from two ventilation stacks.

The M5 East tunnel was designed to improve access between south-western Sydney, the city, Sydney Airport, Port Botany and the major industrial and commercial land areas surrounding the airport. The tunnel ventilation system has an unusual design. The air in the tunnel follows a circuit driven by fans and the piston effect of traffic. Fresh air is drawn into both the EB and WB tubes at an intake, and air is also drawn inwards at all of the portals. Near the ends of each tube, air is directed from one tube to the other in cross-over tubes. The tunnel air is extracted via a 690 m ventilation shaft located approximately two-thirds of the way along the tunnel in the EB direction, and is released via a single ventilation stack. High levels of in-tunnel pollution and poor visibility have been reported for this tunnel (Knibbs et al., 2009), which is due to heavy vehicle usage and frequent congestion (NSW Parliament, 2002).

The characteristics of the major tunnels on the route are summarised in Table 3. All the tunnels are twin bore tunnels, with unidirectional traffic in each bore. The daily traffic volume is highest for the M5 East tunnels (143,000 vehicles/day), followed by the Sydney Harbour tunnels (87,300 vehicles/day), Lane Cove tunnels (86,000 vehicles/day), and Eastern Distributor tunnels (55,000 vehicles/day). The average traffic speed is highest in the Lane Cove EB/WB tunnels, followed by the Eastern Distributor NB, Sydney Harbour NB/SB, and M5 East EB tunnel. The lowest speeds are in the Eastern Distributor SB and M5 East WB tunnels.

Table 3: Characteristics of major tunnels

Tunnel[a]	Length (km)	Maximum/minimum gradient (%)	Average traffic volume (vehicles/day)	Heavy vehicle usage (%)	Average transit duration (s)[f]	Average speed (km/h)[f]
Lane Cove EB	3.6	+4/-4.6	43,000[b]	14[d]	203 ± 50	66 ± 10
Lane Cove WB	3.6	+4/-3.9	43,000[b]	14[d]	179 ± 14	73 ± 5
Sydney Harbour NB	2.3	+8/-8	45,300[c]	6[c]	139 ± 27	61 ± 11
Sydney Harbour SB	2.3	+8/-8	42,000[c]	6[c]	175 ± 108	57 ± 18
Eastern Distributor NB	1.7	Unknown	27,500[b]	5[c]	96 ± 40	65 ± 13
Eastern Distributor SB	1.7	Unknown	27,500[b]	5[c]	180 ± 86	42 ± 18
M5 East (EB)	4.0	+8.3 /-0.5	71,500[b]	12[e]	277 ± 148	56 ± 11
M5 East (WB)	4.0	+0.5 / - 8.3	71,500[b]	13[e]	459 ± 146	35 ± 15

(a) NB: northbound, SB: southbound, EB: eastbound, WB: westbound;
(b) Toll transactions per day from September quarter (Transurban, 2015);
(c) Traffic data for 2015 from NSW RMS (2015);
(d) Traffic counting data at Hills M2 Motorway west of Pennant Hills Road (RMS, 2014);
(e) Traffic counting data in M5 East Motorway tunnel east of Bexley Road (RMS, 2014);
(f) Measured in this study (variability represents the standard deviation).

2.5.2 Minor tunnels and surface roads

The study route included three minor tunnels: the Domain tunnel, the Airport tunnel, and the Cooks River tunnel (350, 550 and 550 m in length respectively). Another minor tunnel on the route was the Art Gallery tunnel, but due to its short length (150 m) it was regarded as a surface road in the study.

The major surface roads on the route were (in order from north to south): M2 Hills Motorway, M1 Motorway, M1 Motorway-Eastern Distributor, M1 Motorway-Southern Cross Drive, and M5 East Motorway.

2.6 Data analysis

All measured parameters were synchronised and stored in a database. Transit-average NO_2 concentrations were calculated for each tunnel by averaging one-second concentrations from a single tunnel transit. Analysis of variance (ANOVA) with a multiple comparison test, Student-Newman-Keuls (SNK), were used to determine the significance of the difference between the mean transit-average concentrations in tunnels at the 95% level of confidence.

3 Results and discussion

3.1 Trip summary

In total, 59 complete trips along the study route (and several partially-completed trips) were conducted, which equated to a total distance driven of more than 1,750 km. The numbers of valid transits conducted for each vehicle, tunnel and direction of travel are shown in Table 4. Between 121 and 131 transits were measured for each tunnel, and the total number of transits through all tunnels was 495. Between 29 and 90 transits were obtained for each test vehicle, and there was an average of 55 transits per vehicle. The transits were generally distributed evenly across the tunnels, directions of travel and (although less so) vehicles, and no systematic bias in the results is expected to have resulted from the sampling.

The majority of trips (70%) were conducted during the inter-peak period (09:00 – 16:30). The percentages of trips conducted during the morning peak (06:00 – 09:00) and afternoon peak (16:30 – 19:00) periods were 10% and 15%, respectively. The remaining trips (5%) were conducted during the evening period (19:00 – 20:00).

Table 4: Number of transits by vehicle, tunnel and direction of travel

Vehicle	Number of transits by tunnel and direction[a]								Total
	Lane Cove tunnel		Sydney Harbour tunnel		Eastern Distributor tunnel		M5 East tunnel		
	EB	WB	NB	SB	NB	SB	EB	WB	
V1: Ford Fiesta	7	7	6	6	6	6	6	6	**50**
V2: Audi A3	10	8	8	7	8	8	8	8	**65**
V3: Subaru Outback	4	4	4	3	4	3	4	3	**29**
V4: Fiat Punto	7	6	7	7	7	7	7	7	**55**
V5: Toyota Corolla	10	8	8	8	8	8	8	8	**66**
V6: Holden Astra Wagon	8	7	7	8	8	7	7	7	**59**
V7: Hyundai i30	6	8	6	6	6	6	6	6	**50**
V8: Holden Cruze	12	11	11	11	11	11	12	11	**90**
V9: BMW X3	4	4	4	4	4	3	4	4	**31**
All vehicles	**68**	**63**	**61**	**60**	**62**	**59**	**62**	**60**	**495**

(a) NB: northbound, SB: southbound, EB: eastbound, and WB: westbound.

3.2 Outside-vehicle NO_2 concentrations

3.2.1 Overview

One-second average outside-vehicle NO_2 concentrations during a typical trip are shown in Figure 2. In this example, the highest NO_2 concentrations were measured in the Lane Cove tunnel, Eastern Distributor tunnel and M5 East tunnel. Despite being a major tunnel, NO_2 concentrations in the Sydney Harbour tunnel were similar to those for surface roads and <100 ppb. The minor tunnels are characterised by outside-vehicle NO_2 concentrations that are 100 – 200 ppb.

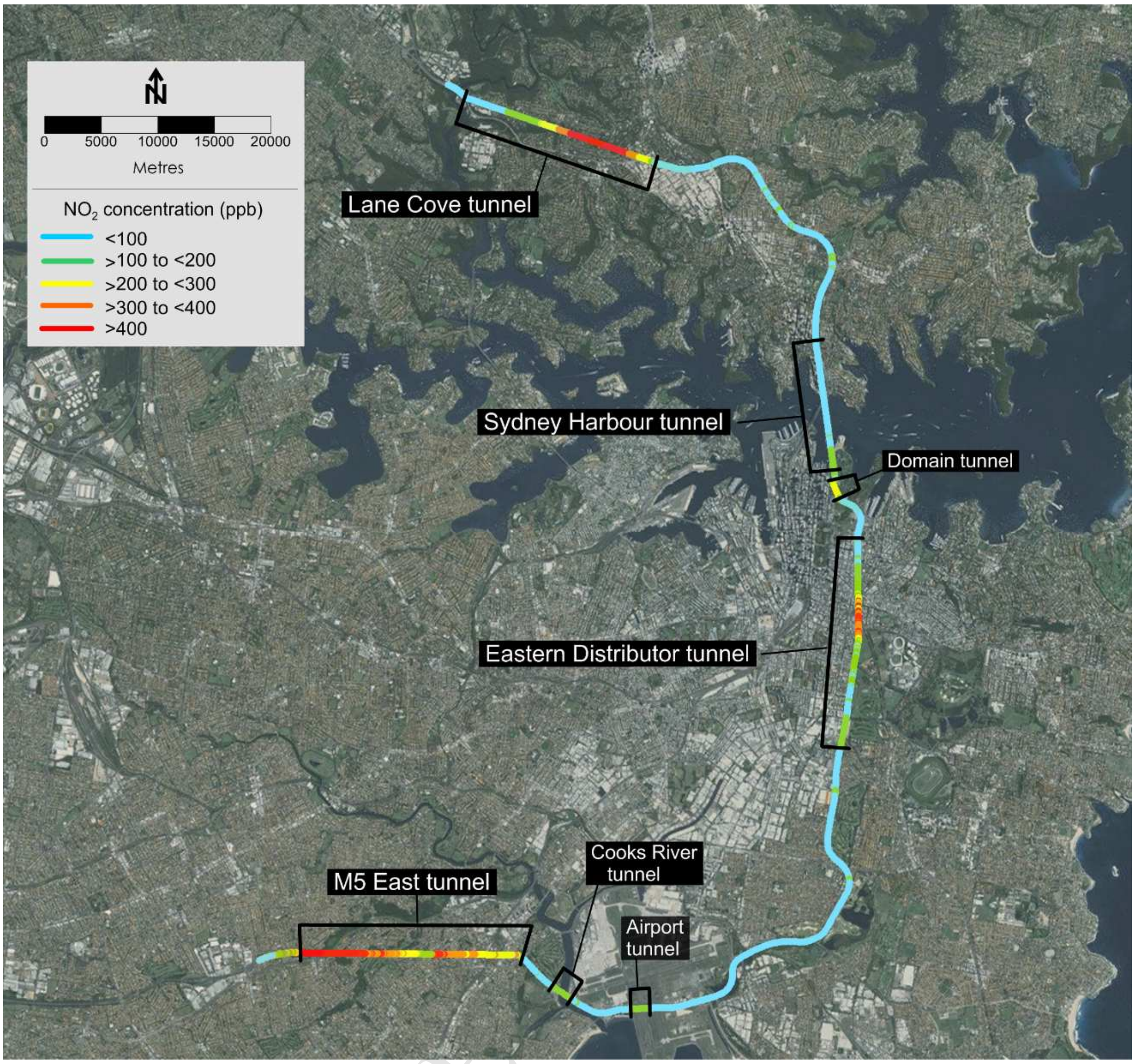
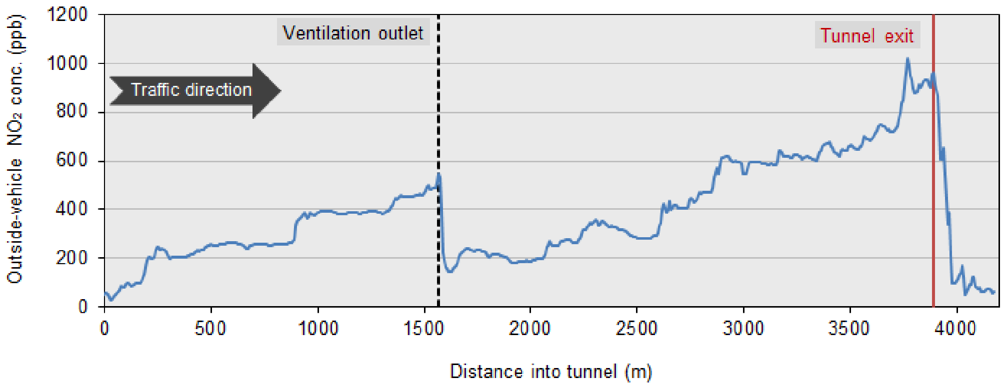


Figure 2: Example of outside-vehicle NO_2 concentrations along the study route (southbound route, 26/08/15, 07:55-08:40)

An example of the influence of a tunnel ventilation point on outside-vehicle NO_2 concentrations is shown in Figure 3, which provides an example of one-second outside-vehicle NO_2 concentrations in the M5 East tunnel. In the WB M5 East Tunnel (Figure 3a), concentrations increased steadily from around 50 ppb at the entrance of the tunnel to around 500 ppb approximately 1.5 km into the tunnel, where concentrations decreased sharply to below 200 ppb. This decrease reflected the extraction of tunnel air at the M5 East tunnel's ventilation shaft. After the shaft, outside-vehicle NO_2 concentrations increased again to a maximum of around 1,000 ppb at the tunnel exit, and then decreased rapidly to less than 100 ppb after exiting the tunnel. In the example for the EB M5 East tunnel (Figure 3b) the NO_2 concentration decreased at the ventilation shaft from around 700 to 10 ppb. Figure 4 shows an outside-vehicle NO_2 profile in the Lane Cove EB tunnel, which is serviced by a more conventional longitudinal ventilation system. The NO_2 concentrations increased consistently from the tunnel entrance to the tunnel exit. The concentration profile is also a function of the tunnel gradient, which is uphill from about 1.3 km into the EB tunnel. This results in increased in NO_2 emissions in the second half of the tunnel associated with the additional loads on vehicle engines (and therefore additional fuel combustion) from this point.

(a) Westbound



(b) Eastbound

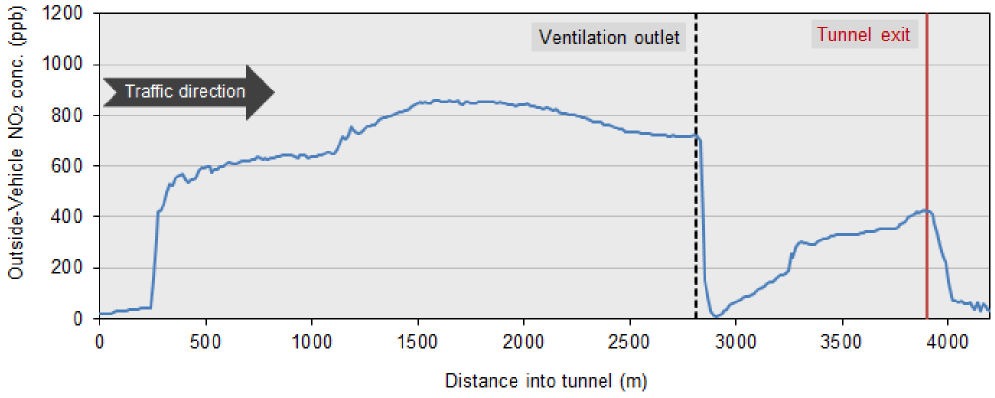


Figure 3: Example of one-second outside-vehicle NO_2 concentrations in the M5 East tunnel

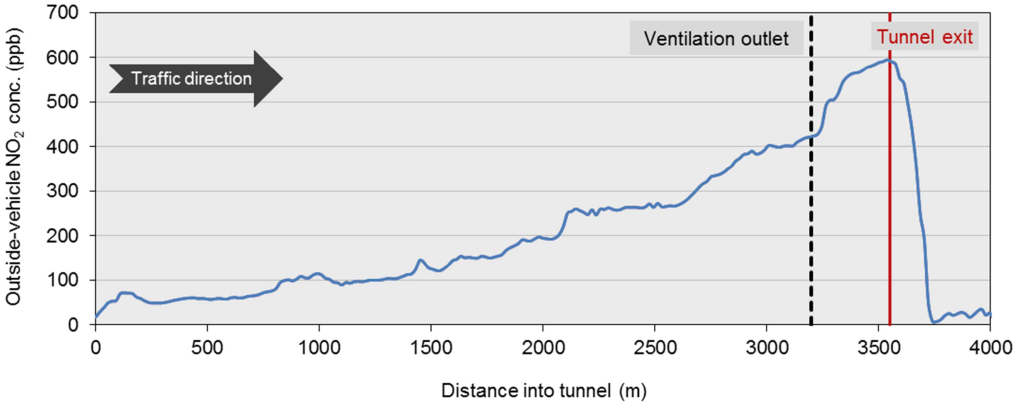


Figure 4: Example of one-second outside-vehicle NO_2 concentrations in the Lane Cove EB tunnel

3.2.2 Major tunnels

The distributions of transit-average outside-vehicle NO_2 concentrations in the major tunnels, minor tunnels and surface roads (separated by direction of travel) are summarised using box-whisker plots in Figure 5. Each box-whisker plot includes the data for all vehicles. The Lane Cove EB, M5 East EB and M5 East WB tunnels had maximum individual transit-average concentrations of 640, 720, and 550 ppb respectively. The relatively high NO_2 concentrations in the M5 East tunnel are linked to the high traffic volume (71,500 vehicles/day in each direction, Table 3), which is almost 40% more traffic than in any of the other major tunnels. Furthermore, the M5 East tunnel (both EB and WB) has a high proportion of heavy vehicle usage. Yamada et al. (2016) also noted that outside-vehicle NO_2 concentrations were related to the proportion of heavy vehicles. Higher NO_2 concentrations in the Lane Cove EB tunnel compared with the Lane Cove WB tunnel are due to the EB tunnel being predominantly uphill, whereas the gradient is predominantly downhill in the WB direction.

Lower in-vehicle NO_2 concentrations (<500 ppb for >75% of transits) in the Eastern Distributor and Sydney Harbour tunnels are attributed to these tunnels being the shortest and carrying the lowest traffic volumes (Table 3). The overall mean transit-average outside-vehicle NO_2 concentrations in each tunnel (across all vehicles and transits) ranged from 85 ± 5 ppb in the Sydney Harbour SB tunnel to 430 ± 14 ppb in the M5 East tunnel EB.

An ANOVA test showed that the between-case differences were significant for all major tunnels and directions of travel with the exception of Lane Cove WB and Eastern Distributor NB, in which there was no significant difference between the mean concentrations. Therefore, the inclusion of all tunnels and directions of travel in the experimental design was justified.

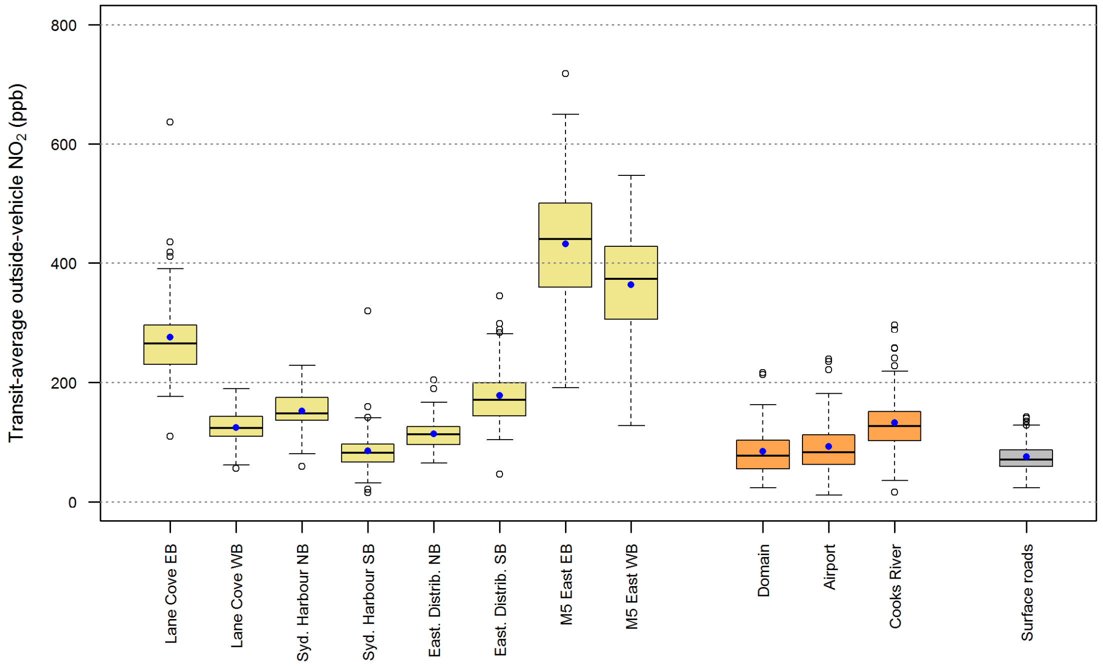


Figure 5: Transit-average outside-vehicle NO_2 concentrations for major tunnels, minor tunnels and surface roads (including data from all test vehicles). Blue dots represent the mean, upper and lower whiskers represent the 1st and 3rd quartiles, and white circles represent outliers (>1.5 times the interquartile range).

3.2.3 Minor tunnels and surface roads

The transit-average outside-vehicle NO_2 concentrations for the minor tunnels and surface roads are also shown in Figure 5. Outside-vehicle NO_2 concentrations were similar between the three minor tunnels, and concentrations for all transits were less than 300 ppb. Overall mean concentrations in the minor tunnels ranged from 85 ± 5.4 ppb in the Domain tunnel to 130 ± 5 ppb in the Cooks River tunnel. The outside-vehicle NO_2 concentrations for surface roads were generally less than 150 ppb, with the overall mean concentration being 76 ± 2 ppb.

The SNK test revealed that the NO_2 concentrations in the Cooks River tunnel were significantly higher than those in the other minor tunnels and on surface roads, as well as in the Sydney Harbour SB tunnel, but not significantly different from those in some of the major tunnels (Lane Cove WB, Eastern Distributor NB). Thesefore, some relatively short tunnels can have elevated outside-vehicle NO_2 concentrations relative to surface roads and even longer tunnels, but the duration of exposure will typically be very short (e.g. 30 seconds).

3.3 Comparison between NO_2 and CO_2 concentrations

One-second outside-vehicle NO_2 and CO_2 concentrations are compared for each major tunnel and direction of travel in Figure 6, with a linear regression model fitted to each set of data. These analyses were carried out to compare the NO_2 emissions per (approximate) unit of fuel consumed in the different tunnels. There was a fairly strong linear relationship between the outside-vehicle CO_2 and NO_2 concentrations in each tunnel ($R^2 = 0.64$ – 0.89), except for the Eastern Distributor NB tunnel ($R^2 = 0.39$). This is because CO_2 and NO_2 are both emitted by road vehicles during the combustion process. The positive intercept on the x axis at just over 400 ppm reflects the background concentration of CO_2 in the ambient air.

There was some variation in the slope of the regression line between the tunnels and directions of travel (Figure 6), suggesting that the NO_2 emission per unit of fuel consumed varied. For the Lane Cove tunnel the slope was larger in the EB direction than in the WB direction. This is indicative of a difference in NO_2 emissions per unit of fuel consumed for uphill and downhill driving. For the other tunnels the differences between the slopes for the directions of travel were smaller. The highest slopes were obtained for the M5 East tunnel, probably due to the relatively high proportion of heavy vehicles (Table 3).

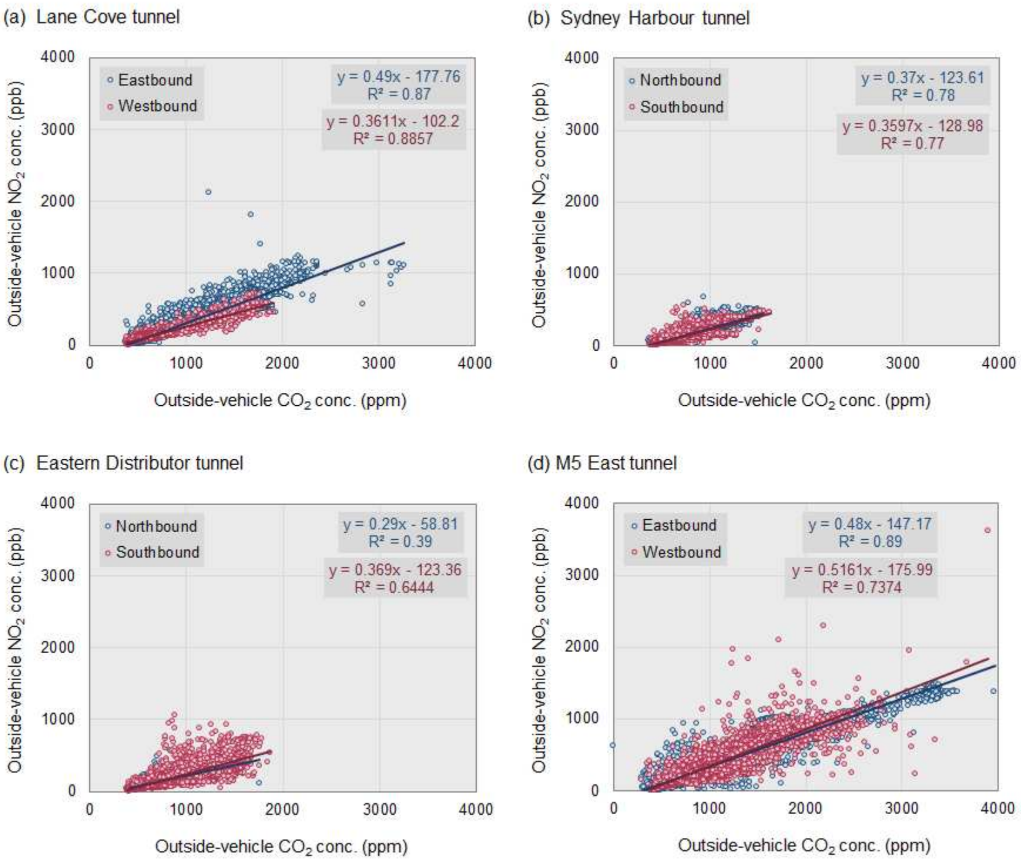


Figure 6: One-second outside-vehicle CO_2 vs one-second outside-vehicle NO_2 for the major tunnels (including data from all test vehicles).

3.4 In-vehicle concentrations and I/O ratios for NO_2

3.4.1 Overview

Example profiles of one-second in-vehicle and outside-vehicle NO_2 concentrations, and I/O ratios are shown in Figure 7. These profiles were measured during two complete trips from the start of the eastbound Lane Cove tunnel to the end of the eastbound M5 East tunnel. Figure 7A shows a trip completed in the Holden Astra with RC off during peak hour AM traffic and therefore reflects the worst-case scenario. During peak hour AM traffic, concentrations in the Lane Cove and Eastern Distributor tunnels reached around 500 ppb, and concentrations in the M5 East tunnel exceeded 1,000 ppb. This resulted in in-vehicle NO_2 concentrations exceeding 400 ppb. There was a time lag between in-vehicle and outside-vehicle concentrations, reflecting the gradual mixing of in-vehicle and outside-vehicle air with RC switched off. Despite the higher AER with RC switched off, in-vehicle concentrations remained high on surface roads following tunnel transits, as reflected by high I/O ratios, e.g. following exit of the Lane Cove and Eastern Distributor tunnels.

Figure 7B shows a trip completed in the Hyundai i30 with RC switched on during inter-peak traffic. Despite outside-vehicle NO_2 concentrations reaching 1,000 ppb, in-vehicle concentrations were unaffected by outside-vehicle NO_2 concentrations with RC switched on, and I/O ratios were generally less than unity.

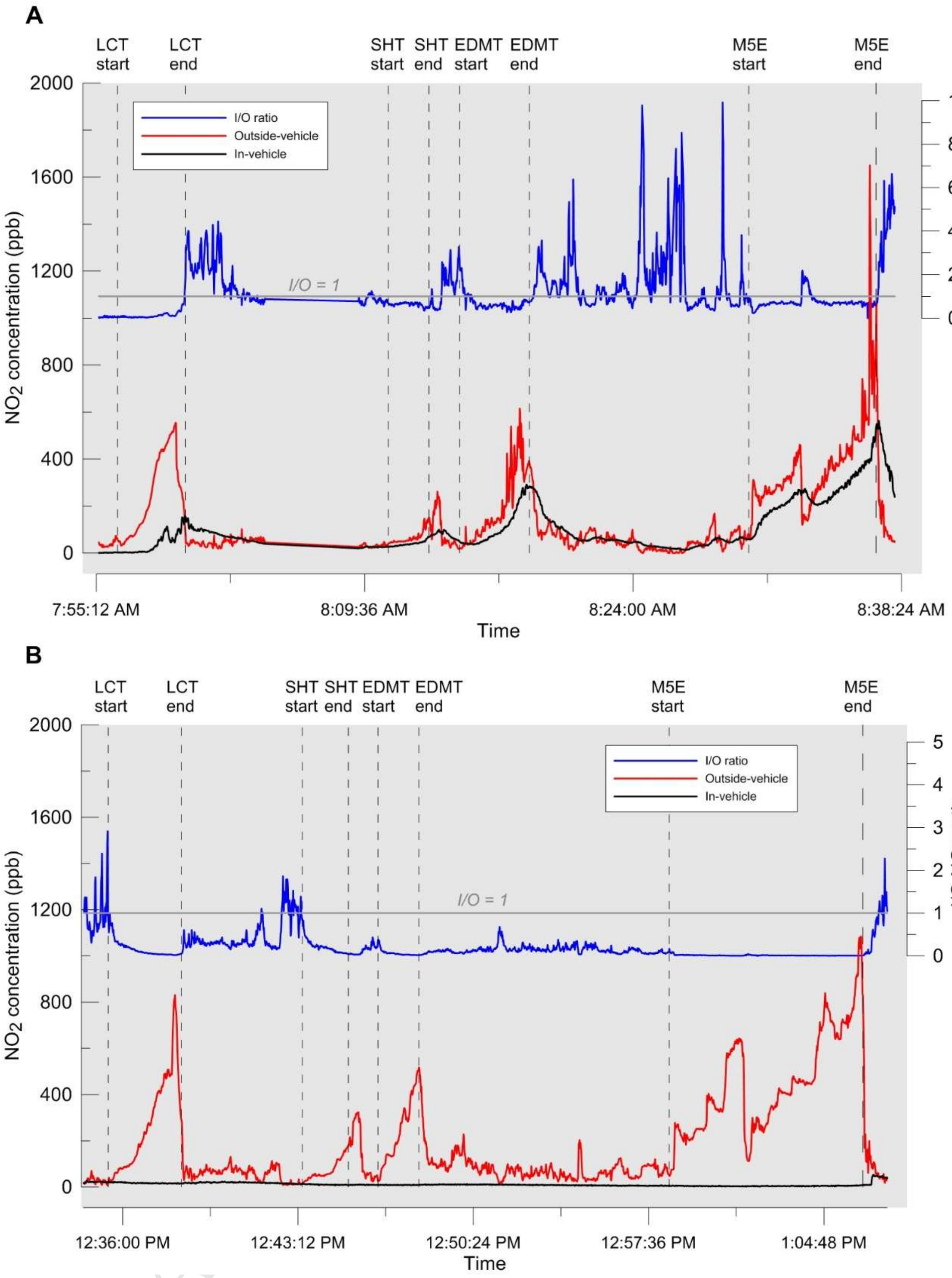


Figure 7: Example profile of outside-vehicle NO_2, in-vehicle NO_2, and I/O ratios for a) 2008 Holden Astra Wagon and mode MD4 (26/08/15 7:55am-8:40am); and b) 2014 Hyundai i30 using mode MD2 (26/08/15 7:55am-8:40am) where LCT: Lane Cove tunnel, SHT: Sydney Harbour tunnel, EDMT: Eastern Distributor Motorway tunnel, and M5E: M5 East tunnel.

3.4.2 Effects of recirculation mode

Major tunnels

Concentrations in the major tunnels with RC switched off and with RC switched on (for all vehicles) are shown in Figure 8. By comparing Figure 8 with Figure 5 it can be seen that, even with RC switched off, transit-average in-vehicle NO_2 concentrations were lower than outside-vehicle concentrations.

The review by Jalaludin (2015) did not identify any studies that showed health effects below an NO_2 concentration of 200 ppb. With RC switched off, the transit-average in-vehicle concentration was above 200 ppb for around 40% of transits of the M5 East tunnel and 5% of transits of the Lane Cove tunnel. Overall mean transit-average concentrations ranged from 43 ± 4 ppb in the Sydney Harbour SB tunnel to 200 ± 23 ppb in the M5 East EB tunnel.

With RC switched on, the transit-average in-vehicle NO_2 concentrations were well below 100 ppb for most transits. A transit-average value above 200 ppb was only recorded during one transit of the M5 East EB tunnel. Overall means ranged from 25 ± 2 ppb in the Sydney Harbour SB tunnel to 77 ± 14 ppb in the M5 East EB tunnel.

The mean transit-average in-vehicle NO_2 concentrations were significantly lower in all tunnels with RC on compared with RC off (unpaired sample t-test, $p<0.004$). This suggests that vehicle occupants can substantially lower their exposure to NO_2 in tunnels by switching RC on.

The distributions of transit-average I/O ratios for NO_2 in the major tunnels with RC switched off and RC switched on are summarised in Figure 9. In all tunnels mean I/O ratios were significantly lower with RC switched on than with RC switched off (unpaired sample t-test, $p<0.01$). For individual transits the I/O ratio varied greatly, ranging from 0.01 to 1.12 with RC off, and from 0.01 to 1.27 with RC on. With RC 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. In some cases the I/O ratios were greater than unity with RC on. This is attributed to the accumulation of NO_2 in the vehicle cabin. However, I/O ratios with RC on were less than 0.60 in all tunnels except the Sydney Harbour SB tunnel, and the value of 1.27 for this tunnel was an outlier. The higher ratios in the Sydney Harbour SB tunnel may have been due to the relatively low in-tunnel concentrations (Figure 5) resulting in the background NO_2 levels having a proportionally larger impact on the I/O ratio. Overall mean transit-average I/O ratios ranged from 0.39 to 0.64 with RC off, and from 0.14 to 0.36 with RC on. These ranges are similar to the mean I/O ratios for a tunnel in Toyko, (Yamada et al., 2016), which were around 0.6 and 0.2 with RC off and RC on, respectively.

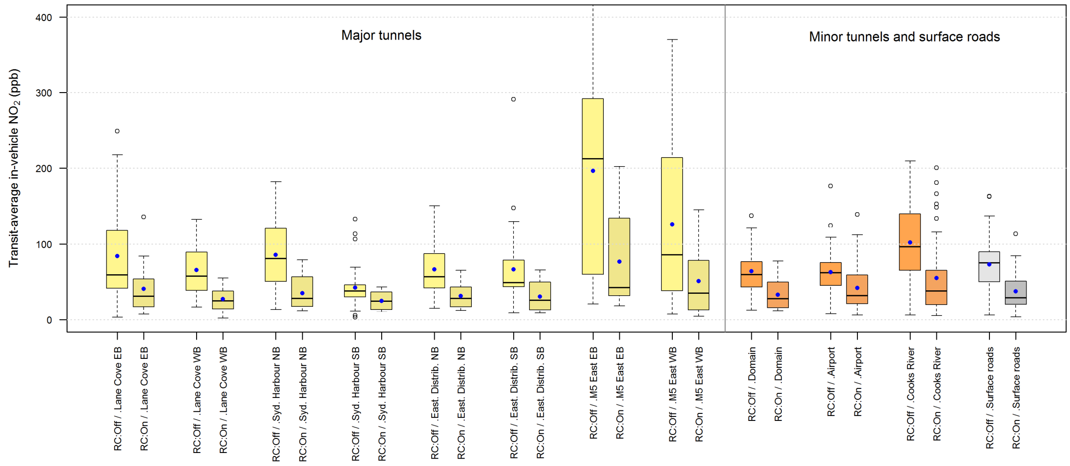


Figure 8: Transit-average in-vehicle NO_2 concentrations for major tunnels (yellow boxes), minor tunnels (orange boxes), and surface roads (grey boxes) with RC off and RC on (including data from all test vehicles). Blue dots represent the mean, upper and lower whiskers represent the 1st and 3rd quartiles, and white circles represent outliers (>1.5 times the interquartile range).

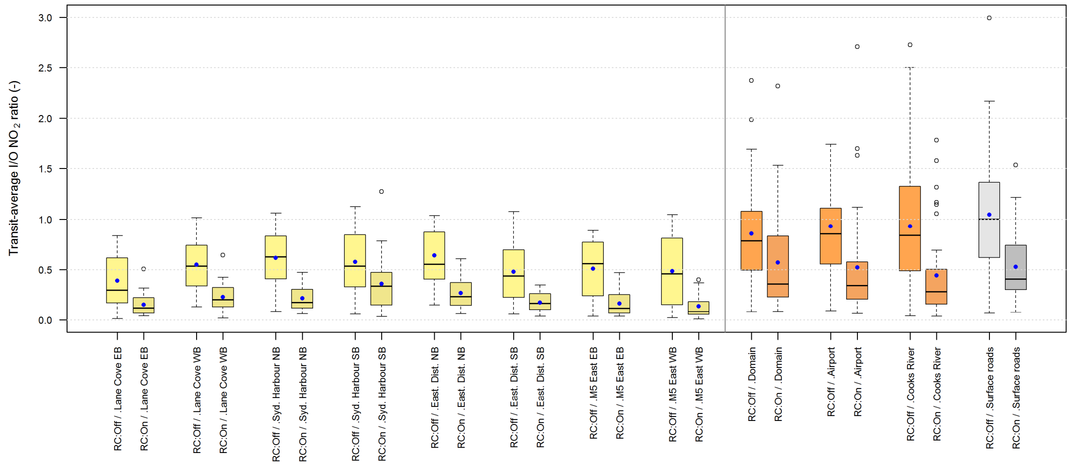


Figure 9: Transit-average I/O NO_2 ratios for major tunnels (yellow boxes), minor tunnels (orange boxes), and surface roads (grey boxes) with RC off and RC on (including data from all test vehicles). Blue dots represent the mean, upper and lower whiskers represent the 1st and 3rd quartiles, and white circles represent outliers (>1.5 times the interquartile range).

Minor tunnels and surface roads

Figure 8 shows that, for the minor tunnels and surface roads, during individual transits the transit-average in-vehicle NO_2 concentration was generally <150 ppb with RC off, and generally <75 ppb with RC on. For an individual transit, an in-vehicle concentration above 200 ppb was only exceeded in the Cooks River tunnel. Overall mean concentrations with RC off means ranged from 65 ± 6 ppb in the Domain tunnel to 100 ± 7 ppb in the Cooks River tunnel. With RC on the overall means ranged from 34 ± 4 ppb in the Domain tunnel to 55 ± 8 ppb in the Cooks River tunnel. In all three minor tunnels and for surface roads the mean concentrations were significantly lower with RC switched on than with RC switched off (unpaired sample t-test, $p<0.002$).

For individual transits the I/O ratio varied even more than in the major tunnels (Figure 9), ranging from 0.04 to 3.98 with RC off, and from 0.04 to 2.71 with RC on. The higher maximum 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 transits.

Overall mean transit-average I/O ratios ranged from 0.86 to 1.04 with RC off, and from 0.44 to 0.57 with RC on. In the Airport and Cooks River tunnels, and on surface roads, the overall mean I/O ratios were significantly lower with RC switched on than with RC switched off (unpaired sample t-test, $p<0.002$). In the Domain tunnel the difference was not significant ($p = 0.051$).

3.4.3 Effects of other vehicle ventilation settings

The effects of vehicle ventilation settings (air conditioning on/off, and fan speed) on the I/O ratio for NO_2 are shown in Figure 10; note that this includes data from all test vehicles. For a given fan speed and RC setting, switching air conditioning systems on had little effect on the I/O ratio for NO_2 as the median I/O ratios were similar with air conditioning on and off (0.16 and 0.17, respectively). Increasing the fan speed from 0% to 50% with RC off shifted the I/O ratio distribution towards significantly higher values (median increasing from 0.21 to 0.64). Furthermore, increasing the fan speed to 100% further increased the I/O ratio (median of 0.83). This is attributed to the increased intake rate of outside-vehicle air with a high NO_2 concentration.

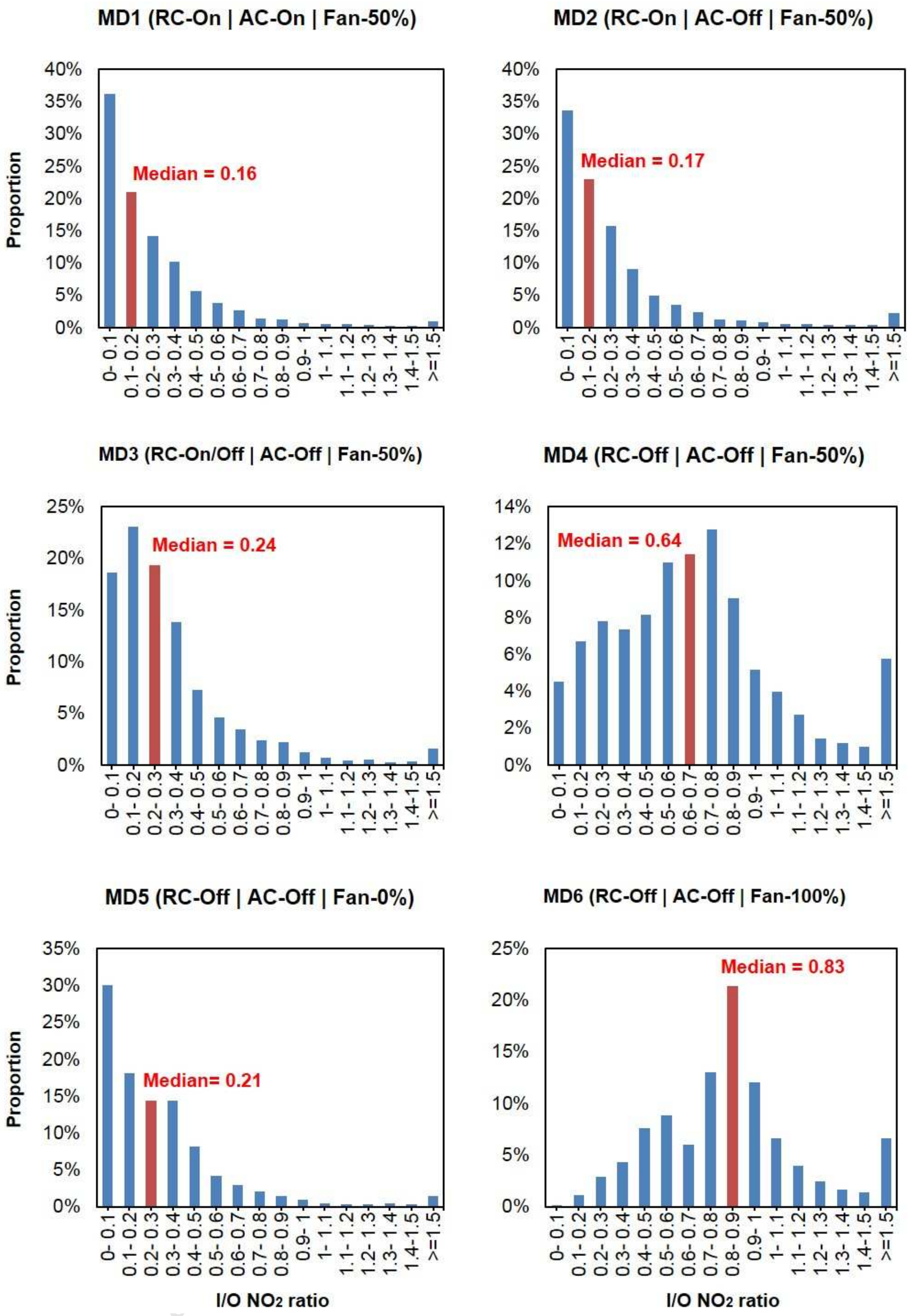


Figure 10: Distributions of I/O ratios for NO_2 using different vehicle ventilation settings (including data from all test vehicles).

3.4.4 Effect of switching recirculation on and off at a tunnel

With RC 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. A test therefore involved switching RC on at a tunnel entrance and switching RC off upon exiting the tunnel (ventilation setting M3, Table 2). With RC on (ventilation setting: M2), in-vehicle NO_2 concentrations typically remained lower than outside-vehicle concentrations after exiting a tunnel, e.g. Figure 7B. In some cases, switching RC off after exiting a tunnel had little effect as in-vehicle NO_2 concentrations also remained lower than outside-vehicle concentrations, e.g. following exit of the Sydney Harbour tunnel (Figure 11). However, in cases when outside-vehicle concentrations were elevated, switching RC off following exit of a tunnel increased in-vehicle NO_2 concentrations and the I/O ratio, e.g. exit of the Lane Cove, Eastern Distributor, and M5 East tunnels (Figure 11). This suggests that there is no benefit to switching from RC on to RC off following exit of a tunnel. However, it may be beneficial to flush the cabin by opening the windows shortly after leaving a tunnel (Section 3.4.5).

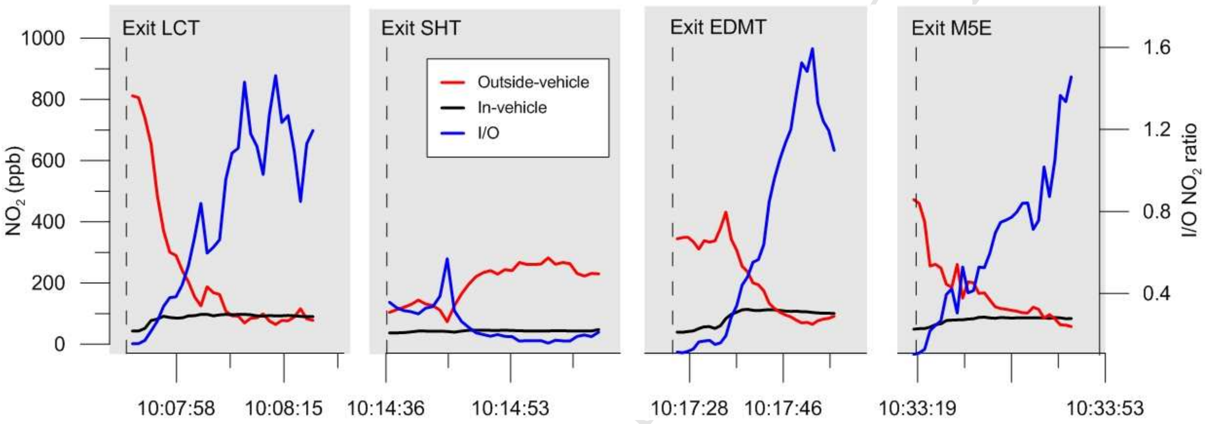


Figure 11: In-vehicle/outside-vehicle NO_2 concentrations and I/O ratios following tunnel exits in the 2007 Toyota Corolla using ventilation setting M3 (26/08/15 10:07am-10:33am) where LCT: Lane Cove tunnel, SHT: Sydney Harbour tunnel, EDMT: Eastern Distributor Motorway tunnel, and M5E: M5 East tunnel.

3.4.5 Effects of opening windows following tunnel exit

Limited tests were carried out to examine the effects of opening the vehicle's front driver windows at the end of the study route (exit of WB M5 East tunnel). With RC on and windows remaining closed following exit of the tunnels, in-vehicle NO_2 concentrations remained low and the I/O ratio was typically less than unity, as shown in the example profile of in-vehicle NO_2 concentrations using the Hyundai i30 (V7) where (Figure 7B). Opening the front window following tunnel exit with RC on typically increased in-vehicle NO_2 concentrations and the I/O ratio (Figure 12). This is attributed to elevated outside-vehicle NO_2 concentrations at tunnel exits. Therefore, opening the front windows immediately following tunnel exits is not recommended.

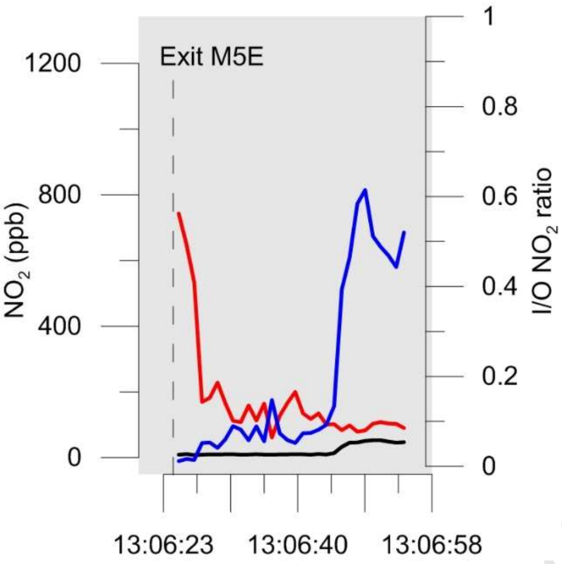


Figure 12 Effects of opening front driver window following exit of the westbound M5 East tunnel using V7: Hyundai i30

3.4.6 Effects of vehicle characteristics

Transit-average I/O NO_2 ratios for each test vehicle with RC off and RC on are presented in Figure 13. This plot only contains data for the major tunnels. For context, the transit-average in-vehicle NO_2 concentrations for each test vehicle with RC off and RC on are given in Table 5.

With RC off, the transit-average I/O ratios ranged from 0.01 to 1.12. The ratio on most transits of the major tunnels was considerably less than unity, suggesting that all the vehicles in the sample were sufficiently well sealed to ensure that in-vehicle concentrations remain well below those in the outside tunnel air for the typical duration of the transit through a tunnel. The overall mean I/O ratio for each test vehicle with RC off ranged from 0.30 ± 0.02 (V2: Audi A3) to 0.80 ± 0.02 for the (V4: Fiat Punto), and the mean transit-average in-vehicle NO_2 concentrations ranged from 57 to 106 ppb. Yamada et al. (2016) and Chan and Chung (2003) measured a similar mean I/O ratio for NO_2 with RC off (I/O ≈ 0.6) for tunnels in Japan and Hong Kong using a modern Toyota bD (vehicle age pre-2015) and a Ford Econovan (vehicle age pre-2002).

With RC on the transit-average I/O ratios ranged from 0.01 to 1.27, but the value of 1.27 was an outlier. In addition, around 95% of the I/O ratios with RC on were less than 0.50. The overall mean I/O ratios for a vehicle ranged from 0.08 ± 0.01 for the Hyundai i30 (V7) to 0.36 ± 0.07 for the Ford Fiesta (V1), which represents a decrease of >34% for all test vehicles (excluding the Audi A3, V2) A similar decrease in the mean I/O NO_2 ratio (~66%) was measured by both Yamada et al. (2016) and Chan and Chung (2003). This suggests that all vehicles - regardless of manufacturer, model or age - can potentially maintain much lower in-vehicle NO_2 concentrations than outside-vehicle NO_2 concentrations in tunnels with RC on.

The best performing vehicles - with overall mean I/O ratios less than 0.20 with RC on - were the Hyundai i30 (0.08), Toyota Corolla (0.11), BMW X3 (0.14) and Fiat Punto (0.20). The two oldest vehicles in the study – the Audi A3 (V2) and the Ford Fiesta (V1) – had the highest mean I/O ratios with RC on (0.35 and 0.36 respectively). The difference between the I/O ratio with RC off and RC on was significant for all vehicles

($p<0.004$) except the Audi A3 ($p = 0.15$). Moreover, the Audi A3 was the only vehicle having a higher I/O ratio with RC on than with RC off. This suggests that the RC mode of the Audi A3 was either poorly designed or not functioning correctly. Higher I/O ratios for older vehicles is attributed to their higher AERs, as predicted by the model from Hudda et al. (2012).

The application of a SNK test showed that, with RC off, there was no significant difference between the overall mean I/O ratios for old and intermediate vehicles, but for new vehicles the I/O ratio was significantly lower. However, the same test showed that, with RC on, there was no significant difference between the I/O ratios for new and intermediate vehicles, but the ratio for older vehicles was significantly higher.

Table 5 Transit-average in-vehicle NO_2 and I/O ratio by vehicle with RC off and RC on (including data from major tunnels only)

Code	Make and model	RC off		RC on		I/O variation by switching RC on (%)
		Average in-vehicle NO_2 (ppb)	Average I/O NO_2	Average in-vehicle NO_2 (ppb)	Average I/O NO_2	
V1	Ford Fiesta	120	0.66	52	0.36	-45%
V2	Audi A3	57	0.30	72	0.35	16%
V3	Subaru Outback	156	0.74	44	0.22	-70%
V4	Fiat Punto	143	0.80	31	0.20	-75%
V5	Toyota Corolla	118	0.55	19	0.11	-80%
V6	Holden Astra	113	0.66	20	0.23	-65%
V7	Hyundai i30	119	0.55	13	0.08	-86%
V8	Holden Cruze	75	0.36	56	0.24	-34%
V9	BMW X3	63	0.33	23	0.14	-56%

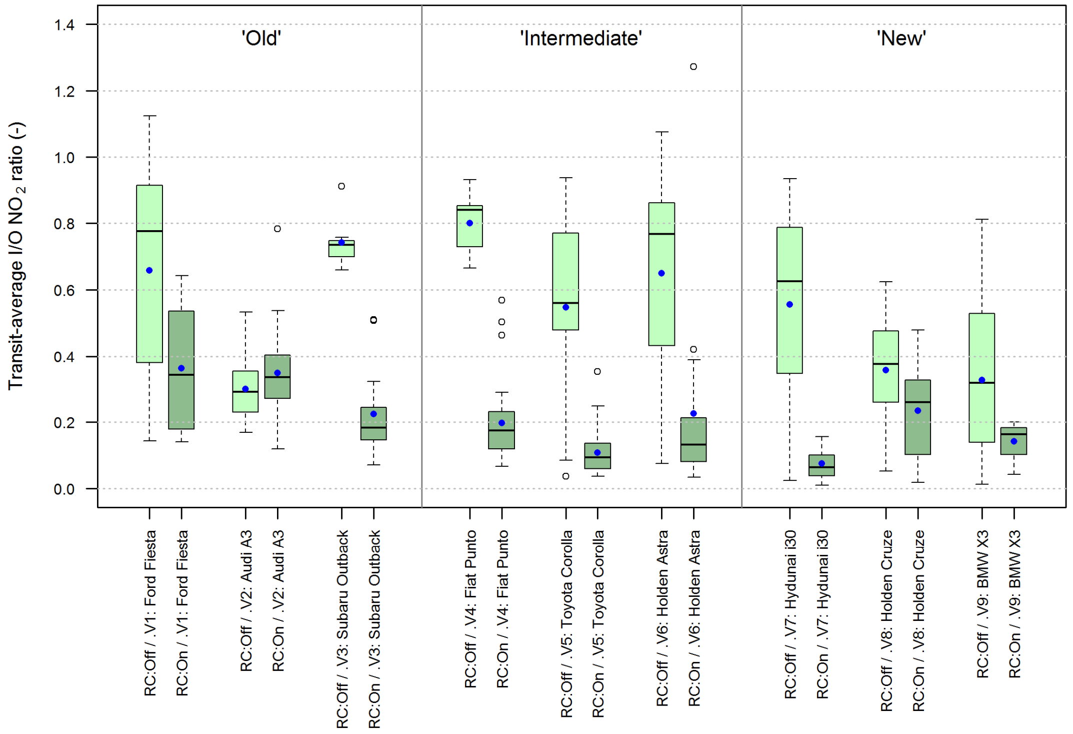


Figure 13: Transit-average I/O ratio by vehicle with RC off and RC on (including data from major tunnels only)

4 Conclusions

This study has provided high-resolution in-vehicle and outside-vehicle measurements of NO_2 in several urban road tunnels in Sydney, Australia for nine cars. The results from the study can be used to inform the design and operation of future road tunnels. The M5 East tunnel is presented as the worst-case condition in terms of NO_2 outside-vehicle concentrations. While this is a function of the traffic volumes and fleet composition (high proportion of heavy vehicles), it is also as a result of tunnel geometry and ventilation design.

Despite elevated outside-vehicle NO_2 concentrations in tunnels, transit-average in-vehicle NO_2 concentrations in tunnels were lower than outside-vehicle concentrations, even with RC switched off. The I/O ratios for most transits through major tunnels were considerably less than unity. This suggests that most typical passenger vehicles are sufficiently well sealed to ensure that in-vehicle concentrations remain well below those in the outside air for the typical duration of a transit through a tunnel.

The I/O ratios for individual vehicles ranged from 0.08 – 0.36 and were significantly lower with RC on compared with RC off for all vehicles ($p<0.004$), except for the 2002 Audi A3. With RC on, the transit-average in-vehicle NO_2 concentrations were well below 100 ppb for most transits. This suggests that vehicle occupants can substantially lower their exposure to NO_2 in tunnels by switching RC on with the resulting in-vehicle NO_2 concentrations being substantially <200 ppb, the level below which no health effects have been previously identified.

The highest mean I/O ratios with RC on were measured for the two oldest vehicles in the study: the 2002 Audi A3 and the 2002 Ford Fiesta (0.35 and 0.36 respectively). Similar in-vehicle NO_2 concentration were measured for the 2002 Audi A3 with RC on and RC off, suggesting that as this was an older vehicle, the vehicle's RC function was either poorly designed or not operating correctly. The lowest I/O ratios were recorded for modern vehicles produced in higher quality manufacturing regions. These findings are consistent with the predictions of an AER model from Hudda et al. (2012).

Overall, it is considered advisable to encourage vehicle operators to use RC mode in road tunnels. Further information is required on the effects of flushing the vehicle cabin by opening the vehicle windows following a tunnel transit, but the measurements suggest that this should be beneficial for occupants when RC has been switched on in the tunnel. This recommendation is considered universally applicable for road tunnel usage to mitigate the effects of NO_2 exposure.

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Highlights

- High-resolution measurements of nitrogen dioxide concentrations in urban road tunnels
- Quantified in-vehicle nitrogen dioxide concentrations for typical passenger vehicles
- Compared vehicles in terms of the inside-to-outside-vehicle nitrogen dioxide ratios